Integrating Spatial Information Systems and Hydrodynamic Modelling for Cyclone Risk Management

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Abstract: There are reasons to believe that the role of geographic information systems (GIS) for natural hazard disaster risk management will expand as spatial databases become widely available, the cost of software decreases and as spatial models become more sophisticated. Invariably, risk managers will also demand access to decision support tools that allow them to manage and understand the complexity associated with natural hazard risk. Spatial information systems have routinely been used to evaluate and map the risk to urban communities from cyclone-induced flooding. These approaches however, commonly neglect the complexity associated with storm surge events and simplify the dynamic nature of the hazard event. This research presents an innovative integration of hydrodynamic storm surge modelling via Mike21 software coupled with urban databases stored in GIS to evaluate and map risk. This integration is described in the context of the Cairns study site in Far-North Queensland. With the addition of a user interface and pre-defined analysis routines, the combination of GIS and hydrodynamic modelling provides a decision support environment for hazard risk managers and decision makers. A unique feature of this research is the development of a relational database management system to facilitate rapid urban flood risk assessment. The end results is a series of digital 'look-up-maps' for future risk assessment and decision making. This paper addresses the technical issues associated with linking GIS and hydrodynamic models and presents the results in terms of risk for one cyclone scenario. This research represents one of the first efforts in Australia to integrate such modelling for coastal storm surge risk management and decision support.

Keywords: Cyclones, GIS, SDSS, Mike21, Risk Management, Storm Surge

1. INTRODUCTION

Historically, cyclone inundation risk is a relatively common occurrence in tropical Australia. However, climatic evidence shows that high magnitude cyclonic events occurred before the current high levels of urbanisation. The combination of historical evidence and the increased urbanisation means that a real and ever growing risk exists. Invariably, cyclone risk managers and urban planners will demand access to decision support tools that allow them to manage and understand the complexity associated with cyclone risk. This research is an extension of earlier work conducted with risk managers in Cairns and Mackay. Earlier work has shown that managers are seeking additional temporal predictive resolution for their risk management, in addition to more robust decision support tools.

Spatial information systems have routinely been used to evaluate and map the risk to urban communities from cyclone-induced flooding. These earlier approaches however, commonly neglect the complexity associated with storm surge events and simplify the dynamic nature of the hazard event. For example, the models assume still-water surge heights or only map inundation zones for individual events, such as the 1 in 100 year event, with no reference to multiple scenarios or multiple time steps.

This paper presents an innovative integration of hydrodynamic modelling, geographic information systems and relational database technologies to provide risk managers with decision support tools to assist with evacuation planning and landuse management. Most notable is the ability of the system to provide risk managers with time series risk information at urban decision making scales. This has been achieved by coupling urban databases stored in a GIS with a hydrodynamic storm surge model. This paper addresses the technical issues associated with linking GIS and hydrodynamic models and presents the risk results for one likely cyclone scenario in Cairns in Far-North Queensland.

2. THE STUDY SITE AND THE HAZARD

A storm surge (commonly called 'storm tide' when combined with tidal influences) is the term used to describe an anomalous elevation of water typically some 50 kilometres across generated by the action of a cyclone and the coastal bathymetry. Cairns, (Figure 1) situated in Far North Queensland with a population of approximately 100,000, is one of Australia's most storm surge-prone regional centres. The linear nature of the coastal range in Cairns, combined with the desire for beach frontages, restricts urbanisation to a north-south corridor that leads to a greater risk. Although the incidence of major cyclone disaster in Australia is uncommon, events such as Cyclones Tracy (1974), Justin (1997) and Steve (2000) remind residents and policy makers that a substantial risk exists.

3. STORM SURGE MODELLING

Modelling surge hazard inundation in vulnerable urban regions is an important component of broader disaster risk management objectives. For instance, accurate surge inundation models are important for evacuation planning, for developing urban zoning that accounts for inundation risk, for developing mitigation measures such as building construction codes and for planning post-disaster recovery.

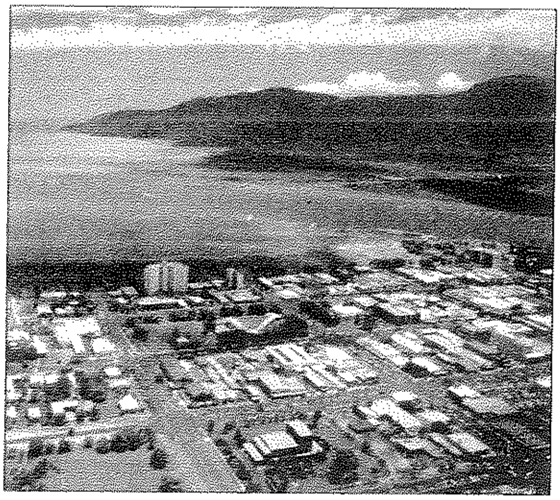

Figure 1. Cairns, Far North Queensland. Looking eastward from the coastal range over the central business district.

