MODELING STORM WATER RISKS OF ALTERNATIVE PLANNED DEVELOPMENTS BY COMBINING GIS AND HYDROLOGY SIMULATION

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ABSTRACT

Urban development continues to pose human and environmental risks due to urban development induced flooding. Selection of better development designs could reduce flooding. A prototype evaluation framework for modeling storm water results of alternative development designs is reviewed. A GIS and the storm water modeling system SWMM evaluate proposed changes in site design, layout, density and location. Results show that the selection of more environmentally sensitive design might reduce storm water flow rates by fifty percent and could delay and reduce maximum storm water volumes.

INTRODUCTION

Urban development continues to increase throughout the world. The changes induced by the process of urbanization increase the frequency and impact of flooding in urban areas and in downstream locations. Flooding poses significant environmental and human risks due to impacts by both the quantity and quality of storm water. In addition, changes in surface water flows that result from urbanization also tend to exacerbate the difficulties of dealing with emergencies resulting from spills and accidental depositions of chemicals within an urbanized watershed (Newkirk, 1995).

Urbanization leads to significant and nonreversable changes in the effective hydrology of areas through the modification of land form, soil slope, vegetation, stream channeling, land drainage, etc. Once natural areas lose their natural buffering and infiltration characteristics, the rate of runoff is increased and less surface water is available to recharge ground water and sub surface aquifers. In addition, urban activity and land maintenance deposit quantities of contaminants that wash off in storm water. 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 is, at times, 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. Storm water transported contaminants, whether present in the urban area due to atmospheric deposition, resident or industrial application, or spill emergency, can compromise the quality of groundwater and supply of potable water for urban areas (Laurent *et al.*, 1995).

The location, density, and nature of building development within a watershed are some key determinants of urban storm water volume and quality. Yet, in many areas of the world, urban development impacts on the quantity and quality of storm water are only considered *post hoc* if at all. Even in jurisdictions where governments review and issue permits for development, it is usual that storm water assessment is only completed for larger scale projects, and it is only applies to the final project design to ensure that storm water management facilities will provide adequate service. Except in special cases, an overview storm water assessment is not completed as part of a designer's project evaluations early in the design process. This is because detailed hydrology modeling requires the services of specialist engineering firms and is considered expensive by most developers and designers. An assessment framework that would allow designers and planners to obtain a rough assessment of potential impacts of alternative conceptual development designs on storm water could provide a means of evolving more environmentally sensitive designs earlier in the planning process (Newkirk, 1995).

OBJECTIVES

This research was initiated to help strengthen watershed planning with new applications of environmental information now more widely available, and to facilitate the use of GIS and modeling for decision support. In particular, this work investigates an approach to assess storm water as it relates to different forms and locations of urban development in a watershed. It also attempts to demonstrate that storm water quantity and quality can be effected by changes in subdivision design. A prototype analysis framework was developed for use by planners to allow an initial assessment of storm water considerations as part of the development and evaluation of conceptual development plans. As much as possible, the framework should demonstrate "what if" assessment of alternatives based on available data resources and readily available and tested computer application packages that could be operated by planners.

APPROACH

To provide a manageable but useful test scale, the prototype analysis framework was implemented for selected small (approximately 125 acre) subwatersheds that had been identified in a recent major study of the Laurel Creek Watershed (Waterloo, Ontario).Using a subwatershed helped reduce modeling complexity due to in and out flows of surface and subsurface water from or to adjacent areas. An initial storm water modeling framework was established to represent the base line performance of the subwatershed. Alternative development designs and locations were imposed on the subwatershed framework by altering storm water modeling parameters of the specific areas proposed for development. This was done by using both GIS and a storm water modeling system since current GIS requires access to external storm water processing to estimate the quantity and quality of water flows (Newkirk, 1995).

The Arc/Info GIS was used to develop key information to structure the storm water model and to help calculate changes in model parameters required to simulate the impact of proposed alternative designs. Storm water modeling used SWMM the Storm Water Management Model. It is a very large special purpose 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 have tended to be storm water specialists (i.e., consulting engineers and researchers). SWMMDuet, a special purpose expert system preprocessor to SWMM, was used experimentally by Pascoe (1996) to develop some of the analysis models.

