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12

Flood Progression Modelling and Impact Analysis

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1. Introduction

People living in the lower valley of the St. John River, New Brunswick, Canada, frequently experience flooding when the river overflows its banks during spring ice melt and rain.
Media reports reveal devastating effects of the latest floods that hit New Brunswick, Canada during the summer of 2008 (CTV, 2008). The rising water levels forced the closure of the New Brunswick Legislature, and also resulted in the temporary closures of the international bridge that links the Province to the United States of America. It also closed the operation of the Gagetown ferry. Fredericton experienced its worst floods in 1973, when the St John River reached the 8.6 m mark (ENB-MAL, 1979).
The 2008 flood was recorded as one of the major floods experienced in Fredericton after the 1973 flood (see Figures 1 and 2). On April 24th 2008, due to rapid melting of snow set by an unusually severe winter and combined with intense rainfall, the water level of St. John River reached 7.2 m (TC, 2008). The water levels in Fredericton raised by a meter overnight to 8.33 m on May 1st. Raising St. John River levels peaked at 8.36 m on May 2nd, almost reaching the previous record of 8.61 m set in 1973 (CIWD, 1974).
The closure of roads, government buildings followed by the evacuation of people and their possessions during floods is necessary to avoid the loss of life and property. Raising river water levels could affect electrical, water and telecommunication facilities. It could also affect the sewage system. In such a situation, the public buildings washrooms cannot be used. The question that the government officials are facing is: "When can an office be declared risky to occupy?" The decisions to close public utilities require strong reasons. Such decisions have social, economic and political impacts on the community.
City Managers will require reliable support for the decision to close down government infrastructure. To facilitate this process, we propose the use of 3D flood modelling,

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embedded on 3D terrain together with infrastructure (electrical power, water, telecommunications) and buildings to make correct decisions on when buildings and infrastructure are declared unsafe to use.

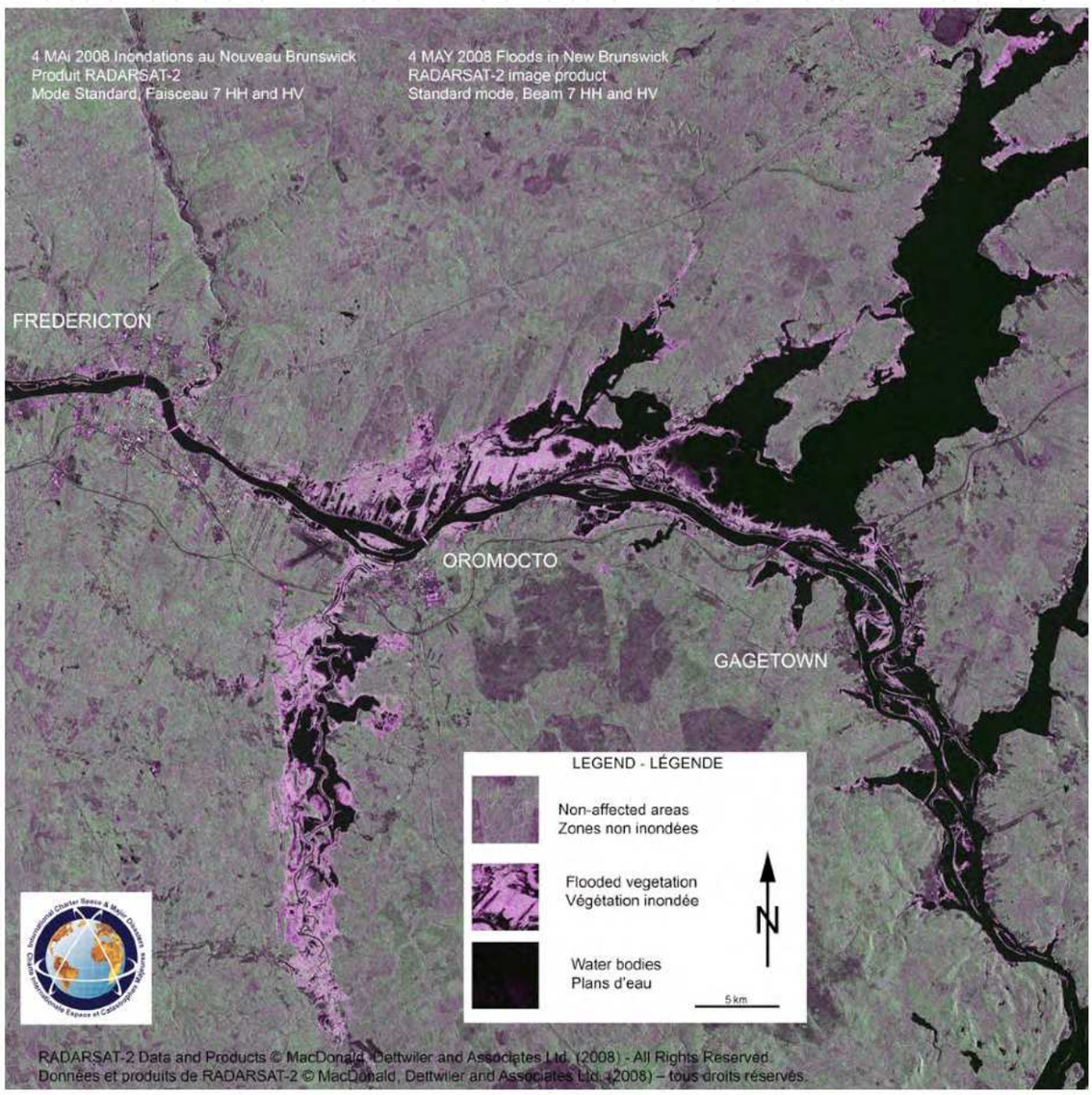


Fig. 1. Flood monitoring using satellite imagery

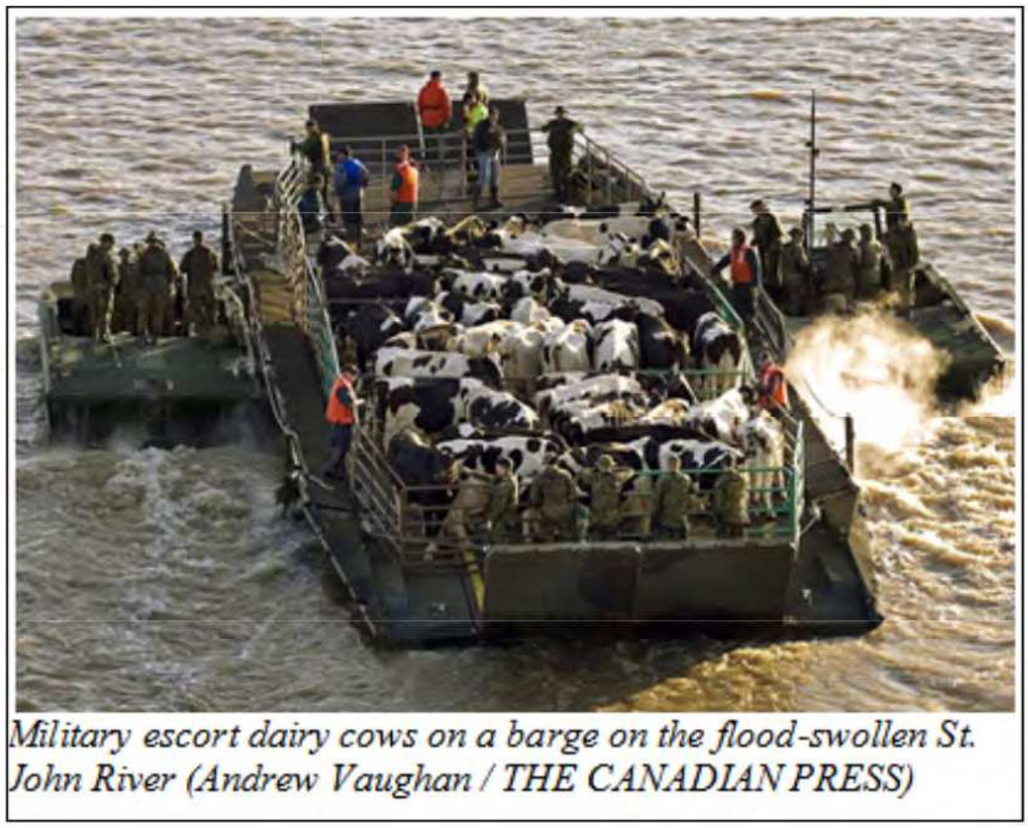


Fig. 2. Evacuation of diary cows during the flood in 2008

2. Previous research

Since ancient times, humans have developed means to monitor flood levels and to some extent, predict the rate of flood rise. People in medieval times marked animals and pushed them down the river to see how deep the river was. According to the director of EMO, Ernest McGillivray, his grandfather had a self-calibrated stick that he used to insert in the river to compare and forecast river flood levels.

