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# INTEGRATED DISASTER DECISION SUPPORT SYSTEM INCORPORATING MITIGATION PORTFOLIO OPTIMISATION

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# TABLE OF CONTENTS

# ABSTRACT

Investing in mitigation activities before a natural disaster occurs can be very effective in reducing disaster losses. However, there can be a number of obstacles to developing and implementing long term mitigation schemes, including a tendency to invest in works with clearer short-term benefits, and the difficulty in accurately attributing risk and benefits to natural disasters and mitigation options, respectively. Decision support systems (DSSs) can be advantageous in helping overcome these obstacles, because of their analytical capabilities to combine various sources of information and support trade-off analysis. However, DSSs for natural disaster mitigation have so far tended to focus on disaster preparedness and the immediate and post-crisis response to emergencies. Consequently, an integrated natural hazard mitigation DSS is being developed. This DSS will optimise the choice of mitigation options in a multicriteria sense, through assessing the performance of various policy options in the long term. Models will be used to evaluate the performance of mitigation options across a number of natural hazards in an integrated way, whilst taking account of land use and climate change. The system will be developed through participatory processes, involving stakeholders from various organisations responsible for hazard mitigation, to ensure the system addresses the most pertinent issues, as well as the decision making process for hazard mitigation. To test the approach in different contexts, it will be applied to three case studies, the first being Greater Adelaide. This paper introduces the proposed DSS.

# INTRODUCTION

The effects of natural disasters on society are of great concern due to their impact on economies, communities and the environment. In 2013, there were 890 loss events worldwide (excluding famine) that resulted in 20,500 fatalities, and US$135 billion in losses. Although this economic loss is a small portion (less than 0.2%) of the US$87 trillion global GDP, natural disasters are localised and may have severe impact on local economies and communities, and recovery may take a very long time.

Because natural disasters are low probability, high impact events, the potential losses can far exceed those that have occurred in recent years. For example, Shah (1994) predicted that a magnitude 7 earthquake hitting Los Angeles would cause over US$170 billion in economic losses, over US$95 billion in insured losses, over 3,000 deaths and up to 20,000 injuries. A repeat of the 1906 San Francisco earthquake would result in similar losses, and the repeat of the 1923 Tokyo earthquake is predicted to cause over US$2.0 trillion in economic losses, over US$30 billion in insured losses, and over 40,000 deaths (See also Grossi and Muir-Wood 2006).

Pertinently, the losses that occur from natural hazards can often be reduced through mitigation measures. Mitigation has been shown to be very effective, and economically responsible. For example, Rose *et al.* (2007) found that the overall benefit-cost ratio (BCR) across nearly 5,500 US Federal Emergency Management Agency (FEMA) mitigation grants was about 4:1. The UK Environment Agency reports that strategies for maintaining existing and investing in new flood risk management assets across England have BCRs ranging from 4:1 to 11:1 (UK Environment Agency 2009), and Deloitte Access Economics (2013) analysed three Australian mitigation projects and found that the BCRs for these projects were all greater than one, with BCRs up to 9 possible when investments are made that target high risk locations with appropriate combinations of structural and non-structural mitigation measures.

Despite its obvious advantages, investment in mitigation is relatively low. For example, over the last six years, the Australian government has contributed AU$7.2 billion in response and relief funding through the National/Natural Disaster Relief and Recovery Arrangement payments, but only 2.3% of this amount (AU$171 million) has been spent on mitigation through the Natural Disaster Reduction Program. This can be attributed to a number of factors that have been identified within the literature (For example, see Wood 2004; Sadiq and Weible 2010; Vaziri *et al.* 2010; Hennessy *et al.* 2014; IPCC 2014b; Stein and Stein 2014). One of these is the lack of data to make a business case for mitigation, as this requires analysis to quantify the expected benefits of mitigation activities, using a transparent process and a scientifically robust methodology. Additional factors include competing objectives and a lack of measurable criteria. Furthermore, given the large number of mitigation options, and limited mitigation budgets, it is important to sift through and select options that result in optimal trade-offs between objectives.

