# The Application of Numerical Modelling in Natural Disaster Risk Management

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**Summary:** The paper presents an overview and outline of the application of numerical modelling techniques derived from engineering approaches which can be effectively used to address problems of natural disaster risk management. The various types of numerical models and their basic characteristics and uses are introduced together with an indication of their potential value to management. A case study is presented of the application of a complex multi-dimensional numerical model to the tropical cyclone hazard at Townsville in North Queensland which shows how such models can readily be extended to cover wider management issues.

## 1. INTRODUCTION

Natural disaster risk management is increasingly on the modern agenda. Some would argue the frequency and intensity of natural disasters are on the rise worldwide and this is directly related to a collective abuse of the planet. Certainly this theory has gained popular acceptance, especially in the media, but there is little evidence of this fact in Australia. What we do know is that the growth in population and changing demographics of our expansive continental nation are increasingly placing more of our population at risk to influences along the coastal margins where many risks exist. Ironically, there is also perhaps a growing expectation from society that government can and should manage nature more effectively in these days of "high technology".

This paper sets out to introduce to risk managers the very significant benefits that numerical models can deliver in providing insight into relative risks, causes and impacts of natural hazards. Management needs information, planning advice and scenario testing in order to be prepared for the effects of natural disasters - whether the risks are to human or economic elements.

## 2. WHAT IS A NUMERICAL MODEL?

Numerical models can and often do take many forms but all can be broadly described as the representation of a *system* using a series of entities which can be described by mathematical functions, typically constructed in software on a computer system. The simplest form of a numerical model might be described by the schematic of Figure 1 whereby an *input* is provided to a *process* which then provides an *output*. The *process* is based on the conceptual model of the particular reality or *system* to be described. In the present paper we are concerned with *systems* which represent manifestations of natural disasters, eg. flood, earthquake, cyclone, bushfire, severe thunderstorm and their impacts or interactions with our society.


Figure 1: A Simple Schematic "Model"

The manner in which the model is constructed very much depends on the problem to be solved:

- Natural systems are often best approached from a physical viewpoint. This normally involves representing the essential physics of the problem such as mass, momentum, thermodynamics, friction, energy transfer etc and obeying the intrinsic conservation laws of these properties. Entities might include windfield models of a tropical cyclone or thunderstorm, the flame propagation in a bushfire, the generation of a storm surge etc.
- Human systems are often represented in a causal system of inter-relationships and decision making. Factors such as emotions, errors of judgement, organisational heirarchy, communications and expertise are the entities used.
- Hybrid systems are often required where human systems and natural systems interact, such as for example the potential melt-down of a nuclear reactor or the explosive loss of an offshore gas production platform. Part of the system may represent physical behaviour while the remainder represents individual or organisational behaviour.

Exactly how the entities are represented is a function of the problem to be solved, the state of knowledge and the required accuracy, eg.

- Analytical methods might be employed where relationships are explicit and well defined.
- Empirical methods might need to be used where data or knowledge of the true behaviour is only partly known, understood or even identified.
- Numerical methods are needed where the relationships are complex, multi-dimesioned or require optimisation. In this case iterative computational methods are often required.
- Stochastic methods are needed where the behaviour of a system is of a randomly-forced nature and the sequence or relevance of potential events is not known in advance.
- Heuristic methods may be needed where a model needs to self-learn and improve its axioms. Some so-called "expert systems" are in this category.

Numerical models can also be classified in terms of how they represent the intended system as a whole:

- Discrete models deal with individual elements of the process in a detailed way, often directly on a cause and effect basis.
- Continuous models involve an integration of a number of factors, bulked together without the individual details showing, often covering large spatial or temporal steps.
- Deterministic models produce a defined set of outputs from a defined set of inputs and answer "what if" problems.
- Probabilistic models allow a range of possible inputs and outputs based on essentially a stochastic system.

The design and construction of a numerical model is often said to be as much an art as a science but it must be founded on demonstratively robust relationships and be able to deliver utility, insight and results. The methodology must suit the scale of the problem in terms of detail, relevance and desired outcomes. Accuracy is always of fundamental interest and the act of *calibration* against relevant data is paramount in establishing the basic integrity of a model. Finally, *verification* of the model against an independent data set (preferably more than one) cements confidence in its predictive power. A well designed numerical model should also embody *self-checking*, *sensitivity testing* of its parameters or estimates of the *confidence* of its predictions. Because of their ability to change and evolve in response to calibration and verification cycles, numerical models can often become extremely effective decision making tools, embodying all of our collective knowledge about extremely complex natural and human systems. As observed by Rapoport (1) all knowledge is tentative while propositions based on hypothesis are tested - this is the realm of numerical modelling.

Figure 2 therefore expands on the earlier simple process model to show how many of the above separate model elements can be brought to together and combined to solve a particular problem - such as the case study presented in Section 5.