Today, more innovative technologies have been developed to study floodings (Jones, 2004; Marks & Bates 2000). These include satellite remote sensing, aerial photogrammetry and LiDAR. Such technologies are combined with computer terrain modelling tools to create scenarios for analysis, as in the case of Geographic Information Systems (GIS).

Previously, the New Brunswick Emergency Measures Organization (EMO) in collaboration with the University of New Brunswick, Canada developed a flood model (available from http://www.gnb.ca/public/Riverwatch/index-e.asp) for the area of lower St. John River, New Brunswick, Canada (EMO, 2008).

The research done so far on early mapping and flood monitoring in the lower St. John produced a web-based system for flood warning (Mioc et al., 2008; Mioc et al., 2010), publicly available to the population living in this area (see Figures 3 and 4). However, the accuracy of existing elevation data was a major problem in this project. The maps we were able to produce were not accurate enough to effectively warn the population and to plan the evacuation. Another problem we faced in the 2008 flood was that even though the buildings were not affected by the flood the electrical and water facilities were not functioning, so the

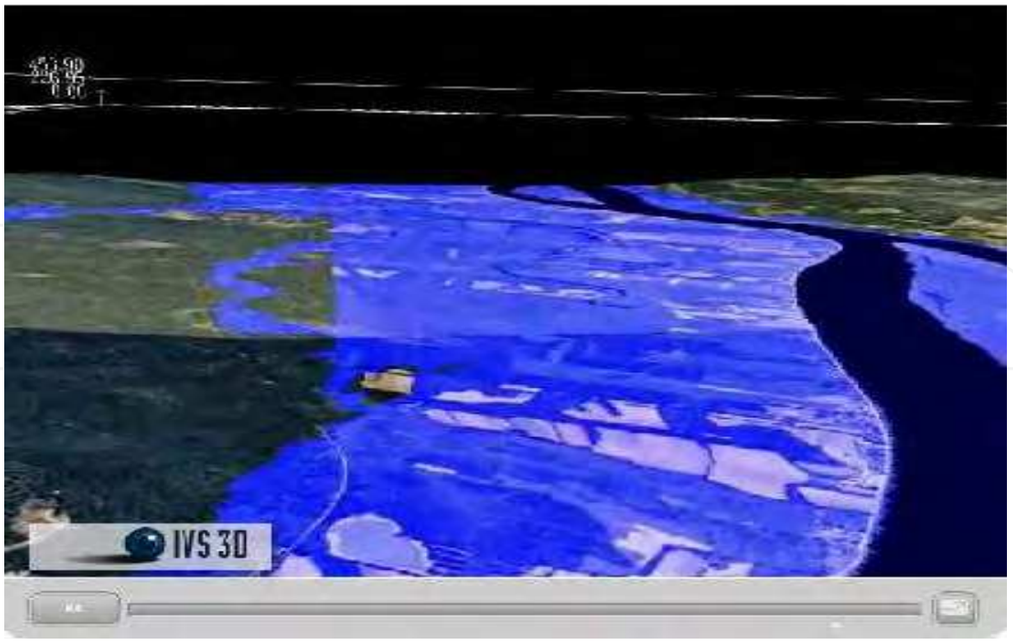


Fig. 3. Fly through simulation of the extreme flood in 1973

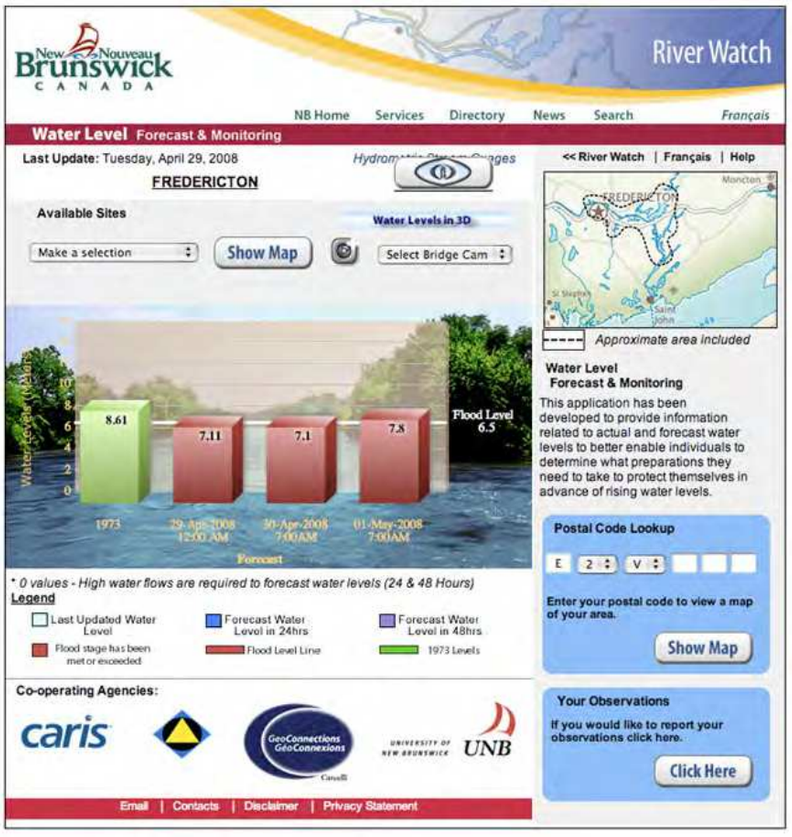


Fig. 4. Riverwatch website for flood warning

buildings and houses were inhabitable. The elevated groundwater levels would affect the power cables causing power outages and the old plumbing installations would cause sewer back-propagation due to the pressure of the rising water from St. John River.
Current visualization methods cannot adequately represent the different perspectives of the affected infrastructure. It can be seen that the building models are represented by polygons only and the detailed 3D views of the buildings and terrain affected by the flooding do not exist. As a result, the public may not have adequate technical or analytical know-how to analyze the polygons. Therefore, they may not find the River watch website very useful (see Figure 4). To overcome these problems we had to develop a new digital terrain model and new techniques for flood modelling. In order to improve the existing digital elevation model we needed to use new technologies for data acquisition (Moore et al., 2005).

3. Data collection and processing

In our research efforts to improve the accuracy of the elevation data, we used new Light Detection and Ranging (LiDAR) data acquisition and LiDAR data processing. Furthermore, the hydrological modelling was integrated with processed LiDAR data within a 3D GIS application.

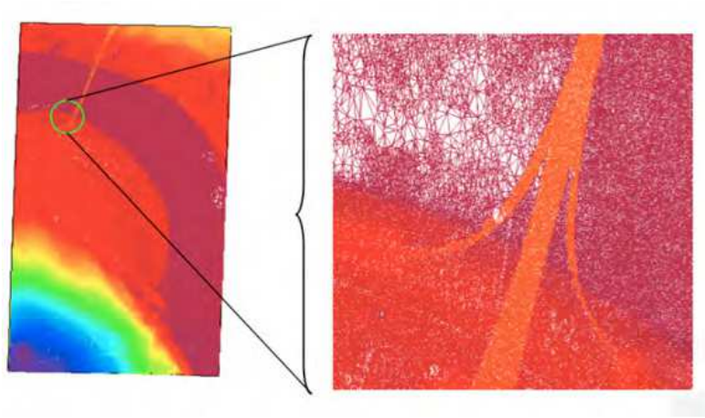


Fig. 5. LiDAR data processing

Light Detection and Ranging (LiDAR) (see Figure 5) has become a useful technology for collecting point cloud data for three-dimensional surface representations. The ability to quantify vegetation height, the roughness of the ground surface, ground elevation, and nearby buildings has greatly improved the parameterization of the two-dimensional hydraulic models, currently at the forefront of flood impact assessment studies (Kraus & Pfeifer, 2001; Hodgson & Bresnahan, 2004).