Predicting over-land inundation in Australia has received little attention [Sanderson et al., 1995, Hubbert and McInnes, 1999]. Research has focused on modelling the behaviour of the surge at sea from meteorological parameters including cyclone central pressures, velocities, radius of maximum winds, approach angles and the coastal bathymetry. Modelling inundation is also limited by the availability of high accuracy databases, the complexity of surge behaviour over barriers and around buildings and the computational demands of modelling its dynamic behaviour.

Storm surge models in Australia include the Australian Bureau of Meteorology MEOWs technique, which is a macro scale approach that subdivides the Queensland coast into three model domains [Sanderson et al., 1995]. The MEOWS technique is restricted to a 7.5 km grid and provides surge heights over the ocean and hence its utility for urban risk management is limited. The CSIRO high resolution GCOM2D model [Hubbert and McInnes, 1999] has been applied in northwestern Australia at Port Hedland and in Port Phillip Bay, Victoria and provides relatively detailed surge estimate for coastal-zone planning.

4. RISK MANAGEMENT DECISION MAKING REQUIREMENTS

Earlier research work by the authors in coastal Queensland has examined the practical decision making requirements of risk managers. This research attempts to overcome some of the earlier limitations. First, overland surge models are required to improve the reality of risk assessments as current approaches do not capture the dynamic behaviour of storm surge on land. Second, detailed user needs assessments with emergency managers in Mackay and Cairns have shown that they require additional temporal resolution rather than improved spatial resolution. Semi-structured interviews showed that risk managers would sacrifice the spatial resolution inherent in the GIS building database for more detailed time series information for evacuation planning. And finally, the response phase of cyclone inundation decision-making requires instantaneous risk assessments and hence hydrodynamic models cannot be run in real time. These three limitations of the earlier research have been overcome in this work.

5. SYSTEM DEVELOPMENT

5.1. Risk Database Development

Detailed spatial databases for Cairns are a key input for risk modelling. From fieldwork and existing council databases, information on 24,669 commercial and residential buildings in Cairns has been integrated into a GIS. The database also includes building attributes such as floor heights (for inundation modelling) and building construction material (for future cyclone wind field modelling). In addition to the built environment, key input parameters for modelling inundation are high accuracy digital elevation models (DEMs).

The DEM, in combination with the floor heights, is critical for the accurate prediction of the number of buildings likely to be inundated by a particular scenario. ANUDEM [Hutchinson, 1996] surface interpolation software was used to generate a 20 metre DEM from 1:25,000 scale contours, spot heights and drainage networks. 294 sub-centimetre accuracy surveyed control points were used to verify the final DEM accuracy. The entire database has been developed in an ArcView GIS [ESRI, 1999] environment.

5.2. Hydrodynamic Storm Surge Modelling

Mike21 is a modelling system for 2-dimensional free-surface flows [DHI, 2000]. It has recently been accepted by the US Federal Emergency Management Agency (FEMA) as an approved coastal storm surge model for its National Flood Insurance Program. Water levels and fluxes are resolved in Mike21 for a rectangular grid representing the area of interest (Figure 2) using inputs including bathymetry, boundary conditions, bed resistance and wind fields (among other parameters). Over-land inundation modelling of storm surge, including the flooding and drying component of inundation, is critical for this research hence the importance of Mike21.

A 100 metre resolution bathymetric grid was created by digitising existing bathymetric maps of Cairns. ANUDEM was used to generate the continuous bathymetry surface from the digitised data for use in Mike21. Water level datum information was provided by Queensland Transport (Maritime Division) and was used to adjust the bathymetry surface to the Australian Height Datum (AHD). The inclusion of flooding and drying in the model requires detailed topographic information for the urban area of Cairns. The existing 20 metre DEM was merged with the bathymetry to create the complete model domain shown in Figure 2 at a combined grid resolution of 100 metres.

In comparison to other attempts to model storm surge in Australia, this is represents a relatively detailed hydrodynamic model. Such detailed modelling was critical for Cairns, as similarly detailed spatial databases were available and risk management needs demanded individual building risk estimates. Therefore, using this approach it is possible to assess the effect of subtle landuse changes including land clearing, urbanisation and road creation in Cairns.

