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SIMULATION OPTIMISATION FOR NATURAL HAZARD RISK MANAGEMENT

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EXECUTIVE SUMMARY

In this report, we outline a decision-support framework for natural hazard management that combines the use of simulation and optimisation for exploring what risk reduction measures best achieve management priorities. This framework addressed several needs that practitioners have with regard to risk and adaptation assessment. First, it uses optimisation approaches to screen through and identify those management options that perform best across a number of decision criteria. This is important, as there are a very diverse range of management options which could be combined in an extremely large number of ways to make portfolios of management options and it is difficult to screen through all potential portfolios to shortlist a small number for further consideration. Second, it simulates the effectiveness of management options over long-term planning horizons. This is important, for management options may have long lead-in-times, and/or may have long lifetimes, are not easily/readily changed, and so need to be effective over a broad range of plausible future conditions, which likely include larger populations, increased economic development and climate change. Third, the framework emphasises holistic assessment, wherein the Integrated assessment modelling (IAM) simulates the effect of management options across a number of criteria, therefore allowing practitioners to explore the trade-offs between risk reduction with other community goals, including environmental, social and economic outcomes.

The value of this framework arises from the greater demands that are being placed on planners to effectively manage natural hazard risk, whether from politicians or from the public who have an increasingly reduced appetite for hazard losses. This creates a need for analytic frameworks for exploring how to best manage risk, and this framework addresses this gap.

Through application to a case study, this report shows how the framework is able to increase the effectiveness and efficiency by which IAM can be applied to natural hazard risk management. The role of the optimisation was seen not to be prescriptive, but to enable better exploration of risk management options. The framework was therefore able to provide rich information on the effectiveness of management portfolios by which better risk management plans could be formed.

The case study to which the framework was applied considered coastal flood risk within Greater Adelaide and explored the combinations of zonal exclusion areas along the coast which prevented further development. If unmitigated, coastal risk could increase by 10% over the next three decades. However, results of the case study application showed that zonal exclusion policies could effectively reduce this growth of coastal risk, however this required excluding further development from 7000 Ha of land along the coast. Saying that, the growth in risk could be limited to 3% (i.e. a reduction in growth by 60%), through excluding coastal development from only 1500 Ha.

1 INTRODUCTION

This report has been developed under funding obtained from the Bushfire and Natural Hazards Cooperative Research Centre (BNHCRC). This funding initiated the research project titled "Decision Support System (DSS) for Assessment of Policy & Planning Investment Options for Optimal Natural Hazard Mitigation," which is investigating the utility of optimisation for sifting through and selecting mitigation options for the management of natural hazard risk. Previously in this project, an integrated spatial DSS for modelling the long-term changes in risk has been developed, and in this report, we show how the DSS can be used in conjunction with optimisation to assist decision makers in planning and implementing disaster risk reduction policies and investments.

In this report, we propose that a 'simulation-optimisation' approach to natural hazard risk assessment has immense value for the management of natural hazard risk and demonstrate its applicability through application to a case study. This case study involved the exploration of zonal policy for the management of coastal surge risk across the Greater Adelaide Coastline.

The remainder of the report is structured in the following way:

In the remainder of the introduction (Section 1), we first outline what a simulation-optimisation approach is, and make an argument for the use of simulation-optimisation for managing natural hazard risk;

In Section 2, we develop a simulation-optimisation framework tailored specifically for natural hazard management;

In Section 3, we apply the framework to a case study centred on the Greater Adelaide region of South Australia;

Finally, In Section 4, we make conclusions about the utility of the approach.

1.1 A SIMULATION-OPTIMISATION APPROACH TO NATURAL HAZARD RISK MANAGEMENT

Simulation-optimisation refers to the approach of integrating optimisation techniques into simulation analysis, and has broad utility in difficult decision problems related to the management of complex systems.

