LINKING GIS AND STORM WATER MODELING FOR EMERGENCY RISK ASSESSMENT

Ross T. Newkirk
School of Urban and Regional Planning
Faculty of Environmental Studies
University of Waterloo
Waterloo, Ontario, Canada N2L 5B1

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ABSTRACT

Many emergencies involve the deposition of chemical contaminants on land either as a direct event or as a secondary byproduct. GIS can be useful in estimating the initial deposition area. Chemical product attribute data bases can be accessed to determine the degree that the contaminants might be transportable in a water medium. An important issue is to estimate the potential impact of the deposition on surface and subsurface water flows. This is particularly important since millions of people rely on subsurface ground water as their main source of potable water. Thus, a modeling system is needed by planners and emergency managers to assess the potential for short and long term risks to communities due to storm water transport of deposited contaminants. GIS itself cannot provide the complete analysis. A prototype system to assist in estimating the flows of contaminants related to an emergency has been developed by linking an Arc/Info database, Digital Terrain Model, and SWMM the storm water management modeling system. This system also has important planning applications in assessing alternative land development plans for their impact on ground water recharge and management of storm water.

INTRODUCTION:

Emergencies often involve the deposition of chemical contaminants on land as a direct or indirect consequence. The subsequent diffusion of these contaminants through space is often a serious issue as it pertains to placing human, plant and animal species at risk. Modeling of the contaminant diffusion on the land by water as well as air is required to determine areas in need of evacuation and remedial environmental protection. Often ground level contaminant diffusion is achieved by transport through surface water flows and requires analysis that includes storm water modeling and impact analysis in urbanized areas.

Another related class of emergencies relates to urban flooding. Even if there has not been a previous or associated chemical emergency, flood waters resulting from an intense rain storm are often substantially contaminated from "normal" urban contaminants deposited over time on the land, buildings and vegetation. It is claimed (Bryan, 1972) that urban storm water discharges are as contaminated as the effluent discharged from primary sewage treatment facilities in terms of biological oxygen demand (BOD) and its chemical oxygen demand (COD) can be greater than raw sanitary sewage.

Unfortunately the process of urbanization itself reduces an area's hydrological capacitance. This implies that extreme urban storm water and flood events increase in probability as urbanization takes place. This trend is further exacerbated by two other factors. The first is the natural degradation of urban physical storm water management systems due to age, silting, scaling, etc. The second is the increasing climatic variability due to human activity impacts on the biosphere (Jarman, 1993). This appears to be inducing more variability in droughts and intense rainfall events. This in turn may contribute to more frequent and more severe urban flooding.

Both of these classes of emergencies require consideration of the nature and behavior of storm water in the watershed or subwatershed in which the effected area is located. This analysis must also consider the effects of storm water management facilities that have been installed to alter the natural performance of the watershed. Unfortunately, many storm water management facilities that have been installed to reduce local flooding (eg., sewers) operate as very effective means to transport contaminants that can pollute streams, rivers, and water bodies. This can lead to a number of serious environmental problems including, for example, the destruction of sensitive habitats and downstream urban water supplies.

The contaminant transport problem is not simply a surface water flow analysis problem. Due to infiltration of surface water down to subsurface ground water, surface water contamination can begin to compromise the quality of ground water supplies. Since many urban areas draw substantially on ground water for potable water supply, it is important to be able to identify potential ground water impacts of chemical spills and contaminant transport.

APPROACHES TO ASSESSING RISK OF STORM WATER IMPACTS

For the purpose of this discussion, it is useful to consider two general approaches to assessing risk associated with storm water -- GIS and storm water modeling.

GIS and Flood Plain Studies

It is natural that planners and engineers have turned to Geographic Information Systems (GIS) to help assess, manage, and reduce storm water impacts in urban areas. Perhaps one of the most common applications is in mapping flood prone hazard lands. For example, in Ontario, the Conservation Authorities may designate an official flood plane upon which no permanent structures can be built. GIS applications can use Digital Terrain Model (DTM) data referenced to a statistical estimate of an arbitrary flood event to determine, say, a 25 year flood stage and the lands that would be flooded. This approach is based on a separate statistical estimate of the elevation of the surface of a pool of water above the standard flow elevation of streams and rivers associate with a specific severity rainfall of snow melt. The GIS is used to apply the estimated flood elevation against a map of area elevations to find the likely boundaries of the pool's flood area. These statistically based boundaries establish the area flood plane.

