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# Location-Based Critical Infrastructure Interdependency (LBCII)

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**Defence R&D Canada**  
Technical Report  
DRDC Toronto TR 2009-130  
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Canada



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## Abstract

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This report presents the notion of Location-Based Critical Infrastructure Interdependency (LBCII), and the steps to identifying such interdependency. A scenario is simulated of a shallow 7.3 on the Modified Mercalli Intensity scale (MMI) subduction earthquake in the Strait of Georgia, British Columbia (at latitude 49.45 degrees and longitude 123.941 degrees). Spatial and functional interdependencies were shown in simulation. A total of twenty-three hydro-structures around Vancouver, British Columbia were found to be at risk. Potential damage was most severe to the north of Grant McConachie Way, on Sea Island near the Vancouver airport. The potential for building damage was assessed across ground acceleration zones. Three categories of building damage were identified: high risk, low risk, and safe. Spatial analysis helped identify levels of risk. These levels take into account population density in the building damage zones, and by identifying electrical failure as a consequence of an earthquake. It was possible to visualize the other effected critical infrastructure sectors. This report emphasizes visualization capabilities of (WebGIS) a web-based, geographic information system, and outlines strengths and weaknesses in the spatial models used for web visualization. Issues identified in the development of spatial models for LBCII are related to data access, input and processing requirements.

## Résumé

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Ce rapport présente la notion d'interdépendance géographique des infrastructures essentielles (IGIE), et les mesures permettant de relever ces interdépendances. Dans le scénario que nous décrivons, un séisme de subduction à faible profondeur et d'une intensité de 7,3 sur l'échelle de Mercalli modifiée (MM) est simulé dans le détroit de Géorgie, en Colombie-Britannique (latitude de 49,45° et longitude 123,941°). Les interdépendances spatiales et fonctionnelles ont été illustrées dans la simulation. En tout, 23 structures hydroélectriques autour de Vancouver ont été jugées à risque. Les dommages potentiels les plus graves se sont produits au nord de Grant McConachie Way, sur l'île Sea, près de l'aéroport de Vancouver. Le potentiel de dommages aux bâtiments a été évalué dans les zones d'accélération du sol. Trois catégories de dommages aux bâtiments ont été constatées : risque élevé, risque faible et risque nul. L'analyse spatiale a permis d'identifier les niveaux de risque. Ces niveaux prennent en compte la densité de population dans les zones de dommages aux bâtiments, et ainsi que les pannes électriques dues au séisme. Il a été possible de visualiser les autres secteurs d'infrastructures essentielles touchés. Ce rapport met l'accent sur les capacités de visualisation de WebSIG, un système géographique d'information basé sur le Web, et il décrit les forces et les faiblesses des modèles spatiaux utilisés pour la visualisation sur le Web. Les problèmes constatés dans la mise au point de modèles spatiaux pour l'analyse IGIE ont trait aux exigences d'accès, de saisie et de traitement des données.

## Executive summary

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### Location-Based Critical Infrastructure Interdependency (LBCII):

Rifaat M. Abdalla; Keith K. Niall; DRDC Toronto TR 2009-130; Defence R&D Canada – Toronto; April 2010.

**Introduction:** This report introduces the notion of Location-Based Critical Infrastructure Interdependency (LBCII). LBCII uses the analytical and visualization capabilities of WebGIS, a web-based, geographic information system, to localize geographic types of infrastructure interdependency. It identifies critical infrastructure sectors in a particular spatial domain. LBCII provides an analysis and visualization of spatial interconnectedness based on the extent of sectors. It can be used in emergency management decision-making processes for critical infrastructure protection.

**Results:** The strengths and weaknesses of WebGIS visualization capabilities are evaluated by simulating an earthquake scenario. This report directly pinpoints to the impact of such an earthquake on critical infrastructure sectors.

**Implications:** One issue with infrastructure protection research is the provision of the ability to formalize an understanding of interdependencies between infrastructure sectors in extreme situations. The present work is new in that it addresses issues of critical infrastructure interdependency and geospatial technologies for the simulation and visualization of the interconnection of critical infrastructure sectors. It is envisaged that it will have significant impact on military and public security personnel in joint domestic operations, such as the Vancouver 2010 Olympics.

**Future plans:** LBCII-based multi-tier impact assessment will be conducted for socially vulnerable communities to help with the development of emergency management plans.

# Sommaire

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## **Location-Based Critical Infrastructure Interdependency (LBCII):**

**Rifaat M. Abdalla; Keith K. Niall; DRDC Toronto TR 2009-130; R & D pour la défense Canada – Toronto; avril 2010.**

**Introduction:** Ce rapport présente la notion d'interdépendance géographique des infrastructures essentielles (IGIE). Cette approche utilise les capacités d'analyse et de visualisation de WebSIG, un système géographique d'information basé sur le Web, pour représenter l'interdépendance géographique des infrastructures. Elle permet de répertorier les secteurs d'infrastructures essentielles dans un domaine spatial particulier. L'IGIE permet ainsi d'analyser et de visualiser l'interdépendance spatiale fondée sur l'étendue des secteurs. Un tel système peut être utilisé dans le processus décisionnel en situation d'urgence, afin de protéger les infrastructures essentielles.

**Résultats:** Les forces et les faiblesses des capacités de visualisation de WebSIG sont évaluées par la simulation d'un scénario de séisme. Ce rapport démontre directement l'impact d'un tel séisme sur les secteurs comportant des infrastructures essentielles.

**Conséquences:** Un problème en recherche sur la protection des infrastructures est de parvenir à formaliser la compréhension des interdépendances entre les zones d'infrastructure dans des situations extrêmes. Le travail actuel est nouveau, car il s'appuie sur les technologies géospatiales pour simuler et visualiser l'interdépendance des infrastructures essentielles. Il est prévu que cette méthode aura un impact important sur les organisations militaires et de protection civile dans le cadre des opérations conjointes au Canada, comme ce fut le cas, par exemple, à l'occasion des Jeux olympiques de 2010 à Vancouver.

**Plans futurs:** L'évaluation multiniveau des impacts basée sur l'approche IGIE se fera dans des communautés socialement vulnérables afin de les aider à élaborer des plans de gestion des urgences.

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# 1 Introduction

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Disasters are dynamic processes [1], and by their nature they are spatial [2]. Most current tools for disaster management focus on the temporal component of four phases of a disaster management cycle: preparedness, mitigation, response and recovery [3]. This leaves a gap in dealing with the spatial element. An emphasis on the spatial dimension makes Geographic Information Systems (GIS) [4] technologies ideal for simulating complex spatial relationships among critical infrastructures (i.e., their interdependencies) while integrating other modeling tools. Nash et al. [5] showed how temporal GIS can combine both temporal and spatial dimensions effectively. Several studies [6-11] have outlined the importance of spatio-temporal effects in disaster management. With GIS, these studies have shown the way to establish efficient information systems that can accommodate many events.

This work aims to show how GIS can model Location-Based Critical Infrastructure Interdependency (LBCII). An overview of basic concepts of disaster management and infrastructure interdependency is presented, followed by a discussion of the utility of GIS for infrastructure interdependency research. A scenario-based simulation is given for an earthquake in the city of Vancouver aimed at providing visual models of the geographic co-locality of critical infrastructure sectors.