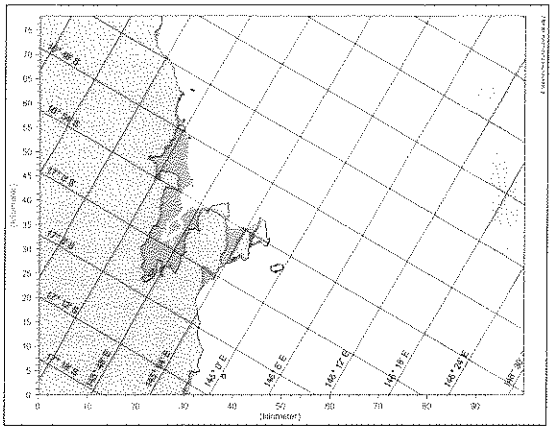

Figure 2. Cairns storm surge model domain.

When combined with the wind and water dynamics, these factors can influence the likelihood of disaster. It is envisaged that the high-resolution Cairns integrated model will act as a 'test-bed' for assessing future scenarios and determining model requirements in other coastal communities in Australia.

Historical tidal data from Queensland Transport (Maritime Division) was supplied for a single tide gauge at Cairns Port. This data was used to establish the initial model boundary conditions. An early check on the water levels being generated was to extract a time-series at Cairns Port and compare this against the tidal data. Anecdotal evidence also provided some calibration, with knowledge that the water levels during the highest tides would inundate the most coastal grid cells. Bed resistance values for the reefs and the main channel were modified to calibrate this water level.

Wind fields were generated with various cyclone parameters. Modelling the wind surface was initially performed using winds that varied in time but not in space (a simple tidal model with uniform wind surface). Models were completed for numerous wind directions and velocities. To model cyclonic winds that vary in time and space, realistic parameters are required for the radius to maximum winds, maximum wind speed, cyclone track and speed, central pressure and neutral pressure. Many of these parameters were derived from the Bureau of Meteorology's Tropical Cyclone Database.

The addition of cyclonic wind fields caused complex surge dynamics and it was necessary to alter the Mike21 model design. A coarse resolution bathymetry (1 km resolution) was generated for a larger study area (48,000 sq/km) over which cyclones could be applied. Using this larger area, transfer boundaries could be extracted to feed a finer resolution (100 metre resolution) nested area (2000 sq/km). This technique of nesting models increases the amount of data preparation, however the overall modelling time is reduced substantially. Transfer boundaries were necessary in this study to ensure that the boundary conditions did not contradict the wind field and cause model instability.

It is important to note that the modelling undertaken in this research is based on a limited amount of calibration and potentially inadequate boundary condition data. The bathymetry for the model area is very detailed, however the boundary conditions are based solely on tidal data. Calibration in this study was difficult due to the absence of historical storm surge events.

5.3. Time Series Data Management

Numeric modelling of storm surge inundations for multiple scenarios results in the generation of massive inundation databases. In this research, a simple model run over 72 hours and analysed at 10 minute intervals leads to 432 raster inundation surfaces. As each surface is approximately 700 Kilobytes in size, this equates to some 30 Megabytes of data for only one model run. To perform a building risk analysis it is necessary to evaluate the inundation for every building in Cairns, for each time step in the scenario, and for multiple scenarios. This quickly generates millions of database records.

As real-time risk modelling over such temporal domains is not feasible, the research pre-modelled realistic cyclone scenarios for Cairns. The objective is to develop and test the concept of electronic 'time-series look-up-maps' for future risk assessments. This dual requirement to manage vast databases, and to provide ongoing access to model results, drove the need for efficient and robust database management. A Microsoft Access2000 Relational Database Management System (RDBMS) was developed to store data and to provide for rapid database query for risk managers.

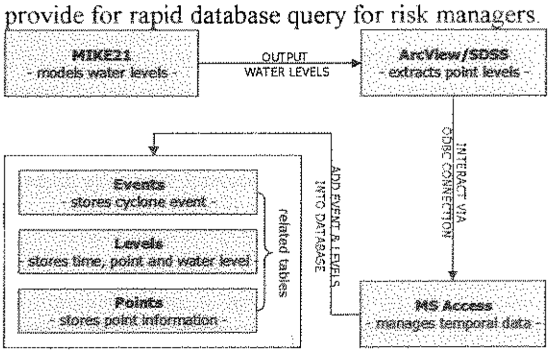

Figure 3. Relational Database System.