There are potential benefits to using decision support systems (DSSs) for developing mitigation plans. This is because DSSs have the ability to combine various sources of information and support trade-off analysis in a transparent way. Because of the obstacles to investment in mitigation identified above, such DSSs should: (1) quantify the expected benefits of mitigation investment across multiple criteria; (2) assess the likelihood and consequences of natural disasters across multiple criteria; and (3) use formal optimisation techniques to find optimal or near-optimal mitigation portfolios.

In this paper, a framework is presented that can be used to identify the optimal set of options for hazard mitigation in a region, which is a deliverable of a project funded by the Bushfire and Natural Hazard Cooperative Research Centre (BNHCRC). This framework is novel, as it (1) combines the use of formal optimisation techniques with simulation approaches, (2) takes a multi hazard perspective, (3) incorporates a spatially-explicit and dynamic land use model to assess land use mitigation policy over the long-term, and (4) takes climate change into account. These aspects have not previously been combined into a single decision support platform in the literature. Based on this framework, a prototype decision support system is introduced for the Greater Adelaide region in South Australia.

# PROPOSED FRAMEWORK FOR DECISION SUPPORT OF MITIGATION PLANNING

The proposed mitigation planning decision support framework is illustrated in Figure 1 and discused in detail in the following subsections.

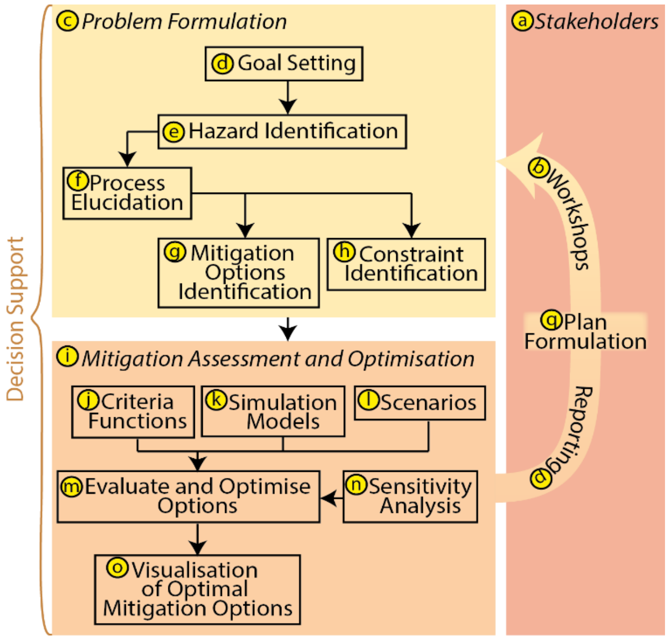

*Figure 1. Proposed framework for the development of mitigation planning decision support systems*

## STAKEHOLDER DRIVEN

As shown in Figure 1(a), stakeholder engagement is an integral component of the proposed DSS framework, as this has long been identified as a critical component of DSS adoption (Belardo and Karwan 1986). As part of the proposed framework, stakeholder engagement is achieved via workshops (Figure 1, part b), whereby (i) workshops are held to formulate the decision tasks that need to be addressed by the decision support system, and (ii) portfolios of optimal mitigation options, as identified by the decision support system, are reported back to the stakeholders for review. The workshops involve an iterative process of communication and social learning amongst decision makers, end-users and other stakeholders, domain knowledge experts, and IT specialists, so architects of the DSS system understand the requirements of users, the nature of the decision problem being addressed, and the process by which decisions are made (Geertman 2006; van Delden *et al.* 2011).

## PROBLEM FORMULATION

Problem formulation concerns the specification of DSS requirements (Figure 1, part c). This includes defining the objectives, constraints and decision variables of the decision task, as in conventional operations research approaches, but also includes the identification of process protocol (the steps that are necessary for arriving at the desired DSS), and information protocol (identifying what information/data is required for the decision task).

