Examining GIS decision utility for natural hazard risk management

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Abstract The research examines the incompatibility between resolution and scale of spatial data in a spatial modelling environment and the resolution and scale of human spatial decision making. This incompatibility is rarely considered when a GIS is applied to natural hazard risk assessment. However, the ultimate success of a risk management project should be assessed in the context of improved decision-making. Decision utility is an emerging theme in GIS literature that focuses on cognitive issues of GIS and human interactions. The research presents a technique for flood risk modelling using GIS and digital elevation models to map relative risk in urban communities. Cairns in North Queensland is used as a case study. The risk model accounts for uncertainties inherent in the elevation data by adapting an existing error simulation technique. Techniques for making spatial model assumptions and model error explicit to flood risk managers are introduced.

1. INTRODUCTION

Our knowledge of hazard phenomena and the processes that drive them are imperfect. It is therefore necessary to develop appropriate models (process, spatial and temporal) to fill the gap. The synthesis of data and the mapping of the relationships between the hazard phenomena and the elements at risk requires the use of tools such as geographic information systems (GIS). There are advantages in developing a fusion between the philosophy of risk management and the strength of GIS as a decision support tool. However, the ultimate success of such an approach should be assessed in the context of improved decision-making.

Coppock (1995) notes that there are grounds for believing that GIS has an important role to play because natural hazards are a multi-dimensional phenomena which have a spatial component. Examples include cartographic approaches for mapping the physical hazard, integrative hazard modelling and spatial decision support systems (de Silva *et al.* 1993) and disaster response planning (Zografos *et al.* 1994)

GIS spatial analysis techniques may introduce problems unique to the technology during the data integration and analysis process (Rejeski 1993). Problems include the degree of uncertainty that can be associated with model results owing to the choice of the model used, and the role of error in the input data and how it effects the outcomes of the risk assessment. These factors contribute to the overall uncertainty in the results of risk models. Because the objective of natural hazard risk assessment is to reduce uncertainty, this should be extended to the GIS and spatial analysis process as well (Rejeski 1993, Emmi and Horton 1995, Murillo and Hunter 1996, Zerger 1998)

This paper describes a GIS-based sensitivity analysis technique for modelling the uncertainty in storm surge inundation risk models in Cairns, Australia. The approach accounts for storm surge inundation model and database uncertainty. Measures of uncertainty are included in the final hazard risk assessment. The objective is to develop a technique which communicates uncertainty and has practical utility for emergency management decision makers in Cairns.

2. STUDY SITE AND SURGE RISK

A storm surge is the term used to describe an anomalous elevation of ocean water typically some 50 kilometres across generated by the action of a cyclone and the coastal bathymetry. Loss of life in Australia from storm surge inundation has been minimal in comparison to events elsewhere. Modelling surge inundation in urban areas vulnerable to storm surge is an important component of risk management for the reasons listed below:

- Emergency management evacuation planning.

- Developing urban zoning that accounts for storm surge inundation.
- As an educational tool to inform citizens of the risks present in their community.
- Identifying risk for insurance premiums.
- Developing building codes to minimise the impacts of surge.
- Cost-benefit analysis for developing mitigation strategies.
- Managing post-disaster recovery.

Cairns is located in Far North Queensland with a population of approximately 100,000. The Queensland coast has been labelled 'The New California' with growth rates that place it in the top ten fastest growing urban areas in the developed world (Skinner *et al.* 1993). The linear nature of the coastal range combined with the desire for beach frontages restricts urbanisation to a North-South corridor (Figure 1). This leads to a greater probability of massive losses from storm surge. In addition, Cairns is the most remote regional centre in Queensland which magnifies the consequences of any cyclone disaster. Although the incidence of major cyclones in Australia is relatively uncommon, events such as cyclone Tracy and Justin remind us that a risk exists.

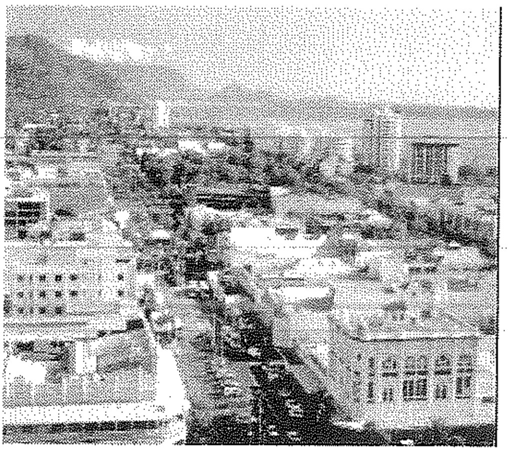

Figure 1 Cairns City looking north

The key to developing emergency response strategies for storm surge in Cairns is to identify spatially where the risk will be greatest. The next section outlines a GIS-based technique for mapping relative inundation risk in Cairns.

