A Network-centric Modeling Approach for Infrastructure Interdependency

Rifaat Abdalla, C. Vincent Tao, Qiuming Cheng, and Jonathan Li

Abstract

This paper discusses the process of designing a spatial "knowledgebase" for infrastructure interdependency. Infrastructure interdependency is a new field of research that deals with interrelationships between critical infrastructure sectors in disaster management. The design and implementation of a spatial knowledgebase that mimics interrelationships between selected critical infrastructure sectors are conducted. This paper contributes to the field of disaster and emergency management by using a network-centric modeling approach and by implementing an infrastructure interdependency knowledgebase in a WEBGIS *environment for effective decision-making process, using the historical scenario of Hurricane Hazel, the well-known hurricane in Canadian history that struck Toronto on 15 October 1954.*

Introduction

A knowledgebase is an organized body of knowledge that provides a formal logical specification for the interpretation of information (Dai *et al.*, 2004). Knowledge about a particular system mainly depends on how this system is observed. The term knowledge synthesis denotes a collection of knowledge sources relevant to the problem at hand (Christakos *et al.*, 2002). Knowledge syntheses provide efficient support for emergency management decision-makers.

A spatial knowledgebase for infrastructure interdependency provides: (a) dynamic and interactive data access for modeling and visualization; (b) spatially explicit knowledge; (c) scalable data handling; and (d) rule-based data processing and information sharing mechanisms. Many researchers (e.g., Huang *et al.*, 2004; Quinn *et al.*, 2005; Suzuki *et al.*, 2004; Bryan, 2003; Knebl *et al.*, 2005) have used a spatial knowledgebase for solving environmental problems.

A scenario-based approach for the design and development of a spatial knowledgebase for infrastructure interdependency during emergencies is employed in this paper. The first level entails scenario modeling by integrating a geographic information system (GIS) with hydraulic modeling tools based on the historical flooding scenario associated with Hurricane Hazel, the most famous hurricane in Canadian history that struck Southern Ontario on 15 October 1954 (TRCA, 2004). The second level transforms information obtained from the flood model and integrates it with all related emergency management information needed in the knowledgebase.

Infrastructure interdependency is defined as link between two or more critical infrastructure systems in which any disturbance on of these systems significantly disturb the operation of other sectors. However, there is no consensus as to a precise definition for the set of activities and operations that shape the field of infrastructure interdependency. Currently there is a limited understanding of Canada's infrastructure interdependencies, infrastructure vulnerabilities, and the methods for measuring and quantifying these relationships. This is due to the increasing complexity of, and interconnectedness among, infrastructures, which has resulted in a number of different interdependencies. These interdependencies have introduced new vulnerabilities and risks.

Study Area and Datasets

Floods are one of the greatest natural disasters in Canada with severe storms being the next most important. In the twentieth century, flooding caused over $3 billion USD in damages and took at least 198 lives in Canada. Flooding occurs whenever water due to rain or snowmelt accumulates faster than soils can absorb it, or rivers can carry it away. Historically, Ontario is known to have undergone a very high rate of flooding (PSEPC, 2002). Between 1900 and 2002, Ontario had the highest frequency of flood events (22 percent) of any of the provinces and territories in Canada (e.g., New Brunswick 14 percent, Quebec 13 percent, Manitoba 11 percent and the rest of Canada 40 percent).

By the end of Hurricane Hazel more than 285 mm of rain had fallen on the already saturated ground and caused the most severe flooding in Canada's history. In its aftermath, 81 people died and over 4,000 families were left homeless in Ontario. The total cost of the destruction in Canada was estimated at $100 million USD, the equivalent of about $1 billion USD today. This was recorded as the most erratic hurricane in Canadian history (Kennedy, 1979). Water Survey of Canada, National Water Quantity Survey Program at Environment Canada **(http://www.wsc.ec.gc.ca/)** provides Data Products and Services, Water Level, and Streamflow Statistics. Figure 1 shows the water surface level

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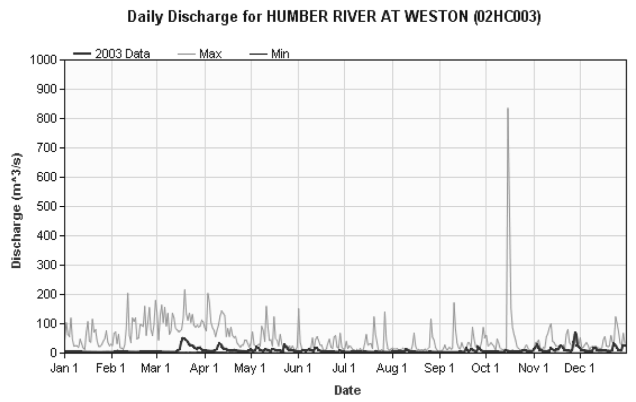

Figure 1. Maximum-minimum discharge of the Humber River at Weston in 1954 (WSC, 2004).

in 1954, which indicates that of 16 October 1954 was the highest in the year.

The Humber Valley was the scene of most of the disasters in the city that night. Bridges were lifted from their pilings and floated downstream. A complete road known as Raymore Drive, south of Lawrence Avenue was destroyed; 36 people were dead and 60 families were homeless, and 1,200 m of street was gone (Kennedy, 1979). The Humber River was reported to have risen dramatically and unexpectedly on that day. A section of the Humber River between Steeles Avenue and Lake Ontario was selected in this study (see Figure 2), based on the scenario reported by Kennedy, (1979) and verification obtained from the Event Tree Analysis. Another reason for selecting this area is that it has a high population density and an extensive infrastructure network.