3.1 Available data

In this research, the newly acquired LiDAR data and Tidal gauge readings from May 1st to May 4th, 2008 were used to delineate the extent of flood during the 2008 flood in Fredericton. Elevation data of Fredericton were obtained using LiDAR techniques and have the vertical accuracy of 15 cm on the hard surface. For this section, only data from Fredericton downtown area are used, as it was the most active area exposed to the flood. The coverage area is shown in Figure 6. Coordinates of river gauges and recorded river levels for four

cross-sections over a period of four days (May 1st to May 4th, 2008) are shown in Table 1. Tidal gauge readings were extended to a profile across the river in order to facilitate spatial analysis.

POINT_X	POINT_Y	NAME	1-May	2-May	3-May	4-May
-66.6533	46.02761	13	8.33	8.36	7.78	7.14
-66.6505	45.95549	13	8.33	8.36	7.78	7.14
-66.6322	46.00999	14	8.27	8.3	7.75	7.12
-66.6487	45.95604	14	8.27	8.3	7.75	7.12
-66.6476	45.95384	15	8.12	8.18	7.66	7.07
-66.5804	45.99036	15	8.12	8.18	7.66	7.07
-66.5681	45.95439	16	7.96	8.04	7.57	7.02
-66.6465	45.94944	16	7.96	8.04	7.57	7.02

Table 1. Tidal Gauge Readings

Light Detection and Ranging (LiDAR) is a data collection technique that uses a beam of light to make range-resolved remote measurement of features within the path of a reflected beam of light. The New Brunswick government, through the Department of the Environment and Emergency Measures Organization (EMO), collected LiDAR data sets for great part of the province of New Brunswick after the flood in 2008.

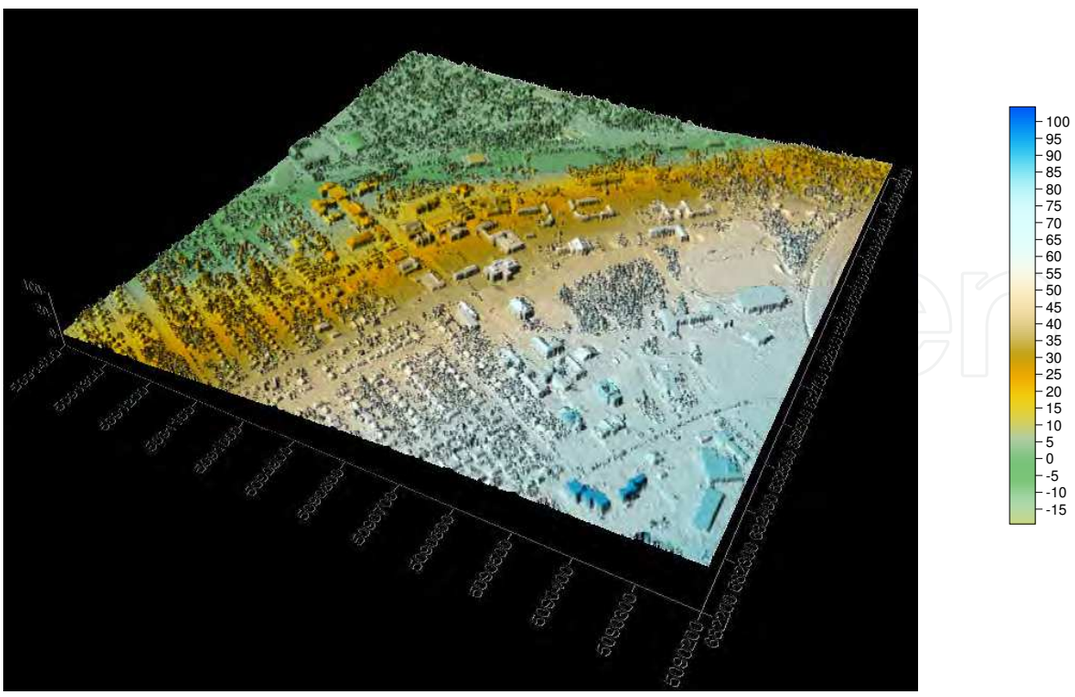


Fig. 6. Downtown Fredericton LiDAR data

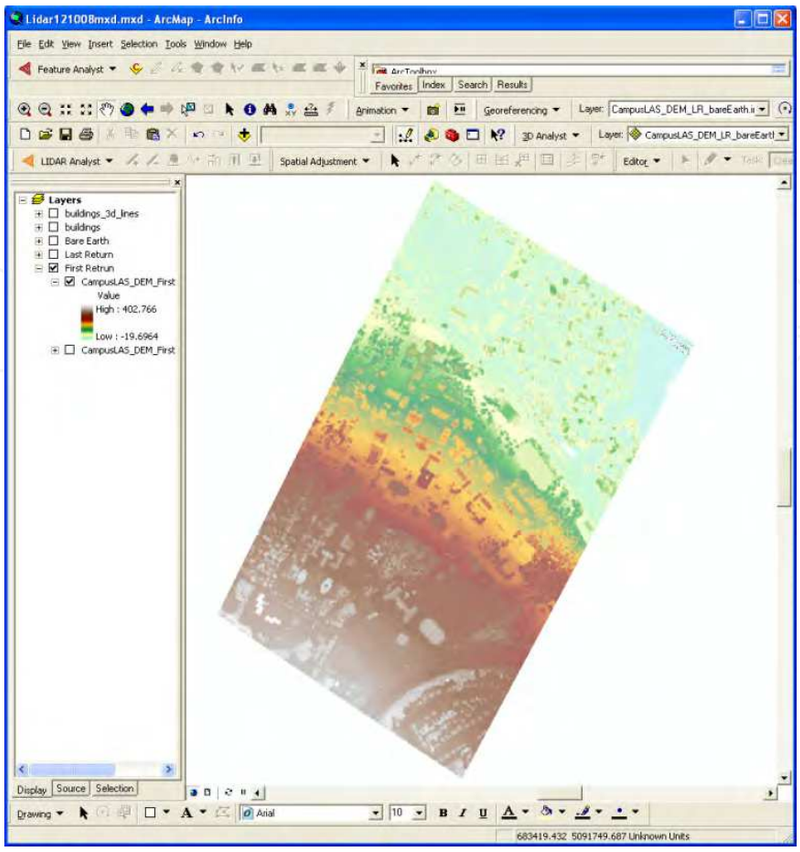


Fig. 7. LiDAR data; First Return, part of Fredericton, NB

3.2 Data processing

For this project, accurate planimetric coordinates and orthometric heights were obtained for the 3D flood modelling. In order to process LiDAR data (Elaksher & Bethel, 2002a, 2002b), we applied the following workflow of tasks:

1. Find LiDAR strip for the project area and extract returns of LiDAR beams (Figures 6 and 7).
2. Extract ground surface, i.e. ground DTM of the area of interest (Figure 8).
3. Extract building footprints from the returns of the LiDAR data (Figure 9).
4. Edit footprints by comparing them with cadastral data. The cadastral map does not contain height values and is not recent. However, based on different predefined parameters, the algorithm used to extract the building footprints produce varying results. The best fit is shown in Figure 10. The results were compared to the digital cadastral map of the study area. Further editing was necessary to correct the planimetric errors from the building footprints obtained from extraction process.
5. Proceed with other modelling tasks (shown in Figure 11) and add attributes and other data necessary for analysis (see Figures 12 and 13). The buildings and utilities, including electrical power, water and telecommunications are all modelled in 3D. Their attributes are also included in the modelling.