## 2 Elements of Comprehensive Emergency Management (CEM)

---

Comprehensive Emergency Management (CEM) covers all aspects of anticipating, minimizing the risks from, preparing for, and recovering from an emergency [12]. There is no country, no community, and no person immune to disaster [13]. According to Mileti [14], many losses from disasters are predictable, hence to some degree they are manageable. Effective disaster management reduces devastation and cost. This section describes the processes of disaster management, including the elements of CEM, and Critical Infrastructure Interdependency. A comprehensive emergency management system takes account of the interactions of institutions, financial mechanisms, regulations, and policies that form a country's approach to disaster risk management [15].

### 2.1 Disaster management cycle

In a sense, human adjustment to disasters is cyclical. Several studies [14-16] discuss the disaster management cycle as a model for managing disasters. This model classifies activities in two stages: pre- and post- disaster. By its implementation, disaster management can also be divided into operational and decision-making phases [14]. The disaster management cycle has four major phases, which are: preparedness, response, recovery and mitigation. (shown in Figure 1)

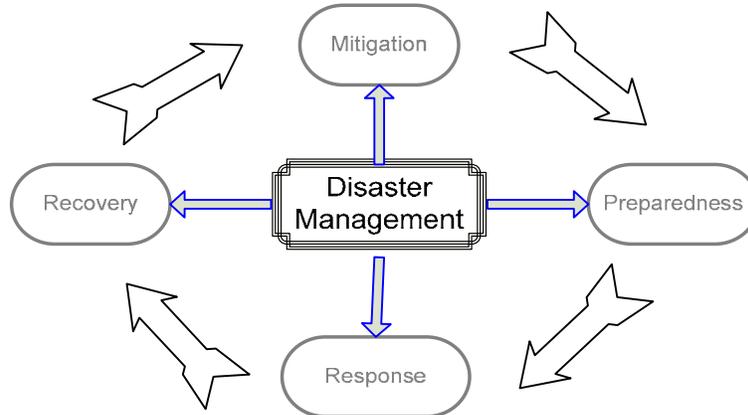


Figure 1. The disaster management cycle (modified from Carter [15]).

- 2.1.1 **Preparedness:** focuses on understanding needs and addressing the situation.
- 2.1.2 **Response:** addresses allocating resources towards timely relief.
- 2.1.3 **Recovery:** involves interdisciplinary effort to address not only the physical aspects of disaster recovery, but also the psychological and social aspects. International efforts may be involved.
- 2.1.4 **Mitigation:** deals with causes and impacts, with the aim of dealing with future disasters. It has two parts: structured mitigation and unstructured mitigation. Structured mitigation involves engineering work to prevent and mitigate disasters. Structural mitigation measures keep hazards away from people and buildings, or try to strengthen buildings and infrastructure to cope with hazards. Levees, dams, and channel diversions are examples of structural mitigation [14]. Non-structured mitigation involves wide interdisciplinary efforts aimed at determining vulnerabilities and threats to handle them efficiently. Policy, education, awareness and building codes are examples of non-structured mitigation.

## 3 Critical Infrastructure Interdependency

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Though infrastructure sectors are well-defined in Canada, there exists no consensus in definition for the activities and operations that shape this field. There is limited understanding of Canada's infrastructure interdependencies, vulnerabilities and methods for measuring and quantifying them. This is due to ever-increasing complexity and interconnectedness in infrastructure. Such interdependencies introduce vulnerability and risk to our society. Decision-making and support tools aided by case studies and scenario development in simulation are key areas for research [17]. Risks to an infrastructure sector cannot be estimated without conceptualization of the associated vulnerabilities and hazards [18]. Research on infrastructure interdependency has evolved as a branch of disaster and emergency management. Following major events (such as the Ontario power blackout in August 2003, and the outbreak of Severe Acute Respiratory Syndrome (SARS) in Toronto of 2003), the importance has been recognized for addressing infrastructure interdependency.

### 3.1 Canada's ten critical infrastructure sectors

Canada's critical infrastructures are the physical and information technologies, networks and assets which, if disrupted or destroyed, would have a serious impact on the health, safety, security or economic well-being of Canadians. They would also affect the functioning of government in Canada [19]. There are ten major infrastructure sectors in Canada [20], namely:

1. Energy and utilities (e.g., electrical power, natural gas, oil production and transmission systems);
2. Communications and information technology (telecommunications, broadcasting systems, software, hardware and networks including the Internet);
3. Finance (banking, securities and investment);
4. Health care (hospitals, health care facilities, blood supply, laboratories and pharmaceuticals);
5. Food (food safety, distribution, and agriculture);
6. Water (drinking water and wastewater management);
7. Transportation (air, rail, marine and surface transport);
8. Safety (chemical, biological, radiological and nuclear safety, hazardous materials, search and rescue, emergency services, and dams);
9. Government (services, facilities, information networks, assets, national sites and monuments); and
10. Manufacturing.

The business of analyzing, modeling and visualizing critical infrastructure is challenging from the perspective of emergency management. Spatial-based approaches are powerful, because they deal with large amounts of complicated data about infrastructure interdependency.

## 3.2 Types of infrastructure interdependency

Four types of infrastructure interdependencies are identified by [21]:

1. Physical interdependency;
2. Cyber interdependency;
3. Geographic interdependency; and
4. Logical interdependency;

Both physical and geographic interdependencies are relevant to spatial modeling and simulation. Two infrastructures are physically interdependent if each is dependent on the material output of the other. Infrastructures are geographically interdependent if the same local environmental event can create changes in all of them. Cyber and logical interdependencies are relevant to operational and financial contexts. An infrastructure has cyber interdependency if it depends on information transmitted through the information infrastructure. Two types of infrastructure are logically interdependent if each depends on the other in a way which is not a physical, cyber, or geographic connection. Traffic congestion provides an example: the logical interdependency between petroleum and transportation infrastructures is the result of human action, not as a result of the types of infrastructure in question.

## 3.3 Dimensions of infrastructure interdependency

Critical infrastructure interdependencies have an immense range of interrelated factors and conditions that can be conceived in six dimensions [21], where each dimension has at least two components. The dimensions are:

1. Type of interdependency;
2. Environment;
3. Coupling and response behaviour;
4. Type of failure;
5. Infrastructure characteristics; and
6. State of operation.

The challenge is to describe these in a succinct and useful way that can be used in decision support for emergency management. Figure 2 illustrates these dimensions and some of their components.

## 3.4 Modeling for infrastructure interdependency

When modeling infrastructure interdependency for disaster and emergency management, one challenge is the availability of modeling tools capable of mimicking complex situations. Another challenge is the accuracy, trustworthiness, and validity of such models. Otherwise, models might misguide informed decision-making under time-critical and extreme situations. How well do

these models behave in extreme situations? How can everyday operations be balanced with security concerns?

