Chapter 19

GIS Based Urban Drainage Modelling

Uzair M. Shamsi and Bruce A. Fletcher

Chester Environmental
P.O. Box 15851, Pittsburgh,
Pennsylvania, 15244

This chapter presents a Geographic Information System (GIS) based urban drainage hydraulic model. The model was used to solve the flooding and pollution problems associated with inadequate urban drainage for a drainage area in Huntington, West Virginia. The GIS analysis was conducted in PC ARC/INFO, a GIS software from Environmental Systems Research Institute (ESRI). Hydraulic modelling was done using the Storm Water Management Model (SWMM), a comprehensive rainfall-runoff simulation model from the U.S. Environmental Protection Agency (EPA). The benefits of using a graphical interface to facilitate the modelling are illustrated.

19.1 Introduction

The City of Huntington, West Virginia, has a combined sewer system with 23 Combined Sewer Overflow (CSO) discharge points permitted under the National Pollution Discharge Elimination System (NPDES) program. Figure 19.1 shows the CSO discharge points, referred to as *CSOs*, and their tributary drainage areas, referred to as *CSO areas*. The combined sewage from each CSO area first enters a regulator or diversion chamber where the combined sewage is separated into dry weather (sanitary) and wet weather (stormwater) components. Dry weather flow is diverted to an interceptor and wet weather flow is discharged

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Figure 19.1
CSO Areas

to receiving waters via outfall pipes. Fifteen CSOs discharge into the Ohio River, while the remaining eight discharge into the tributaries of the Ohio River. The main interceptor running along the Ohio River collects the sanitary flow from the 23 CSO areas before entering a 46 MGD sewage treatment plant. The treatment plant also discharges its treated effluent to the Ohio River.

At the present time, the City of Huntington and its sewer system operating authority, the Huntington Sanitary Board, are confronted with two separate but closely related issues. The first issue is the need to comply with recent NPDES requirements for monitoring CSOs. The primary impetus behind this concern is West Virginia's 1991 CSO strategy mandated by U.S. EPA's 1989 national CSO strategy. The national CSO strategy recognizes the impacts CSOs have on receiving water quality, and it provides a means by which to control and eventually eliminate or reduce CSOs in order to improve receiving water quality. The second issue is a desire to alleviate street flooding in the City through the construction of separate storm sewers or combined relief sewers which will divert water from overloaded combined sewers. The primary concern of the second issue is essentially hydraulic in nature. Nevertheless, the two issues are closely related because a very effective means of reducing CSO discharges is through improved hydraulics, such as maximizing the capacity of combined sewers for in-line storage without causing backup or surcharging problems and enabling the maximum amount of flow to be conveyed to the treatment plant without upsetting normal plant operations.

As a first alternative to comply with the CSO strategy, monitoring of all of the 23 CSO locations was studied. This option required purchase, installation, monitoring, and maintenance of flow monitors, water quality samplers, and raingages. This option was ruled out because of its excessive cost, estimated at over a million dollars. The second option consisted of a combination of monitoring and modelling in which only a few representative CSOs would be monitored and the monitoring data would be used to develop calibrated hydraulic models for the monitored areas. Calibrated model parameters would be used to develop the hydraulic models for the remaining unmonitored CSOs. Hydraulic models would be eventually used to predict quantity and quality of CSO discharges from observed rainfall input to meet the reporting requirements of the CSO strategy. This option, costing approximately one-third of the first option was favored both by EPA and the Sanitary Board and was selected for implementation.

19.2 The Pilot Project Case Study

The case study presented in this chapter is for a pilot area consisting of the drainage area tributary to CSO No. 16 (Fifth Avenue CSO). This 780 acre CSO area has a population of about 5,000 and discharges to the Guyandotte River, a tributary of the Ohio River. Some low elevation areas in the CSO area

experience manhole overflows and street flooding problems during severe storm events. In addition to traffic nuisance and inconvenience, the flooded streets impose a potential public health threat depending on the quality of the overflowed combined sewage, and the flooding problem becomes a pollution problem.