3. SPATIAL DATABASE

A key indicator of surge risk are the buildings and roads that may be inundated. Detailed building databases were developed for Cairns from field work and council databases. Approximately 25,000 buildings were integrated in an Arc/Info (ESRI 1997) spatial database (Figure 2). This included attribute information such as building floor heights, building addresses and the number of stories of each building.

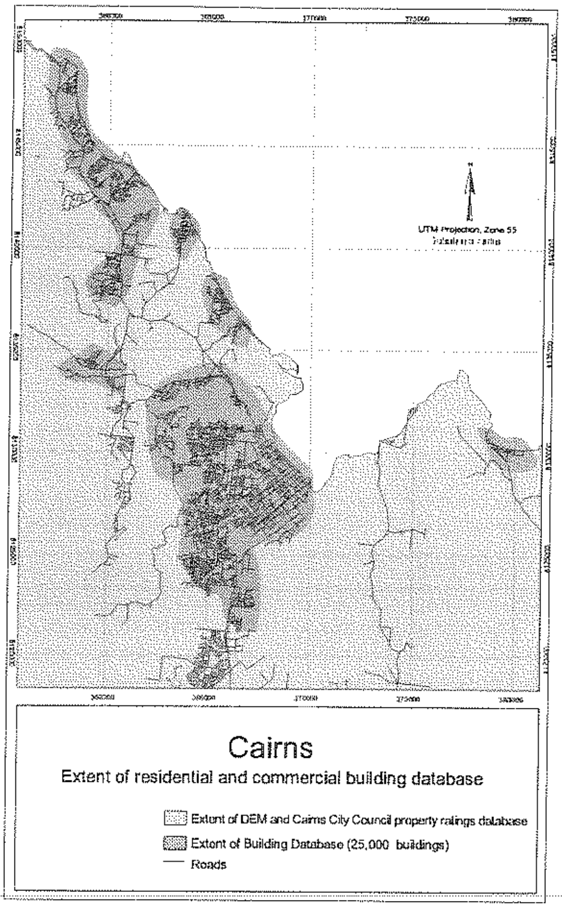

Figure 2. Spatial extent of Cairns GIS database

4. INUNDATION RISK MODELLING

Because an overland storm surge model for Cairns does not exist, a flatwater sensitivity analysis approach was used. Inundations are modelled by systematically increasing the inundation level based on a digital elevation model (DEM) and assessing the resulting building and road flooding from 50 centimetres to 1500 centimetres above the Australian Height Datum (AHD) in increments of 50 centimetres.

Sensitivity analysis is particularly valuable for hazard risk assessment because:

- The relative importance of input parameters can be assessed (floor heights, DEM accuracy and resolution).
- Risk managers can identify emergency management 'hot-spots'. These are regions that have a relatively high risk in the study domain.

- It can identify probable maximum risks where the traditional approach considers probable maximum hazard (in this case storm surge hazard). This paper contends that probable risk is a more appropriate construct for risk management.
- Sensitivity analysis can identify 'cold-spots'. These are regions that can be used as evacuation safe areas.
- It can identify and define emergency management 'catchments' or regions within the study domain that have a similar risk in the context of evacuation planning and decision making.
- It can identify the robustness of risk analysis to errors, scales and uncertainties in GIS data and models.

The model is implemented using the ARC/INFO (ESRI 1997) GIS and the ARC/INFO Macro Language (AML). Inundation is a function of the ground elevation at each building derived from a 20 metre cell resolution DEM constructed for Cairns using ANUDEM surface interpolation algorithms (Hutchinson 1998), building floor heights derived from field work and the flatwater surge inundation model.

5. MODELLING UNCERTAINTY

Uncertainty, in contrast to error, assumes that no prior knowledge of the accuracy of the data exists. Few examples of GIS applications to natural hazards risk assessment consider data or model accuracy, or communicate the inherent uncertainties in data and models in the final risk assessment. Commonly, model and data uncertainty estimates are esoteric concepts which have little practical use to risk managers. These may include measures such as root mean square errors, probability surfaces and classification error matrices.

Three possible sources of error are present in the surge inundation model including the vertical error in the DEM, error in the floor heights and the error in the storm surge model. The accuracy of the elevation model is a function of the scale and accuracy of input topographic data and the ANUDEM interpolation process. DEM error is the focus of the uncertainty modelling methodology in this research. As a first step a measure of DEM error has been derived from high accuracy permanent survey markers in Cairns.