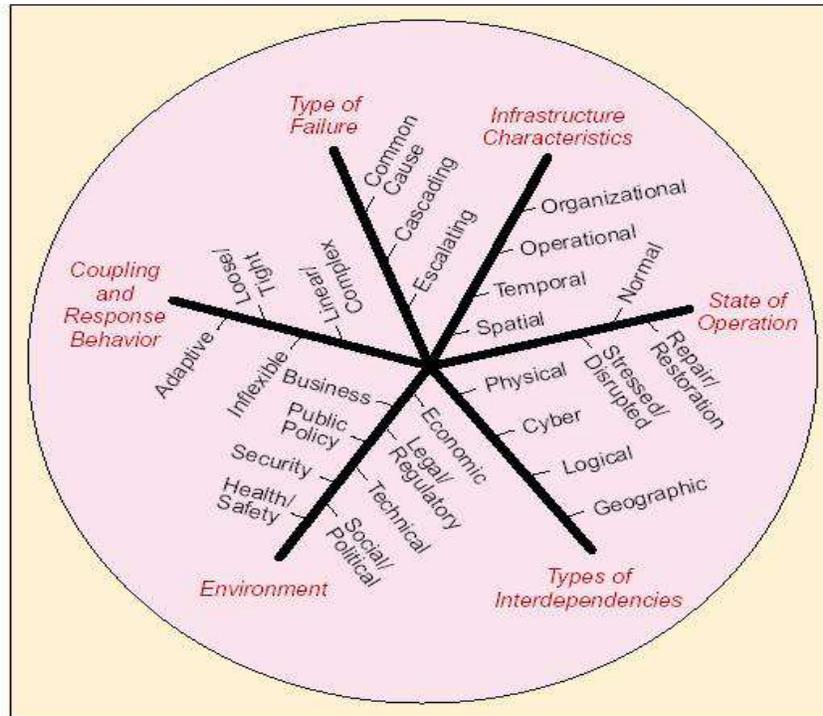


Figure 2. The six dimensions of infrastructure interdependency, after Rinaldi et al. [21].

According to Rinaldi et al. [21] infrastructure interdependency models are classified into six types:

- a) *Aggregate supply and demand tools* evaluate the demand for infrastructure in a region and the ability to supply those services;
- b) *Dynamic simulations* employ simulations to examine infrastructure operation, the effects of disruptions, and downstream consequences;
- c) *Agent-based models* integrate physical components of infrastructure as agents, allowing analyses of operational characteristics and physical states of infrastructure;
- d) *Physics-based models* analyze power flow and stability on energy grid networks (e.g., for modeling electrical grids using standard engineering techniques);
- e) *Population mobility models* examine the movement of entities in urban regions: for example, the entities may be people following daily routines; and

f) *Leontief input-output models* provide a linear, aggregated, time-independent analysis of the generation, flow, and consumption of commodities among infrastructure sectors.

Table 1 illustrates the factors and their implications for the analysis of infrastructure interdependency.

*Table 1. Factors affecting interdependency analysis (extracted from Rinaldi et al. [21])*

<b>Factor</b>	<b>Implications for Analyses</b>
Time scale	Infrastructure dynamics vary in scale from milliseconds (electrical grid disturbances) to decades (construction of major new facilities).
Geographic scale	Scenarios and issues range from cities to national or international levels. Scale affects the resolution and quantity of infrastructure and interdependency data.
Cascading or higher-order effects	Disruptions in one infrastructure can ripple or cascade into other infrastructures, creating second- and higher-order disruptions.
Social and psychological elements	Social networks and behavioural responses can influence infrastructure operations, as evidenced by the spread of an infectious disease and the response by public health infrastructure.
Operational procedures	Company-specific procedures influence the state of an infrastructure, say, by response to market fluctuations.
Business policies	Specific corporate business policies affect infrastructure.
Restoration and recovery procedures	Company-specific procedures influence infrastructure during crises, and coordination among infrastructure owners may be difficult. Cross-infrastructure restoration and recovery procedures may not exist.
Government regulatory, legal, and policy regimes	Government actions influence operations in response to and recovery from disruptions.
Stakeholder concerns	Stakeholders have motivations and concerns that drive simulation requirements.

## 4 The Concept of Location-Based Critical Infrastructure Interdependency (LBCII)

---

Location-Based Critical Infrastructure Interdependency (LBCII) is part of the geographic infrastructure interdependency discussed in Rinaldi et al. [21]. LBCII incorporates physical interdependency. Its major characteristic is that it can integrate spatial factors on a micro-scale with associated physical aspects. LBCII provides decision-makers with an ability to model and visualize each critical infrastructure sector by integrating GIS with other scientific modeling techniques [22]. LBCII enables decision-makers to identify co-existing relationships through answering the following questions:

1. Which sectors are co-located?
2. What are the cascading, escalating and common-cause failures that can co-occur in extreme events?
3. What might cumulative losses be?
4. What kind of individual damage and what combined damages might these sectors sustain?

### 4.1 LBCII as an emergency management concept

LBCII is a preparedness and response concept that uses an efficient tool [4] to integrate modeling capabilities in network-centric visualization for decision support. One must distinguish between standard GIS functionality and LBCII as a concept that uses basic GIS functions to produce information for decision-makers. LBCII uses disaster management principles, GIS functions, and diverse modeling tools for the benefit of decision-makers. Based on the concept of infrastructure interdependency (discussed in Section 3), GIS can be integrated with other modeling software in LBCII can address interdependency questions about cascading effects on particular locations for example. GIS is the backbone to LBCII; it is principally a database (beginning with a Geodatabase model) used to store spatial and non-spatial information from modeling. Hydraulics modeling information, geological information and non-spatial information can all be integrated in the Geodatabase. LBCII uses basic emergency management principles as well as GIS integration and analytical capabilities to provide decision support for disaster management. (A summary of GIS integration capabilities for LBCII is shown as Figure 3.)

LBCII can provide efficient support to decision-makers. Events like the August 2003 blackout in Southern Ontario and in the Northeast region of the United States, underscore the need for detailed knowledge of critical infrastructure and infrastructure dependence.

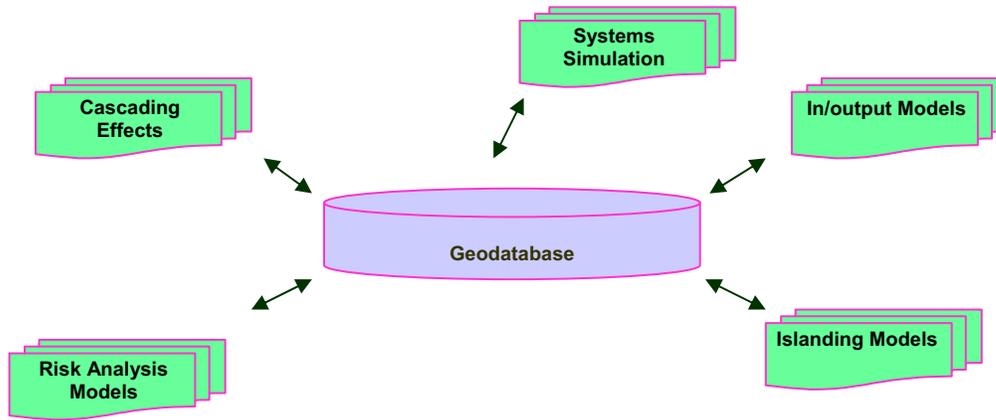


Figure 3. The concept of GIS integration for LBCII.

## 4.2 Identifying LBCII

According to Abdalla et al. [23], using the LBCII concept in a particular scenario is of great importance. The process involves 6 steps as following:

1. Identify critical infrastructure sectors at risk in the study area;
2. Analyze processes and operations for each sector to identify risks;
3. Analyze dependencies and vulnerability to those risks;
4. Determine interdependencies;
5. Model and visualize; and
6. Implement a risk management plan.