The approach requires the 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. GIS analysis helps define the appropriate subunits for analysis. SWMM's calculation of storm water surface flow is based on a non linear reservoir excess flow model (Irvine *et al.*, 1994). It has the ability to model water quality and to include a network of pipes or sewers of several kinds and sizes connecting drainage areas. In addition, it can provide for upper and lower ground water (i.e., subsurface zones) and infiltration calculations.

MODEL DEVELOPMENT ISSUES

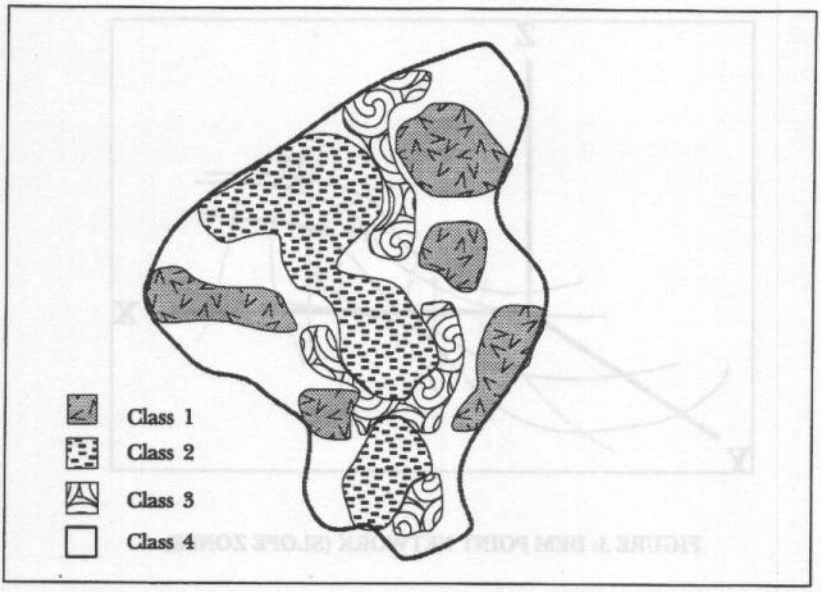
Some selected key issues that effect model development and the accuracy of the predicted values of flow rates and volumes should be considered. Storm water management is very sensitive to spatial variability in a watershed (Meyer *et al.*, 1993) and storm water models are very dependent on the correct parameters. In particular, SWMM is sensitive to percent imperviousness (by unit), depression storage, and infiltration rates (Liong et al., 1991; Irvine, 1994). This might imply the need for a very detailed GIS assessment of watershed features establishing a number of drainage (i.e. catchment) sub areas for analysis. However, storm water analysis 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). Furthermore, SWMM limits the number of drainage or catchment areas to a maximum of 100. Thus, a judicious choice of the number of watershed feature classes is required to minimize the number of classes while avoiding the problem of lumping too much variability within a class. This requires the modeler to have some field knowledge of the area.

SWMM does not yet have capability to model overland flow of storm water. The modeler must approximate this by defining a collection location for each drainage unit and directing the flow to the next unit by a suitable pipe and pour point location. In the field, these connections often involve flows through natural stream beds and vegetation. Currently, flows through natural features are not supported by SWMM.

METHOD

Two graduate student research projects examined aspects of developing a "design stage" storm water pre assessment system and of providing some indication of the potential importance of such prior assessment. One project considered changes to design and land management at the site level and the induced impacts on storm water volume and urban contaminant transport. The other project considered the impacts of altering density and location of development sites within a subwatershed. It also examined initial aspects of automating model development. Standard development densities and layouts based on local practice were imposed on the watershed and analyzed. Following this, alternative densities and layouts were analyzed. This paper reports some general results from the two projects. The reader is encouraged to consult the theses by McKenzie and Pascoe for detailed discussion of the two projects.