The aim of simulation is to package our understanding of processes relevant to a decision problem (e.g. physical, biological, social, and political processes) into mathematical models that run on computers and use these to provide information about the behaviour of the system being modelled. Due to the complexity of managing public resources, simulation tends to involve the integration of a number of separate social, environmental and economic modelling components to form holistic systems models, and this is also true for natural hazard management. For natural hazard management, the simulation models the effect of hazard(s) on the built and non-built environment and communities, including their people and economy. This approach to simulation is also known as integrated assessment modelling (IAM).

When used within management contexts, the aim of simulation models is to improve the functioning of the system in practice. In this case, the model is used as a test-bed for different management options. The inputs to the model are modified to represent the influence of a set of potential management measures and the effect of these measures are then observed using the simulated results. Through this process, the simulation is able to support management processes by exploring how systems respond to different measures and therefore can be used to find sets of measures/options that yield the best outcomes for the system being modelled.

The way in which the best measures/options can be identified using this modelling approach is usually through a trial-and-error approach. This approach is, however, laborious, especially when model runtimes are relatively long and/or there are a very large number of management options to assess. In addition, a trial and error approach may not find the management options that give the best performances.

Optimisation can be used to automate or semi-automate the above trial-and-error approach. To do this, algorithms are developed that are used in conjunction with the simulation model to search for and identify what management options, in combination, give rise to the best system function. Consequently, simulation and optimisation are not necessarily alternative approaches, but can be combined. This combined use of simulation and optimisation is the focus of this report.

1.2 THE CASE FOR SIMULATION-OPTIMISATION WITHIN NATURAL HAZARD RISK MANAGEMENT

Now that we have introduced what a simulation-optimisation approach is, in this section, we make an argument from the literature that the approach has significant utility for natural hazard risk management. Our argument is made as outlined below:

1. That natural hazard risk is significant, is increasing if left unabated through time, but can be managed through mitigation, emergency and recovery planning;

2. That despite the benefits of managing natural hazard risk through planning processes, there are challenges in: (1) assessing the comparative effectiveness of different management options, and (2) in sifting through and identifying the best performing portfolios of management options;

3. That simulation is immensely valuable for characterising the nature, extent and magnitude of risk across space and time, as it provides a quantitative and transparent basis for assessing many criteria pertinent for understanding the effect of different management options; and

4. That optimisation is immensely valuable for sifting through and identifying best performing management options, as it provides an automated, transparent, repeatable and defensible technique to consider a wide range of management options that are too numerous for manual trial-and-error approaches.

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1.2.1 THE SIGNIFICANCE AND MANAGEABILITY OF NATURAL HAZARD RISK

The social and economic losses from natural hazards are potentially staggering. In the decade 2006-2015, losses from disasters triggered from natural hazards have amounted to approximately US$138 billion of direct damages, 70,000 casualties, and affected around 224 million persons, on average, per year (as recorded over natural disaster events within the EM-DAT database; Guha-Sapir et al., 2016). These loss figures could be much worse — the potential impact from natural disasters far exceeds yearly average figures, due to the potential occurrence of infrequent yet more severe disaster events.

Although natural hazard risk is currently severe, it is likely to further increase into the future due to growing vulnerability, higher populations, increased development, and climate change, unless additional risk-reduction interventions are implemented (Hallegatte et al., 2013; Hanson et al., 2011). Climate change is a significant driver for increased risk for many hazards due to higher temperatures and changes to the hydrological cycle. However it is not the only cause of an increased risk into the future, nor is it necessarily the strongest driver of change, as the growth of populations and assets is more significant in many regions (see Kundzewicz et al., 2014). For example, in cities where there is high competition for land, densification of capital is occurring, and development is being pushed into regions that have relatively higher risk, making populations more vulnerable to hazard losses. Consequently, there has been a strong and increasing focus on natural hazard risk management in many jurisdictions (e.g. HM Goverment UK, 2017).

Although we may have limited management control over the sources of natural hazard risk (for example, rainfall for flooding risk), we can exhibit control over hazard pathways as hazards propagate from their sources to the values-at-risk present in the landscape we are managing (in other words, the 'receptors' of natural hazard), and the response of those values-at-risk (in other words, the impact the hazard has). Therefore, natural hazard risk is manageable.