LiDAR data is usually collected with reference to ground control points using GPS methods. Subsequently, the output coordinates are ellipsoidal. To obtain accurate flood modelling

together with Digital Terrain Model, the data originally available in the geographic coordinates using the ellipsoid defined by the WGS84 geodetic datum are finally transformed to UTM and the CGVD28 vertical datum. To reduce the dataset and improve the processing speed, orthometric heights above 20m were filtered out, since we did not expect flood levels to go above this height. The transformed coordinates are used as the input to the GIS system in order to model a Digital Terrain Model (DTM). Layers containing flood profiles and polygons are created for each day of the extreme flood (1st to 4th of May) in 2008. In addition the extreme flood from 1973 was modelled as well and used for comparison. Existing utilities and buildings in downtown Fredericton we modelled in 3D and geo-referenced to the WGS 84 geodetic datum and the CGVD28 vertical datum. All the developed models and DTMs are then combined under the same coordinate system.

For the efficient decision support system, different flood scenarios were modelled for different flood levels (Sanders et al., 2005; Dal Cin et al., 2009). The technologies for 3D modelling are available in commercial and public domain software. One such tool that was used in this project was Google SketchUp (Chopra, 2007). Although limited in its interaction with other spatial features, Google SketchUp provided the tools needed to model the main features of the buildings (buildings geometry and the texture for the façade and the roof) and surrounding utilities for the test area. As part of future work, advanced tools in the CityGML (Kolbe et al., 2008) could be used for more interactive results.

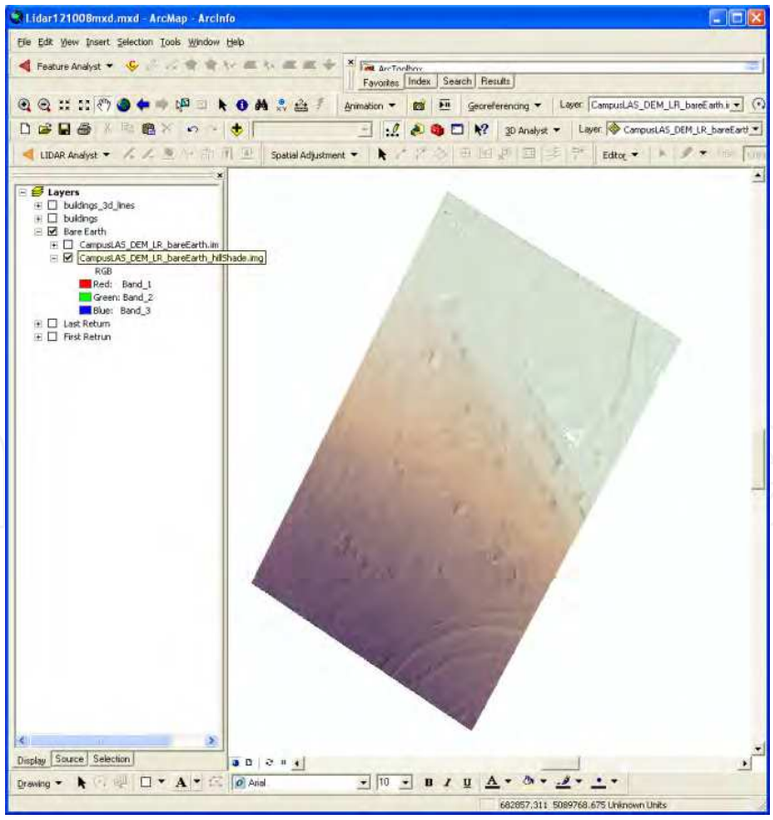


Fig. 8. Extracted ground surface from LiDAR data

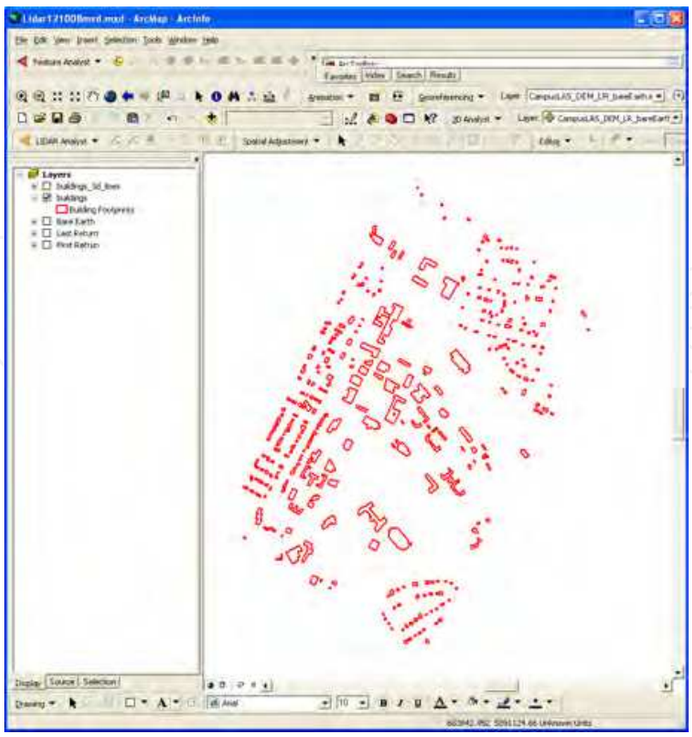


Fig. 9. Extracted Building polygons from LiDAR data

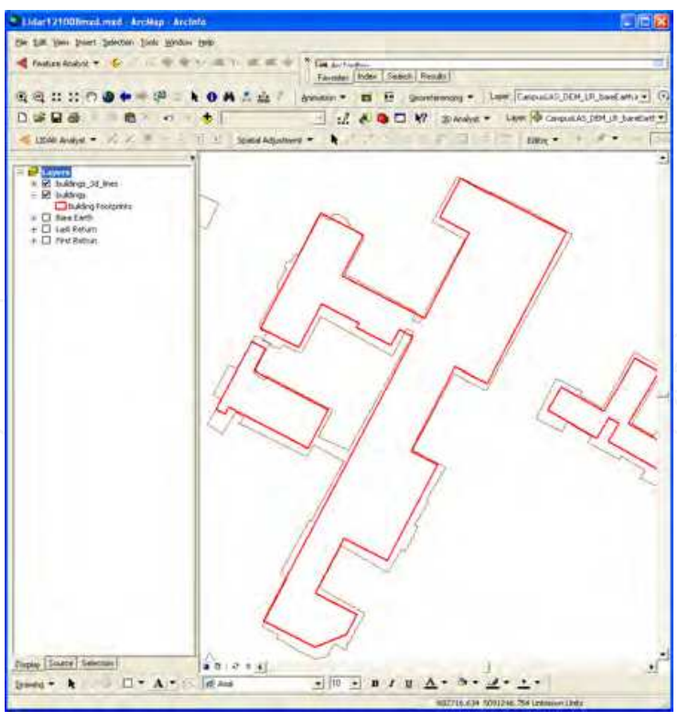


Fig. 10. Extracted building polygons (thin brown lines) compared with Cadastral buildings blueprints (thick red lines)