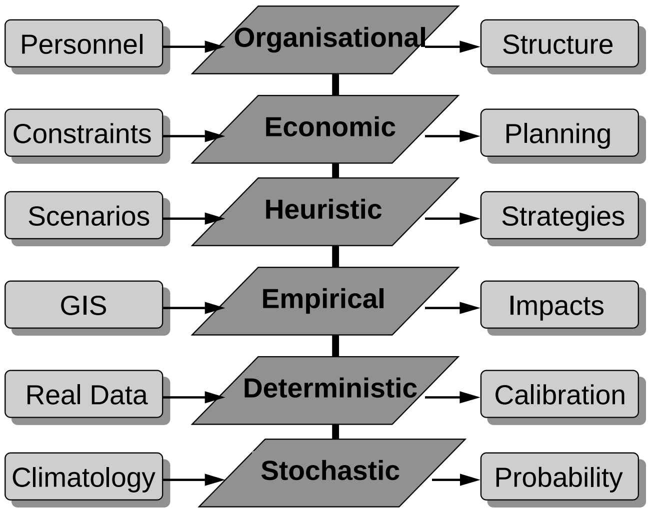


Figure 2: A Complex Integrated Model

### 3. WHY USE A NUMERICAL MODEL?

A numerical model, in order to be functional, must embody predictive capability and do so in the manner just described whereby robust and reliable information is provided on the basis of an overall statement of system behaviour.

Increasingly, software-based data presentation is put forward as a powerful management and decision making tool. GIS, for example, is a rapidly growing and essential tool for data manipulation and presentation which at some levels represents a *numerical model* of a spatial entity. Whilst GIS can take many forms, its predictive and analytical power is restricted by necessarily static data models which, although an essential adjunct to a numerical model in either the input or output phases, is not a numerical model in its own right. This is not to downplay the effectiveness and importance of such systems but to emphasise the powerful added benefits which can derive from going beyond GIS towards an integrated numerical model capable of acting as a strategic decision making and problem solving tool.

A numerical model is often the only rational means of representing the structure of and interactions within a complex system. Models permit conceptualisation, facilitate understanding, allowing planning and management options to be explored.

Typical benefits of the successful implementation of a numerical model are:

- a common conceptual framework
- a multi-disciplinary involvement
- a basis for critique and examination
- a method for enhancement and improvement
- a means of estimating uncertainty and risk
- a cost-effective planning tool

A numerical model can be constructed to represent any type of system - its success can only be measured in terms of its demonstrated utility and accuracy. Clearly, the more complex the system, potentially the more complex the model needing to be developed. However, simpler models can often take longer to develop and can be more effective, since simplicity (with maintained accuracy) represents a more highly advanced representation of the system.

In the context of natural hazard management, the following are a selection of possible uses of numerical models:

– estimating frequency
– predicting severity
– spatial impacts
– temporal impacts
– failure modes
– forecast errors
– intervention strategies
– response mechanisms
– organisational structures
– logistics
– warning scenarios
– evacuation staging and routing
– traffic planning
– contingencies
– casualties
– human response
– trauma
– post-disaster planning
– economic planning
– optimal resource levels and locations
– training
– insurance and community infrastructure losses

## 4. NUMERICAL MODELLING OF NATURAL HAZARDS

An appreciation and understanding of the effects of natural hazards has always been an essential part of professional engineering philosophy when applied to the safe design of human infrastructure needs. Inherent in any engineering design is an implicit allowance for the probability of failure as a result of potentially extreme environmental loadings, be it in regard to isolated structural elements or total infrastructure systems such as water, wastewater, power and transportation. These extreme loadings might take the form of wind, rain, flood, drought, fire, surge, waves, earthquake or human and vehicle loads.

Numerical models have been in wide use since the early 1980's addressing complex engineering design problems in the coastal and ocean area - a high risk environment. Tradititionally, many of these models were originally deterministic in nature but over time, stochastic influences have been included to produce probabalistic outcomes. Such techniques, for example, have made deep ocean oil and gas exploration and production possible and even successful in the face of economic cutbacks and narrowing profitability across the oil and gas sectors. The use of numerical models has enabled a continuous refinement of the traditional engineering design process. This has produced offshore structures which are made inreasingly more safe and reliable but also affordable in harsh natural environments where the potential dynamic loadings are enormous and many unknowns exist (2,3).

Many natural hazards in Australia derive from the sea, reflecting our island status as well as our continent's vast extent encompassing tropical, temperate and sub-antarctic influences. The sea itself is alternately governed by and influences the atmosphere above and these dual fluid environments combine to produce some of the world's most destructive forces in the form of tropical cyclones.

The application of advanced numerical modelling of the sea is now readily applicable to similar land-based activities, albeit with a different focus. Much of our population is coast-bound and so directly influenced by the coastal environment. Sophisticated risk-based models of coastal storm surge have been available since the mid-1980's (4,5,6) and have been used to assist planning and protection of the coastal margin. The threat of large scale population evacuation in the face of a severe cyclonic storm tide remains a constant reality every summer for many centres along the tropical coast of North Queensland. In recent years, the steeply rising costs of international reinsurance (due to a number of major environmental disasters) has prompted many insurance companies to look more seriously at the underlying environmental risk levels in their business and modelling techniques from the engineering sector have found a ready acceptance (7,8).