The analysis of the flooding problems was performed by developing a hydraulic model of the combined sewer system using Version 4.2 of the U.S. EPA's computer program SWMM. The input data describing subarea physical characteristics to model the wet weather flow and subarea demographic characteristics to model the dry weather flow were extracted from a GIS of the project area.

19.3 Hydraulic Model: SWMM

SWMM (Huber and Dickinson, 1991) was developed in the early 1970s and has been continually maintained and updated. It is perhaps the best known and most widely used of the available urban runoff quantity/quality models. SWMM estimates residential dry weather flows from the drainage area demographic and land use classes. Required demographic characteristics are dwelling units, persons per dwelling units, and market value of average dwelling unit. Required land use classes are single-family residential, multi-family residential, commercial, industrial, and open space. Commercial and industrial dry weather flows are not computed by SWMM and their estimates must be provided by the user.

Wet weather flows are estimated from watershed's physical, hydraulic, and hydrologic characteristics. The physical characteristics include area, percent imperviousness, overland flow slope, and overland flow width. Hydraulic characteristics include Green-Ampt or Horton soil infiltration parameters, surface and stream channel roughness coefficients, surface depression storage, and stream channel geometry. For single-event simulations, the required hydrologic input consists of rainfall hyetographs.

By combining dry and wet weather flows, SWMM can be used to predict combined sewage flows. SWMM also provides the ability to conduct detailed analyses of conveyance system performance under a wide range of flow conditions. As such, it is well suited to this study and is the model of choice for use in most combined sewer overflow feasibility studies. The use of SWMM to model Huntington's CSO areas and study their surface drainage problems was considered particularly appropriate for the following reasons:

- 1) SWMM represents the best means of producing estimates of dry and wet weather flow rates from a service area as large and diverse as Huntington. Flows can be estimated from land use conditions,

topography, interceptor sewer characteristics, and selected meteorological conditions.

- 2) SWMM represents the best means of modelling the performance of the interceptor conveyance system under a range of dynamic flow conditions.
- 3) Using SWMM, it would be possible to assess capacity in response to wet weather input. This characteristic can be very useful for subsequent analyses related to abatement of CSOs mandated by the national and state CSO strategies.
- 4) SWMM is capable of modelling water quality and assessing the effectiveness of a range of CSO abatement or treatment options, the most important aspects of the national and state CSO strategy.

19.3.1 Modelling Strategy

SWMM is flexible enough to allow different modelling approaches to the same area. An approach which adequately describes the service area and accurately computes and routes the flows at reasonable computing time and effort should be adopted. After a review of the data, maps, and literature available to complete this study the following modelling strategy, proven to be quite successful in a similar project (Shamsi, 1993), was adopted:

- 1) Divide CSO areas into smaller drainage areas called *subareas* and identify the points where subarea flow enters the sewer system called *inlets*.
- 2) Run SWMM's RUNOFF Block to generate subarea wet weather flow.
- 3) Run SWMM's TRANSPORT Block to generate subarea dry weather flows.
- 4) Import wet weather flows from the RUNOFF Block into the TRANSPORT Block and combine them with the dry weather flows. Enter the combined flows in the sewer system through corresponding inlets.
- 5) Use SWMM's EXTRAN Block to route the combined sewage through the sewer system.
- 6) Use the EXTRAN Block to regulate the dry weather flow entering the interceptor and wet weather flow or CSO discharging to the receiving waters.
- 7) Study sewer system response (capacity, surcharging, manhole overflows, street flooding) from the EXTRAN output using a graphical interface.

19.3.2 Drainage Network Diagram

It is usually recommended that a sewer system schematic diagram be prepared prior to model building to facilitate simplification, orientation and connectivity of the drainage network elements such as subareas, sewers, manholes, pumps, diversion chambers, outfalls, etc. A schematic diagram is developed by discretization, a procedure for the mathematical abstraction of the physical drainage system into a flowchart which approximates the actual system. However, due to advances in computer graphics, schematic diagrams are no longer necessary. Now that the drainage elements can be modelled exactly as they appear in reality, the WYSIWYG (what you see is what you get) property of hydraulic modelling can replace the schematic diagrams with the *drainage network diagrams*. Figure 19.2 shows the drainage network diagram for the project area.