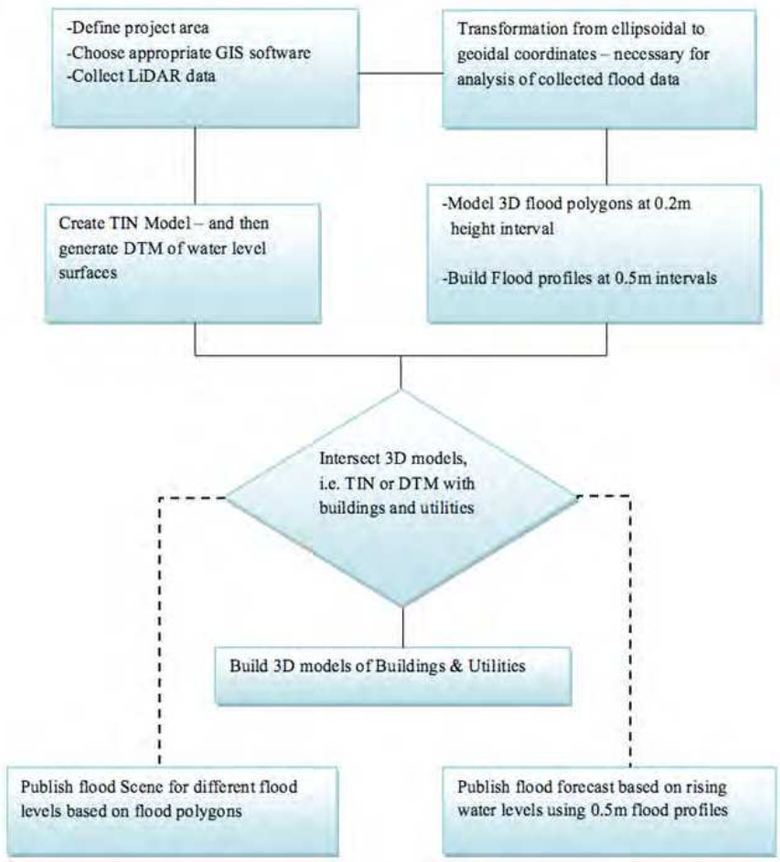


Fig. 11. The workflow of detailed methods and techniques applied for modelling of flooded buildings and infrastructure.

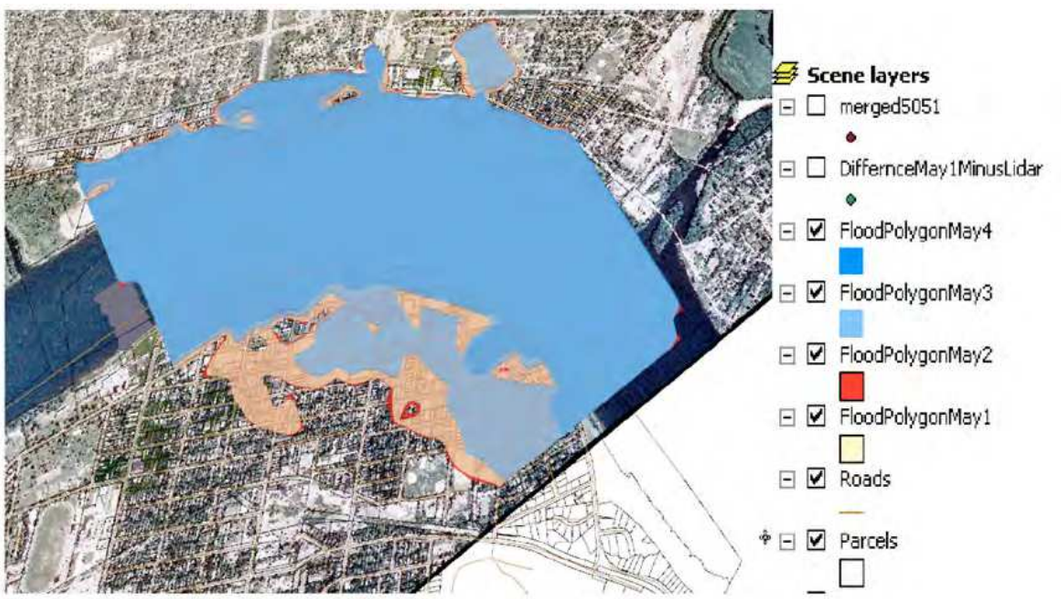


Fig. 12. Flood progression modelling

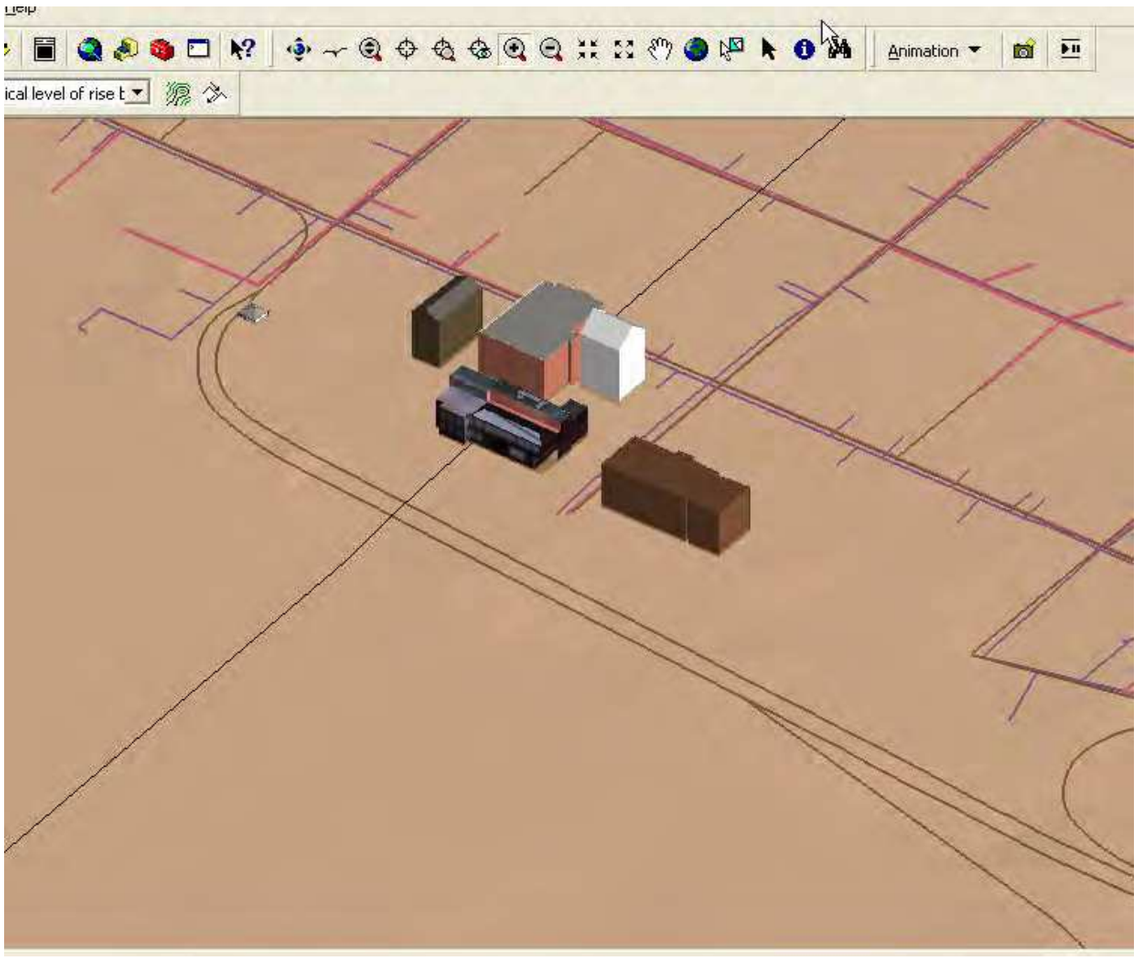


Fig. 13. The 3D model of buildings overlaid over the water and electrical utilities

4. Flood modelling and forecasts

The advanced modelling method we used in this research is based on 3D modelling of flooding, buildings and government infrastructure. The 3D visualizations of the floodplain and its effect on utilities can be discussed in more comprehensive terms, among engineers, government executives and the public. To showcase such a possibility, buildings of downtown Fredericton were extruded in 3D and modelled in detail. Figure 11 shows the processing steps in obtaining 3D models. Embedding the 3D models with the utilities and DTM, through the process of modeling different water rise situations, gives different scenarios of flooding, which can be used for further analysis. Based on this analysis, we show flood levels that could render utilities unavailable and make the government infrastructure risky to occupy.