There are three main ways in which natural hazard risk is managed. First, there is mitigation, which are projects, policies or other measures that reduce natural hazard risk before an event occurs, and which can be achieved through (1) reducing the severity or extent of hazard, (2) moving or preventing values at risk from being exposed to harm, and (3) increasing the resilience (decreasing the vulnerability) of people, communities, capital, businesses and other values-at-risk when they are exposed to harm. Second, there is emergency response, which focusses on managing disaster events themselves, through limiting the losses that arise from the time of forecast, to immediately after the hazard occurs. In the same way as for mitigation, response can be achieved through modifying the hazard, exposure or vulnerability of values-at-risk. Thirdly, natural hazards are managed through recovering/building back what was lost. It is important to note that these three ways in which management occurs are not independent, for mitigation could include improved capability of response or recovery. For example, policies on insurance could greatly aid recovery, while the planning around procurement of response assets (what assets, how many, where they will be located) has an impact on efficacy of response and hence losses.

Furthermore, plans for 'building-back-better' enable the outcomes of recovery to be more substantive.

Although management consists of the three mechanisms outlined above, mitigation is perhaps the most effective means by which risk is reduced. In fact, there is a growing literature showing very favourable benefit-cost ratios (BCRs) for mitigation (e.g. Eucker et al., 2012; Heidari, 2009; Holland, 2008; Holub and Fuchs, 2008; Khan et al., 2012; Khogali and Zewdu, 2009; Kull et al., 2013; Kunreuther and Michel-Kerjan, 2012; Mechler, 2005; Schröter et al., 2008; Shreve and Kelman, 2014; Venton and Burton, 2009; Venton et al., 2010a; 2010b; White and Rorick, 2010). Specifically, Rose et al (2007) found that the modelled BCR for reducing risk across 5500 Federal Emergency Management Agency (FEMA) mitigation grants was about 4:1. A sensitivity analysis indicated that projects that had BCRs above 1, remained so, under a very broad range of conditions. The English Environment Agency tested five funding strategies for maintaining existing and investing in new flood risk management assets across England, and found that the BCR for these strategies ranged from 4:1 to 11:1, when the costs and benefits of managing coastal, tidal and river flooding, and managing coastal erosion were considered (Environment Agency, 2014). In Australia, Harper et al. (2013) analysed the potential for public infrastructure, land use zoning and building code changes to reduce flooding, cyclone and bushfire risk and found that BCRs greater than 1, and up to 9, were possible when mitigation investments are made that target high-risk locations with appropriate combinations of structural and non-structural mitigation options.   Therefore, management, particularly through mitigation, is effective at minimising natural hazard risk.

1.2.2 ASSESSMENT OF RISK AND TESTING AND SELECTION OF MANAGEMENT OPTIONS

While risk is manageable and mitigation effective, there are challenges in balancing investment between response preparation/capability, recovery planning, and mitigation activity, as well as selecting the specific measures to implement for each of these.

First, one needs to select a number of response, recovery and other mitigation measures from a large number of potential options that best reduce risk while also considering the implications of these choices on other community goals (Godschalk et al., 1998; Mance et al., 2002; May and Deyle, 1998; Spaliviero et al., 2011). Measures to reduce risk do not necessarily lead to BCRs greater than one (Rose et al., 2007), and often have negative side-effects and therefore building a natural hazard management plan that balances risk reduction, costs and other community goals across all stakeholders is difficult (Levy, 2005; Wheater and Evans, 2009). In addition, as mentioned above, there are a number of ways in which risk can be reduced, ranging from structural measures to non-structural measures such as increasing awareness through education and information, land use planning, improved warning, response capability, recovery in a way that builds resilience, financial measures (e.g. insurance), and environmental/landscape management practices (Bouwer et al., 2013; Klijn et al., 2015); and these measures can be implemented at different locations and many different points in the future, meaning the 'decision space' is potentially

very large (Hall and Solomatine, 2008). Furthermore, management options are not independent of each other with regard to their reduction of risk or impact on other objectives. To demonstrate, consider one of the main traditional ways in which floods have been managed: using a number of flood storage reservoirs in series. The contribution of a downstream reservoir to risk-reduction would often be significantly less with the upstream reservoir than without it. Although this is a simple example, it demonstrates that management options act as components in an integrated system to reduce risk in certain locations across certain flow conditions (whilst often increasing risk elsewhere). Consequently, risk needs to be calculated for each set of management options - and cannot be estimated from a simple sum of their contributions in isolation from each other (that is, they are non-additive). Finally, mitigation budgets are limited, and opportunity costs are very significant factors in mitigation decision-making (Sayers et al., 2015).