As can be seen in Figure 1(d), the first task is identifying the goals of the stakeholders. These can include the minimisation of the total expected costs of natural disaster management and other community objectives, such as maximising economic growth, natural amenity, community resilience and environmental measures of ecosystem health. Next, the natural hazards that would impact these goals need to be identified (Figure 1, part e). From this, domain knowledge experts are called upon to identify the environmental and social processes that give rise to these hazards (Figure 1, part f). The identification of these processes enables the comprehensive identification of relevant mitigation options, as mitigation measures act to reduce losses through the modification of these processes (Figure 1, part g).

Mitigation options can be categorised into structural works, management techniques and land use planning tools (Burby 1998). Structural works include elevating, protecting and strengthening structures, sea walls, dikes, groynes, dams, and levees. Management techniques relate to how landscapes and structures are managed and maintained. For example, management measures for bushfire mitigation include fuel load reduction and maintenance of fire retarding measures constructed into buildings. However, in recent decades the predominant form of mitigation has been through land use management, as the level of hazard in a location is very sensitive to the land use occurring at that location.

In this respect, land use strategies for disaster impact mitigation include building standards (regulations for new and retrofit buildings), development regulations (including zoning and setback requirements), property acquisition in high risk areas, taxation and other fiscal policies (Olshansky and Kartez 1998). These land use management options often take many years to become fully effective. For example, building codes applicable to new buildings only affect 1.3% of the total building stock in any year (Deloitte Access Economics 2013); and changing the zone of a land parcel does not directly cause the land use to change. This is because development is a gradual process in which land is transformed into residential, commercial, and industrial areas.

The final step in the problem formulation, as shown in Figure 1(h), is the identification of constraints that are placed on the decision making process (such as budgetary ceilings, land use, demographic and environmental constraints, and constraints relating to the incompatibility of various mitigation options). It should be noted that the availability of simulation models, which are required in order to assess the impact of particular mitigation options on the desired goals, should also be considered during the problem formulation stage, as discussed in the following section. The gaps that exist between the problem formulation and what models are available can be addressed in later versions of the DSS, as DSSs are developed for long term use and can be improved over time.

## MITIGATION ASSESSMENT AND OPTIMISATION

In the second phase, a first prototype of the DSS can be developed, based on the inputs from the problem definition phase and according to the steps outlined in Figure 1(i). First, criteria functions, simulation models and scenarios are selected. Using the goals identified during the workshop, criteria functions are developed with which to evaluate the utility of mitigation portfolios, which consist of a subset of the options also identified within the workshop.

As can be seen in Figure 1(j), values of the criteria functions corresponding to different mitigation portfolios are obtained with the aid of simulation models. Two factors are important in relation to the selection of these models. Firstly, they should adequately simulate the relevant processes, such that the system impacts of mitigation options are captured. Secondly, criteria functions should be calculable from the model outputs. It should be noted that in some situations, such models might not be available or not be able to be developed, which might affect which mitigation options and objectives can be considered. Consequently, this issue needs to be considered during the problem formulation stage, as mentioned previously.

Also, as mentioned previously, land use management is the predominant form of natural hazard mitigation. Given the strong relationship between land use and natural hazard risk, and the slow rate of land use change, it is important to simulate long-term land use changes through spatially-explicit and dynamic land use models within mitigation DSSs (Figure 1, part k). In addition, populations and economic development are continuing to increase. This has historically caused populations and investments to be increasingly concentrated in vulnerable locations, causing a larger magnitude of losses (Changnon and Pielke Jr 2000; Neumayer and Barthel 2011; Deloitte Access Economics 2013). Therefore models of population and economic growth should be included in the DSS.

Finally, climate change is generally causing natural hazard events to become more frequent and severe. The 5th IPCC assessment report concludes that climate change is increasing the hazards associated with storm surges, heat stress, extreme precipitation, inland and coastal flooding, landslides, drought, aridity, water scarcity, and bushfires, which will have widespread negative impacts on communities and on economies and ecosystems (IPCC 2014a, 2014b). Therefore, assessing the impact of mitigation options over the long term requires the use of models that take the impacts of climate change into account, which need to be run for scenarios representing various plausible future conditions. Consequently, the evaluation of different mitigation portfolios is achieved by running the integrated hazard model across different scenarios and using the model outputs to calculate the required criteria functions (Figure 1, part l).