Both spatial and non-spatial data were used to conducting effective emergency management operations. A flood database typically includes hydrologic, administrative, and population data (Levy, 2005). The data sets used in this study are summarized as follows:

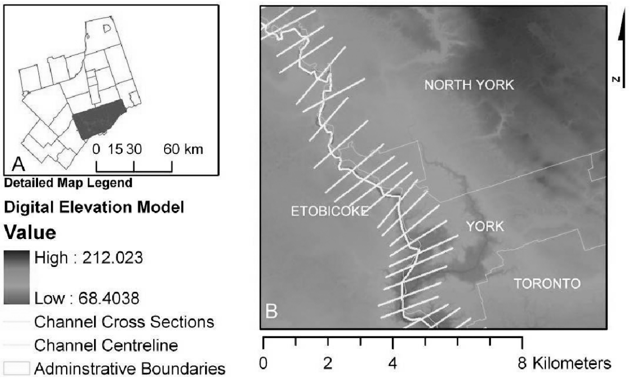

Figure 2. The study area: (A) Location of the Humber River area in relation to municipal boundaries within the Greater Toronto Area (GTA), Ontario, and (B) the constructed channel geometry of the Humber River.

- Toronto and Region Conservation Authority (TRCA) vector data 2003, including watersheds, water bodies, digital elevation models (DEMs) and topography.
- National Topographic Database (NTDB) data, including 1:50 000 map sheets 30M11 and 30M12.
- DMTI 8.2, including all Canadian route logistics data and DEMs.
- City of Toronto data, including 1 m resolution digital orthophotos of 2003 and the critical infrastructure data.
- Hydraulic data obtained from Water Survey Canada (WSC) **(http://www.wsc.ec.gc.ca/)** in the form of flow data (m^3/sec) were collected from the four stations located in the Humber Valley. However, only the flow data from the two stations were used in this study because of the available data collected before 1954.

Methodology

In this paper, we present a three-step integrated modeling approach with emphasis on identifying emergency management knowledgebase components based on a disaster management scenario. The overview of the methodology is illustrated in Figure 3. The first step consists of event tree analysis (ETA). In the second step, a GIS-based flood simulation is generated. The third step consists of identifying data and information needs from the scenario and implementing this as part of a spatial knowledgebase.

Event Tree Analysis

Visual representation in the form of a graphic model is used for analyzing the consequences of Hurricane Hazel. The consequences of the event were translated into tree branches, each of which represents a unique event that took place as a result of the hurricane disaster. ETA provides a systematic approach for investigating scenarios involved in complex systems (Nivolianitou *et al.*, 2004). It is a relatively simple and a useful framework for analyzing possible outcomes of

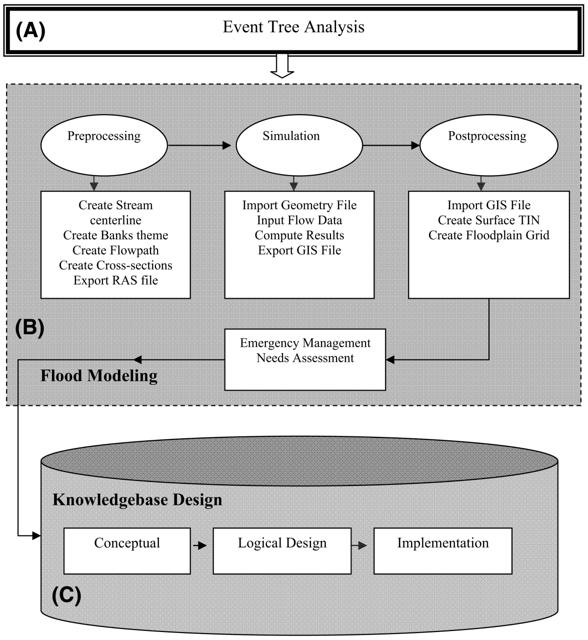

Figure 3. Overview of the methodology: (A) event tree analysis, (B) flood modeling, and (C) knowledgebase design.

particular environmental event. ETA provides visual representation of graphic models which found to be efficient in emergency management (Andrews and Dunnett, 2000). The application of ETA in environmental risk assessment is very popular (Bui, 2000; Magnusson *et al.*, 1996; Newhall and Hoblitt, 2002; Whitman, 2000; Hoffmann, 1994).

In ETA, each branch of the tree leads from a necessary prior event to a more specific outcome (Newhall and Hoblitt, 2002), e.g., from hurricane event to flood in particular section of a stream. In general, event tree methods are designed to illustrate static relationships between logical variables (Siu, 1994) and are very efficient in identifying system interrelationships due to shared events (Xu and Dugan, 2004).

The Relex software is used for conducting this analysis in this study. Figure 4 shows a schematic of the event tree analysis reproduced from the original diagram produced by the Relex software. The ETA is conducted to show Hurricane Hazel sequence of events. The initial event of Hurricane Hazel was branched to subsequent events, based on the storyline provided by Kennedy (1979). In this tree, each branch leads to specific outcome as a result to the hurricane.