## 5 Case Study

Spatial technologies have proven to be crucial for collaborative decision-making in disaster management [24]. With emphasis on LBCII, this demonstration aims at exploring a range of modeling and visualization capabilities for emergency management, towards the identification of functional requirements for modeling and visualizing emergency scenarios.

### 5.1 Scenario

An earthquake scenario was developed in consultation with the Geological Survey of Canada (GSC), the provincial government of British Columbia, and the city of Vancouver's Emergency Management Department. The scenario is realistic in that it has reasonable probability, based on the tectonic geology and the history of the region. The case highlights the usability of network-centric GIS in providing data visualization. The storyline for the earthquake scenario focuses on a shallow 7.3 event in the Modified Mercalli Intensity Scale (MMIS)[25], a subduction earthquake in the Strait of Georgia (Latitude 49.45 degrees, Longitude 123.941 degrees) with no surface rupture. At this magnitude and location the following is plausible: a landslide on Hornby Island, fracture damage to buildings in Vancouver, and a dam breach with inundation on the west coast of the mainland. Figure 4 shows the location.

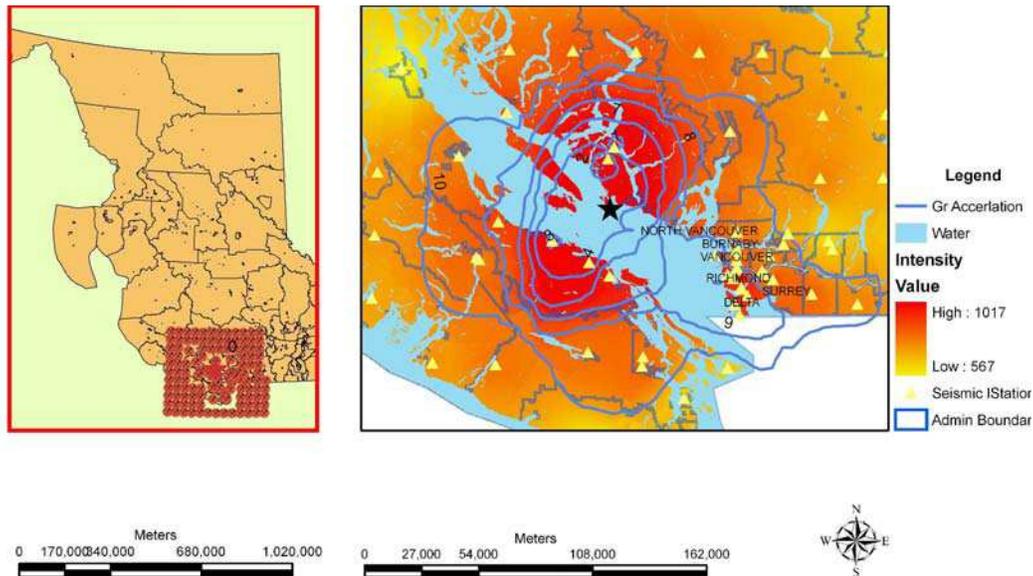


Figure 4. Event location and a colour-coded Shakemap of the study area, Southwest British Columbia. The map on the left shows the province of British Columbia and the study area.

Analyses of different modeling and visualization techniques were made. An investigation of data and processing requirements for modeling were also conducted, followed by an analysis of functional requirements (in terms of what GIS operations are required for LBCII). The chain of logical modeling is shown in Figure 5. This Figure illustrates three pillars for the physical modeling of critical infrastructure interdependency.

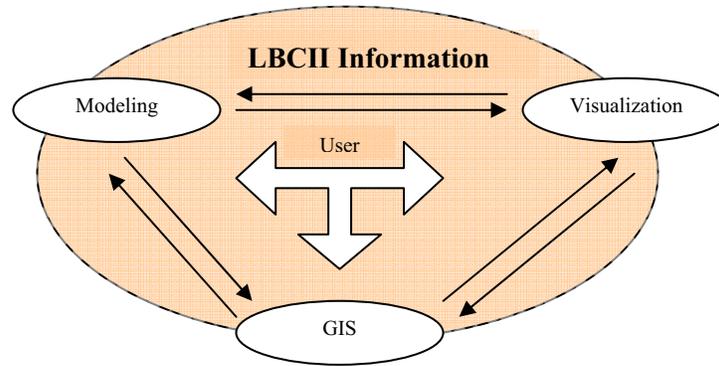


Figure 5. The development of a logical model for analyzing LBCII.

## 5.2 Spatial modeling for disaster management

This phase involved event-driven simulation scenarios based on a natural disaster (an earthquake) in the major metropolitan centre of Vancouver. The scenario was selected because it poses a significant and probable hazard. Data from GSC, British Columbia Emergency Measures, Greater Vancouver Regional District, and DMTI Spatial (DMTI) were used. The spatial modeling techniques were based on a proprietary GIS package known as GeoServNet<sup>®</sup>, which was developed by the GeoICT Lab at York University, Toronto, Ontario.

### 5.2.1 Data requirements

There are problems with availability, access and use of reliable and up-to-date data for disaster management [24]. Data sets were provided by several agencies: they consisted of vector shapefiles, IKONOS satellite imagery and an earth Shakemap. Shakemaps represent ground motions as recorded and extrapolated from knowledge of surface soil conditions. Shakemaps show a two-dimensional (2D) map of an event location, colour coded by earthquake magnitude. The area nearest the epicentre with high magnitude is coloured in red; colour grades move towards yellow as one moves away from the epicentre. Data from the Canada Centre for Remote Sensing (CCRS), Statistics Canada, the City of Vancouver, DMTI Inc., GSC and the Province of British Columbia have been of great help to this study. Vector datasets represented by obstruction layers and raster data sets (in the form of Digital Elevation Models or DEM) were used for the analysis [26].

## 5.2.2 Data processing

Data processing was performed in two stages: desktop and network-centric processing. Desktop processing involved data processing and manipulation operations, and was conducted using Environmental Systems Research Institute (ESRI) ArcGIS 9 desktop package. The network-centric processing involved GeoServNet<sup>®</sup> for the visualization of results. The details of these two phases are described below.

### 5.2.2.1 Desktop processing

Data processing was an important component of analysis because the data were made available by different providers. Population, roads, and other infrastructure data were obtained, and found to be crucial in damage assessment. Editing and processing operations included clipping, georeferencing, attribution, and vector/raster conversion. They were applied as necessary to maintain consistency between data sets. Figure 6 shows the desktop-based modelling process.