Flood plane statistical analysis is based on extrapolating confidence limits of means and deviations of flood histories for nearby flood gauges with adjustments for "nature of land use". Usually, there is not direct computational consideration of future changes due to the process of urbanization nor a detailed analysis of the impact of present and future storm water management facilities. Essentially, the GIS flood plane approach provides a one time analysis of areas possibly susceptible to flooding, but it does not involve itself with analysis of surface or subsurface water flows. While such mapping exercises are very important to designate areas where humans should not be allowed to live or to operate commercial and industrial activities, they are of little value in assessing the potential impact of a spill emergency that requires estimates of the flow of surface and ground water or the flow of flood waters, movement of flood crests, transport of contaminants, etc. If ground water aquifer recharge areas have been identified and previously mapped, a GIS could be useful in identifying and displaying areas of concern in the event of a chemical spill and flooding. However, GIS do not constitute a complete spatial decision support system (Carver, 1991), and current GIS do not have the water flow and analysis tools to provide much beyond the usual map overlay and buffering functions. Newkirk (1993) discusses the requirements for an emergency planning or management GIS. Such a system needs, as well, the capability to calculate storm water flows. Unfortunately, current GIS requires external analysis using a special storm water modeling system or framework.

Storm Water Modeling

A number of major initiatives have taken place over the past two decades to provide computational storm water modeling tools. Their detailed examination is beyond the scope of this paper -- although some of their attributes are useful to consider. In general, most are numerical modeling systems driven by spatial and area parameters and they have no or minor GIS capabilities of their own.

They require a study area (i.e., a watershed or subwatershed) to be decomposed into a series of mutually exclusive and distinct analysis subunits. Storm water modeling is applied to each analysis unit with flow amounts being transferred from subunit to subunit as appropriate. Most modeling systems deal with flow quantity estimates for single event scenarios -- however some allow for water quality and continuous event studies. As a storm water model is being structured, it can benefit from GIS analysis to help define the appropriate subunits for analysis. In addition, GIS can provide important location and performance information about any storm water management facilities that could impact on modeling results.

Like many other computational models, storm water models are very dependent on the correct parameters. Once the parameters have been set, the user provides one or several hydrographs that describe the expected precipitation over time. The modeling system calculates hydrographs (in graph and tabular format) that describe the resulting performance at specified points. Most modeling systems have been influenced by one or both of the following methods: SCS and SWMM.

The Soil Conservation Society (SCS) Method.

The United States Department of Agriculture, Soil Conservation Service, has developed a storm water quantity model (usually called the SCS model) that draws upon extensive SCS soils data (USDA/SCS, 1975). It is a popular system or basis for customized systems due to its relative simplicity. McCuen provides a helpful description of its nature and application (McCuen, 1982).

It requires a decomposition of an area under study into suitable subareas to which the model is applied. The modeling framework is designed to be sensitive to an association between:

- soil characteristics, land form and practices, and
- land cover and land use

in each subarea. A table of associations between these two aspects provide a "curve number" (designated CN -- see McCuen, 1982, for tabular examples) that becomes part of the computation. Tabular entries relate, in part, to the well developed and widely accessible Soil Conservation Service soils maps. If the subareas are relatively homogenous, the determination of the appropriate curve number could be obtained from a GIS by an appropriate table driven classification. In cases where there are differences in the associations within a subarea, the method allows for a lumped estimate of CN that is derived by means of weighted averages of the corresponding area covered. The key surface water flow equations in the basic model are (McCuen, 1982):

$$I_E = \frac{(P - I_a)^2}{P - I_a + S}$$

and

$$S = \frac{1000 - 10CN}{CN}$$

When:

Symbol	Meaning
I_E	Accumulated direct runoff (rainfall excess)
P	Accumulated precipitation
I_a	Initial surface storage
S	Maximum potential retention
CN	Curve number (from table)

A brief inspection shows that the information required to operate the key equations is relatively straight forward. Accordingly it has proved a relatively easy framework to implement in computer programs. Many other equations are included in the SCS modeling system. They include equations for modeling channelized flow of the resulting runoff water and estimates of ground infiltration. The SCS method has shown good accuracy in small urban water sheds (Berry and Sailor, 1987), and has been effective at "representing the infiltration characteristics of a watershed" (Sheaffer, *et al.*, 1982, pg. 121). However, it seems to be sensitive to the number of subunits used in a study. Too large a number of subunits appears to lead to an overestimate of flows (Berry and Sailor, 1987). The method is not adequately developed for calculating water quality (i.e., the transport of chemical contaminants) or the influence of storm water management facilities.