## 5. CASE STUDY - TROPICAL CYCLONE HAZARDS IN TOWNSVILLE, NORTH QUEENSLAND

The following series of examples of a complex numerical model are provided to demonstrate how a successful model methodology can continue to evolve and encompass an increasing range of risk elements. The same methodology can be applied to a wide range of environmental problems and even extend to include the human and organisational systems necessary to manage natural disasters.

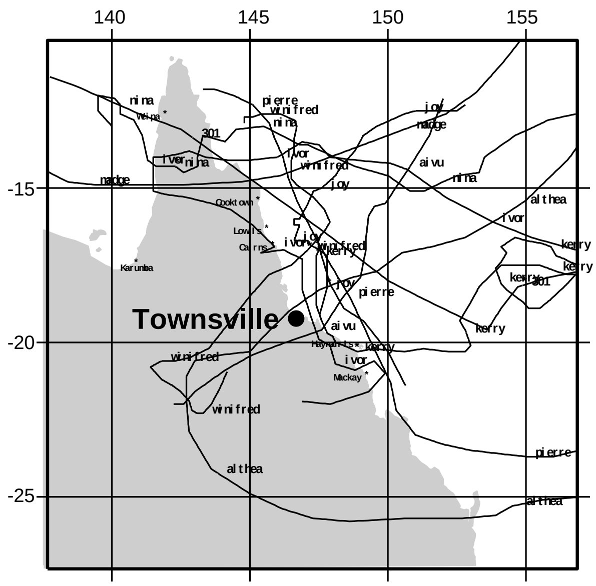


Figure 3: Sample Tropical Cyclone Paths

### 5.1 Tropical Cyclone Climatology

The northern Queensland port city of Townsville is located in an area particularly subject to tropical cyclone influences. Based on cyclone statistics since 1959, on average two

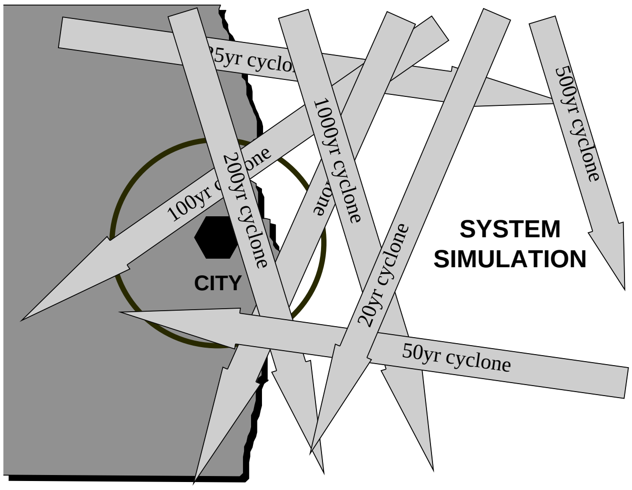


Figure 4: A Schematised Climatology

cyclones per year come within 500km of the city for a period of 24 hours. At least one cyclone per year comes within 200km. Near latitude 19°S, Townsville is well positioned to experience locally generated Coral Sea cyclones, often moving coast-parallel from the north, as well as Western Pacific cyclones which may have travelled thousands of kilometres from the east north east. Figure 3 presents a sample of tracks of some of the more severe cyclones in the region - those recording the "top 10" wind speeds at a number of coastal measuring stations. Tropical cyclone *Althea* from December 1971 is amongst these and at 952hPa, crossing the coast some 45km to the north, is still the most intense cyclone known to have affected the city.

The first step in developing a numerical model of the tropical cyclone risk at a location such as Townsville is to schematise the climatology of the region. Whilst cyclone paths are erratic and their intensity and forward speed is quite variable, this does not prevent simplification of the risk in a way amenable to numerical modelling. For example, within close proximity to the city, it is often reasonable to assume cyclones move along straightline paths and maintain a constant intensity, as depicted in Figure 4. Provided the statistical variability of this schematised behaviour is retained, it is not necessary to reproduce entire life cycles. This means that the model must therefore make allowance for the likely range of cyclone parameters. Some parameters are easily reproduced, such as track and forward speed. Others, such as intensity, require more detailed statistical modelling to ensure adequate extrapolation to more severe cyclones - ones that may not yet have occurred - so they can be represented in the model. There also remain *scale* parameters such as the radius to maximum winds and the wind profile peakedness which are not available from the historical record and need to be independently assessed. When assembled, the numerical model of climatology should be capable of reproducing nearly identical sets of "pseudo-historical" records of cyclones in the Townsville region. Furthermore, it must be able to demonstrate that it is reasonably *accurate* in doing so.

### 5.2 Modelling the Wind Peril

Whilst there is still much to learn of the detailed thermodynamics and kinematics of tropical cyclone structure, analytical models of the wind and pressure fields of tropical cyclones have been available for a number of years (9). Through extensive testing and application (3,10) we know that such models can be quite accurate in predicting open ocean windspeeds for mature tropical cyclones.

