Supporting Flood Disaster Management with Numerical Modelling and Spatial Mapping Tools

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Abstract
The use of GIS technologies and computer models pervades all aspects of water management, supporting wealth creation through products and services, contributing to many improvements in the quality of life. As a result, there is a growing increase in demands for better use, productivity, flexibility, robustness and quality of such systems. Nowadays, the philosophy of stormwater system and floodplain management cannot be conceived without the use of modelling and spatial technologies. In this context, the purpose of such systems is at understanding and predicting the behaviour and performance of stormwater systems so that the effective solutions to flood-related structural and operational problems can be derived and evaluated within a decision-making framework. With instantiated physically-based computational models, it is possible to calculate potential behaviour of floods, their rates of rise, evolving extents, and areas of high hazards with lead times prior to the area concerned being flooded. The real-time measurements, coupled with remote sensing of land use and terrain levels, forecasts of rainfall based on weather radar and ensemble predictions from global circulation of the atmosphere and associated local area models, routine asset inspections and maintenance, and stakeholder and customer reports, can help to provide a digital overview of the risks associated with potential disasters. Furthermore, in order to assess risk it is necessary to generate scenarios of the possible initiation of disasters coupled with their consequences in the light of different control and mitigation actions. This paper addresses the use of modelling and spatial technologies in the context of urban flood hazard analysis and disaster preparedness.

1. Urban Flood Disasters

Natural disasters take an enormous toll on the development of a country. In so doing, they pose a significant threat to prospects for achieving the Millennium Development Goals which are directed to a reduction of human vulnerability to natural hazards. According to UN reports, about 196 million people in more than 90 countries were found to be exposed on average every year to catastrophic flooding. Some 170,010 deaths were associated with floods worldwide between 1980 and 2000. Geospatial analyses with respect to populations exposed to floods show that the largest exposed populations are in Asian countries. Many conurbations, such as Jakarta, Manila, Ho Chi Minh City, Bangkok, Shanghai, Dhaka or Mumbai, are situated on major rivers or coasts, and as such are subject to flash flooding from surrounding hills, or extreme rainfall events (e.g. thunderstorms) occurring directly on the urban area. Such floods can damage the drainage system and can generate landslides, which can lead to extreme pollution in urban areas and streams and loss of lives. In many situations it is the poor living on the perimeters of urban areas that are the most prone to disaster. Furthermore, the relentless migration of people from rural areas to cities puts growing pressure on urban services, and especially on the management of emergencies and disasters. City managers and the directors of the various emergency services are under social pressure because of the apparent growing frequency of such disasters, and the difficulties in assessing risk and managing appropriate responses in emergencies. Given the threats of climate change, natural disasters are likely to increase in coming years. Emergency or disaster management is the preparation, support and reconstruction of society when natural or man-made disasters occur. This is not intended to be an intermittent sequence of events but an ongoing process by which individuals, groups and communities manage hazards in an effort to avoid or ameliorate the impact of disasters resulting from the hazards. At the preparation stage for natural disasters, the focus is on preventing hazards from developing into disasters altogether, or reducing the effects of disasters when they occur. The reduction and even the elimination of risk are brought about by the introduction of long term measures. One way of improving the preparation for natural disasters is by investing in the ‘digital city’ (Price and

Vojinovic, 2008). In this respect, the application of models and spatial systems in urban water disaster management plays a vital role. The present paper discusses the key elements of urban flood disaster management planning, which in this case attempts to provide the 'central knowledge content' intervening between domain data and end users in the context of managing natural disasters.