4.1 Floodplain computations

To accurately compute the floodplain it is important to obtain topography of floodplain areas; the bathymetry of rivers; snow information; storm surges (rainfall forecast); and temperature information to create hydraulic models for effective prediction of inundation

areas and risk probabilities. However, water levels obtained by hydraulic modelling do not tell much about the severity and extent of a flood. This motivates the modelling and a visualization of predicted flood areas using GIS. The spatial delineation of flood zones using GIS has become a new research area following the advancement of technologies for data collection (Noman et al, 2001, 2003).

This research uses different spatial analysis tools to create floodplains from LiDAR data in Fredericton area and water gauges for Saint John River. For hydrological modelling we used DWOPER (Fread, 1992, 1993 ; Fread & Lewis, 1998) (as described in Mioc et al., 2010). The results of hydrological modelling were then used within a GIS for 3-dimensional modelling of flood extents (Mioc et al., 2010).

Following our processing workflow (see Figure 11), there were two main objectives in this part of the research:

1. Compare the DTM resulting from LiDAR data with DTMs resulting from water gauges to find the flood extents for Fredericton downtown area.
2. The second objective is to create a single TIN for both LiDAR data and water gauges to calculate the difference of the volume, which represents the floodplain.

The flood progression from May 1st to May 4th, 2008 is analyzed (see Figure 12). Using the results of spatial analysis, a flood prediction model was developed for emergency planning during future floods. In this phase of our research, we were able to obtain the delineation of flood zones using LiDAR and Tidal height information (available from water gauges). In addition, we were able to integrate a number of processes that make flood forecast possible: the acquisition and processing of the elevation data; the use of hydrological software to simulate models of flow across floodplains; the use of spatial analysis software (GIS) that turns the modelling results into maps and overlays them on other layers (thematic maps or aerial photographs); and software that makes these models and predictions available on the Internet in a flexible and user-friendly way.

From the computed floodplain, displayed as superimposed polygon layers, we visualize that the major flood extent occurred from May 1st to May 2nd, with the peak for flood on May 2nd. Furthermore, the flood subsided from May 3rd to May 4th. The system we developed allows the computation of floodplain for predicted flood peak (shown in red on Figure 12) that is critical for emergency managers. Furthermore, the flood modelling results are used to develop a three dimensional model of flooded buildings combined with some city infrastructure, roads, water and electrical utilities (see Figures 14, 15 and 16).

4.2 3D modelling of flooded buildings and infrastructure

The method of simulating and predicting floods and its effects on buildings and utilities provides powerful visual representation for decision making on when the buildings in the flood zone may be safe for people to occupy. Traditional paper maps and digital maps may not give us the possibility to do a 3D visualization in order to study the detailed effect of a flood situation on utilities.

In this research, we used LiDAR data and the application of 3D modelling in order to provide an analysis of the risk of floods on government buildings and utilities. LiDAR data provides a cheaper, faster and denser 3D coverage of features for 3D mapping. LiDAR data was acquired for the city of Fredericton after the flood in 2008 and processed to generate 3D animated views. To further enhance visual perception, 3D buildings, infrastructure and utilities were integrated within a 3D GIS application. The resulting 3D view does not only

display a clear-to-nature scenario, but provides also a more realistic outlook of the buildings and infrastructure during floods. Finally, a flood scene was produced for each of the forecasted flood levels for visualization via Web interface.

Using different extrusion heights to represent different flood scenes, it is possible to simulate different flood progression events. The pictorial scene, representation of the building, floods and its effects can be clearly visualized and analyzed. Figure 15 shows a 3D view of the flooding in May 2008. The 3D buildings and utilities can be seen consecutively as a result of applying transparency to the thematic layers. In Figure 16, the utility lines are embedded in the 3D models. Figures 17 and 18 present a 3D visual model of the submerged newly built Public Washroom at the Military Guard Square, in Fredericton, Canada in an extreme flood scenario. At this level of water rise, the electrical boxes would be flooded. It is visible from the model that during flooding, surrounding areas including the Public Library, the Armory and the Military depots will be out of use and certainly inaccessible.

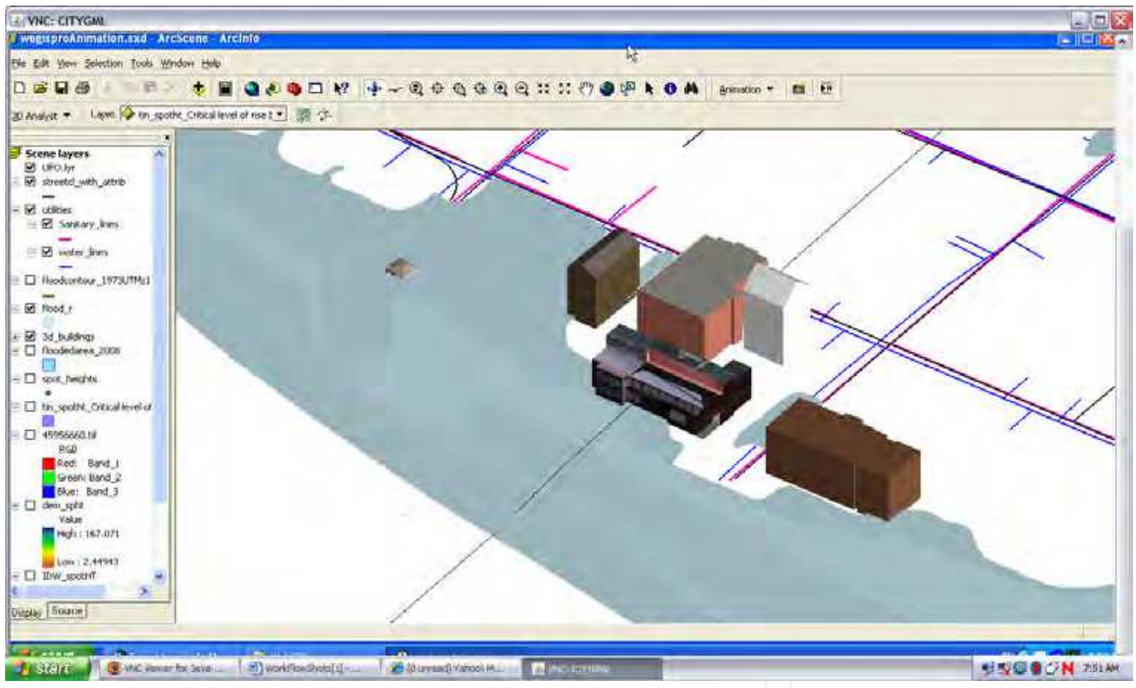


Fig. 14. The 3D model of buildings overlaid over the water and electrical utilities that will be affected by the flood

The DTMs in Figures 15 and 16 show the natural critical point at which water will begin to flow upwards. When ground water rises up to this level, waste matter from the sewage system will flow upward, under pressure from rising water from the river. The washroom facility may not be used under these circumstances. Computing the floodplain for the 20 year statistical flood showed that many parts of Fredericton may have been build on a floodplain. The new analysis of DTMs combined with the groundwater levels shows that, if

ground water levels rise across the city, many homes and governmental buildings will be flooded. The electrical utilities and sewage system that are laid in the underground will be affected as well resulting with the sewer back-propagation and the electric power outages. The situation is worse in the downtown area, which has the lowest heights. Priority emergency decisions can be made in this situation to close the downtown offices and infrastructure first, at the start of rising water levels. Based on the results of the overlaying the floodplains with existing utilities and infrastructure, it can be decided when it is risky to occupy or use the buildings or the infrastructure.