Taking the example of *Althea*, Figure 5 shows the model representation of the wind field circulating around the eye of the cyclone as it approached the coastline north of Townsville. The region of peak wind gusts at this time is to the north east of Cape Cleveland but due to sweep across the city.

The weather station at Townsville airport provided a detailed

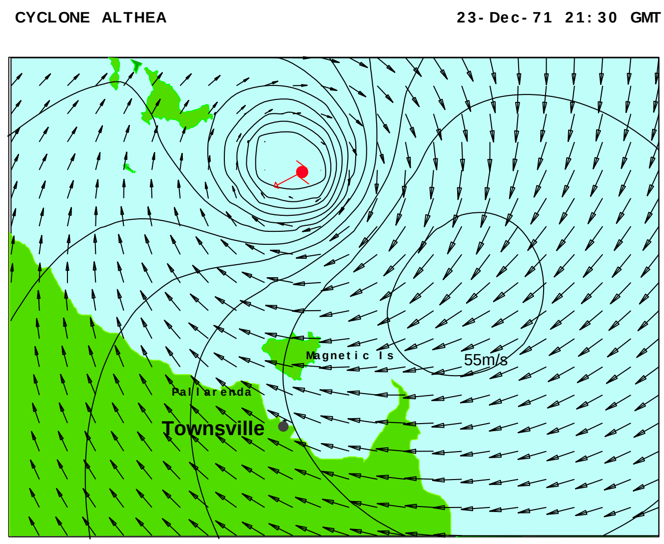


Figure 5: Model Representation of *Althea's* Windfield

record of the peak winds and minimum pressure as *Althea* passed by, reaching a maximum gust speed of 55 m/s and a lowest pressure of 971 hPa. Figure 6 presents the record of both the 10 minute mean wind, the 3 s gust and the MSL pressure. Superimposed on this figure are the predictions from the analytic model, showing excellent agreement with the measurements during the period of passage of the cyclone. These and many similar comparisons with other

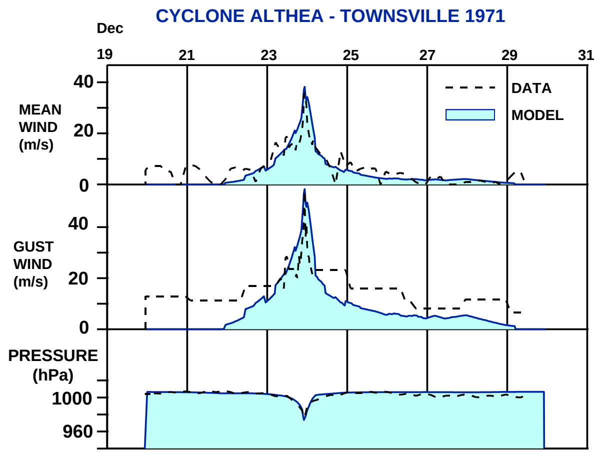


Figure 6: Measured and Modelled Wind and Pressure at Townsville

tropical cyclones show that models of this type can provide very good accuracy.

To provide estimates of wind speed across an entire city region, however, requires a further model of the wind flow characteristics over land. As the winds cross the coast they begin to be influenced by the increased roughness of the ground surface relative to the more smooth surface of the ocean. Trees and buildings interrupt the flow, causing turbulence, which results in a gradual reduction of the wind with distance travelled. However, in the presence of hills, wind speeds can accelerate to higher levels and all of these aspects can be included in a numerical model which includes the topographic features, as shown in Figure 7 for Townsville.

While it is important to test the model in terms of individual events such as *Althea*, ultimately the model must be shown

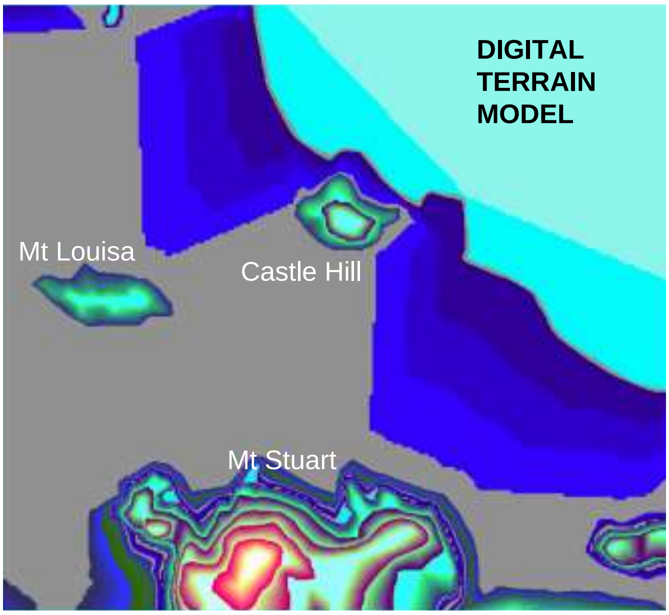


Figure 7: Digital Elevation Model of Townsville

to reliably predict the overall wind risk in probability terms. This is achieved through the *stochastic* capability of the model whereby the schematised climatology of cyclones is randomly (but in a controlled way) sampled. The wind speed model is then applied in many thousands of different situations simulating the equivalent of up to 100,000 "years" of exposure. By accumulating the statistics of these events it is posible to derive the average *return period* or recurrence interval of a given wind speed at Townsville. Comparing the simulated results with measured (summer) wind data since 1942 at Townsville airport gives the result shown in Figure 8. The individual recorded data points are shown, topped by the 55 m/s peak of *Althea* and the simulation result is seen to closely follow the data set for return periods beyond five years. This indicates that the schematised climatology, combined with the wind model, is accurately reproducing the Townsville extreme wind environment.