FIGURE 1: SOILS, LANDFORM, COVER



Sensitivity analysis of model runs show that the results are most sensitive to: percent impervious of each analysis unit, area of unit, and slope. Percent impervious is directly related to soil, land form, and land cover that varies over a study area and can be classified with the assistance of a GIS overlay analysis. As shown in Figure 1, an initial classification, based on detailed digital data sets, generalized the sub watershed into general infiltration classes by associating specific classes of soils, land form type, and ground cover. Some site measurements were used to verify infiltration rates in the major classes. The characteristics of each of these classes were stored in a table to provide parameter input to an appropriate SWMM model.

A decomposition of the sub watershed into slope zone classes was accomplished by GIS processing of digital elevation model (DEM) data. Figure 2 shows a schematic of the basis for a DEM. A DEM is developed by sampling elevations at specific locations and providing a file of the 3 tuples in (x,y,z). For example, each of points P1, P2, and P3 are represented by three (x,y,z) coordinate sets in a data file. DEMs can be developed by interpretation of air photographs or field surveyed using GPS technology. In general a DEM contains a large number of point elevation observations. Even a modest area of, say, 150 acres can involve approximately 40,000 data points. The Arc/Info GIS can use the data set to establish a DEM point

FIGURE 2: DIGITAL ELEVATION MODEL (DEM)

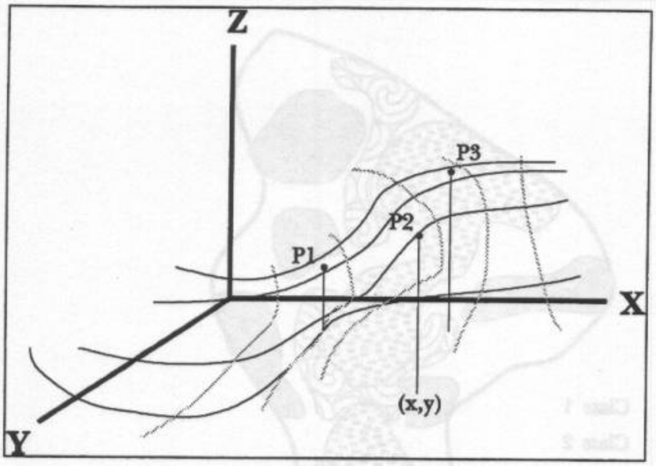


FIGURE 3: DEM POINT NETWORK (SLOPE ZONES)

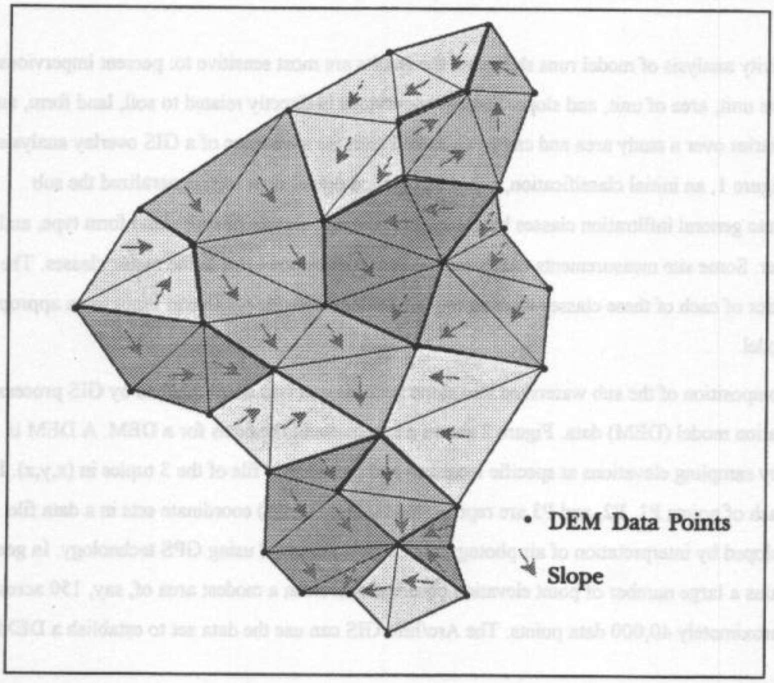
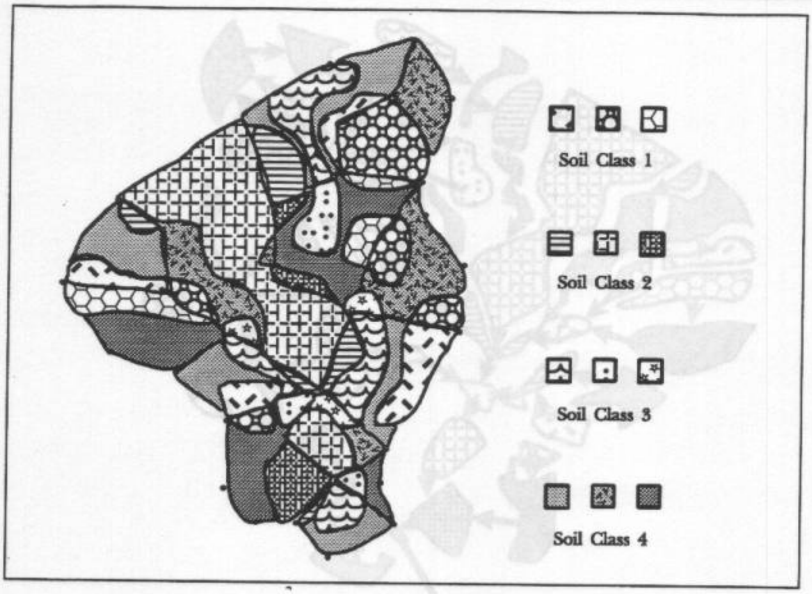