19.3.3 Graphical Interface

Most engineers have now become accustomed to modern computer graphics features such as pull-down menus, spreadsheet data input and editing, color plots, on-line help, etc., which are not currently available in SWMM. SWMM does not display the drainage network, making detection and correction of connectivity related errors very difficult. SWMM's ASCII format output is long, boring, and difficult to interpret. A graphical interface called Model Turbo View (MTV) was, therefore, employed to overcome these deficiencies (10 Brooks Software, 1992). The graphical interface animates the underground phenomena by dynamically displaying three dimensional plan views and profiles of the drainage system hydraulic gradient line (HGL). Such WYSIWYG features make the modelling process more interesting and interpretation of model results more convenient. Just as *a picture is worth a thousand words* in the business of fashion modelling, *a graph is worth a thousand numbers* in the business of hydraulic modelling. Some benefits of employing a graphical interface are:

- 1) Preparation of network schematics is not essential. Digitized plots of sewers and subarea boundaries can be used to create a drainage network diagram on a computer screen.
- 2) Flow and HGL data from the SWMM output can be displayed in either plan or profile view, providing an animated display of the HGL during the simulation time steps.
- 3) Zoom and pan features display even large networks conveniently on the screen.
- 4) Flow and HGL time-series plots can be displayed for any conduit or node in the hydraulic network.

Figure 19.2
 Drainage network diagram

- 5) Field collected flow and depth data can be displayed along with the model output for model calibration and verification.
- 6) Connectivity data errors are easily detected and can be edited while still in the program. Instabilities in the model output, often the most difficult errors to find, are also easily located.
- 7) Network graphics and model output in the plan and profile views can be generated using AutoCAD^(tm) DXF format to aid in report preparation.

The above features indicate that a graphical interface greatly simplifies the process of building and debugging the network models. However, a post-processor like MTV processes a SWMM output file only after a model run has been made. This limitation requires the user to jump back and forth between the application (SWMM), the post-processor (MTV), and plotter (AutoCAD) which is not very efficient. Furthermore, the compatibility of a post-processor is limited to a specific version of the application software. The post-processor must be updated with every update of the application program that modifies the output format even slightly. It is recommended that future research and development should integrate all the three steps of modelling, graphics, and plotting in one consolidated package. Furthermore, all the SWMM modules (RUNOFF, TRANSPORT, EXTRAN, STORAGE TREATMENT, RAIN, TEMP, and STATS) should be integrated with a common interface that manages all the data for various modules from a central graphical database.

19.4 CSO Area Geographic Information System (CAGIS)

This project developed and analyzed a GIS for the CSO areas called *CAGIS* in order to provide input to the watershed SWMM. An analysis of the land use, demographics, terrain, hydrography, and locations of major trunk and interceptor sewers was conducted to develop CAGIS. CAGIS consisted of data layers of 24 digitized subarea boundaries, land use, census blocks, USGS Digital Elevation Models (DEMs), and transportation network.

19.4.1 Land Use

Land use maps were prepared from a manual interpretation of NHAP (National High Altitude Photography) aerial photographs of the study area. Initially, seven major land use types were classified: low-density residential, medium-density residential, high-density residential, commercial, industrial, open space, and water. Each land use class was assigned a percent impervious value. These values were based on the Soil Conservation Service (SCS)

estimates for similar land use types. Subsequently, the initial land use classes were reclassified in the five land use types required for SWMM input: single family residential, multi-family residential, commercial, industrial, and open space.