The RDBMS structure was designed so that any number of Mike21 simulations could be stored (Figure 3). After inundation surfaces are created within Mike21, an algorithm extracts the water depth for each building and populates the RDBMS with the inundation level (relative to AHD). The RDBMS is linked to the ArcView GIS via an open database connection (ODBC) and a unique feature identifier for each building. A key feature of the system that facilitates rapid data processing is a spatial algorithm embedded in the GIS that restricts analysis to only those buildings that are inundated above property level. This algorithm reduces computation times substantially, thus making the system suitable for large building datasets and short modelling time steps over multiple days.

Another important benefit of the approach is the model results are stored only for locations that are of immediate interest to risk managers. In this instance this includes roads and buildings. Even with such efficiencies, however, the size of the RDBMS is significant. For instance, 18 model runs for Mike21 containing data in ten minute time-steps over two days generates an Access file of 290 Megabytes. However, this is a major improvement over saving the raster surfaces produced by Mike21, or any other hydrodynamic model.

5.4. Decision Support System Architecture

The three critical components of the system are the Mike21 inundation model, the RDBMS and the GIS-based urban risk databases. The hydrodynamic model permits the simulation of storm surge inundations for various time steps and cyclone parameters. The GIS provides an environment for data integration, analysis and visualisation, while the RDBMS facilitates temporal database management. In their own right these components are critical to perform a risk assessment. However, without integration these components are of little utility to decision makers in Cairns.

Through the integration of these components and a customised GIS interface, a spatial decision support system (SDSS) has been developed that allows risk managers to perform detailed temporal risk assessments (Figure 4). The SDSS has two major functions including processing and analysis. The processing module integrates the model results and urban datasets to populate the RDBMS with water levels for each time step. The analysis module is designed for working with pre-modelled events, by extracting them from the database and displaying time series inundation data. This module also generates inundation statistics and graphs.

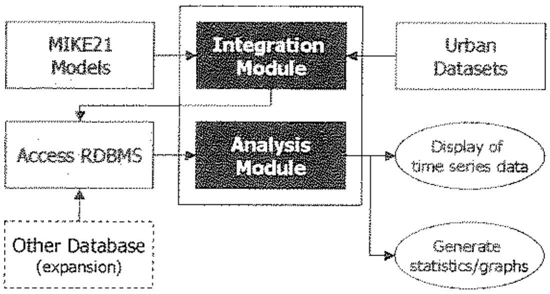

Figure 4. SDSS structure.

6. RESULTS AND DISCUSSION

The results presented here are for a hypothetical, but realistic cyclone striking just north of Cairns harbour called Cyclone Fred. Information obtained from the Bureau of Meteorology in Brisbane suggests that the maximum storm surge in Cairns occurs after the cyclone crosses land to the north. Cyclone Fred has cyclonic winds with central pressures as low as 950 hPa, maximum winds reaching 100 knots and a radius to maximum winds of 80km. This could be described as a severe 'midget' cyclone reaching landfall 40 km north of Cairns.

The model was run over a period of three days starting on February 15th at 1200hrs. The cyclone was designed to cross the Cairns coastline at 1800hrs on February 16th. This scenario illustrates how fictional, but realistic, cyclone parameters can be translated into building inundation estimates. The model outputs were processed and analysed using the decision support system and inundation at the peak of the fictional event shows widespread inundation throughout the township of Cairns (Figure 5). It is important to note that this spatial representation represents merely one snapshot within the three day model duration.

Although modelling the maximum storm tide is useful for estimating the absolute disaster threat, this methodology becomes particularly valuable for evacuation planning when we consider the temporal component of an event. The ability to present varying risk in terms of buildings (and road networks) inundated adds a critical component to risk management planning. Figure 6 shows the number of buildings inundated both over-floor and over-ground for Cyclone Fred.

The results suggest that there is a lag of about two hours between when the cyclone crosses the coast, and when the maximum building inundation is observed. The graph also shows that the temporal coincidence between tides and cyclone crossing time can alter the risk to buildings. For example, over-floor building inundation commences at 0800hrs on February 16th and is somewhat nullified by the low tide at 1200hrs, February 16th. The rate of over-floor building inundation observed with the approach of the cyclone eye is also useful for evacuation planning.