Second, to identify the best set of mitigation measures, one needs to carefully compare the performance of the various options in reducing risk and their impact on other community goals. This is made difficult, as the way in which management options reduce risk, the length of their life-cycle and the time-lag in their effect following implementation vary considerably between options (Johnstone and Lence, 2009), requiring the development and acquisition of different modelling chains/tools. In addition, hazard, exposure and vulnerability are nonstationary, and therefore assessment of risk into the future is important (Merz et al., 2010; Rosner et al., 2014). Furthermore, there is a range of uncertainties as well as ambiguities over the effectiveness of most management options, including on how their effectiveness will change into the future, that are very significant and need to be considered (Bates et al., 2005; Hall and Solomatine, 2008).

1.2.3 INTEGRATED ASSESSMENT MODELLING FOR CHARACTERISING THE NATURE OF RISK AND THE EFFECTIVENESS OF MANAGEMENT OPTIONS

Integrated assessment modelling (IAM) approaches are available to address the challenges in assessing the extensiveness of risk and the effectiveness of management options. Integrated assessment models typically consist of multiple interlinked sub-modelling components arising from multiple academic disciplines that together are helpful for exploring different options available for decision problems. Within the natural hazard management space, they could consist of components that describe the source and propagation of hazards in the landscape, the characteristics and movement of values-at-risk in the same landscape, the processes by which values-at-risk are directly affected by hazards, and the indirect, flow-on impacts to the wider community, as well as the side-effects, whether positive or negative, of management options on other community values and/or goals. They are not primarily predictive/forecasting models, but rather are useful tools for exploring what could happen when 'disaster' strikes, and subsequently, how effective management options are to reduce this risk. In this exploration, they allow a comparison of management options in a holistic manner while accounting for interconnectivities.

The advantages of a simulation approach are further brought to the fore, when considering the limited historical data available in Australia (especially for non-hazard exposure or vulnerability factors) and because the nature of natural hazard risk is changing. Therefore, relying on the past is not sufficient for informed management. In addition, simulation provides a transparent, science-based approach and helps reduce bias when comparing the performance of different management options.

When it comes to constructing a model to simulate the way socio-environmental-economic systems respond to natural hazard, there are well established ways for simulating the source and propagation of hazards for all major hazard types (HAZUS used by FEMA in the USA is one example). However, for an integrated assessment that considers a broad range of management options that reduce risk in varied ways, and not just through controlling hazard, modelling components characterising the social and economic processes as well as the physical responses of people and assets are needed. Fortunately, there is a growing literature on modelling components for this, and based on these modelling components, a number of spatiotemporal modelling systems have been built for assessing natural hazard risk that have been successfully used within decision making contexts. The decision support system developed by this project is a cutting-edge example of this (van Delden et al., 2015).

1.2.4 USE OF OPTIMISATION FOR SCREENING THROUGH AND IDENTIFYING BEST PERFORMING MANAGEMENT OPTIONS

Optimisation is a valuable means for screening through and identifying best performing management options because it is an automated or semi-automated approach that can be used in conjunction with models to test a large number of potential management portfolios and to gain knowledge on what management options work best with one another. Optimisation works with a set of potential management options, and based on the evaluated performance of these, generates new sets of management options that are likely to be better, using mathematical-and-computer-science-based reasoning techniques. By doing this repeatedly in an iterative fashion, whereby in each iteration the performance of the portfolios gradually improves, the technique is able to identify the best performing management options.