### 5.3 Modelling Wind Induced Damage and Losses

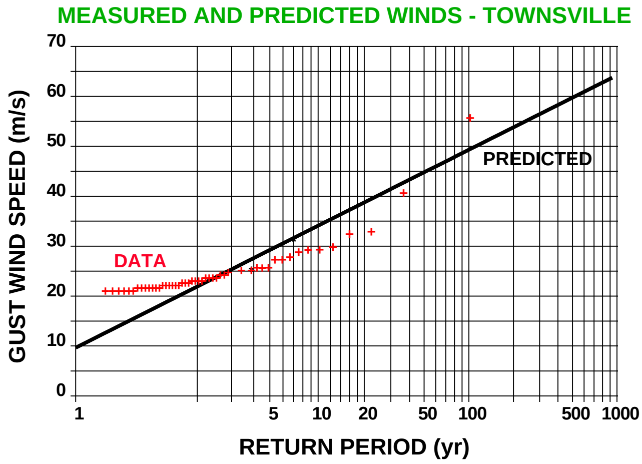


Figure 8: Measured and Predicted Extreme Winds at Townsville

*Althea* in 1971 was the first tropical cyclone in modern history which caused extensive damage to housing and infrastructure on a wide scale to an Australian city. The total insured loss was estimated as over $25M in 1971 dollar terms, representing about 6.7% of the total insured value of domestic housing in the city (11). By analysing the recorded damage caused by events such as *Althea*, *Tracy* and hurricane *Andrew* in the USA, *empirical* relationships between wind speed and incurred damage to a range of different building types can be constructed. Figure 9 shows a typical loss versus wind speed relationship whereby damage begins above a threshold speed and rises steadily, the curve steepening as the wind increases and ultimately becoming catastrophic above a certain value. By including such a relationship in a numerical model it is possible to investigate the likely

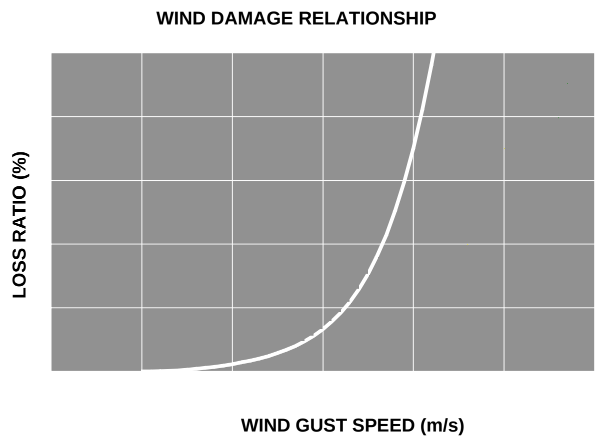


Figure 9: Example Loss versus Wind Speed Relationship

damage which could be expected if a more severe cyclone were to affect the city.

Figure 10 provides insight into this very problem. It shows the expected losses in % terms for a range of peak wind speeds at Townsville Airport. The losses in this case have been integrated from all over the nine postcode districts covering the city, including Magnetic Island. Each postcode contributes a different proportion of the total loss and, as can be seen, the difference between the total modelled loss and

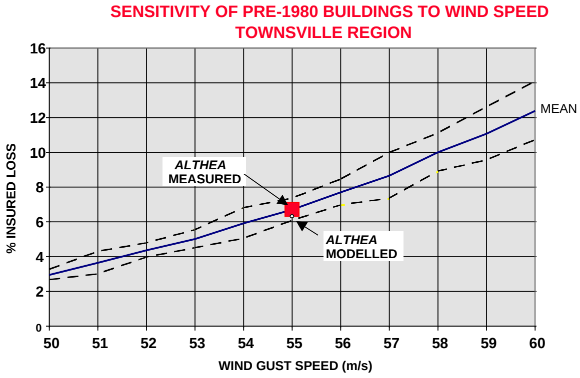


Figure 10: Predicted "Pre-1980" Building Losses in Townsville

the actual recoded loss is very slight - indicating that the model is correctly *calibrated*.

As a result of both *Althea* in Townsville and later *Tracy* affecting Darwin in 1974, significant changes to the domestic building codes were developed and generally adopted around 1980. Figure 10 represents the expected losses in Townsville for the case of pre-1980 construction quality only and cannot be applied to the present day situation where expected losses are much lower.