Three major elements, rainfall, flood, and wind as consequences of Hurricane Hazel are depicted in the first level. The consequences for each of these branches are detailed in the second and the third level. The third level consequences were found to be more in the Humber River, which is in agreement with Kennedy (1979).

Hydraulic Modeling

GIS has significantly evolved to provide efficient spatial modeling, environmental model integration, and visualization capabilities. Several researchers (e.g., Levy *et al.*, 2005; Goodchild and Janelle, 2004; Wang *et al.*, 2006; Maguire *et al.*, 2005) highlighted the unique and powerful model coupling capabilities of GIS. ArcView® GIS and Hydrologic Engineering Center River Analysis System (HEC-RAS) (HEC, 2002) are used to simulate a flood scenario for the Humber River. The first step of the flood simulation consists of preprocessing the spatial data and exporting an ASCII file to be used by HEC-RAS as channel geometry information. The following steps entail inputting data flow parameters, including water flow and the channel boundary condition into HEC-RAS to produce water surface layers that are useable by ArcGIS® in providing flood delineation maps.

Preprocessing

Preprocessing is the first stage in the GIS generation process. It involves a number of tools that are used to create shapefiles that will be used in developing the geometry of the section under study. A DEM in the form of an ASCII raster along with topographic data in the form of shapefiles was used. A new DEM, in the form of a Triangular Irregular Network (TIN), was constructed. Based on the GIS data, and with the help of HEC-GEORAS, themes were created in order to extract geometric data for the purpose of hydraulic simulation. These four themes are: (a) Stream Centerline: used to establish the river network; (b) Banks: used to establish boundary lines for stream banks; (c) Flow Path and Centerline: used to determine downstream reach lengths between cross sections in the channel and over bank areas; and (d) Cross-sectional Cut Lines: used to identify the location at which cross-sectional data will be extracted from the terrain TIN and for bank stations and downstream length. This process established the connectivity and directionality of the reach. Once the 3D stream centerline and the 3D cross-section surface line themes are complete, then it is possible to write an RAS GIS import file. The RAS GIS import file was created, and a complete file with a header, stream network, and the cross-section information was generated. Figure 5 shows the channel centerline and channel cross-sections produced using ArcView®.

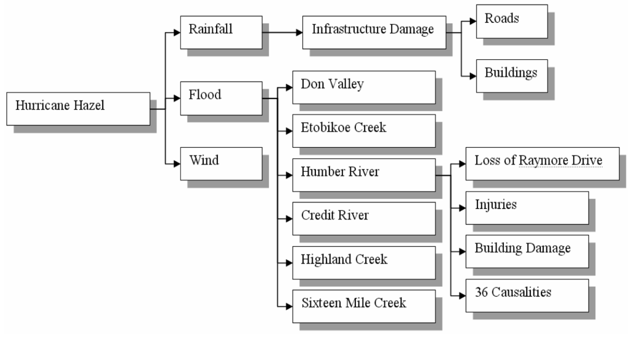

Figure 4. Event tree analysis for Hurricane Hazel.

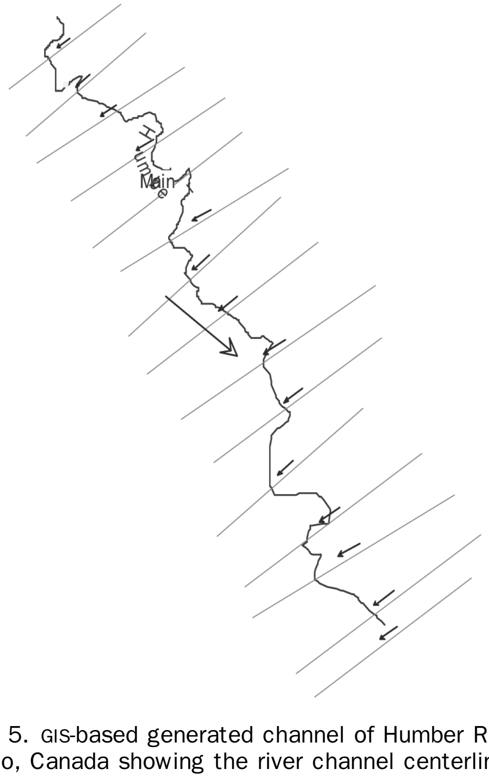

Figure 5. GIS-based generated channel of Humber River in Toronto, Canada showing the river channel centerline and cross-sections. Both are constructed based on a DEM.

Running HEC-RAS

HEC-RAS is a powerful hydraulic modeling package that was developed by the U.S. Army Corps of Engineers. It is an integrated package of hydraulic analysis with an ArcView® extension known as HEC-GEORAS. This extension, along with HEC-RAS, is capable of performing steady, unsteady, and mixed flow-water surface profile calculations. GIS provides a key contribution by allowing for the acquisition of channel cross-section data, channel geometry, and boundary conditions of the channel. Channel cross-sections are required at representative locations throughout the stream and at locations where changes in discharge, slope, shape, and roughness occur. Stream flow data along with water surface elevation boundary conditions can be directly used as an input to this model.

Five major steps were performed as part of the hydraulic simulation. The first step was to create a new project for river simulation. The second step involved utilizing the GIS data, through which the GIS-imported information takes the form of detailed geometry data that displays the derived geometry. The third step entailed running the model. This step was achieved in two different stages. The first was conducted by entering flow profiles for the cross sections generated for the focus section of the study area, and the second was conducted by entering water surface profiles.