2. Needs for Integrated Management, Spatial Mapping and Modelling

When dealing with such phenomenon as urban flooding, an integrated approach to sustainable stormwater management, where different structural and non-structural measures are initially evaluated within the model and then implemented, is required. Solving the flood damage reduction problems while concurrently protecting and enhancing the floodplain environment, requires the full use and proper consideration of both types of measures. Neither the structural nor the non-structural approach can solve all the problems by itself. Whether the challenge is with the protection of an individual, a community, or the catchment area as a whole, both types of measures must be evaluated by the use of numerical models and integrated into the solutions to attain to an appropriate damage minimisation (Vojinovic and van Teeffelen, 2007). Physically based computational modelling is invaluable for this purpose. With instantiated models, it is possible to explore the generation of disasters and to simulate the consequent effects in response to any control actions. The generation of new information using these approaches can inform decision makers through appropriate decision support systems. These systems can be coupled with data acquisition and modelling systems to provide warnings of impending disasters and advice to various levels of authority, the emergency services, and to the public. The appropriate level of modelling for the assessment of disaster risk or for forecasting depends crucially on the nature of the physical situation and on the availability of data. Urban topography, drainage network layouts and even detailed geometry of the networks can be readily surveyed using current technology. It is more difficult to measure the temporal dynamics of rainfall and flows, especially in extreme events. There is considerable need to find better ways of monitoring rainfall over urban areas, and water levels and velocities during flood events, not only for forecasting but for planning, which demands where possible the availability of reliable historical data and this is one of the most important challenges facing hydroinformaticians today. Geographic Information Systems (GIS) and remote sensing in the stormwater management context play an important role in this process. For example, remote sensing technologies, such as Airborne Laser Scanning (ALS) or Light Detection and Ranging (LIDAR), are used to provide a comprehensive topographic coverage of entire floodplain areas in an accurate and economic manner. Digital Elevation Models (DEMs) offer the possibility to extract catchment characteristics automatically by providing flow directions and their subcatchment boundary maps. The generation of flow direction maps is usually determined by calculating the steepest downhill slope for each cell. Furthermore, a sufficiently fine resolution of ALS data can provide a good spatial framework to compensate for a coarse resolution of the hydrodynamic model. Such a framework makes it possible to map water level and velocity results onto a terrain model and to visualise the quantification of flood hazards across the floodplain. The ability to map different hazard categories to cadastre automatically has recently been realised using GIS technologies and as such this has prompted a greater dependency of flood plain modelling results on spatial representation. Furthermore, GIS tools have been developed to provide geo-reference time-varying results from hydrodynamic models related to a spatial framework (or to a grid which includes a model of the terrain). Thus, for any time step of either one-dimensional or two-dimensional model results, depth, velocity and hazard can be determined for each grid element in the two-dimensional spatial framework. Such maps, which represent the extent of flood hazards, can then provide a basis for defining not only ameliorating measures but also the most suitable flood emergency response actions. The flood visualisation component of GIS technology enables engineers and emergency-response planners to become familiar with the potential behaviour of flooding, its rates of rise, evolving flood extents, and areas of high flood hazard with lead times prior to the area concerned being flooded. With the use of GIS technology, model results can be linked to the cadastre and property databases and as such used very efficiently in the overall urban planning process. Having the model results mapped to the spatial framework of an ALS allows a flood to be more realistically simulated against an aerial image. Figures 1 and 2 show examples of how the model results (such as depth and velocities) can be superimposed, together with cadastre data (or aerial image) within a GIS framework. It shows how the use of GIS technologies can be of a vital importance in the overall flood management and disaster coordination activities. Geo-referenced results from 1D or even 1D-2D coupled models can readily be used to communicate the risk of flooding and to gain insights into the nature of floods and their impacts on communities. The knowledge gained can then be transformed into a set of effective and acceptable actions to be taken by all who are affected. In this context, spatial visualisation tools play an essential role to facilitate an exchange of information and views. In order to evaluate the risk to communities, properties and infrastructure effectively, it is important to estimate the distribution of hazards and the magnitudes of flood-related damages. Generally, such damages are divided into *tangible* and *intangible* damages. Those that can be estimated and expressed directly in monetary terms are referred to as *tangible* damages (e.g., damages to properties, infrastructure, etc.); see Penning-Rowsell and Chatterton (1977), Kanchanarat (1989). Damages that are difficult to identify in monetary terms are referred to as *intangible* damages (e.g., loss of social values, loss of life, anxiety, etc.); see Lekuthai and Vongvisessomjai (2001).