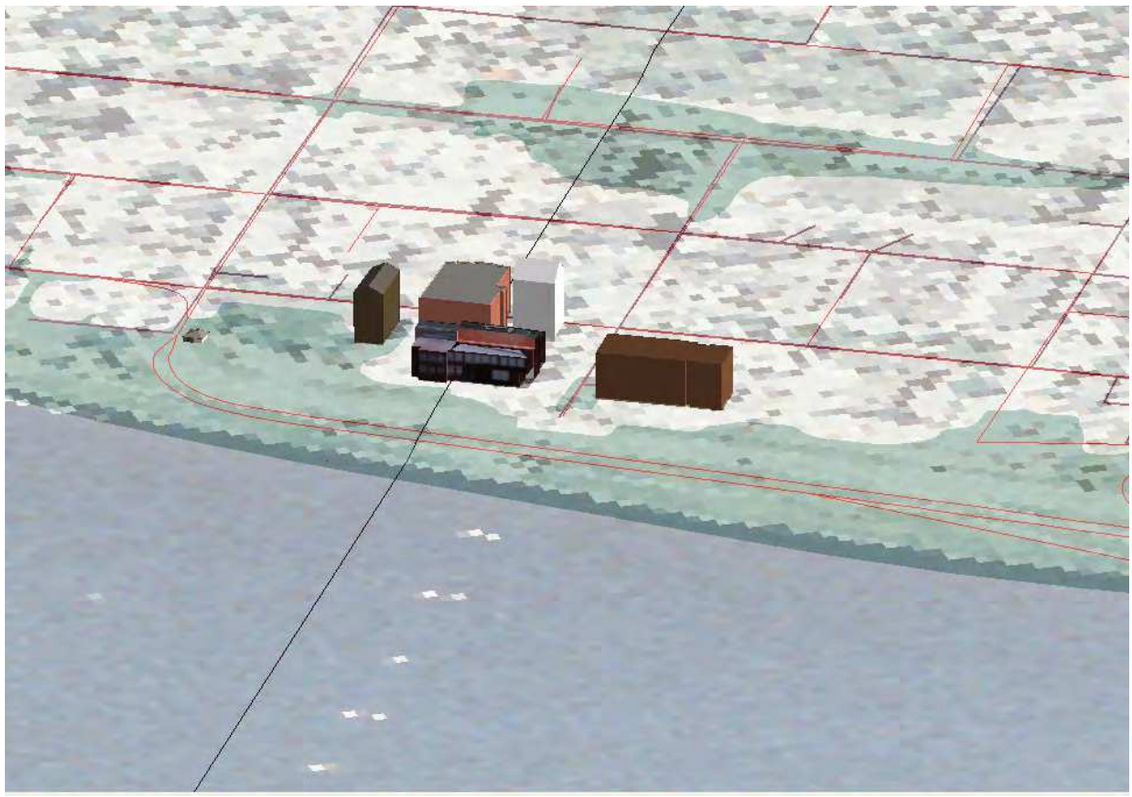


Fig. 15. 3D models of selected buildings in Fredericton integrated with DTM and flood model

Daily automatic generation of flood polygons from the data provided by the existing online River Watch application (see http://www.gnb.ca/public/Riverwatch/index-e.asp) can produce an animated 3D video, which can be uploaded on the Riverwatch website to provide updated 3D models to residents.
It can be seen clearly from the comparison of the model and the picture (shown in the Figure 19) captured during the 2008 flood, that the levels of flooding are the same. The water just touches the back gates of the Fredericton Public library on both of these. The accuracy of the flood model depends on the vertical accuracy of the LiDAR datasets and the accuracy of the hydrological modelling.

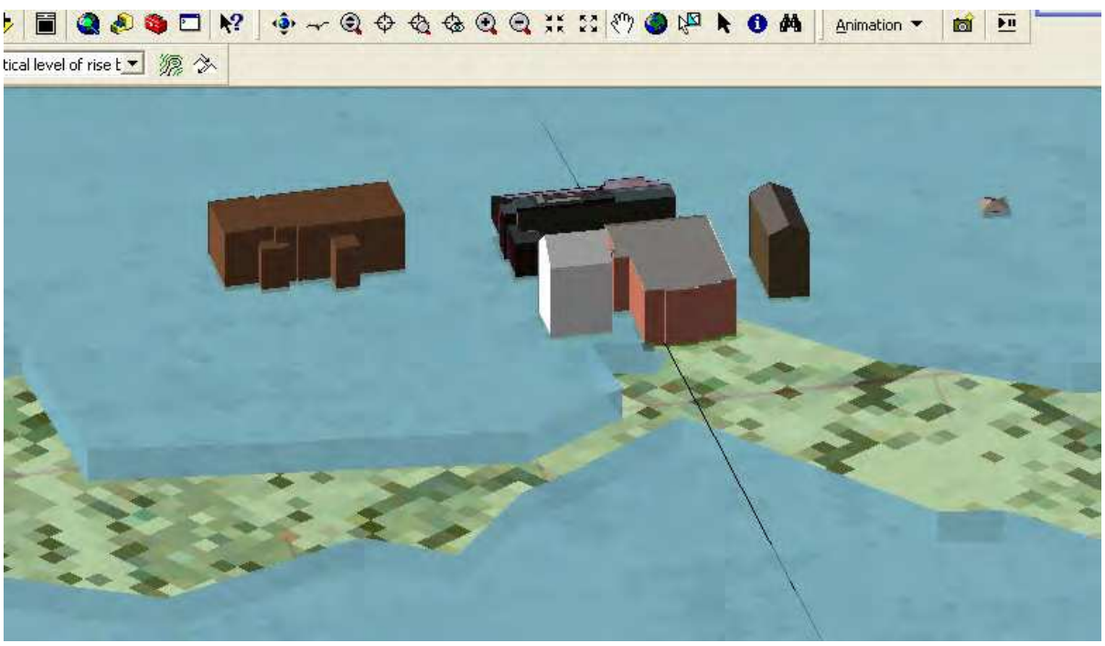


Fig. 16. 3D models of selected buildings in Fredericton affected by the flood

The 3D GIS application provides a better platform for visualizing flood situations than previously done in 2D maps. All exterior parts of a building could be visualized in detail during a flood event. This provides a better tool for analyzing and preparing for emergency measures. It also presents a near to reality situation that can easily be understood. Provincial Ministers and decision makers who may not be familiar with GIS analytical tools and Query Languages can now understand technical discussions on flood analysis through the use of 3D flood models, which are close to reality. It is also possible to simulate floodplain polygons for different river water levels in order to produce different flood scenarios. Simulation can also be used to trace and analyze underground utilities by making thematic layers transparent. Flood scene animations can be published to website for public access.