The Storm Water Management Model (SWMM)

The Storm Water Management Model is a very large integrated model jointly developed in the early 1970's by several contractors with support from the US Environmental Protection Agency. It consists of four major computation subsystems (Runoff, Transport, Extended Transport, Storage & Treatment) plus a number of computation "service" components. Its main users are specialists (i.e., consulting engineers and researchers). Since its inception, it has experienced continual development and update. Various software implementations are in current use.

SWMM provides a means to model both quantity and quality (up to 10 contaminants) of storm water. Special processing is available for snow accumulation, snow pack, and snow melt. It can process the effects of various storm water management facilities. This includes the ability to include a network of sewers of several kinds and sizes. In addition, it provides for upper and lower ground water (i.e., subsurface zones) and infiltration calculations.

Similar to other models, it requires the user to desegregate a watershed or subwatershed into a set of mutually exclusive and distinct subunits for analysis. The calculation of storm water surface flow is based on a non linear reservoir excess flow according to the following equations (Irvine *et al.*, 1994):

$$\frac{dV}{dt} = A \cdot I_E - Q$$

and

$$Q = W\left(\frac{1.49}{n}\right) \cdot \left(D - D_p\right)^{1.67} \cdot S^{0.5}$$

when:

Symbol	Meaning
V	Volume of water on the surface
I_E	Excess rainfall rate
A	Area of the subunit (subcatchment)
Q	The outflow rate (after Manning)
W	Width of subunit (subcatchment)
D	Water depth in reservoir
D_p	Depth of surface reservoir storage
S	Slope of subunit (subcatchment)

There are many additional equations related to infiltration, contaminant transport and decay. Due to its many capabilities, SWMM requires the user to define a very large set of performance parameters to condition a model run. Table 1 lists this author's summary of the basic number of parameters required by the runoff calculation system. Note that some of these can require multiple specifications.

Table 1: SWMM Basic Model Parameters

Group	Parameters	Repeat Max	Purpose
1	8	1	System parameters
2	3	1	Output control
3	5	1	Time control
4	2	1	Continuous simultion -- subcatchments
5	10	1	Snow input
6	5	1	Wind speeds
7	5	1	Snow depletion on impervious
8	5	1	Snow depletion on pervious
9	var	1	Air temps
10	var	1	Precipitation control hyetograph input
11	var	1	Evaporation rates
12	10	100	Chanel and pipe data
13	4	var	Flow control structures
14	17	200	Subcatchment definitions
15	7	100	Ground water subcatchment definitions
16	14	1	Ground water flow parameters
17	11	200	Snow input by subcatchment
18	16	200	Snow input by cubcatch. (continuous sim.)
19	11	1	Environment context control
20	8	var	Land use descriptions
21	21	10	Contaminant constituents
22	7	1	Erosion control section
23	10	200	Subcatchment surface quality
24	5	1	Print control

SWMM's ability to deal directly with storm water quality as well as quantity, and its ability to model the effects of storm water control infrastructure make it potentially important to emergency planning and management applications. However the very large number of area dependent parameters limits its usefulness unless the user is a SWMM modeling expert. An automated means to help set model parameters is required.

Difficulties In Emergency Planning and Management Use of Storm Water Models

Problems in using current storm water modeling systems for emergency planning and management as well as for "what if" regional and urban planning studies include: establishing the proper model parameters, providing appropriate and up to date data, determining proper study area disaggregation, requirement for trained operators, possible requirement for custom computer programming, and cumbersome linkage to GIS and emergency information systems. It is important to link GIS and storm water modeling in an integrated computing framework.

LINKING GIS AND STORM WATER MODELING

An integrated system to link GIS and storm water modeling is under development as part of a large multidisciplinary project addressing issues of sustainability in an urbanizing watershed. Its main purpose is to provide a general purpose modeling environment that can assist with questions related to urban and regional development and emergency planning and management. The main objective is to use computing capability to allow planners and emergency managers to conduct detailed "what if" studies based on high quality background analysis and well developed municipal and regional data bases.

A schematic diagram of the system is seen in figure 1. The system implementation is based on major software application systems and the development platform is an IBM RS6000 networked Unix system. There are three main major computational components: a full feature GIS (Arc/Info), a full capability storm water modeling system (SWMM), and a process manager and knowledge base system (RAISON).