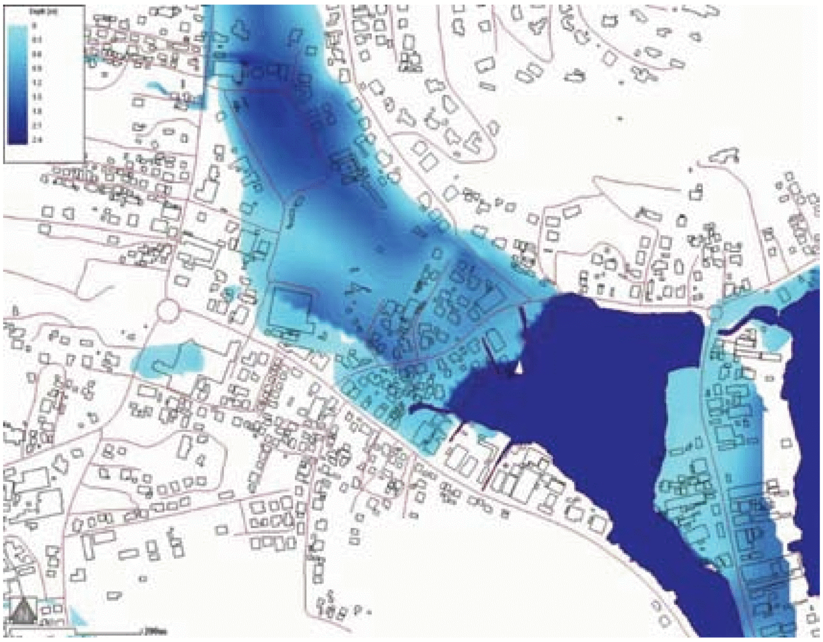

Figure 1: A GIS representation of 1D (MIKE 11) model results (water depths)

Figure 2: A GIS representation of 1D (MIKE 11) model results (velocity distribution / velocity vectors)

3. Digitisation of Data and Filtering

The important role of modelling is in complementing the acquisition of data to improve the information and understanding about the performance of a given drainage network, taking into account the associated urban terrain. The spot height data provided by the ALS survey will typically include tens of millions to even a hundred million points provided in a single long file or a series of files on a DVD. The format is typically an ASCII xyz file or it may have been converted to a GIS (e.g., MapInfo, ArcView) layer. Whatever the format, the file or files are very large and require useful consideration for storage, processing and usage. This requires carefully designed procedures for clipping, thinning, triangulating, interpolating and processing of model result files. Considerable attention needs to be given to the acquisition of good geometric and topographical data at adequate resolution in order to describe the primary features of the flow paths through the urban area: see Figure 3. Where flood flows are confined to well-defined conduits, a robust 1D model can usually be instantiated, and used to generate safe results for decision-making. However, the flows generated in urban flood disasters are normally highly complex because the morphology of the urban surface is eminently artificial, with its highly irregular geometry, and is often contrary to natural flow paths, as shown in Figure 3.

Figure 3: Example of typical urban features which need to be incorporated in urban flood modelling applications

Typically, such features are Modelling flows in such complex geometrical situations is difficult, Hsu et al., (2000), Djordjevic, et al., (2004), Djordjevic, et al., (2005), Chen, et al., (2005), Vojinovic, et al., (2006a) and Vojinovic and Tutulic (2009). Small geometric 'discontinuities' such as road or pavement curbs can play a significant role in diverting the shallow flows that are generated along roads, through fences and around buildings, Figures 4 and 5. Head losses due to flow over or round such structures are difficult to accommodate. In this respect, manual filtering (classification) of LIDAR data poses one of the greatest challenges.