19.4.2 TIGER Files

Census block and transportation network maps were prepared from the U.S. Census Bureau's Topologically Integrated Geographic Encoding and Referencing (TIGER) files. TIGER is the new digital map database that automates the mapping and related geographic activities required to support the census and survey programs of the Census Bureau. The TIGER file contains digital data for the 1990 census map features (such as roads, railroads, and rivers) and the associated collection geography (such as census tracts and blocks), political areas (such as cities and townships), feature names and classification codes, and, within metropolitan areas, address ranges and ZIP Codes for streets. The demographic parameters were extracted at the block level from public law demographic database. Block level data were area weighted to estimate mean subarea values for demographic parameters.

19.4.3 Digital Elevation Models

USGS (United States Geological Survey) DEMs are digital records of terrain elevations for ground positions at regularly spaced intervals. In digital form, terrain elevations are valuable for regional terrain modelling, land use studies, and other engineering applications such as drainage area hydraulic modelling. The 7.5 minute DEMs used in this project are produced from contour maps that have been digitized from high altitude photographs taken at an average scale of 1:78,000. The data are processed to produce a DEM with a 30-meter sampling interval. Each DEM corresponds to a complete 7.5 minute USGS topographic quadrangle map, covering approximately 60 square miles. DEMs were used to compute the subarea slopes. Slope was calculated using ERDAS function SLOPE which calculates the slope of each pixel based on its nearest neighboring pixels. Pixel slopes were averaged for each subarea to estimate the subarea slope.

19.4.4 GIS Software

The software used in this project was primarily PC ARC/INFO^(tm), a vector based GIS from ESRI (Environmental Systems Research Institute, 1992), and ERDAS^(tm), an image processing and raster based GIS. Additional programs were written whenever needed for data format changes or the creation of a product for which the methodology was not available in either of the commercial

packages. This included the determination of percent slope averages, the creation of the percent impervious images, and the construction of tabular output.

19.4.5 GIS Analysis

The vector data format is a topologically constructed set of points, nodes, lines, and polygons which define locations, boundaries, and areas. A raster format is a regular grid of uniform size cells, with a data value associated with each cell. The reason for using both kinds of data processing and handling formats is to take advantage of the best features of each. Data entry of vector information is more easily performed using a file digitized into the vector format. All GIS layers except the elevation data were initially digitized in vector format from their respective base maps utilizing ARC/INFO. The resulting polygon topology was then converted to raster format for GIS analysis.

The final GIS analyses were performed on raster information layers with the following themes: subareas, land use, census blocks, percent slope, and percent imperviousness. The area of each subarea was the basic theme against which the various other themes were summarized. The results are summarized in Tables 19.1 and 19.2.

19.5 Results and Discussion

The objective of the pilot project was to find solutions to street flooding problems in the drainage area tributary to CSO No. 16, especially on Fifth Avenue. The West Virginia Department of Transportation suggests a ten year return frequency storm for designing storm sewers. Thus, a ten year storm was chosen to test the drainage system performance. Since short duration and high intensity storms cause more severe drainage problems, a one hour duration hyetograph distributed according to SCS Type II rainfall distribution was used as the design hyetograph. The total rainfall depth for this storm is 2.1 inches.

The model consisted of 24 subareas, 45 sewers, 45 manholes, one diversion chamber, and one outfall. SWMM was first run for the existing conditions. The results showed severe surcharging and numerous street flooding occurrences throughout the drainage area. Figure 19.3 shows a plan view of the drainage area HGL at peak flows. Figure 19.4 shows a profile view of the peak HGL of the Fifth Avenue sewers. Street flooding is indicated when HGL reaches the ground level. Figures 19.3 and 19.4 show the model results corresponding to only one simulation time step. The graphical interface sequentially shows the similar plots for all the simulation time steps which create an animated view of the HGL. Figures 19.3 and 19.4 show that the first five manholes are flooding at the peak flows. Manhole No. 110 shows the maximum overflow volume which can be attributed to its small depth due to its location in a low elevation area. It is apparent that the existing drainage system does not have the capacity to transport

the ten year flows. Most of the overflowing manholes in the model matched those actually observed to be flooding during severe wet weather conditions.