### 5.4 Modelling Storm Surge Induced Damage and Losses

In addition to the extensive damage caused by winds, *Althea* was also significant in producing a storm surge along the city foreshore of 2.9m above predicted tide (12). Further to the north, coastal damage levels indicated a potentially higher peak surge level. A storm surge is generated by the combined effects of the severe winds about the cyclone and the low atmospheric pressure. When combined with a shallow continental shelf such as offshore Townsville, dynamic effects associated with the forward speed of the cyclone can cause significant amplifictaion of water levels. Figure 11 illustrates how a storm surge can combine with the tide and breaking-wave setup caused by extreme waves, to produce a *storm tide* which may be well in excess of the expected tide level on the day. The storm tide may cause extensive flooding of residential areas and potential loss of life.

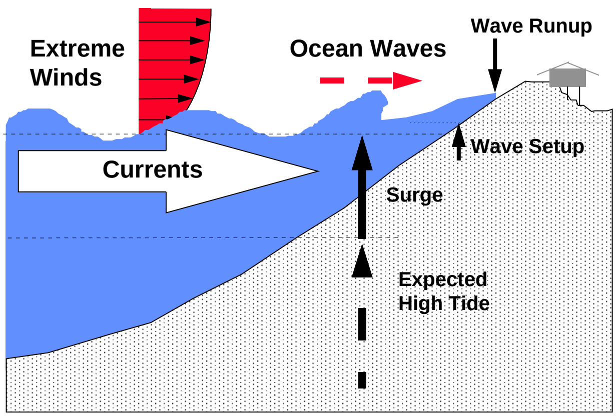


Figure 11: Components of a Storm Tide

The accurate modelling of storm surge levels requires the use of sophisticated numerical hydrodynamic models of the sea, combined with the type of analytical wind and pressure model described earlier. The storm surge from *Althea* was first successfully modelled in 1977 (13) and the generalised storm tide characteristics of much of the Queensland coast were addressed by 1985 (4) using a *parameterised* version of the hydrodynamic model to overcome the considerable computational effort required to model large numbers of different types of cyclones along the entire coastline.

Based on the parametrised storm tide model, Figure 12 shows how the *Althea* storm tide can be reconstructed as the individual components of tide, surge and wave setup - each adding together to give a combined water level which was luckily only about 0.5m above the highest possible tide at Townsville because of the low tide on the day. This still resulted in extensive flooding of seafront properties along The Strand, Rowes Bay and Pallarenda, destroying the sea wall and much of the roadways but not resulting in any loss of life or significant damage to private property.

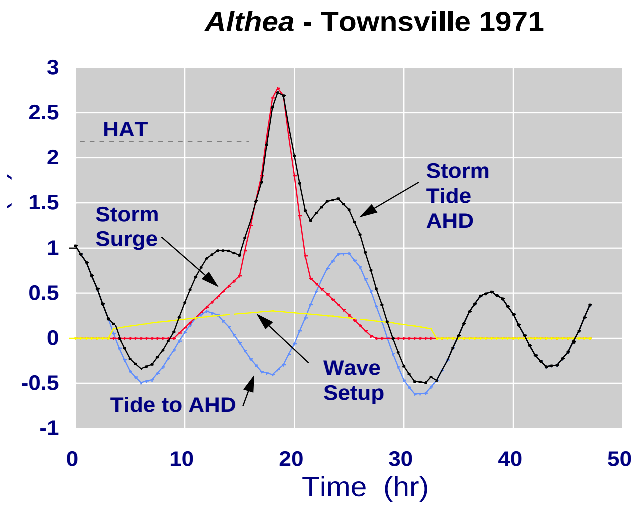


Figure 12: Modelling the *Althea* Storm Tide

Extending the risk model of Townsville to include storm surge effects is accomplished by including the parametric coastal storm surge model and representing in detail those parts of the city which could be prone to inundation. Based on the storm tide maps prepared by Townsville City Council it has been possible to construct a fine scale digital elevation model covering potential water levels up to +7m above HAT (highest astronomical tide). This is illustrated in Figure 13 where the immediate central city and port area surrounding Castle Hill is indicated. Loss and damage due to storm surge was then calculated based on a combination of work done for Darwin (6) and also the US FEMA (14) recommendations.

When applied to the whole city for a range of potential inundation levels, the predicted response is given in Figure 14. Here % loss is shown as a function of water level to AHD datum. *Althea's* level is indicated also, producing a nominal zero loss. After a further 1m increase in inundation, the loss curve is predicted to steadily rise in an almost linear fashion - lacking the steepening shown in the wind damage result because losses are limited to only the nearshore or low lying parts of the city.