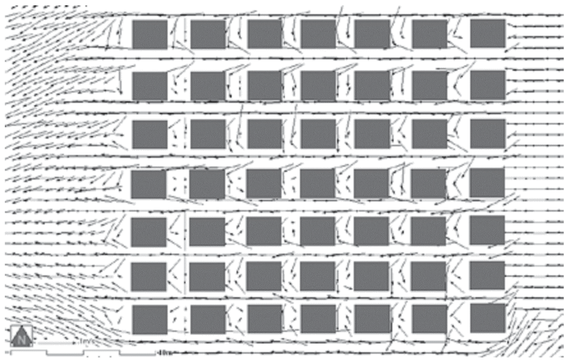

Figure 4: GIS representation of velocity vectors computed by a two-dimensional model with blocks of buildings being modelled

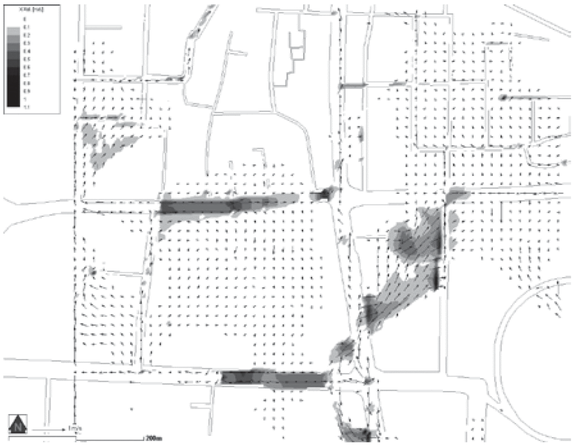

Figure 5: GIS representation of velocity vectors computed by a two-dimensional model with urban features being modelled

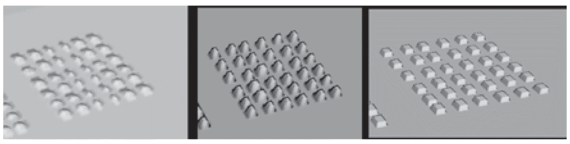

Figure 6: Building blocks with 5m (left), 2.5m (middle) and 1m (right) DTM resolution

Our research efforts must target data filtering algorithms in order to produce better DEMs which can be more suitable for urban flood modelling and disaster management applications. Furthermore, the DTM resolution plays an important role in this application. Low resolution DTM is normally useful for rural areas. However, in urban areas a more refined (or higher resolution) DTM is required because in order to capture all important features that will affect flow dynamics and flood propagation. The following Figure 6 shows the building blocks represented with 5m, 2.5m and 1m DTM resolution. From the recent studies carried out at UNESCO-IHE it was found that the coarse DTM resolution tends to give the wider spread of water across the floodplain and shallower depths (Mwalwaka, 2008). The opposite results were noticed from simulations with a finer DTM, Figure 7. Since different DTM resolutions will give significantly different results a careful attention to the selection of DTM resolution must be given when the objective is 2D modelling of urban flood plains.