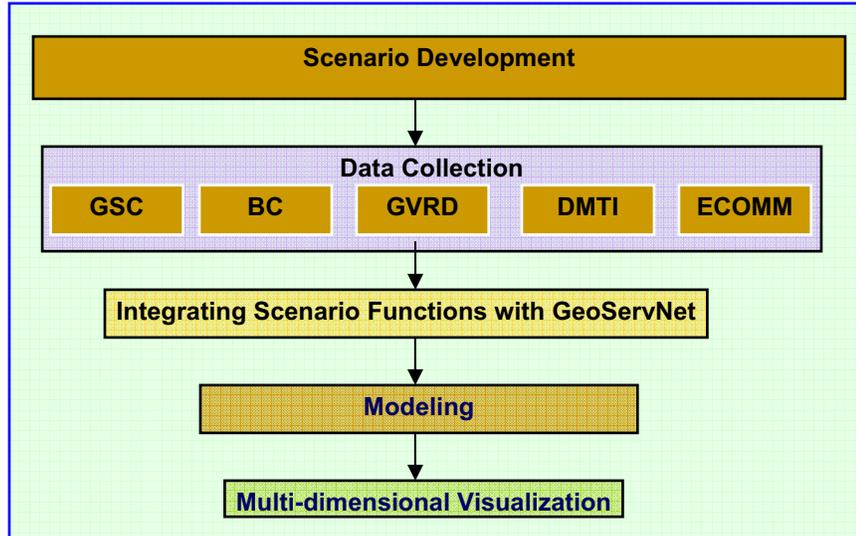


Figure 6. The infrastructure modeling process.

### 5.2.2.2 Network-centric processing

GeoServNet<sup>®</sup> is a 2D/3D web-based GIS package developed by York University's GeoICT Lab. It generates three-dimensional (3D) models that can be used as a meaningful interface for querying features, hyper-linking web-based sensor information, analyzing model results, visualizing model results, and accessing simulation models. GeoServNet<sup>®</sup> (GSN) provided an accessible data publishing facility through its modules (i.e., GSNBuilder, GSAdministrator, GSNServer and GSNPublisher and GSN Viewer) [27]. The task of GSNBuilder is to assemble data (i.e., Shapefiles, JPEG Raster and ASCII DEM) and configure them in registration with the GSNServer, using GSAdministrator.

The main function of GSNPublisher is to set visualization parameters in terms of visual effects (i.e., colour, line thickness and transparency). Another function of GSNPublisher is to generate the application file that is linked to the web, making a project available online. The GSN viewer is any web browser used for the visualization. Figure 7 shows the architecture of GeoServNet® version 1.5; this version expands the use of the five modules shown in the figure below to provide 3D visualization capabilities.

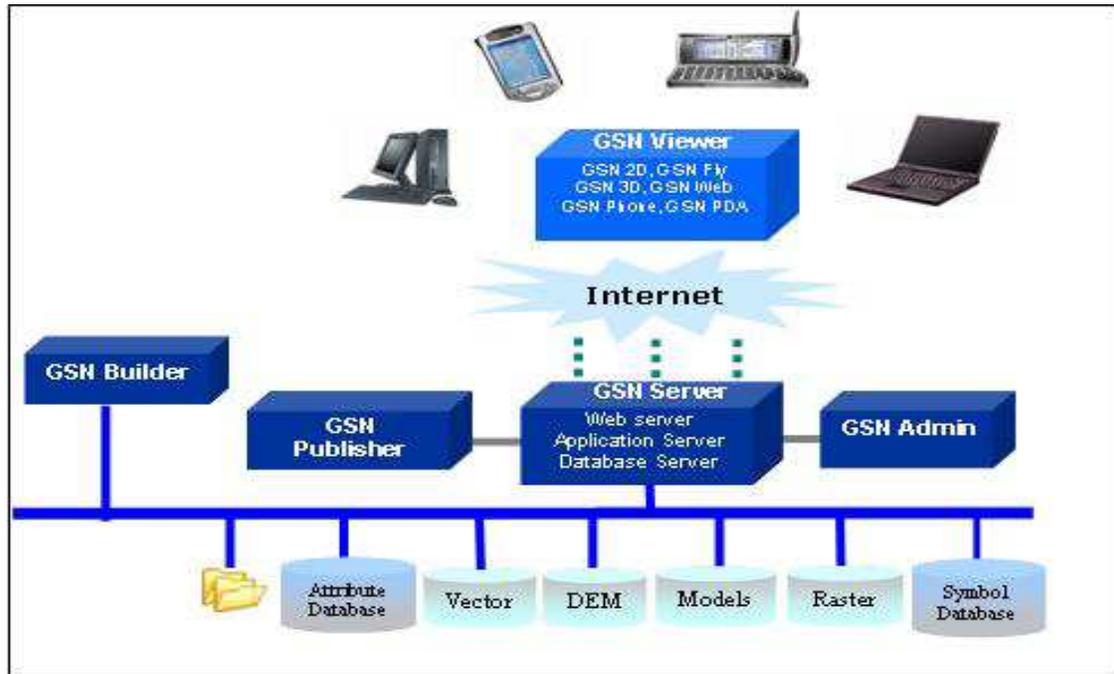


Figure 7. The architecture of GeoServNet®, v. 1.5.

## 5.3 LBCII Analysis

GIS modeling is an efficient technique when dealing with environmental processes [28]. Gunes and Kovel [29] discusses spatial modeling for emergency management, and Sugumaran et al. [30] discuss the role of GIS as it is used by emergency managers to gain understanding of emergency events. GIS can be used as a planning tool to provide “what if” simulation and situational awareness to aid in preparing, mitigating and responding to emergency situations.

### 5.3.1 Spatial Interdependency

The term ‘spatial interdependency’ is defined by Zimmerman [31] as the proximity of one infrastructure to another, as in the major relationship between two systems. In the scenario described herein, GIS analysis was used to identify highways most at risk. It was possible to map highways and railways most likely to be damaged during a 7.3 MMI earthquake (see Figures 8a

and 8b). The results are summarized in Table 2, which is extracted from the GIS database attribute table.

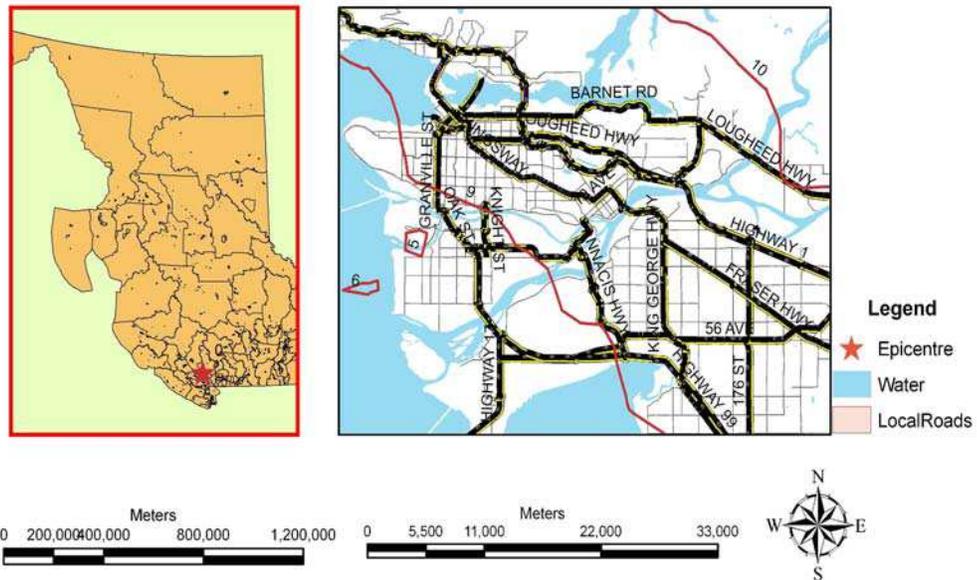


Figure 8a. Vancouver highway critical infrastructure at risk.