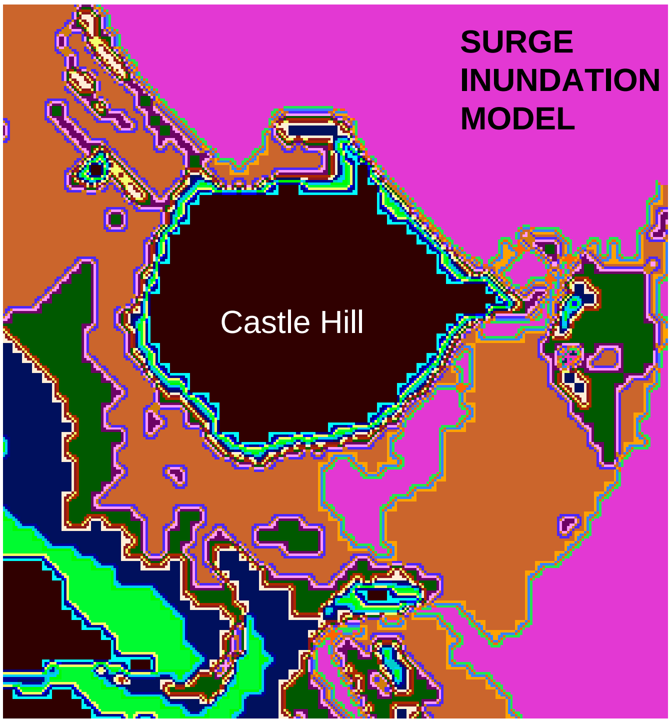


Figure 13: Surge Inundation Model of Townsville

## 6. MODEL APPLICATION TO OTHER SITES AND POTENTIAL EXTENSIONS IN ANALYSIS

The above numerical model has also been applied to Brisbane, Cairns and Mackay with similar success integrating the combined impacts of tropical cyclone wind and surge damage. As demographic data becomes more detailed and the various model sub-components are refined, greater accuracy can be expected from a model of this type.

Beyond the present capabilities however, which have been directed at planning issues, lies the potential for extensive development of the model for emergency management use. Because the model discretely represents the passage of a tropical cyclone (at half hour intervals) it can be used to

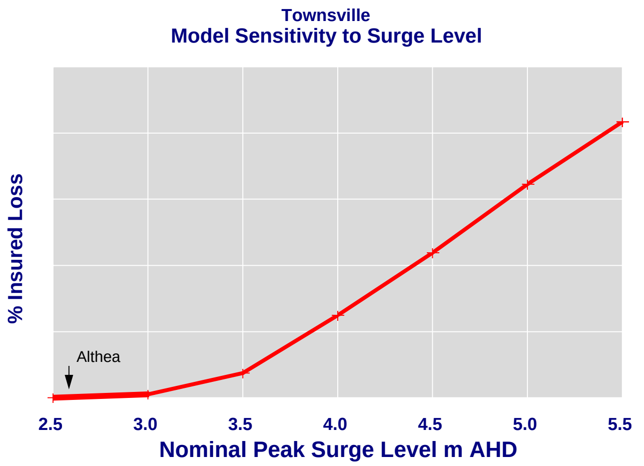


Figure 14: Predicted Insured Losses Due to Storm Surge in Townsville

explore the detailed issues which may arise during an actual event. For example, predicted statistics of wind speed build-up can be accumulated and analysed to determine the appropriate levels of activation of alerts or evacuations. Traffic congestion, infrastructure outage, local flooding and even human responsiveness to evacuation orders could similarly be incorporated to provide a realistic overview of the likely situation as it develops. Theories of preparedness and response could then be readily tested against the statistics generated by the model.

In the specific case of storm surge, extensive information is already available for much of the Queensland coast (15) which can be used in evacuation scenario planning and more information at Mackay and Cairns is being prepared (16). In conjunction with detailed demographic studies by the Emergency Services Department and others, all the necessary data for application of such a model will soon be available. For example, Figure 15 combines risk data from (14) and dwelling data from Smith and Greenaway (17) indicating the community vulnerability to storm tide in Mackay as a function of return period. Taking the 10,000 year return period as the accepted limit of practical protection against loss of life, between 50% to 60% of the properties in Mackay may need to be included in evacuation planning to protect the community against storm tide inundation.

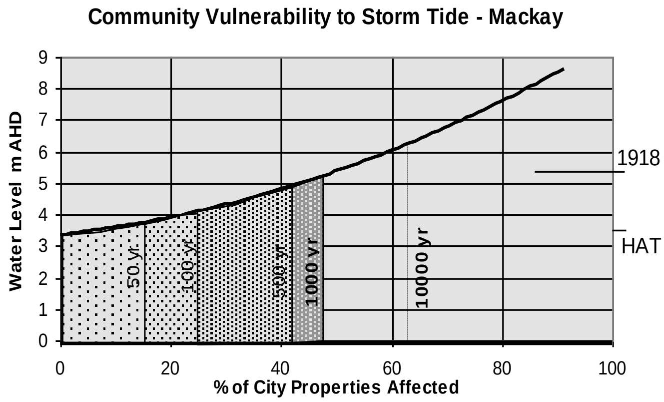


Figure 15: Combining Risk and Vulnerability

Finally, Figure 16 summarises the storm tide risk at other major population centres along the Queensland coast based primarily on (15) and (18). The risk of inundation above HAT is shown in each case on a return period basis up to the 1000 year level. Townsville exhibits the highest risk to inundation of any of these coastal centres, closely followed by Cairns, Yeppoon, Mackay, Brisbane, Gladstone and Hervey Bay. Some intermediate coastal sites have even greater risk of inundation.