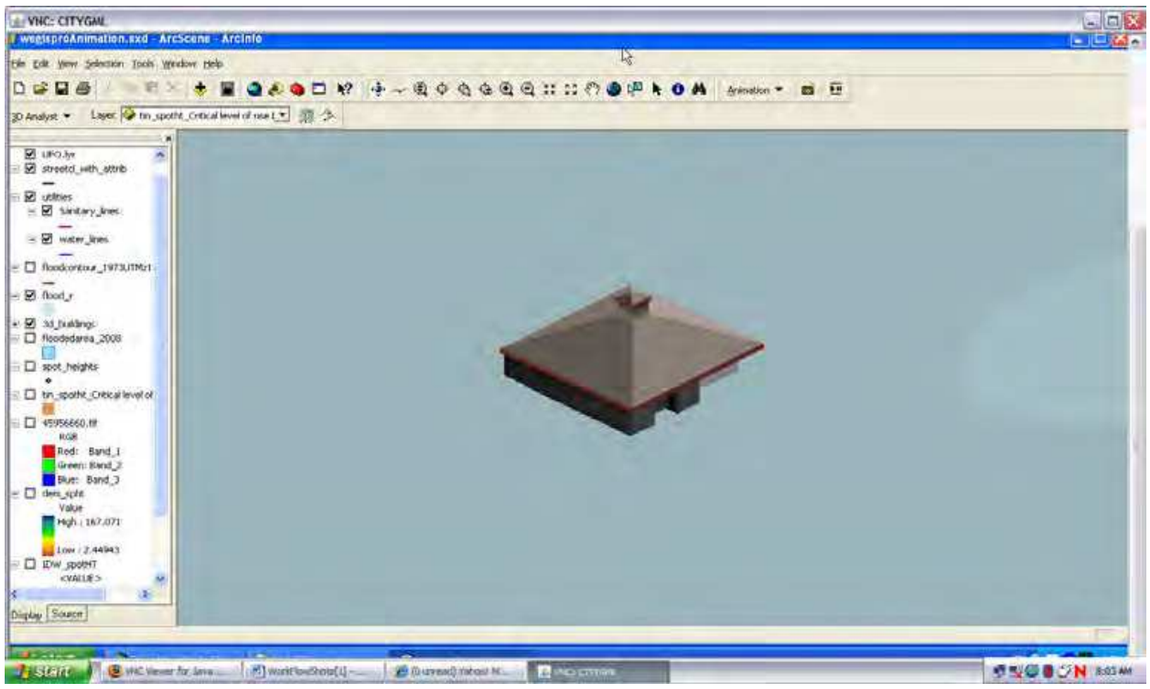


Fig. 17. 3D Washroom, with power box, in the extreme100 year simulated flood

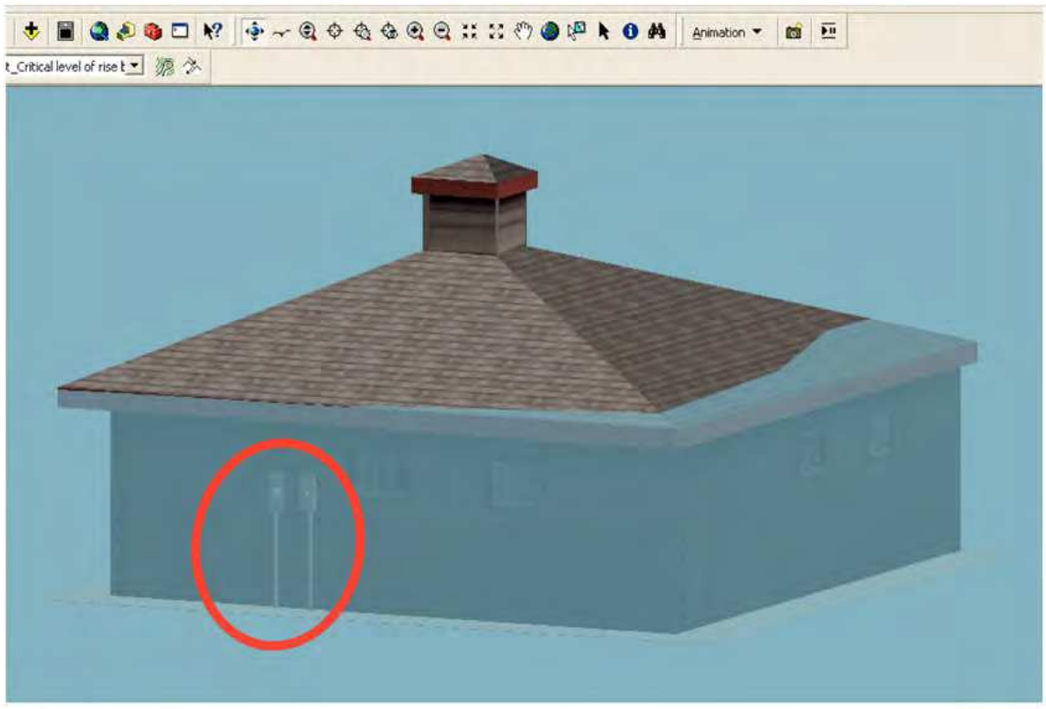


Fig. 18. 3D model of a washroom, with electrical power box, in 1973 simulated flood

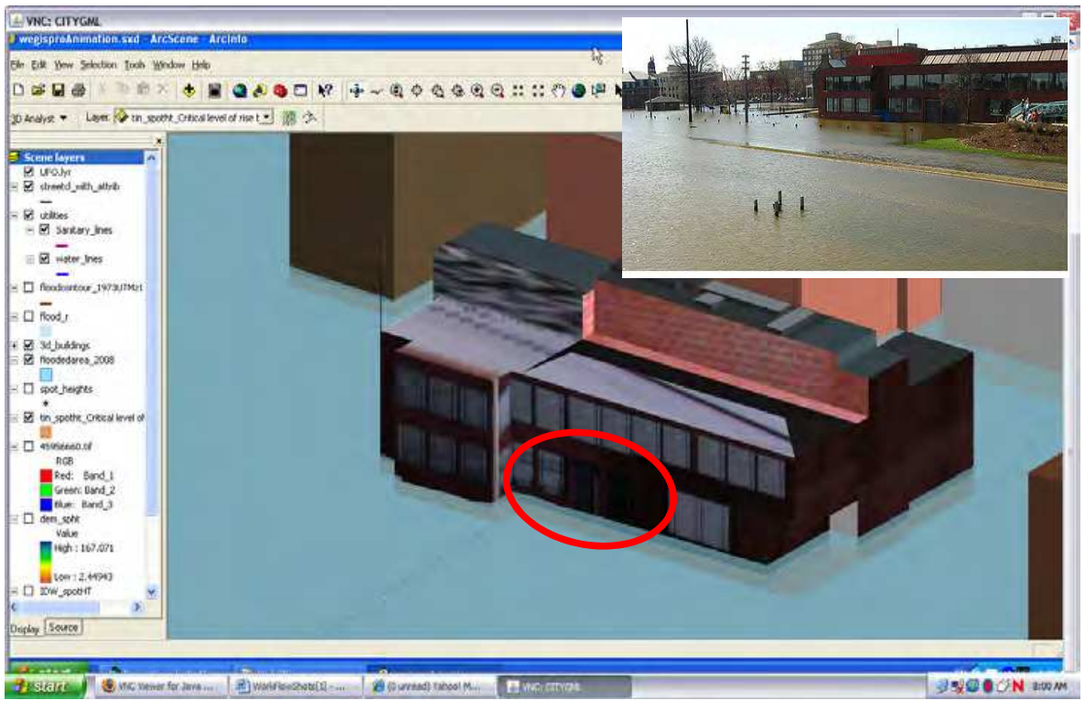


Fig. 19. 3D Model compared with Photograph taken during the flood in 2008

5. Conclusions

The new flood prediction model that computes accurately floodplain polygons directly from the results of hydrological modelling allows emergency managers to access the impact of the flood before it occurs and better prepare for evacuation of the population and flood rescue. The method of simulating and predicting floods and its effects on utilities provides powerful visual representation for decision making on when buildings in the flood zone may be safe for people to occupy. Traditional paper maps and digital maps may not give us the possibility to do a 3D visualization of the detailed effect of a flood on utilities and infrastructure.

This research explores the application of 3D modeling using LiDAR data to provide an analysis of the risk of floods on government buildings and utilities. LiDAR data provides a cheaper, faster and denser coverage of features for 3D mapping. LiDAR data was processed to generate 3D maps. By employing accurate coordinate conversion and transformations with respect to the geoid, a Digital Terrain Model (DTM) was created. Floodplain delineation was computed by intersecting the Digital Terrain Model with the simulated water levels. Furthermore, to enhance visual perception of the upcoming flood, 3D buildings, infrastructure and utilities were modelled for the city downtown area. The DTM and the 3D models of the government buildings, infrastructure and utilities were overlaid and presented as a 3D animation. The resulting 3D view does not only register a clear-to-nature scenario, but also provides a more discerning outlook of the buildings and infrastructure during floods. Finally, in this research we have clearly shown that GIS and LiDAR technologies combined with hydrological modelling can significantly improve the decision making and visualization of flood impact needed for early emergency planning and flood rescue.

6. Acknowledgment

The authors would like to acknowledge the generous contribution of time, materials and resources to this project by the New Brunswick Department of Transportation.

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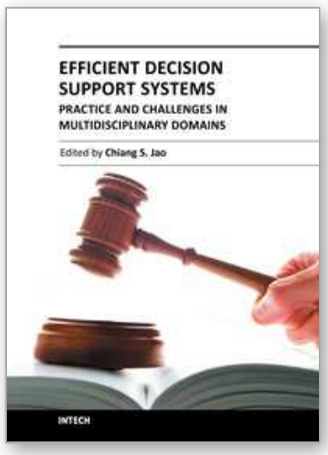
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