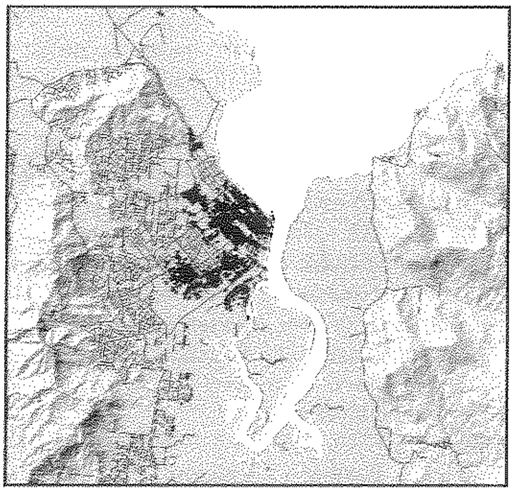

Figure 5. Buildings inundated over floor level for Cyclone Fred (2040hrs, Feb. 16th). Dark dots represent the inundated buildings.

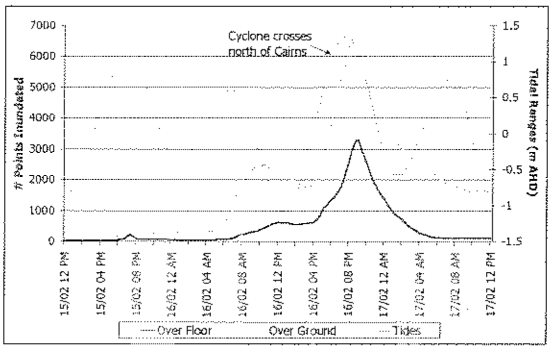

Figure 6. Inundation Graph For Cyclone Fred.

7. CONCLUSION & FUTURE RESEARCH

This research has addressed some of the earlier decision making concerns of risk managers by integrating hydrodynamic modelling results in a GIS framework. The coupling of hydrodynamic modelling with relational database management systems provides data management and analysis options not previously possible. For instance the use of a strictly spatial data model inherent in many GISs constrains users to particular analysis options. Most importantly, the system is very versatile in its treatment of time series data. Specifically, the use of an RDBMS has a number of advantages including:

- The use of standard software connectivity tools such as ODBC means that the model results are portable across multiple GIS platforms. Most commercial GISs support both ODBC and SQL, and with the advent of Internet data dissemination, it is a relatively simple process to serve model runs on-line to multiple users;

- The use of an RDBMS significantly reduces the amount of data that needs to be stored from each hydrodynamic model run. In other words, the methodology only stores model results at risk locations rather than storing a spatial exhaustive gridded data model inherent in most GIS and modelling systems.
- A RDMBS allows risk managers to ask relatively flexible and complex questions using SQL statements. For example, the system could answer the question 'show me all the buildings that were flooded greater than 0.5 metres above floor level for more than two hours for Cyclone 15?'.

However, a number of additional research issues and limitations still remain. These can be grouped into the hydrodynamic modelling challenges and those associated with the broader decision support objectives. Specific hydrodynamic research issues include the need for additional model calibration, use of better boundary conditions and the inclusion of more realistic surface roughness coefficients. From the perspective of the DSS, the limitations of the methodology are two-fold.

First, if the building database grows in the future, the RDBMS needs to be re-populated from the hydrodynamic model outputs. In an operational environment this would need to be done periodically, or when significant urban growth or hydrodynamic model development occurred. However, this is a small computational overhead when compared to advantages introduced by the SQL approach. Second, in terms of database technologies, Microsoft Access remains a relatively simplistic, and even immature technology. For instance, more high-end systems such as Oracle or IBMs DB2 provide more refined query engines. These systems utilise proprietary query optimisers to accommodate massive relational database queries. At present, an SQL request using MS Access can take up to 10 seconds to generate a result. This is particularly a problem when risk managers wish to rapidly step through a cyclone event.

It is envisaged that this innovative methodology could be applied to other Australian coastal communities. Although the research has focused on technical issues of hydrodynamic modelling, database integration and spatial decision support systems, a pressing need exists to conduct a detailed user needs assessment and evaluation of the methodology. This would involve a hypothetical real-time scenario with risk managers in Cairns who would have access to the decision support system to aid planning. It is only once these pragmatic concerns of human decision making needs are addressed, that model and SDSS refinement should continue.

8. ACKNOWLEDGMENTS

Funding for this research was provided by the Australian Research Council Small Grant Scheme (ARC-S4005168). This research benefited from the technical input provided by Andrew McCowan (Water Technology), John Broadbent (Queensland Transport, Maritime Division), Jeff Callaghan and Barry Gordon (Australian Bureau of Meteorology, Brisbane Office).

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