A detailed DEM error assessment found that 90 % of the DEM was correct to within +200 centimetres (root mean square error). The concern with these errors are the implications for risk predictions for low magnitude and high frequency inundation events in Cairns. Significant increases in the number of buildings inundated over floor level are observed at increments less than the vertical accuracy of the DEM. A critical question is; *how much faith can be placed in the inundation results when the model is dependent on DEM accuracy* ? One outcome is that our confidence in surge estimates must be questioned under particular low magnitude scenarios. These events are important in Queensland due to their higher frequency of occurrence.

Openshaw (1989) noted that the problem is not as much the existence of uncertainty, but rather that the traditional response has been to ignore it on the grounds that methods to handle it do not exist. Goodchild *et al.* (1992) note that with the existence of uncertainty in models and spatial data there are three options for how to deal with it: (a) Omit all reference to it, (b) attach some form of description to the output, and (c) show samples from the range of maps or outputs possible.

The first is unacceptable for hazard risk management and evacuation planning and the second may not adequately communicate this complex concept to risk managers. Examining the third option is preferable because '*it would appear to have the greatest potential benefit in both communicating uncertainty and at the same time educating the user community to the significance of the issue*' (Hunter *et al.* 1994). The third option is adapted for modelling storm surge inundation uncertainty in Cairns.

5.1 Grid Cell Model of Uncertainty

A variety of methods exist for handling uncertainty in spatial data including methods such as analytical error propagation models and empirical stochastic approaches. The research adapts the grid cell model of uncertainty (GCUM) (Hunter *et al.* 1994). The model has been used previously to determine the uncertainty of slope and aspect estimates derived from spatial databases, for estimating the influence of uncertainty on wildfire mapping using remotely sensed imagery and for landslide susceptibility mapping.

The GCUM applies *noise* to a source DEM to simulate the error present in the data by randomly perturbing the elevation values to create new *realisations* of the DEM. The DEM realisation is then used in the model and new risk results are derived. The realisations must be both stochastic, yet sufficiently spatially correlated to truly represent the spatial dependencies inherent in elevation. The model constrains the random perturbations by a spatial autocorrelation index (Cliff and Ord 1981).

6. INUNDATION RESULTS

The output provided by the model is a probability of over-floor flooding for each building in the range 0-100%. Continuous risk probability maps can be re-classed into binary maps of risk by selecting a threshold value below which flooding is not likely. This should be avoided because valuable information would be lost and such representations reinforce the perception of risk as an absolute. Results from the model of building and road network inundation for Cairns are stored as digital animations at http://www.geom.unimelb.edu.au/zerger/maps.html. A sample inundation result is shown in Figure 3.

Figure 3. Risk model results for a 3 metre inundation in Cairns showing the probability of flooding for each building (relative risk).

Results confirm that the greatest changes in risk occur at relatively low inundation (< 400 centimetres above AHD). Although probable maximum storm surges (approximately 600 centimetres above AHD) may have dramatic consequences, results show that these would not be significantly greater than consequences for relatively low inundations. The animations also highlight the importance of critical threshold inundations in the study domain.

The inclusion of uncertainty estimates into inundation risk models has perceived advantages over binary maps of risk. First, it includes measures of uncertainty into the risk model and data and model assumptions are made explicit to end-users. In other words, spatial uncertainty can be visualised in the final risk maps. And second, the techniques provide an indication of the relative risk of inundation. Prioritising evacuation zones based on these results may lead to more informed emergency management decision-making. The following discussion examines the practical decision utility of these results for risk management.

7. ASSESSING GIS DECISION UTILITY

Computer and paper maps are powerful tools for communicating risk analysis and assessment results and to aid decision-making. A responsibility exists for GIS risk practitioners to ensure that model assumptions have been presented and that the cartographic representation is conducive to improved decision-making. Decision utility is an emerging theme in GIS literature that focuses on cognitive issues of GIS and human interactions (Rejeski 1993). It recognises that a fundamental objective of GIS modelling is to reduce the uncertainty inherent in spatial decision-making. It is therefore critical that GIS design should be assessed in the context of improved decision-making.