An improvement scenario was modelled next. Stormwater from the area south of Fifth Avenue was diverted to a relief sewer covering about 40% of Fifth Avenue on the east side. Larger sewers reduce manhole overflows by providing greater in-line storage. The size of the relief sewer was increased incrementally until manhole overflows no longer receded. This alternative did not reduce the Fifth Avenue manhole overflow volumes significantly, because, as Figures 19.3 and 19.4 indicate, the overflows occur on the west side of the Fifth Avenue sewer. This alternative was, therefore, ruled out as an effective solution.

Table 19.1
GIS based subarea physical parameters

Subarea ID	Area (acres)	Overland Flow Width (ft)	Percent Imperviousness	Slope (ft/ft)
10	18.9	3167	13.6	0.0101
20	18.5	3079	8.0	0.0220
30	10.0	1986	52.0	0.0093
40	23.9	4901	32.4	0.0095
50	42.8	1645	34.9	0.0347
60	33.0	1085	58.6	0.0040
70	33.6	7185	56.0	0.0060
80	71.0	2862	41.5	0.0228
90	19.4	715	57.3	0.0044
100	28.7	1384	56.9	0.0050
105	9.1	960	57.7	0.0282
110	7.0	960	57.7	0.0282
116	6.0	960	57.7	0.0282
117	2.7	480	57.7	0.0282
120	109.4	2883	20.8	0.1450
130	77.0	2649	72.3	0.0140
140	146.5	5242	14.4	0.0698
150	11.7	3257	43.4	0.1447
160	7.3	1394	62.6	0.0295
170	13.8	2259	46.2	0.1145
180	14.7	1941	16.7	0.0995
190	20.9	2675	22.1	0.0780
200	17.2	3860	17.8	0.0300
210	35.5	2965	12.0	0.0680

After modelling various potential improvement scenarios, similar to the one described above, it was found that parallel reinforcing sewers for the entire length of Fifth Avenue would be the most effective alternative to eliminate the Fifth Avenue street flooding. Figure 19.4 also shows the new HGL; i.e. the HGL after constructing parallel sewers. The peak HGL remains below the ground level for the entire length of the Fifth Avenue. The existing and new peak flows are also shown. Most of the new peak flows are smaller than their existing counterparts. The difference between the existing and new flows represents the amount of water being diverted to the parallel sewers. The results show that the

Table 19.2
GIS based subarea demographic parameters

Subarea ID	Dwelling Units	Persons Per Dwelling Unit	Market Value of Dwelling Unit (\$1000)
10	29	2.9	39.2
20	7	2.9	39.2
30	81	2.9	39.2
40	91	2.2	28.7
50	165	2.9	36.2
60	143	2.9	37.5
70	181	2.9	38.9
80	336	2.3	41.8
90	135	2.9	37.2
100	104	2.9	36.6
105	20	3.0	35.1
110	16	3.0	35.1
116	14	3.0	35.1
117	6	3.0	35.1
120	45	3.0	32.1
130	6	3.0	34.8
140	387	3.0	31.1
150	58	2.9	29.1
160	46	2.9	29.0
170	94	2.8	28.2
180	51	2.9	29.0
190	102	2.9	29.0
200	78	2.9	33.2
210	99	2.3	30.9

Figure 19.3
Planview of system HGL

Figure 19.4
HGL profile

recommended parallel sewers would completely eliminate the street flooding events on Fifth Avenue due to ten year or smaller storms. SWMM was run repeatedly with different combinations of reinforcing sewer sizes to optimize the recommended design. Design optimization consisted of determining the minimum sewer sizes capable of eliminating the street flooding. The optimized sewer sizes ranged from 3 feet near the drainage area boundary, to 6 and 8 feet in the middle, to 9 feet near the drainage area outlet.

19.6 Conclusions

A rainfall-runoff simulation model, that receives most of its input from a GIS, combined with a sewer system hydraulic model capable of displaying the results graphically, is an effective tool to study urban drainage problems, design the solutions, and optimize the designs for cost-effectiveness.

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