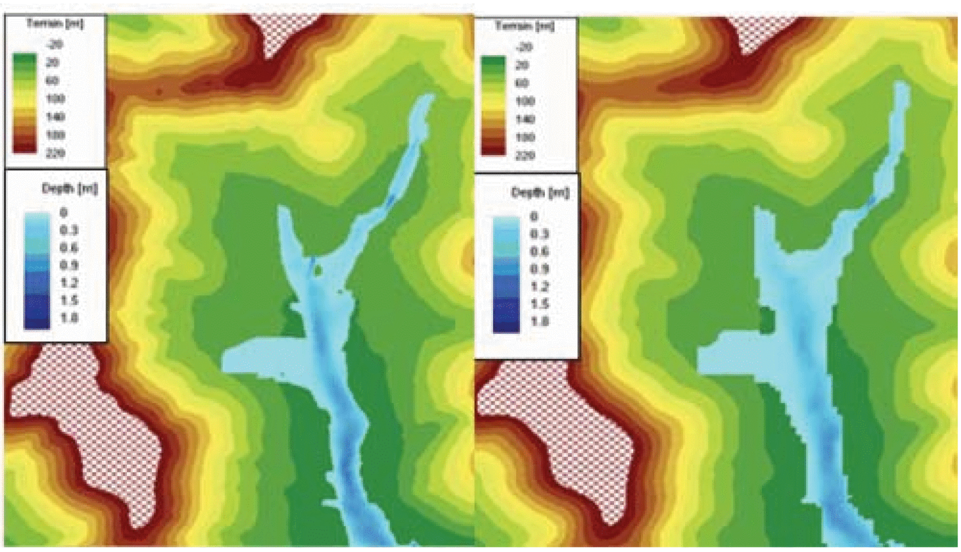

Figure 7: Model results with 5m (left) and 20m (right) DTM

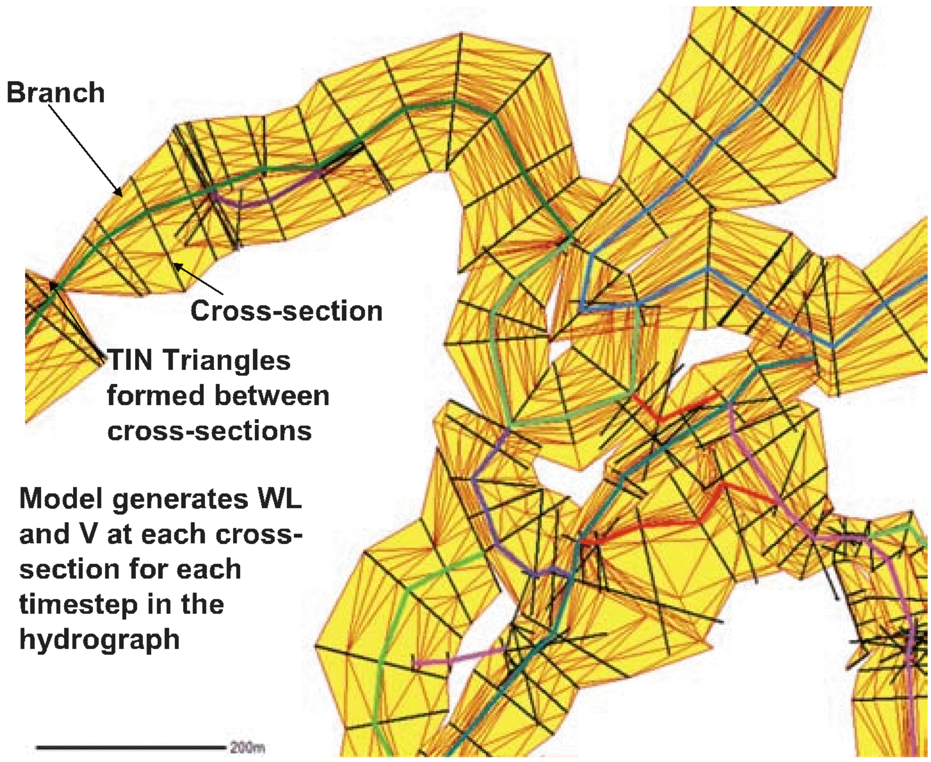

Figure 8: Triangulated irregular network (TIN) of hydraulic model network data

4. Processing of Flood Model Data

Flood models determine water level and velocity in time increments for a simulated rainfall event. Typically, the water levels and velocities are determined only at the cross-sections and along the connecting branches, respectively, of a branched model network and at the nodes and links, respectively, of a link node model network. As such the model data is discrete. The data can be converted to a spatial framework by creating a TIN of the model network. Essentially this ensures that all model results are linked by triangles and an interpolated value of water level or velocity can be determined at any point by planar geometry, Figure 8. The TIN structure created of hydraulic model network is used as a basis for processing model results at each time step. The model results TIN is on a scale dictated by the model network and is much coarser than an ALS spatial framework. Because water level and velocity, to a lesser extent, usually represent gradually varying results surfaces, estimates of the variation of these fundamental model results can be interpolated within this coarse framework. The model results TIN is mapped onto the much finer spatial framework of the ALS data by taking every node of the fine meshed ALS framework and determining the model results of water level and velocity within the triangles of the model results TIN. This translation is repeated for every time set of model results. The translation means that at every node or point of the ALS the ground elevation as well as the interpolated values of the time varying water levels and velocities are stored. This can be conceptualised as a "cube of data" where the first slice is the model result set the first time step interpolated to the scale of the ALS spatial framework, Figure 9.