Unfortunately, due to the large number of mitigation portfolios that could be implemented, evaluating each potential portfolio is computationally intractable. However, it is important to identify portfolios that result in good outcomes according to stakeholder goals, in order to understand the tradeoffs between these goals in an unbiased way, and to ensure the most efficient use of mitigation budgets. Therefore, there is value in the use of formal optimisation techniques to assist with sifting through the available options in order to identify mitigation portfolios that result in better trade-offs between the selected criteria (Figure 1, part m). Evolutionary algorithms (EAs) such as genetic algorithms (GAs), ant colony optimisation (ACO) and differential evolution (DE) are used as the optimisation engine in the proposed approach as they tend to be robust towards problems characterised by nonlinearity, multi-modality, large decision spaces and interactions between decision variables. While not guaranteeing convergence to near-optimal designs over polynomial time, they have shown to do so across a wide spectrum of test problems. In addition, EAs can be adapted for multi-objective optimisation with relative ease.

Once optimal portfolios of mitigation options have been identified, sensitivity analysis may be conducted to test the robustness of optimal mitigation portfolios against a number of modelling assumptions (Figure 1, part n). The results of these analyses need to be visualised in a meaningful way (Figure 1, part o) with results reported back to stakeholders and decision makers so that the best mitigation options can be selected more effectively (Figure 1, part p).

Finally, based on the results of the process described above, stakeholders may identify additional scope and modelling improvements that should be included, thereby reformulating the decision task. Therefore, an iterative refinement of the DSS through a number of workshops will generally be required to ensure the system is fit for purpose and to foster system adoption for the formulation of mitigation plans (Figure 1, part q).

# THE GREATER ADELAIDE MITIGATION DECISION SUPPORT SYSTEM

As part of the BNHCRC project, this framework will be applied to three case studies, producing a prototype DSS for each. The first of these case studies is focussed on the Greater Adelaide region, as shown in Figure 2, which is home to 1.3 million people. This section will describe the Greater Adelaide DSS being developed for this case study.