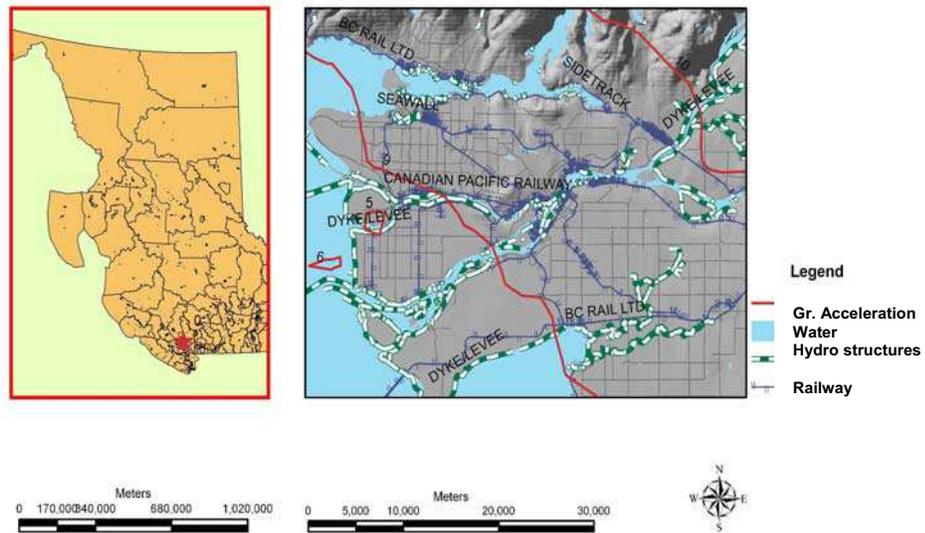


Figure 8b. Vancouver's railway critical infrastructure at risk.

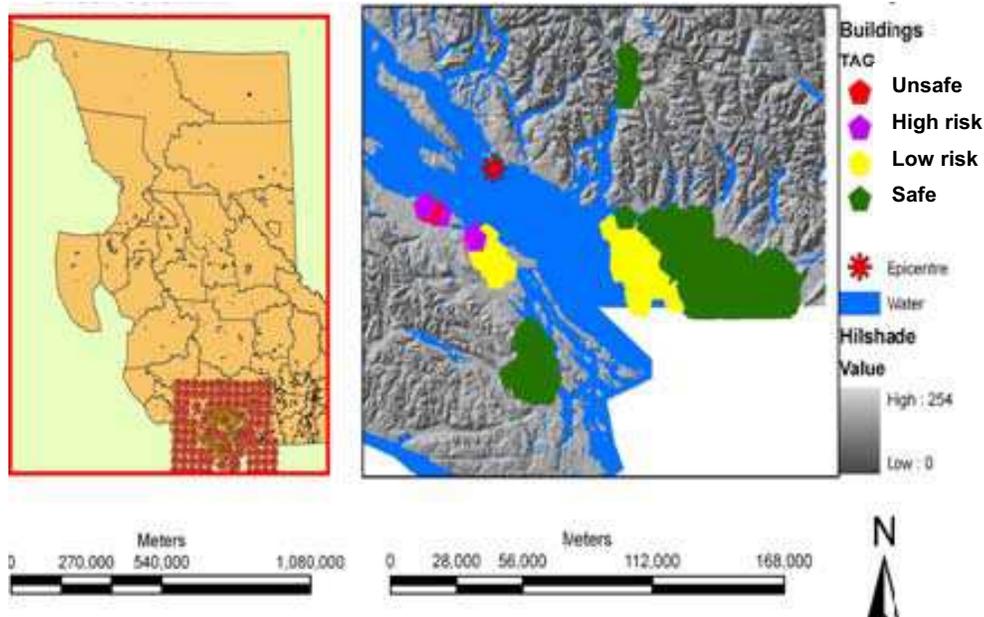
Table 2. Classification of buildings at risk.

OBJECTID*	CODE	FEATURE	CATEGORY	Shape_Length
1	106	ARENA	Recreation and Entertainment	0.002291
2	131	HALL	Government and Institutional	0.001373
3	147	OTHER	Other	0.001924
4	147	OTHER	Other	0.002512
5	147	OTHER	Other	0.003704
6	160	SCHOOL	Education	0.002040
7	160	SCHOOL	Education	0.004102
8	160	SCHOOL	Education	0.004290
9	160	SCHOOL	Education	0.001430
10	160	SCHOOL	Education	0.001405
11	165	SHOPPING CENTRE	Shopping and Services	0.003012
12	165	SHOPPING CENTRE	Shopping and Services	0.009859
13	165	SHOPPING CENTRE	Shopping and Services	0.007576
14	176	LODGING FACILITIES	Food and Lodgings	0.001627
15	179	EDUCATIONAL BUILDING	Education	0.003073

The difficulty in GIS modeling and analysis lies in identifying tools and techniques that are best suited to task [32]. The ArcGIS ‘spatial analyst’ extension was used to produce data models, including population concentration density, building damage zones, and earthquake intensity. Buildings in the study area were classified into: high risk buildings, low risk buildings, safe buildings. Spatial analysis techniques identified the location of each of these identified categories. By comparing the distribution of buildings with the Shakemap and percentage ground acceleration (PGA) layer, it is evident that most severe damage occurs near the epicentre. Twenty-four buildings are found to be at risk of total destruction. Of these, nineteen are classified as ‘barn/machinery shed’, while another six buildings are classed as religious institutions. All are located northwest of Vancouver in a rural area. Infrastructure sector vulnerability gives detailed information about the types of buildings that are at risk. Each building is identified (as in Table 2) as, say, a school, a college or a government building. This categorization is important in emergency preparedness, since it provides decision-makers with an accurate picture of needs. Detailed analysis of risk zone maps and building layers reveals the spatial distribution of buildings and infrastructure within each risk zone. This can help in protecting the public by leading to the enforcement of building standards, and an indication of which standards can be incorporated in civil engineering earthquake loss-estimation models.

It was possible to visualize critical infrastructures and to identify the areas most vulnerable to damage using the LBCII concept (Figure 9a). All infrastructure sectors at risk were selected

using GIS analysis functions. After they were identified on the map, Table 2 was produced to list these vulnerable segments. Twenty-three hydro structures around Vancouver are at risk. The most severe damage to hydro structures would be north of Grant McConachie Way on Sea Island. The dyke west of No. 1 Road would also sustain severe damage (Figures 8b and 9b show hydro structures at risk). The ground acceleration line defines the intensity and severity of risk at each zone of the area's ten MMI zones. Forty-four telecommunication towers are also at risk in the same area. Figure 9b illustrates some consequences for Personal Communications Systems (PCS) towers.