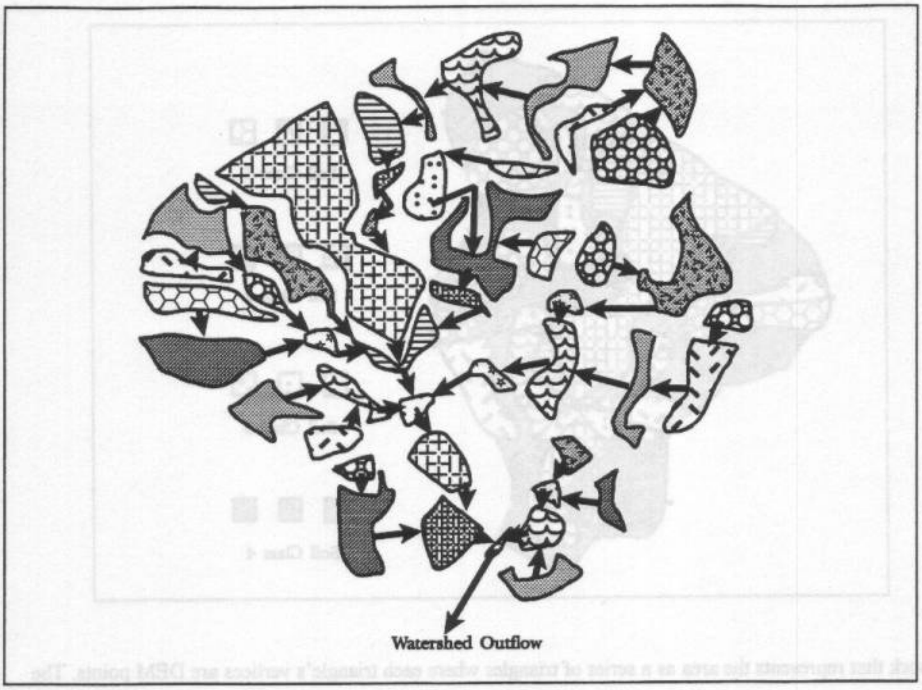
FIGURE 4: SUB WATERSHED DRAINAGE ZONES



network that represents the area as a series of triangles where each triangle's vertices are DEM points. The GIS can then calculate the face slope for each triangle. This information can be classified into slope zones as shown by shadings conceptually in Figure 3. The actual process to obtain generalized slope zones using Arc/Info involves several steps using its *flowdirection, streamlink*, and *watershed* commands. The raster based result must be converted to vector format for map overlay and drainage sub area calculations for input to a SWMM model. This step required human intervention to provide smoothed slope area boundaries.