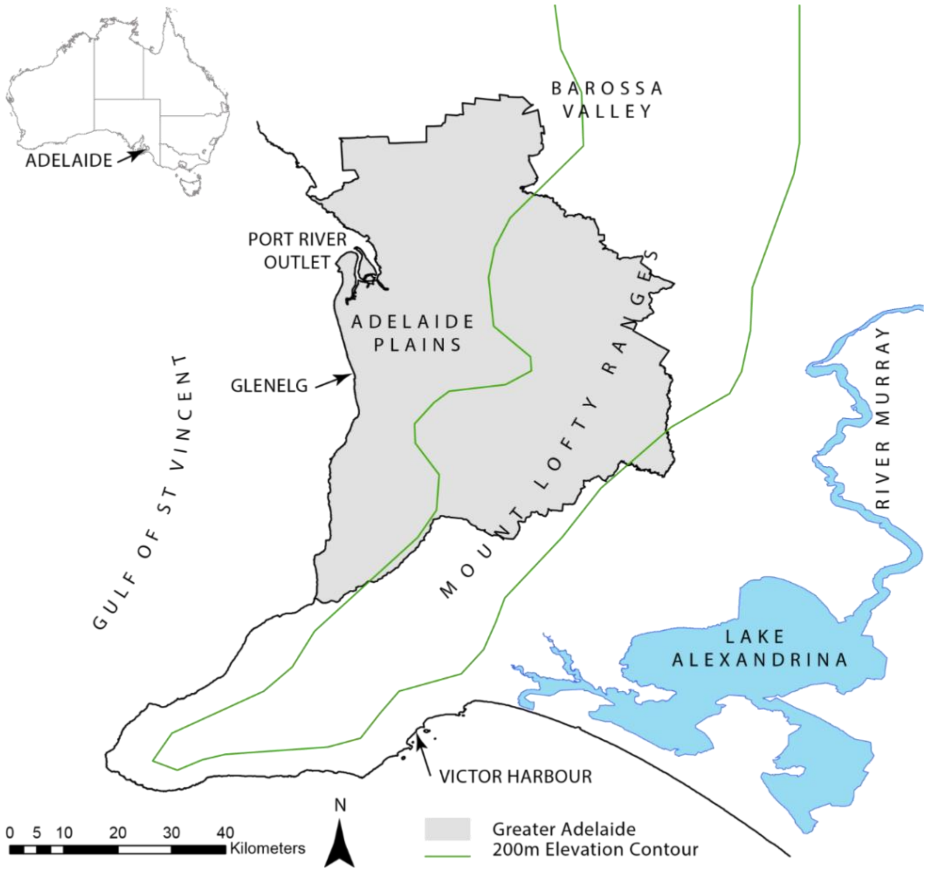

*Figure 2. The Greater Adelaide Region in South Australia*

## PROBLEM FORMULATION

The hazards that will be considered in this DSS are flooding (both coastal and floodplain), bushfire, earthquake, storms and heat waves. With regard to flooding, sustained periods of high rainfall are rare in the Greater Adelaide region. However, short intense storm events are more common, which can bring localised flooding across the Adelaide plains (South Australian Government 2004). Low lying areas near the Port River outlet are most susceptible to coastal flooding and surge. Concerning bushfire, regions of South Eastern Australia are generally considered to have some of the greatest risks of bushfire in the world (South Australian Government 2004). Within Greater Adelaide, the Mt Lofty Ranges contain most of the region's high bushfire risk areas, with large tracts of highly flammable vegetation. Greater Adelaide also has one of the highest earthquake risks amongst all Australian capital cities. However, amongst these natural hazards, storms and heat waves cause the greatest losses. Storms bring the greatest economic damage to infrastructure and property, while heat waves claim the most lives in the study region.

The first workshop for developing the Greater Adelaide DSS is scheduled to be held in September 2014. Attendees at this workshop include registered end users of the decision support system, South Australian practitioners and subject matter experts, and interstate practitioners likely to be involved in the development of the remaining two DSS case studies conducted as part of this research program. The workshop will consist of a pre-workshop interview, involvement in round-table discussions during the workshops, and the completion of a post-workshop survey. Through this engagement, this workshop aims to solicit information in relation to (1) the distribution of mitigation decisions and activity across government agencies in Greater Adelaide, and how these decision are made (including what data and models may be used), (2) the key factors that will affect mitigation activity in Greater Adelaide, both in the present and the future, (3) the mitigation options that could be considered, both now and in the future, and (4) feedback from the demonstration of a prototype DSS developed for the case study (Figure 3).

## MITIGATION ASSESSMENT AND OPTIMISATION

The Greater Adelaide decision support system is being developed using the Metronamica modelling framework. Metronamica is a flexible software framework that includes a spatially explicit and dynamic land use model based on cellular automaton simulation; and a software interface that is designed for the integration of other spatially explicit simulation models. This software interface will be used to integrate the natural hazard data and/or models currently being used for the Greater Adelaide region.

As shown in Figure 3(a), the DSS is able to simulate the impact of different external factors, policy measures, model parameters, and scenarios through specifying these options through the main window. Once the model is run (Figure 3, part b), the DSS allows the visualisation of these options through dynamic year-by-year maps of spatially explicit land use, economic, ecologic and social indicators, as show in Figure 3(c), therefore allowing the user to explore the spatial and temporal impact of different mitigation options.