Rather than develop a special purpose limited capability built in GIS, the major commercial GIS, Arc/Info, was chosen to be linked with the Knowledge Base Manager. This provides the project with a full range of vector based GIS processing (eg., overlay, buffering, interpolation, etc.), and access to substantial data bases of regional and municipal information.

In spite of the effort required to determine the parameters of the SWMM storm water modeling system, it was chosen to be linked with the Knowledge Base Manager because it provides: both quantity and quality modeling of storm water, ability to deal with ground water and infiltration, and the effects of existing or proposed storm water management facilities. Thus the project includes an important subproject that is examining ways that a knowledge base system can invoke data and analysis capabilities in the Arc/Info system to set the parameters for SWMM analysis.

The RAISON system is a recent joint development by Dr. David Swayne in the Department of Computer and Information Science at the University of Guelph and the Canadian Centre for Inland Waters. Its main features are a georeferenced mapping display and statistical capability plus ID3 -- a rule based expert system shell with an effective programming language. RAISON's knowledge base processing and programming language capability facilitates developing the necessary control scripts to send to Arc/Info and SWMM. It provides a menu system and graphical user interface that can be readily tailored to develop prototypes for user/system interaction.

System development is being tested on a moderate scale case study of the Laurel Creek Watershed where there has been a very recent large scale consulting study related to future urban development. (Laurel Creek is a subwatershed of the Grand River Watershed). This provides the project with extensive data sets, some detailed hydrographic studies, and a link to several other active studies (including land use and vegetation studies). This will provide an opportunity to test automated processing against independent consultant studies.

Two major graduate research themes are involved: (a) contaminant transport in surface storm water and how this is influenced by changing individual building lot and subdivision design, and (b) ground water infiltration as it relates to alternative approaches to subdivision design.

All necessary data sets are now stored in the GIS. Current development activity is related to developing the SWMM parameters and the RAISON process control scripts to develop and manage GIS and storm water analysis.

This should provide an effective system that enables emergency planners, municipal managers and engineers to address storm water issues.

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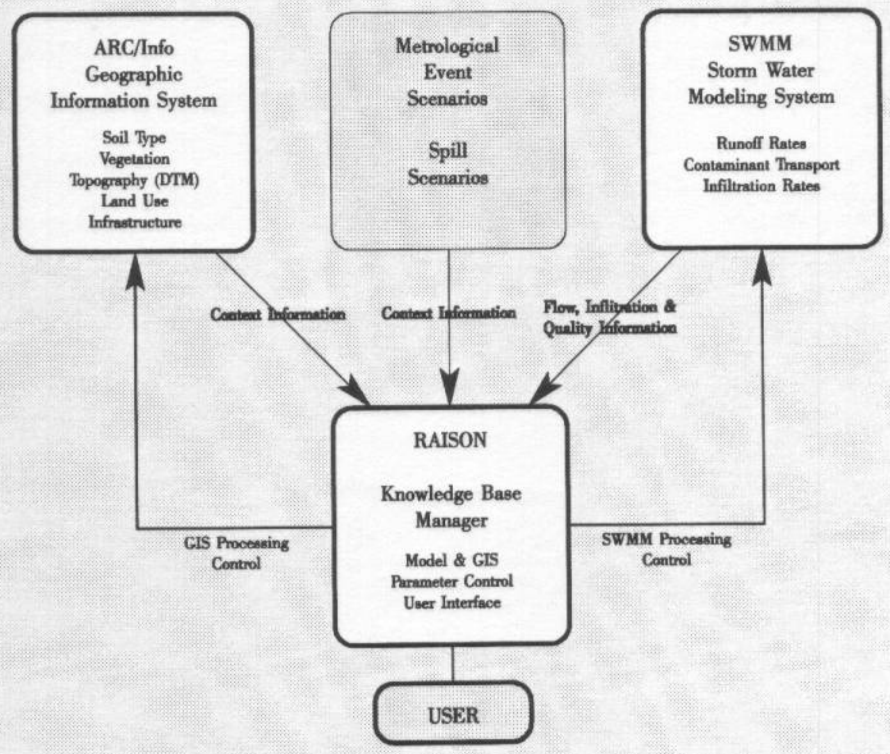

Figure 1: GIS & Storm Water Modeling for Planning