## 7. CONCLUSIONS

Numerical modelling offers a wide range of options for representing the occurrence, severity and impact of many different types of natural hazards. Numerical models can be extended to cover new knowledge, better data or changed procedures for managing the impacts of natural disasters.

Risk managers should look for elements of technical and statistical robustness, accuracy and evidence of calibration and verification. Where possible, models should offer self-checking, sensitivity checks or confidence limits on their predictions.

Numerical models should be viewed as valuable tools for conceptualising complex problems, providing a common framework and forming building blocks to aid the increased understanding needed in the risk modelling of natural disasters.

In Australia today, the effects of natural disasters cost our nation an average of about $200M per year, based on insurance losses alone (19).

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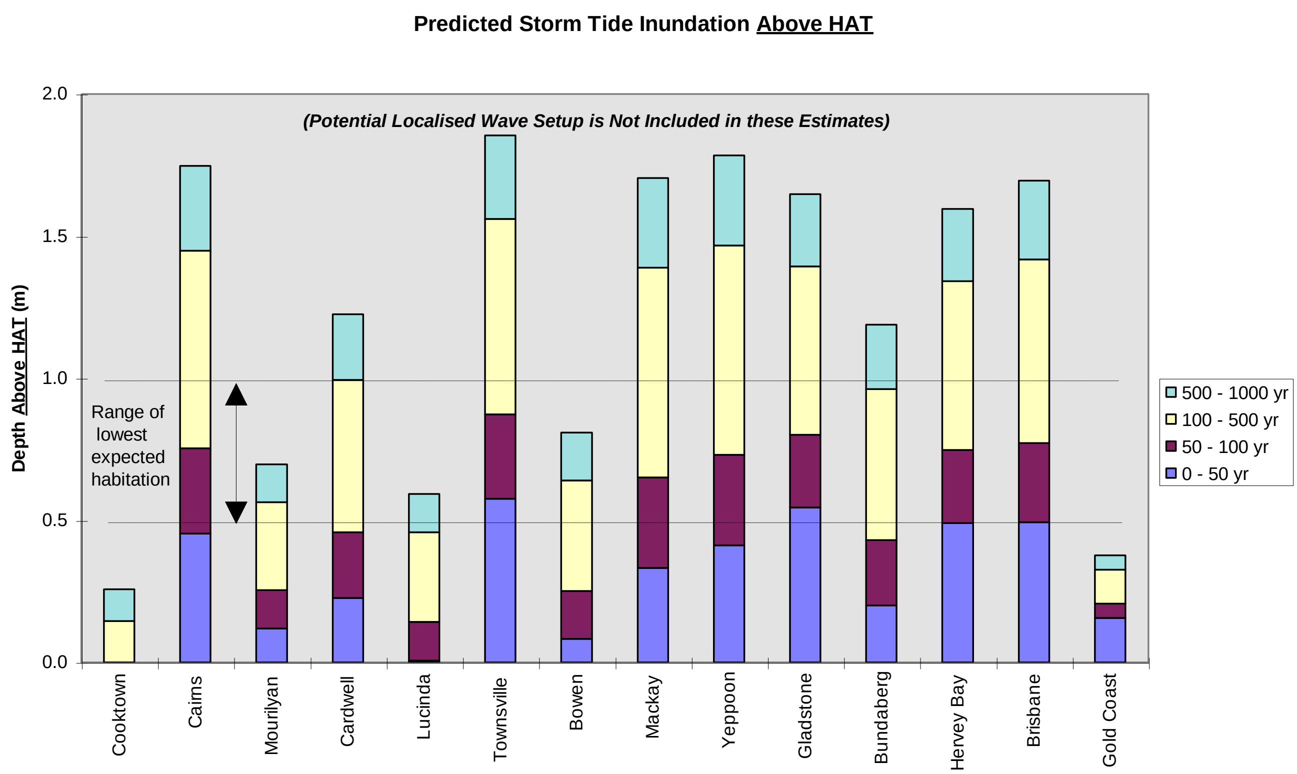


Figure 16: Summary Storm Tide Inundation Risk Along the Queensland Coast

**THE APPLICATION OF NUMERICAL MODELLING IN NATURAL DISASTER RISK MANAGEMENT**

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**KEYWORDS**: Numerical Modelling, Risk Management, cyclone, surge, systems.

**ABSTRACT**:

The paper presents an overview and outline of the application of numerical modelling techniques derived from engineering approaches which can be effectively used to address problems of natural disaster risk management. The various types of numerical models and their basic characteristics and uses are introduced together with an indication of their potential value to management. A case study is presented of the application of a complex multi-dimensional numerical model to the tropical cyclone hazard at Townsville in North Queensland which shows how such models can readily be extended to cover wider management issues.