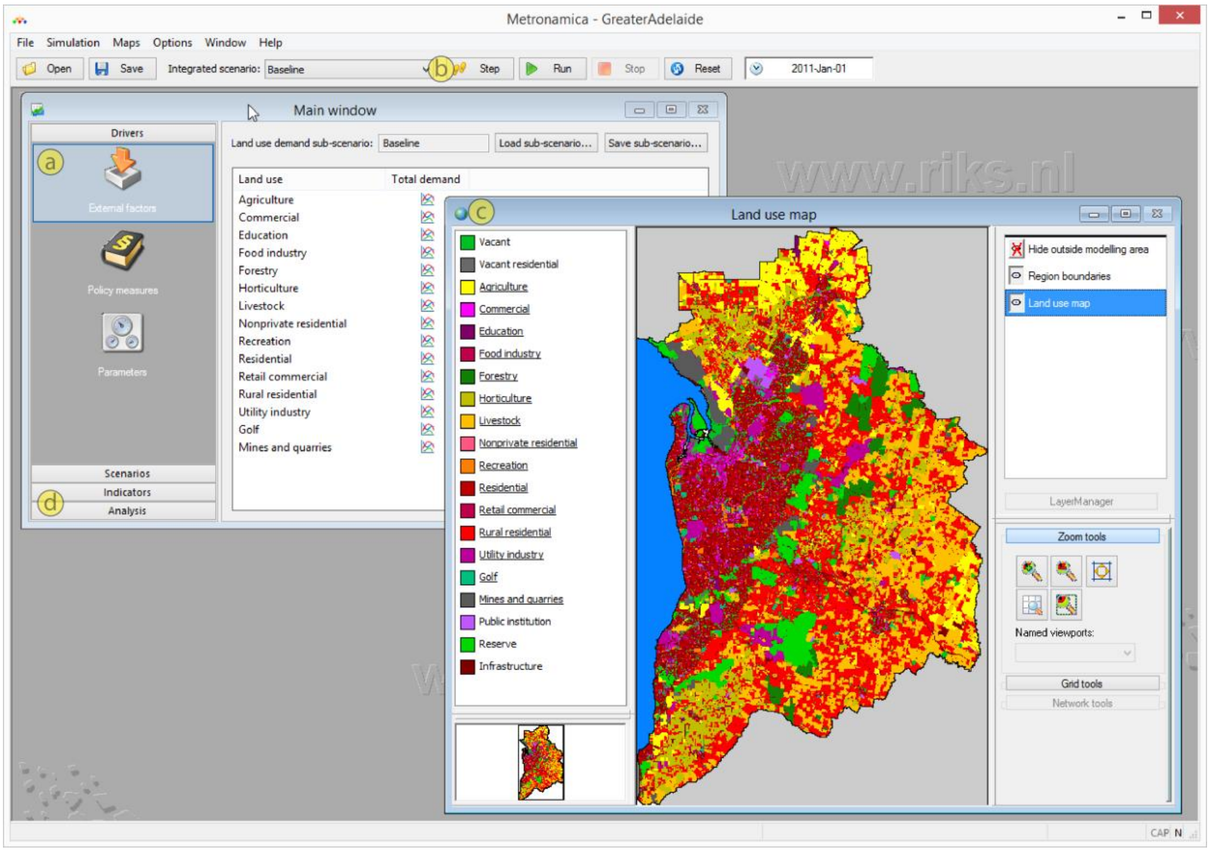

*Figure 3. Screenshot of the Greater Adelaide mitigation plannning decision support system*

The specific indicators to record during the model run, and what statistical analysis to perform on these indicators can also be specified by the user in the main window (Figure 3, part d).

Metronamica will be linked to a multi objective EA for the sifting through and selection of mitigation options that result in optimal trade-offs between criteria. Due to long model run times (in the order of minutes for a run of 30 years into the future) and the relatively high computational cost of EAs, work is being undertaken to parallelise the evolutionary algorithm across clusters of computers.

# CONCLUSION

In this paper, a framework has been presented for the development and use of DSSs to aid the development of disaster impact mitigation plans. This framework includes a participatory approach for developing simulation-optimisation DSS software that sifts through and presents portfolios of mitigation options that result in optimal trade-offs between decision criteria for comparing different mitigation options. The framework is sufficiently general so that it can be applied to hazard mitigation in different regions of the world.

Using the framework, a prototype DSS is currently being developed for Greater Adelaide. The advantages of this planned DSS are:

- The incorporation of a spatially-explicit and dynamic land use model that allows assessment of the impacts of land planning on hazard mitigation under various socio-economic and climate scenarios.
- The incorporation of evolutionary algorithms for identifying optimal tradeoffs between performance criteria.
- A user interface targeted towards mitigation impact assessment.

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