HEC-RAS uses a number of parameters in order to conduct the hydraulic analysis of the channel geometry, stream, and water flow. The basic purpose for using these parameters is for establishing cross-sections along the stream. Each cross-section in HEC-RAS uses different input parameters to identify the elevation and shape of the stream. As shown in Figure 6, the 3D channel model was generated from the assembly of all cross-sections. HEC-RAS assumes the energy head is constant across the cross-section and that the velocity vector is perpendicular to the cross-section (Tate 1999). Therefore, after defining the stream geometry from GIS data, flow values are the critical model inputs that are used for model computation.

Surface flow in open channels is always governed by energy head, velocity head, and pressure head (Hwang and Hita, 1987). The HEC-RAS simulates open channel flow and is able to operate with sub-critical, super-critical, and mixed-flow regimes. For instance, the following two equations are used for modeling sub-critical flow using an iterative procedure for the downstream (Equation 1) and upstream (Equation 2) sections, respectively (HEC, 2002)

$$WS_2 + (\alpha_2 V_2)/2g = WS_1 + (\alpha_1 V_1)/2g + h_e \qquad (1)$$

$$h_e = L\, S_f + C\,[(\alpha_2 V_{22})/2g - (\alpha_1 V_{12})/2g] \qquad (2)$$

where WS_1 and WS_2 are the water surface elevations at ends of reach, V_1 and V_2 are the mean velocities at ends of reach, and α_1 and α_2 are the velocity or energy coefficients for flow at ends of reach, h_e is the energy head loss, g is the gravitational constant, L is the discharge-weighted reach length, S_f is the representative friction slope for reach, and C is the expansion or concentration loss coefficient.

After the HEC-RAS successfully computes the results, it provides several methods of visualization. Output can be in the form of profile plots (Figure 6), cross-section plots (see Figure 7) or 3D channel geometry with water surface (see Figure 8). There are other reporting capabilities through which HEC-RAS can provide visual and textual output.

Postprocessing

Postprocessing is the third stage in producing the Humber River hydraulic model. HEC-RAS data can be read into the GIS mainly through ArcView® and HEC-GEORAS, with a steady flow model export file created, postprocessing functions are used to drape the flood plain over the TIN. Once the GIS export file has been processed, it is not a difficult task to create water surface data sets. Postprocessing is performed in three separate steps using the HEC-GEORAS extension.

GeoServNet (GSN), a web-based GIS system developed in the GeoICT Lab at York University is used as the methodology development environment in this study. GeoServNet is a

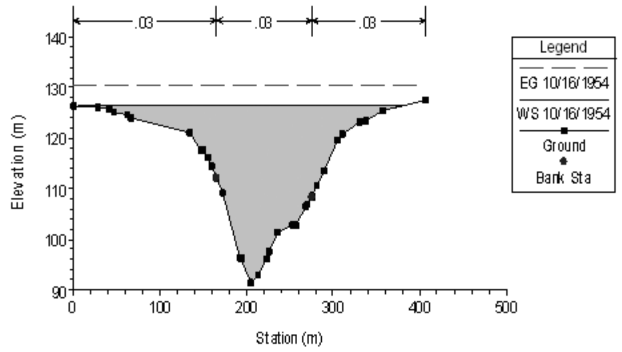

Figure 7. HEC-RAS-generated cross-sectional plot showing a Humber river water surface elevation for one cross-section of the stream network on 16 October 1954 (EG = energy head, WS = water surface elevation, and Bank Sta = bank stations).

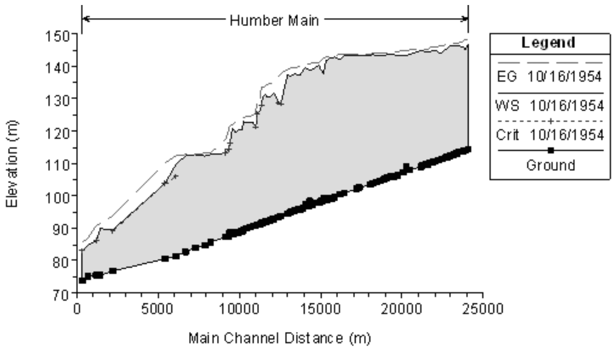

Figure 6. HEC-RAS-generated profile of the Humber River channel showing the flooding scenario water surface elevation on 16 October 1954 (EG = energy head, WS = water surface elevation, and Crit = critical surface).

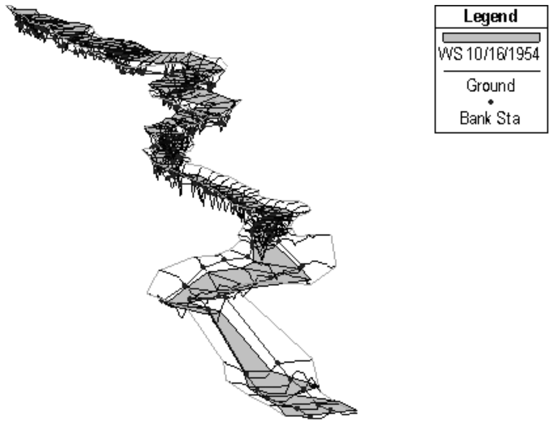

Figure 8. HEC-RAS-generated 3D channel model showing flood level on the Humber River on 16 October 1954.

suite of software that enables the distribution of both 2D and 3D geospatial information over a network. It has a Services Oriented Architecture (SOA) that is scalable, transparent, and distributed. It utilizes Java and Java 3D technology and can be deployed with any platform. With GeoServNet, geospatial information can be accessed anytime anywhere. GeoServNet, version 1.5 has five modules with different web browsers (see Figure 9). Among them the primary function of GSN Publisher is to set visualization parameters in terms of visual effects (i.e., color, line thickness, and transparency). The other function of GSN Publisher is in generating the application file that is linked to the web, thus making the project available online.