Because the essence of evacuation planning is the rapid spatial movement of people, goods and services, maps are one of the best media to depict this (Dymon and Winter 1993). This paper contends that in GIS-based natural hazard risk assessment (and other spatial modelling for that matter), an incompatibility exists between the resolution and scale of spatial data in a GIS and the resolution and scale of human spatial decision-making. Rejeski (1993 p.323) highlights this incompatibility:

> *There can be no doubt that increasing the believability and honesty of GIS products will increase their utility for decision makers. However, developing a close fit between map analysis and policy goals is of such critical importance that it requires a considerable level of effort and foresight on the part of the analysts and map makers. When maps fail to have impact, it often has little to do with model nuances or data gaps, but more to do with a lack of fit between cartography and decision reality.*

In this research, decision-making is concerned with evacuation planning by emergency managers. Few studies have attempted to integrate decision-scale and resolution into GIS-based risk modelling and fewer have assessed the utility of uncertainty-based cartographic representations. Semi-structured interviews were presented to key emergency management stakeholders to determine the utility of uncertainty-based risk maps for evacuation planning and decision support (15 stakeholders in total). Stakeholders included Cairns city council risk managers, Queensland Department of Emergency Services policy staff and police officers.

7.1 Results Of Decision Utility Assessment

The aim of the interview process was to determine the utility of uncertainty-based risk maps for evacuation planning and decision support. The overwhelming conclusion was that for practical storm surge evacuation planning, the maps provide too much spatial detail to be practical. However, this conclusion should be considered in the context of the functional purpose of the maps ie. risk mapping for storm surge emergency management evacuation planning. For other functional purposes including urban planning, riverine flood evacuation and mitigation cost-benefit analysis the conclusions will differ. In general, risk managers concluded that storm surge evacuation decision-making operates at a coarser spatial resolution than the uncertainty-based GIS risk mapping. In addition:

- Risk managers already account for a range of other uncertainties when delineating evacuation zones such as the uncertainty inherent in Bureau of Meteorology forecasts. These were noted to overwhelm the uncertainties inherent in inundation models.
- Because the risk management objective is to encourage self-evacuation, prioritisation of evacuation is not as critical as first contended. Also, risk managers will prioritise on the basis of vulnerability rather than on hazard zonations.
- Risk managers commonly assume a worst-case scenario. At high inundations the maps effectively become binary maps of risk because the coastal regions are topographically homogenous and any delineation of relative risk is ignored.
- Risk managers currently evacuate entire regions rather than individual buildings. The resolution of the database is too fine for evacuation planning.
- Although risk management 'hot-spots' have been identified in the maps, risk managers prefer to identify 'risk catchments'. Catchments are areas that have similar risk estimates and require similar risk treatments (evacuation instructions).
- There is a resistance to provide uncertainty-based maps to the public because they imply policy uncertainty and may result in individual decision ambiguity. This is a major problem when evacuation orders are issued.

Responses also highlight the common incompatibility between scientific modelling objectives and practical decision making. Coarser resolution and less accurate spatial data may be adequate for evacuation decision making. If user considerations are assessed early in the risk modelling process, GIS practitioners can minimise data capture, avoid unnecessary levels of complexity in the spatial modelling and generally improve the utility of the risk modelling for decision making. A decision utility assessment should be a key step in future applications of GIS to hazard risk management.

Although it was concluded that uncertainty-based risk maps are too detailed for evacuation planning, these representations of relative risk are nevertheless useful for other hazard risk management activities. Most respondents identified the suitability of this approach for slow-onset riverine flooding. Risk managers working on policy formulation suggested the methodology would be important for assessing mitigation strategies where a sensitivity analysis is required. The uncertainty methodology is more appropriate for planning, preparedness and assessing mitigation options, than for hazard event response.

A unique behavioural interpretation of the maps was observed with all risk managers. Most had little or no experience with root mean square error estimates (as calculated for DEMs) and few had practical GIS experience. Describing the concept of spatial uncertainty proved challenging and describing the uncertainty modelling technique was difficult. However, when risk managers were challenged to make evacuation decisions on the basis of the maps, they intrinsically identified the red points as high risk areas and the grey as having a lower risk. The underlying methodology behind this relative risk modelling was rarely questioned and there was an intrinsic acceptance of uncertainty-based results, regardless of their understanding of this complex concept. Therefore cartographic representations are important for presenting uncertainty information without explicitly identifying it as such. This is both a strength and a weakness of GIS-based risk modelling.

8. CONCLUSION

The application of a GIS for natural hazard risk management is an emerging science and the ability to provide a spatial context for risk is critically important for risk reduction. A precautionary outlook is required because GIS-based risk modelling introduces concepts such as uncertainty that are relatively new to risk managers. The recent interest by commercial GIS vendors in emergency services and risk management places undue emphasis on software and hardware issues.

Research has shown that non-technical issues such as assessing and planning for decision utility and the fitness of use of spatial data may be greater barriers to successful GIS model implementation. Regardless of the natural hazard, GIS software, spatial data or the risk model, the use of a GIS for risk management should be assessed in the context of improved decision-making. This has important implications for other spatially explicit modelling that aims to address decision support needs.

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