The maps shown as Figures 1 and 3 can be readily overlaid by the GIS resulting in the identification of a number of slope/soil, land form, cover sub watershed drainage zones as shown in Figure 4. Map overlay usually requires operator editing interaction to deal with very small fragmented polygons that are a natural result of the overlaying process. The interaction between the classes in Figure 1 and zones in Figure 3 yields a number of distinctly different drainage zones whose parameters can be specified in the SWMM model. When the final set of drainage zones is obtained, the area, coverage, slope, and infiltration attributes of each zone are available to provide the critical watershed dependent SWMM parameters. The next stage

FIGURE 5: WATERSHED DRAINAGE LINKAGE (46 ZONES)



is the definition of water flow connections, via pseudo pipes, between the drainage sub catchments. Figure 5 shows conceptually how the series of analysis areas are linked for storm water flow modeling. As discussed (Pascoe, 1996) SWMM model specification was assisted by SWMMDuet (rather than RAISON as proposed by Newkirk (1995) due to SWMMDuet's recent availability).

RESULTS

Only selected results are reported here to demonstrate to potential usefulness of the overall approach. Several rainfall scenarios were used in the studies, but the outcomes reported here relate to one heavy summer rain when the ground was saturated from recent previous rains.

McKenzie evaluated different site related development designs in fixed locations; this included consideration of landscaping and landscape maintenance practices. While he considered the storm water

FIGURE 6: SITE DESIGN STORM WATER FLOW

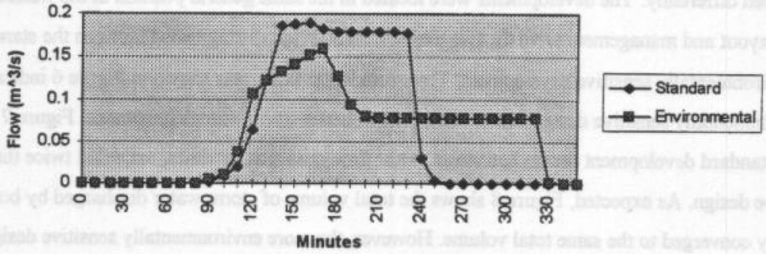


FIGURE 7: SITE DESIGN FLOW RATIOS

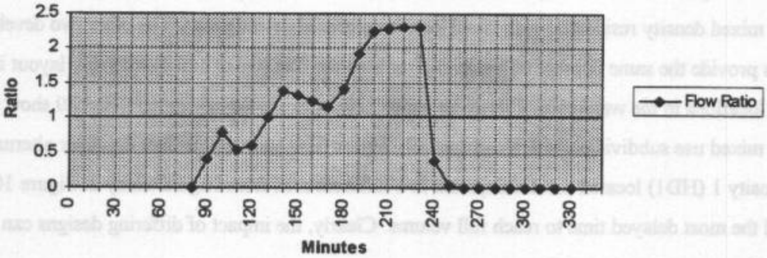
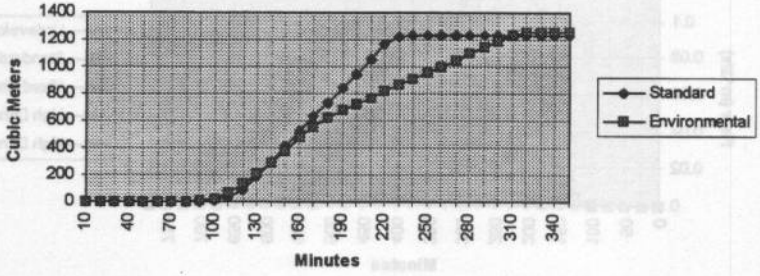