The generation of the bounding polygon and cross-section alignments provides a conceptual stream flow model and generates the necessary GIS themes for simulation the river flow. Figure 10 shows a three-time analysis of the spatial extent of the flood before, during, and after the hurricane; the peak flood value on this map was used for developing the knowledgebase, mainly to accounting for the worst case scenario.

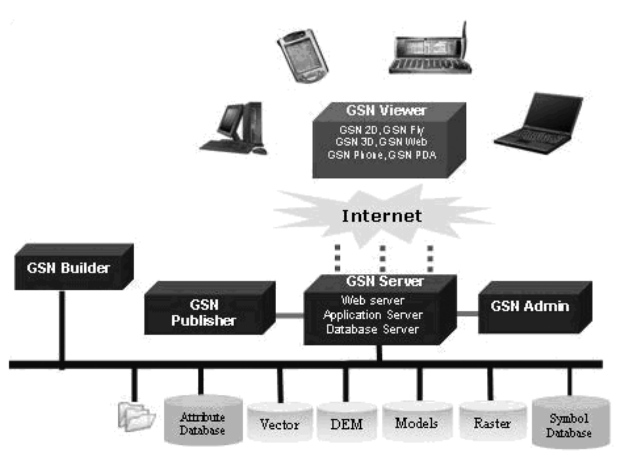

Figure 9. Diagram showing the architecture of GeoServNet, version 1.5.

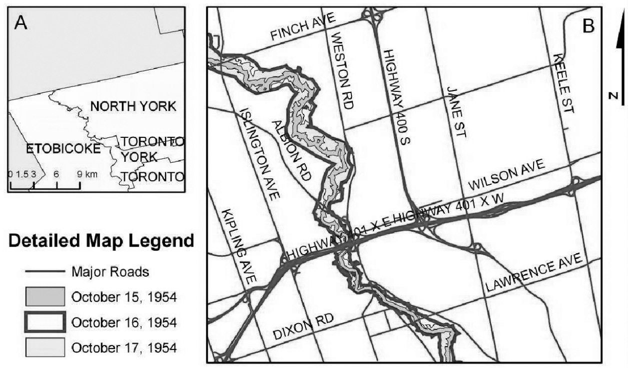

Figure 10. Spatiotemporal visualization of flood levels: (A) Location of the Humber River study area in relation to municipal boundaries within the GTA, Ontario; and (B) spatiotemporal variation of flood levels in the Humber River.

Model Validation

Flood modeling plays a very important role in disaster management since it assists decision-makers with the prevention and prediction of flood events. Although the main objective of this work is merely to derive the knowledgebase components from the flood model, the assessment of the computations of water surface elevation is also important. The importance of validation activities in hydraulic simulation comes from the fact that deriving a case-specific knowledgebase requires complete and accurate definition of the knowledgebase components within the flood extent.

Validation of the HEC-RAS water surface profile model was completed by comparing measured profiles of the simulated reach at different average flow rates for 15, 16, 17, and 18 October 1954, with observed flow obtained from discharge graphs provided by Water Survey of Canada (WSC). The HEC-RAS model is calibrated against the Manning's roughness coefficient (n-value) using the measured water surface elevation data provided by Environment Canada. An n-value is estimated based on the parameters provided by Hwang and Hita (1987). There is a very minor discrepancy in the model validation error between the observed and simulated flow. This can be primarily attributed to the limited simulation time span. The reported friction error (R^2) is found to be 0.89. Figure 11 shows a flood modeling validation graph. The observed flow data were obtained the WSC. The simulation was run only for the period spanning 15 October to 18 October 1954.

There are a number of issues that limit the accuracy of flood simulation, including the availability of observation data for model validation and the accuracy of the digital elevation model (DEM). Flood simulation for emergency management may be a time consuming process. It has strong data requirements and entails channel geometry construction, in addition to validation and calibration (Knebla *et al.*, 2005). There is no assurance that independent stream cross-sections can fit a terrain model with perfect accuracy. This stems from uncertainty inherent in the digital elevation model. Conducting a flood simulation using two different models (i.e., HEC-RAS and MIKE-11) is potentially very useful

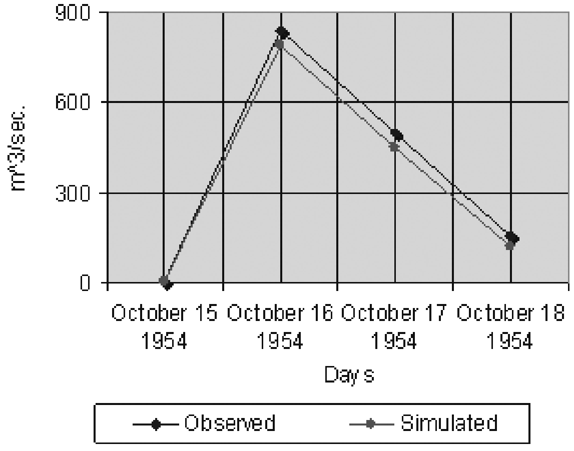

Figure 11. Model validation of Humber River HEC-RAS-produced Model, showing the plot of the change in flow rate over time for the observed flow versus the simulated flow for the days of Hurricane Hazel.

in providing a clear picture of how two different flood accuracies can be compared (Snead, 2000).