*Figure 9a. Building vulnerability around the City of Vancouver. The province of British Columbia and the location of the study area are shown on the left.*

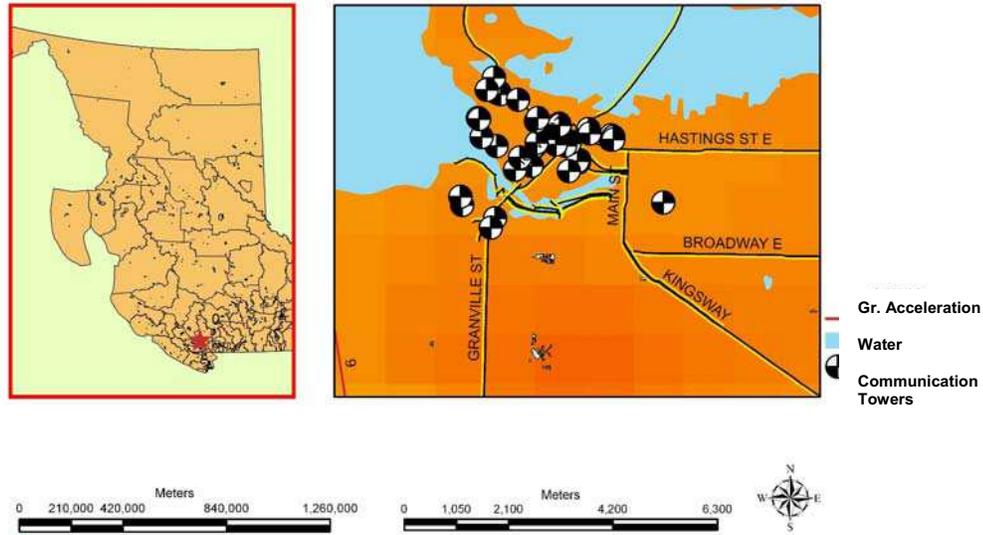


Figure 9b. Telecommunication towers affected in Vancouver.

### 5.3.2 Population at risk

Earthquakes can be devastating with large losses in population. Scawthorn [33] discusses the process of earthquake risk management, and indicates how emergency management begins with the *population* at risk from earthquakes. GIS modeling is effective in identifying populations at risk under a variety of hazard scenarios. Casciati et al. [34] have used GIS to design a flexible and rapid GIS damage assessment system.

Census data were obtained from Statistics Canada, an earth Shakemap from GSC, and some infrastructure data from the City of Vancouver (see Figure 10 for composite population concentration). Using the Shakemap, it was possible to identify population categories at each risk zone (high risk, low risk, and safe zone as shown in Figure 11). Similarly, Amdahl [35] used a Shakemap of California's Northridge earthquake to identify soil classification as an indicator of the most vulnerable zones. The density of populations at risk in each Vancouver zone was computed with the data obtained in this study. The results are in agreement with results from the building damage density analysis in Figure 12.

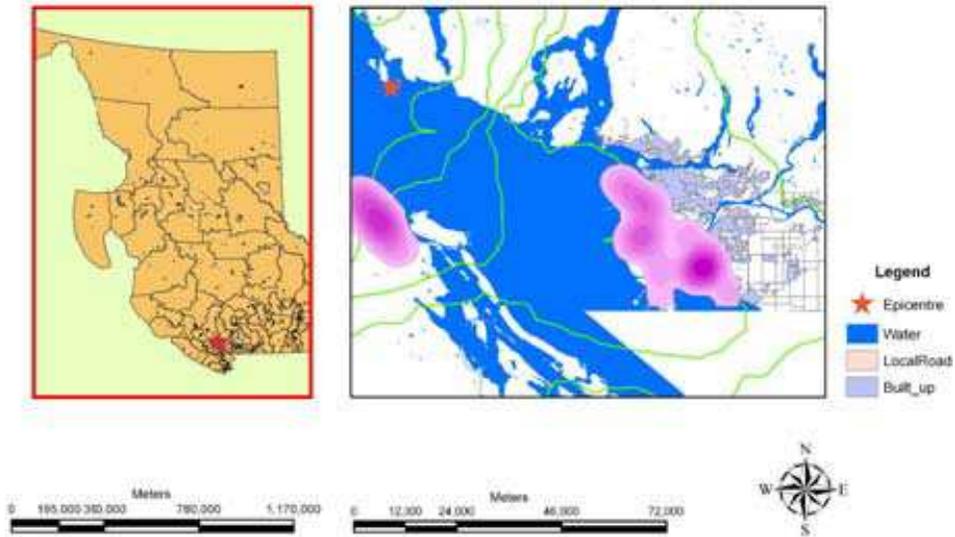


Figure 10. Population concentration in the city of Vancouver.

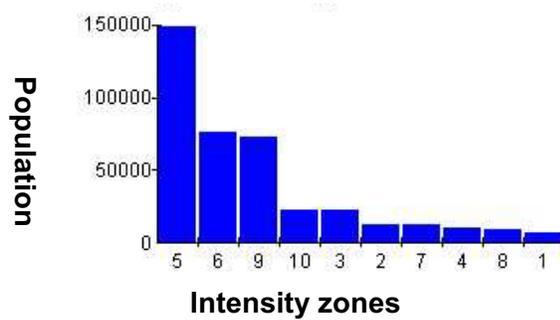


Figure 11. Distribution of population at risk by MMI Zone.

## 5.4 Visualization of LBCII

Many researchers [8, 36-41] have recognized the advantage of GIS visualization capability, which allows for detailed logical and conceptual understanding of complex relationships in data [42]. Effective use of spatial models requires effective methods for visualization. According to Kreuseler [42], GIS data visualization is the presentation of data using digital images, vector data, digital elevation models, tabular information, and virtual reality, in either 2D or 3D presentations, in static or animated form. Many visualization techniques can be applied to real-world problems

[43]. Davis [44] indicated that GIS visualization helps decision-makers to identify spatial patterns and processes. Problems at hand are easier to solve, especially when multiple perspective views are readily available.

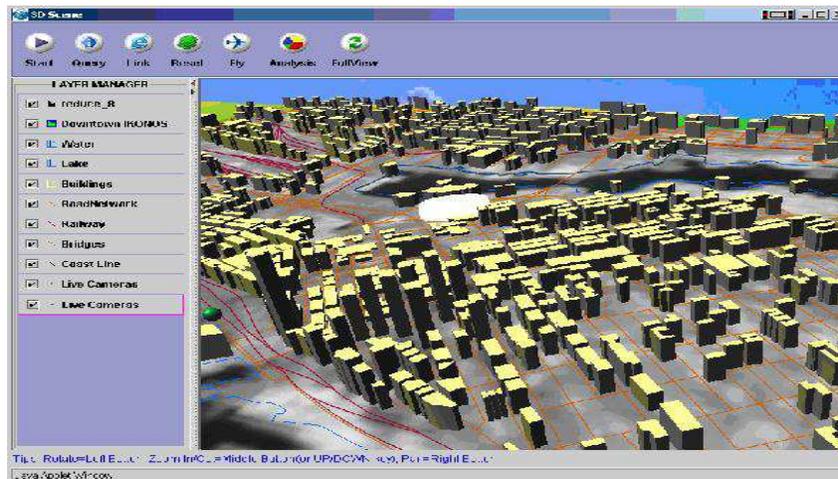


Figure 12. GSN 3D damage assessment model of downtown Vancouver.

#### 5.4.1 3D network-centric visualization with GeoServNet® (GSN)

The rapid emergence of the Internet in the past decade has allowed the development of technologies such as network-centric visualization [45]. Developments in both computer hardware and software have removed limitations to the process of large volumes of data. High-end digital storage, computer processors, and expanded memory are now inexpensive and efficient for handling large volumes of data [46]. Internet clients (i.e., Internet Explorer, Netscape and Firefox) as well as programming languages (such as Java, HTML and XML) have revolutionized web-based visualization. Visualization capabilities are now accessible for disaster and emergency management, all of which makes visualization integral to GIS.