FIGURE 8: SITE DESIGN TOTAL DISCHARGE



transport of insecticide and herbicide contaminants associated with the designs, these are not reported here. He assessed two development scenarios that involved the same number of residential units of similar size but grouped differently. The developments were located in the same general position in the watershed. Site specific layout and management were the two major variables that distinguished between the standard and a more environmentally sensitive development. The storm water flow rates shown in Figure 6 indicate that the environmentally sensitive design demonstrated much better storm water capacitance. Figure 7 shows that the standard development design had storm water flow rates that, at times, exceeded twice that of the alternative design. As expected, Figure 8 shows the total volume of storm water discharged by both designs eventually converged to the same total volume. However, the more environmentally sensitive design delayed the volume by approximately an hour and a half in this rainfall event. Laurent *et al.* (1995) remark that storm water travel time is of significant importance.

Pascoe evaluated different development densities located in alternate locations in four scenarios. The first two development scenarios represent a standard low density residential spread development and a standard mixed density residential with small local commercial development. The other two development scenarios provide the same number of residential units as the first two in a higher density layout in two different locations in the watershed. The storm water flow rates shown in Figures 9 and 10 show the standard mixed use subdivision with a substantially higher flow and volume than the other alternatives. High Density 1 (HD1) located the development in a different area from High Density 2. Figure 10 that HD1 had the most delayed time to reach full volume. Clearly, the impact of differing designs can have very important impacts on storm water.

FIGURE 9: STORM WATER FLOW
(Density/Location of Development)

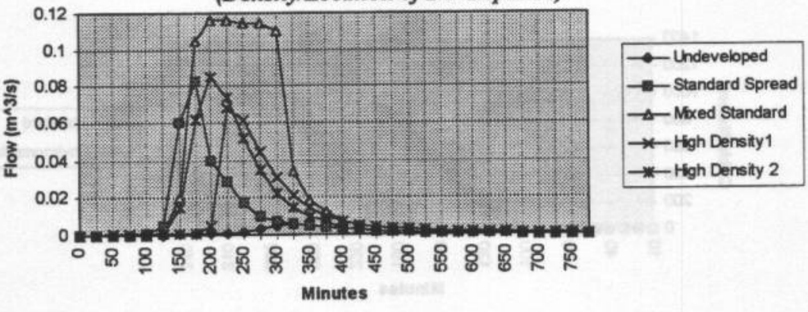
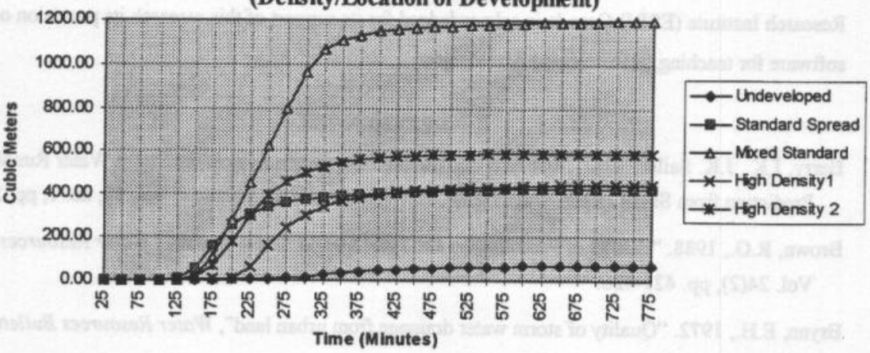


FIGURE 10: STORM WATER VOLUME (Density/Location of Development)



CONCLUSIONS

The examples show that some important difference in storm water volume and flow rates may be related to development design. There is potential for reducing substantially storm water flow rates, volume, and time to peak flow through adjusting subdivision site designs and locating developments appropriately. This is independent of any impact of special storm water management facilities. Design stage assessment of the potential impact of alternative development designs and development locations with in a watershed could lead to urban development that requires less investment in storm water management facilities and reduced down stream flooding impacts. It is important to recognize that the approach used in this work is intended to provide approximate indications of storm water consequences of conceptual designs early in the design process. It is not intended that this approach should replace detailed storm water assessment of final development designs. The analysis process remains technically demanding but within capabilities of specially trained planning and design professionals.

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