Knowledgebase Design

The design of spatial knowledgebase can be a complex and time-consuming process (Storey *et al.*, 1995). A case-specific knowledgebase provides knowledge about a specific situation (Christakos *et al.*, 2002). This type of spatial knowledgebase provides knowledge that the need for is recognized, but the information is not available. As such, it provides information that is immediately available to the user or decision-maker in this case. In this study, a spatial knowledgebase is designed based on the ESRI Geodatabase Model. Conceptual, logical, and physical design processes are utilized in building this knowledgebase.

Design Principles

Several researchers (Choi and Luk, 1992; Jones *et al.*, 1996; Liang *et al.*, 2004; Zhou and Jones, 2001; Metternicht *et al.*, 2005) have discussed the basic principles of designing spatial databases. The following are the five major steps for the pre-design phase of geographic databases: (a) providing a comprehensive framework of the database; (b) allowing the database to be viewed in its entirety so that interaction and linkages between elements can be defined and evaluated; (c) permitting identification of potential bottlenecks and problem areas so that design alternatives can be considered; (d) identifying the essential and correct data to be included in your database and filter out irrelevant data; and (e) defining update procedures so that newer data can be readily incorporated in the future.

The design of the spatial database includes three major elements (Goodchild and Kemp, 1990). The first of these is *Conceptual Design*, which involves laying down the application requirements and specifying the end-utilization of the database. The effective design of a database management system (DBMS) repository for a GIS requires that user expectations and intended uses be known in as much detail as possible (Stefanakis and Sellis, 1996).

Conceptual design involves four major steps, namely: (a) specifying the use of spatial database; (b) specifying the level of detail; (c) specifying the spatial elements of GIS databases; and (d) specifying the type of non-spatial elements that will be exploited in the database (e.g., labels, text, attributes). Other considerations, such as data availability, source of spatial and non-spatial data, age of data, and coordinate system type must be accounted for. However, this seems to be less and less of an issue with the advances in GIS data capture, software, and hardware capabilities. The second stage of designing a spatial database is the *Logical Design*, which entails identifying what type of database system and what GIS packages are appropriate to the particular application. Other important aspects to be considered in the logical design of spatial databases are the coordinate system definitions of database tolerance as well as of the spatial relationships. The third stage of designing a spatial database is the *Physical Design*, which refers to the process of identifying the hardware and software requirements for particular applications. In this stage, consideration of basic system components is crucial. These components include: file structure, data formats, memory, disk space, processing time speed, and graphic cards.

Conceptual Design

Much attention has been directed toward conceptual design of database models (Mannisto *et al.*, 2001; McKay *et al.*, 1996). The conceptual design of the spatial knowledgebase aims to define all of the components that are to be incorporated. Within the present context, emergency management data sets, spatial relationships and all components of the knowledgebase are identified based on the simulated Hurricane Hazel flood scenario. The second part of the conceptual design of this geodatabase is based on the data needs of the emergency manager. The questions to be considered were: “What data is required for building this model?”, “Is it simple vector data for drawing maps or a raster data for this type of analysis?” “Is it specific data for specific software or is it data to be digitized directly and visualized through data explorer (Arctur and Zeiler, 2004)?” Based on these questions, it was possible to group the data layers as shown in Table 1. The scale and area of interest were constrained by the type of data collected and by the usability and requirements for this type of information. Figure 12 shows a knowledgebase feature dataset as well as feature classes of the infrastructure layer. According to Dey *et al.* (1999), a key consideration is the extracting of sufficient information from a real-world situation, and then being able to represent it properly in a conceptual design.

Logical Design

Information modeling in databases can be carried out at two different levels: (a) conceptual data modeling, and (b) logical database modeling (Ma, 2005). Logical design of spatial databases is implementation-independent (Beynondavies, 1992). This phase of the knowledgebase design involved identifying feature classes and groups and linking them to attributes and data domains. In this phase, database rules were identified. The UML schematic shown in Figure 12 defines the type of information needed for the design and implementation. This phase involved the following steps:

- Identifying spatial relationships and interdependencies based on spatial and non-spatial data collected in the first part of this study.
- Identifying the spatial properties and attributes for the collected data sets, including database precision and accuracy.
- Proposal of spatial database geodatabase design using the UML data modeling technique.

UML Modeling

UML is the standard graphical language that is used for modeling business processes and software application needs (Booch *et al.*, 2005). It uses a data-centric modeling approach for database and systems design. It consists of a set of notations for modeling systems from a variety of views and at varying levels of abstraction (France *et al.*, 1998). It allows for a variety of modeling techniques to visually present the proposed design for particular systems including databases. UML is a very flexible language.