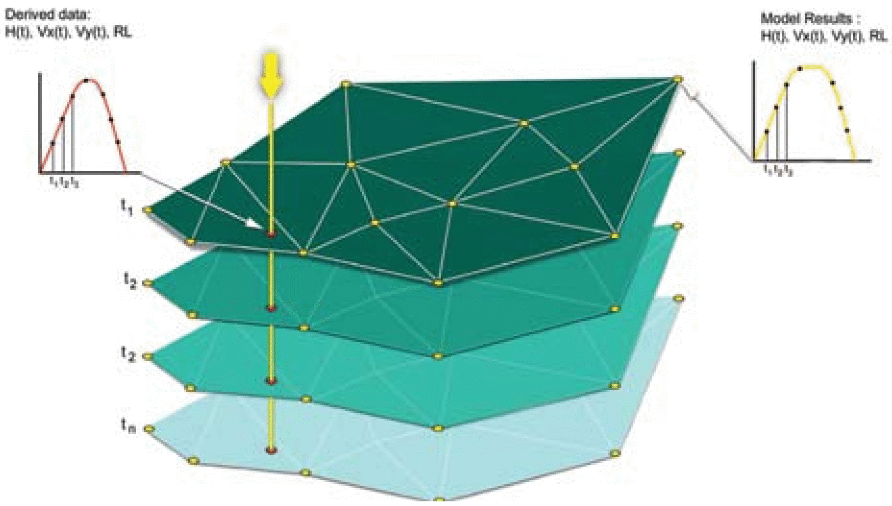

Figure 9: Mapping model results for each time step into a number of surfaces

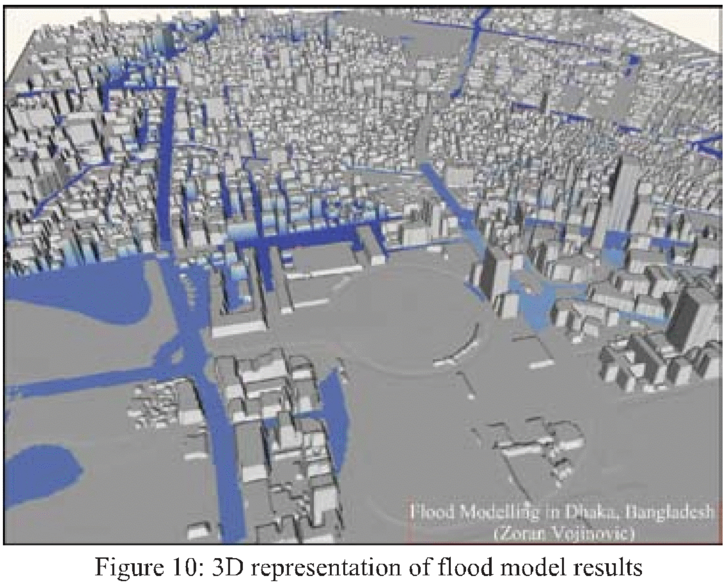

Figure 10: 3D representation of flood model results

Following slices represent the spatial frameworks of subsequent time steps. The cube of data is a homogeneous dataset from which derived hydraulic data can be easily determined and mapped. The time varying water depth is usually determined by subtracting the ground elevation form the water level stored at each node, in each slice of the cube. Also, flood hazard is usually determined by multiplying the depth with the velocity at each node of the ALS framework. The derived variables are calculated for every node at every time step in the cube, and they can be animated as a time varying thematic map. A derived data set which is of particular value to floodplain management is the peak data set i.e., the peak value of any variable at each node, regardless of time. This is easily determined by searching through the slices of the cube, for each node, and selecting the peak value and preparing a thematic map of the peak value of all nodes. The confidence in flood models is invariably measured against how well the model can replicate an evolving flood inundation surface. The appreciation of flood behaviour embodies observations of where riverbanks first overtop (or sewers surcharge on the ground), the direction of movement of early flood waters over the land, where roads are first cut, which parts of an urban area flood first and the direction of flow across different parts of the floodplain. All these observations reflect the rising flood waters hunting across a flood plain to occupy low lying gullies and depressions. If a model can be shown to replicate these observations, it will have credibility with the community. Most flood models simulate the longitudinal water surface gradient well. When model results are mapped onto the fine scale spatial framework of an ALS, the time varying flood inundation surface is determined by the intersection of the water surface with the DTM. This process is directly analogous to what happens in nature and because the ALS provides accurate, fine scale ground elevations, the simulated water surface can replicate most community observations. Hence the availability of ALS data gives flood models more public credibility. Having the model results mapped to the spatial framework of an ALS allows a flood to be more realistically simulated against an aerial image. A topographically accurate animation correctly portrays the risk associated with rapid inundation of low-lying land and the possible cutting of evacuation routes leading to potentially dangerous isolation of communities. A clear appreciation of flood hazards is important when considering the risks associated with floods larger than those of living memory.Having model results converted to a spatial framework provides substantial analysis capabilities such as:

- The primary model variables of water level and velocity are freely available in time and space throughout a simulated flood;

- Derivatives of these primary variables, such as depth or hazard (which is usually a product of velocity and depth) are similarly freely available;

- The spatial framework of primary and derived model results can be integrated with other spatial data. These capabilities provide the basis for a very powerful floodplain decision support system. Flood models are given a planning context in which model results can be shown interactively with air photographs, cadastre, property data and GIS layers.

5. Visualising of Floods in 3D Urban Environment via Internet

Since GIS plays an important role in city planning, flood modelling and disaster management there is a need for better visualisation of urban flood model data and realistic 3D presentation of the real world, Figure 10. Furthermore, there is a need to publish our model results on web pages. Internet and World Wide Web (WWW) have been widely applied in delivering, processing, and publishing geospatial data; however very little has been done with respect to flood modelling data. Web-based GIS, has a wide variety of applications and this is yet another area where our efforts must be focused. In the recent years, web-based three-dimensional (3D) GIS for visualising geospatial data have attracted many researchers. In urban flood modelling applications, there is a need to design a system which can work under a client/server architecture that integrates Internet GIS and multi-tier web application for creation of a 3D city model with flood model results.

6. Conclusions

This paper discusses some of the main issues facing application of spatial and modelling technologies for urban flood disaster management. The particular focus of the paper is on urban flood disaster management. Such floods are generated either by flows originating from outside the urban area, which then pass through it, and/or by excess rainfall-runoff on the urban area itself. Controlling factors for a corresponding disaster include a large volume of water accumulating rapidly (and perhaps unexpectedly), or involving high velocities which sweep away vehicles and buildings, or the dislodging of soil and other materials in generating landslides. The topography of the local urban area is often critical in affecting the degree of flooding and therefore the potential disaster. The paper highlights the need to address several challenges in order to make our systems more effective in managing urban flood disasters.

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