Abdalla et al. [47] indicate that 3D GIS provides ‘close-to-reality’ models, allowing users to recognize and understand changes in elevation, patterns, and features quickly. Many studies [48-50] have shown that the advantage of 3D lies in the way one sees information. 3D displays enhance realization of the spatiality of the world. By living in a 3D world, it is natural that one perceives and visualizes information in 3D better than in 2D.

GSN was used to produce network-centric models of a desktop earthquake scenario in this study. Figure 12 illustrates the effect of 3D GIS in modeling and visualization. Results from this simulation model show that GSN handles multiple scenarios well. This makes it feasible to integrate a variety of data sources in the production of models for disaster management.

## 5.5 Challenges for modeling and visualization of LBCII

Infrastructure interdependency is a new field; only a few researchers are working in the area. A lack of background literature increases the complexity of the study. A primary challenge is that there is no one definition for types of interdependency, or for types of failure. One of the challenges is the interdisciplinary nature of disaster management research and the difficulty in addressing different issues at the same level of complexity simultaneously. Lack of references and resources adds to the complexity of modeling such real-world situations [31, 51].

In addition, most current technologies address issues related to a single infrastructure sector. By contrast, there are limited software solutions for the modeling and visualization of infrastructure interdependency. Technologies for addressing collective impact are beginning to evolve. For example, Rinaldi et al. [21] indicate that a comprehensive architecture to address LBCII issues is a major challenge because of the complex interconnectedness between critical infrastructure sectors. Most current technologies focus on temporal properties, and leave an obvious gap in the spatial aspects.

Further, there are other issues that may lead to delays, such as critical infrastructure data availability and accessibility. Restrictions on access emerge from business competition factors or from security issues; for example, such restrictions are prominent in dealing with data for telecommunications and energy.

## 6 Conclusions

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LBCII helps to identify geographic infrastructure interdependencies in critical infrastructure sectors that are co-located in a domain. LBCII incorporates location, along with basic and advanced GIS analysis, to provide decision-makers with solutions that are transferable among infrastructure sectors. LBCII is a solution to the issue of modeling critical infrastructure interdependency at the micro level. GIS can be used as a planning tool to provide “what if” simulation and situational awareness. This helps emergency managers in preparing, mitigating and responding to emergencies. WebGIS methods and techniques are best used in detailing the spatial coexistence and spatial interdependencies of infrastructure sectors. This approach was tested using earthquake scenarios. LBCII can also be used to elucidate scenarios with infrastructure systems such as surface transportation, surface water and utilities.

In this study, LBCII was used to examine an earthquake scenario in the city of Vancouver. It was found that the mapped highways and railways in and around the city of Vancouver are likely to be damaged in a 7.3 MMI earthquake. Twenty-three hydro structures around Vancouver were found to be at risk. The most severe damage to hydro structures would be north of Grant McConachie Way, on Sea Island near Vancouver airport. The dyke west of No 1 Road would also be affected strongly. Buildings in the study area were classified into three categories: high risk, low risk and safe zone. Spatial analysis was used to identify the location of each group, and to identify risk level with consideration of population concentration and building damage by zone. By taking electrical failure as one result of the earthquake, many critical infrastructures were shown to be affected. The immediate and highest impact would be on emergency services; 911 emergency operations would be unable to function at full and secure capacity. Traffic would not flow normally after the primary shock. Traffic delays would be caused by loss of synchronization of traffic lights. Though this approach can be developed for other infrastructures like health care and utilities, LBCII is based on geographic infrastructure. However, implementation of this approach might not suit all ten of Canada’s major infrastructure sectors, because a spatial component is not prominent in all of them (in contrast to logical interdependencies).

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## List of symbols/abbreviations/acronyms/initialisms

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2D	Two-dimensional
3D	Three-dimensional
BC	British Columbia
CCRS	Canada Centre for Remote Sensing
CEM	Comprehensive Emergency Management
DEM	Digital Elevation Model
DMTI	DMTI Spatial - Commercial GIS Data Provider
DRDC	Defence Research & Development Canada
ESRI	Environmental Systems Research Institute
GIS	Geographic Information Systems
GSC	Geological Survey of Canada
GSN	GeoServNet®
GVRD	Greater Vancouver Regional District
IKONOS	IKONOS Satellite Imagery
LBCII	Location-Based Infrastructure Interdependency
MMI	Modified Mercalli Intensity scale
PGA	Percentage Ground Acceleration
PCS	Personal Communications Systems
SARS	Severe Acute Respiratory Syndrome
WebGIS	Web-based Geographic Information Systems

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(U) This report presents the notion of Location-Based Critical Infrastructure Interdependency (LBCII), and the steps to identifying such interdependency. A scenario is simulated of a shallow 7.3 on the Modified Mercalli Intensity Scale (MMIS) subduction earthquake in the Strait of Georgia, British Columbia (at latitude 49.45 degrees and longitude 123.941 degrees). Spatial and functional interdependencies were shown in simulation. A total of twenty-three hydro-structures around Vancouver, British Columbia were found to be at risk. Potential damage was most severe to the north of Grant McConachie Way, on Sea Island near the Vancouver airport. The potential for building damage was assessed across ground acceleration zones. Three categories of building damage were identified: high risk, low risk, and safe. Spatial analysis helped identify levels of risk. These levels take into account population density in the building damage zones, and by identifying electrical failure as a consequence of an earthquake. It was possible to visualize the other effected critical infrastructure sectors. This report emphasizes visualization capabilities of (WebGIS) a web-based, geographic information system, and outlines strengths and weaknesses in the spatial models used for web visualization. Issues identified in the development of spatial models for LBII are related to data access, input and processing requirements.

(U) Ce rapport présente la notion d'interdépendance géographique des infrastructures essentielles (IGIE), et les mesures permettant de relever ces interdépendances. Dans le scénario que nous décrivons, un séisme de subduction à faible profondeur et d'une intensité de 7,3 sur l'échelle de Mercalli modifiée (MM) est simulé dans le détroit de Géorgie, en Colombie-Britannique (latitude de 49,45° et longitude 123,941°). Les interdépendances spatiales et fonctionnelles ont été illustrées dans la simulation. En tout, 23 structures hydroélectriques autour de Vancouver ont été jugées à risque. Les dommages potentiels les plus graves se sont produits au nord de Grant McConachie Way, sur l'île Sea, près de l'aéroport de Vancouver. Le potentiel de dommages aux bâtiments a été évalué dans les zones d'accélération du sol. Trois catégories de dommages aux bâtiments ont été constatées : risque élevé, risque faible et risque nul. L'analyse spatiale a permis d'identifier les niveaux de risque. Ces niveaux prennent en compte la densité de population dans les zones de dommages aux bâtiments, et ainsi que les pannes électriques dues au séisme. Il a été possible de visualiser les autres secteurs d'infrastructures essentielles touchés. Ce rapport met l'accent sur les capacités de visualisation de WebSIG, un système géographique d'information basé sur le Web, et il décrit les forces et les faiblesses des modèles spatiaux utilisés pour la visualisation sur le Web. Les problèmes constatés dans la mise au point de modèles spatiaux pour l'analyse IGIE ont trait aux exigences d'accès, de saisie et de traitement des données.

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(U) Infrastructure Interdependency, WebGIS, Disaster and Emergency Management



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