This flexibility allows UML to be used for modeling different processes, ranging from business development to database architecture. It allows for the sharing of a common understanding for the process and provides revisable and enhanced engineering design mechanisms. Table 2 shows database components used in UML modeling. The major challenge with data–centric approaches is that they are outdated quickly due to objects relationships change over time (Boggs and Boggs, 1999). The flexibility also allows for rapid update of the process. One drawback is that there is no single way of visually presenting design information using UML, rather there are many. This characteristic in particular could lead to heterogeneous visual representation methods.

Although UML diagrams vary, there is a standard procedure for documenting relationships through a UML chart. As Table 2 shows, UML models are classified into eight groups according to (Booch *et al.*, 2005). In this paper a database

Table 1. Database Conceptual Design Layers

Emergency	Data Requirements	Infrastructure Group	Emergency Management Group	Location Information Group	Emergency Contacts
Flood	-Region topographic GIS data	-Water Sector	Stream channel	-Nearby health care services	-Region emergency operations center
	-Region GIS elevation data		-Floodplain	-Nearby stations for emergency medical services	-Region fire Marshall or representative
	-Region watershed data		-Population distribution	-Nearby shelters	
	-Hydraulics data		-Historical flood information	-Nearby fire stations	
	-Census track data			-Nearby police stations	

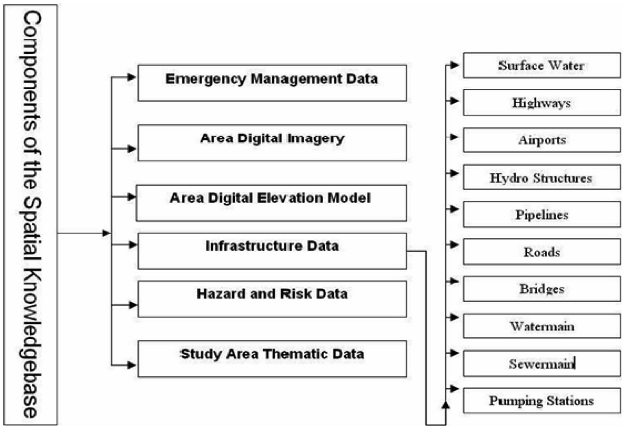

Figure 12. Feature datasets of the knowledgebase with details feature classes of infrastructure feature dataset.

Table 2. Example of Relationships in the Knowledgebase

Layer 1	Layer 2	Cardinality
Buildings	Flood	Many to One
Buildings	Historical events	Many to Many
EMS	Contact information	One to Many
Senior homes	EMS	Many to One
Hydro structures	highways	Many to Many
Roads	Flood	Many to One
Highways	Floods	Many to One
Senior homes	Ice storms	Many to One
Surface water	Floods	Many to One
Water mains	Highways	Many to Many
Water mains	Floods	Many to One

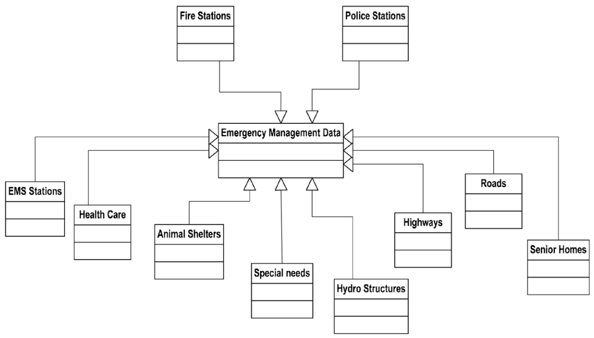

Figure 13. UML diagram for the emergency management feature dataset.

diagram is used to show and to document the logical development of the model Figure 13. Utilizing UML capabilities for visualizing the requirements helps with the development of an efficient database design model. The proposed logical model can be implemented through a variety of platforms.

Implementation

The seamless join between conceptual, logical, and physical design work is feasible when dealing with designing spatial databases (Beynondavies, 1992). However, the implementation may take a different approach based on the logical model. The physical implementation identifies the software and hardware requirements for building the spatial knowledgebase. This is based on the conceptual modeling of the data requirements such as the size and extent, and based on the relationships identified in the logical model, and whether these relationships can be modeled using a particular schema or not.

In this stage the collected datasets shown and identified in the conceptual model were grouped into feature datasets. Each feature data set contains a number of layers, including (a) emergency management, (b) historical hazards, (c) infrastructure, and (d) study area.

Interdependency Relations in the Knowledgebase

The database schema produced from the logical model allowed for implementing the spatial relationships in the knowledgebase. Object-based representations methods on the database associate attribute data with individual objects. This is cortically important when dealing infrastructure interdependency, because it controls the relationship between spatial and non-spatial objects in the database. Utilizing the LBII, concept relationships between spatial objects are modeled in the database using cardinalities identified in the logical model based on identified relationships in the conceptual design for each of the layers in the geodatabase model, as shown in Table 3.

The following step identifies the spatial relationships and interdependencies in the database. The implementation phase transformed mapped relationships in the logical model are into new layer known as relationship class. The relationship class can incorporate spatial and non-spatial data, as well as features within particular feature datasets (see Figure 14). Relationships represent the rules of the geodatabase, providing detailed information about the

Table 3. Example of Relationships in the Knowledgebase

Layer 1	Layer 2	Cardinality
Buildings	Flood	Many to One
Buildings	Historical events	Many to Many
EMS	Contact information	One to Many
Senior homes	EMS	Many to One
Hydro structures	highways	Many to Many
Roads	Flood	Many to One
Highways	Floods	Many to One
Senior homes	Ice storms	Many to One
Surface water	Floods	Many to One
Water mains	Highways	Many to Many
Water mains	Floods	Many to One

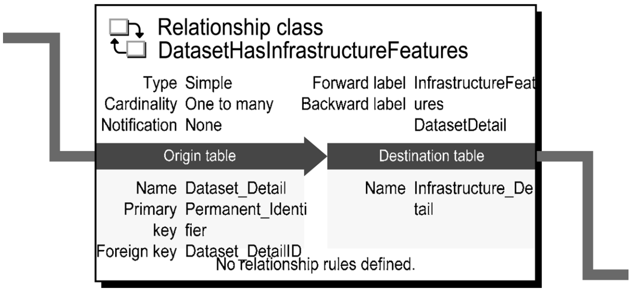

Figure 14. Graphical details of the relationship class in the geodatabase.

behavior allowed for database features; this includes how features can intersect, and overlap. The domain rules identify behaviors in the knowledgebase in terms of attribute inheritance and processing.

The following step involved collecting non-spatial data and assembling and integrating these into the same database. This includes all tabular information identified in the spatial design of the knowledgebase.

The last control measure applied in the implementation included the subtype rules to be implemented in the knowledgebase. These rules provide details about the features that can be implemented as part of this geodatabase, and provide control measures when processing queries within the knowledgebase.

Discussion

The knowledgebase developed in this paper is problem and location specific and provides a transferable solution. Based on design requirements, the approach can be customized to provide a solution for a specific problem, and thereby has the capability to address emergency management decision-makers needs. There are particular issues of importance related to event-driven emergency management knowledgebase design and implementation. These issues are discussed in the following sections.

Digital data is easy to process, highly accessible, and less expensive than traditional approaches to the delineation of floodplain boundaries (Levy, 2005). A major strength of the developed approach has utilized the availability of spatial data and attempted to leverage these data to different users or decision-makers. There are five major issues that need to be accounted for when dealing with knowledgebase design, these are: (a) Database Scalability: This refers to the potential for increasing the database storage capacity as well as for hardware/software upgrading capabilities based on the size and capacity of the project; (b) Database Accessibility: The ease of accessing the database, paging it and querying database attributes; (c) Database Availability: The ability to access and query information from the database; (d) Database Security: The ability to protect and control access to database content; and (e) Database Interoperability: The ability to provide access by multiple users to the database.

The integration of several different modeling technologies provides the key strength underlying this approach. It provides unique case-specific information to specialized users.

Data Acquisition, Maintenance, and Update

Due to the rapid response required when dealing with emergencies; issues related to data acquisition, data maintenance, and update are very important from an emergency management perspective. Usually different departments are involved and may take different roles in updating a database. Data interoperability is crucial in this regard. This helps to minimize the time between when data is first acquired and when it is integrated into the system; it also insures consistency between the departments involved.

One issue with obtaining hydraulics data from Water Service of Canada for the selected study area is that most of the monitoring stations were installed after the simulation scenario. (i.e., after 1954); only one station within the studied reach was installed before 1954. However, complete hydraulics data is available for the Humber River system after 1958.

Data Quality

A fundamental problem when dealing with infrastructure interdependency is data integrity. The importance of critical infrastructures systems changes with time, which would influence how those systems are represented in the database and in the relationships between spatial data and non-spatial data associated with these objects. A strict control protocol is required to insure data quality and the ability to conduct fast processing of GIS data maintenance operations. Availability of metadata (i.e., data about data) for this project was a vital issue.

Haklay and Tobon (2003) discussed the feasibility of involving the public in utilizing GIS in decision making. Bush *et al.* (2005) demanded public participation in sustainable development projects if such projects are to be successful. The public utility of GIS to support decision makers stems mainly from the utility of web-based applications (e.g., Hytonen *et al.*, 2002; Kearns *et al.*, 2003; Smith, 2002). Network-centric GIS requires less technical expertise for the end user.

Conclusions

The novel approach presented by this paper is very efficient on how a simulation scenario can evolve to provide a comprehensive spatial knowledgebase, and how scenario-based simulations are effective in modeling and simulation for emergency management. Conceptualization of data needs, processes, and development of a knowledgebase has shown to what extent GIS databases can integrate different types and information sources solely for the sake of effectively addressing the issues of infrastructure interdependency during emergencies. The knowledgebase implementation protocol has resulted in a unique data model that serves as a spatial knowledgebase engine for modeling infrastructure interdependency, in which an object-relational database model was used to provide a geodatabase for infrastructure interdependency. The uniqueness of the developed knowledgebase can be summarized as follows:

- It is scalable and accommodates any size of spatial data.
- It is transferable and can be modified and used for similar infrastructure sectors.
- It has the capability to be integrated with other infrastructure interdependency modeling tools.
- It provides strong visual products and reporting capabilities.

Enhancing the intelligence of the designed spatial knowledgebase could contribute significantly to the process of providing knowledge. The intelligence of this knowledgebase can be enhanced in two respects by: (a) adding more rules and relationships to this knowledgebase, can allow for more advanced functionality for modeling LBII. (However, this will depend on the first point, namely: what additional input has been added to the knowledgebase), and (b) developing an advanced interactive ArcGIS® user interface, such interface can be developed by customizing ArcGIS® to provide more detailed functions as required for infrastructure interdependency.

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