When paired with IAM simulation, the purpose of optimisation is not to develop an 'expert system' whereby optimal portfolios are developed and implemented without further appraisal. Rather, optimisation is used to reduce the laboriousness of using the IAM to test different risk management strategies, in order to derive better insights as to what portfolios work best, while reducing bias that can hinder manual approaches.

1.3 RESEARCH GAP ADDRESSED IN THIS REPORT

In the previous section, we developed an argument for a simulation-optimisation approach that incorporates integrated assessment modelling for exploring what combinations of management options are best for reducing natural hazard risk. To our knowledge, this approach has not been developed in the literature

before, and thus is a new development. Saying that, there have been a few studies reported in the literature that used optimisation on decision problems related to natural hazard risk management, although there have been significant limitations in these that are addressed in our proposed framework, as briefly surveyed in Table 1 and discussed below.

Paper	Uses formal optimisation	Simulation approach with integrated process dynamics	Temporal dynamics into long-term future considered	Social and environmental criteria used	Broad range of management options considered
Woodward et al. (2014a)	Y	Y			
Woodward et al. (2014b)	Y	Y			
Zhu et al. (2007)	Y		Y		
Li et al. (2007)	Y				
Afshar et al. (2009)	Y				
Yazdi and Neyshabouri (2012)	Y	Y			Y
Karamouz et al. (2008)	Y				
Amendola et al (2000)	Y				
Ermoliev et al. (2000a, 2000b, 2000c)	Y				
Ermoliev et al. (2012)	Y	Y			
Apivatanagul et al., (2011); Dodo et al., (2007, 2005); Legg et al., (2013); Li et al., (2011); Xu et al., (2007)	Y				

TABLE 1. PREVIOUS STUDIES IN THE LITERATURE USING OPTIMISATION FOR NATURAL HAZARD RISK MANAGEMENT CASE STUDIES

Yurii Ermoliev and his collaborators at the International Institute for Applied Systems Analysis (IIASA) have combined the use of models, optimisation and decision support systems to help develop mitigation strategies. In Amendola et al. (2000) and Ermoliev et al. (2000c), an optimisation approach that took the space-time dynamics of natural hazards, policy mechanisms, and dependency between different disaster events and mitigation measures into account was presented. In Ermoliev et al. (2000a) and Ermoliev et al. (2000b) this approach was illustrated using a case study that considered insurance premiums and risk spreading through reinsurance and catastrophe bonds in relation to earthquake hazard in Irkutsk, Russia. The research at the IIASA was later extended to earthquake risk in Italy and flood risk in the Upper Tisza River region in Hungary (Ermoliev et al., 2012). However, the approach undertaken at the IIASA focussed on financial instruments, particularly insurance, and did not consider the broadest range of potential mitigation options. In addition, their work has

focussed on a single hazard type, and has not considered climate, population demographics and land use change. All these factors will likely result in maladaptation or suboptimal selection of management options to reduce current and future changes to risk.

Rachel Davidson and her collaborators at Cornell University and the University of Delaware have developed optimisation approaches that focus on mitigation decisions from a public policy perspective, mainly in relation to earthquake risk (Apivatanagul et al., 2011; Dodo et al., 2007; 2005; Legg et al., 2013; A. C. Y. Li et al., 2011; Xu et al., 2007). As part of these approaches, the models that represent loss are simplified (they are linearised) and do not consider the broader social, economic and environmental impacts of hazards and the side effects of management options. While the simplification is done so as to use linear optimisation techniques that are guaranteed to find globally optimal solutions to the simplified problem, we argue that it is better to maintain a more realistic problem formulation through an IAM approach as proposed in this report, when applying optimisation to these types of real-world public-resource applications.

Finally, there have been a number of papers applying optimisation for flood management problems including Woodward et al. (2014a), Woodward et al. (2014b), Zhu et al. {(2007), Li et al. (2007), Afshar et al. (2009), Yazdi & Neyshabouri (2012), and Karamouz et al. (2008); yet none of these considered temporal dynamics of risk into the long-term future, any social or environmental criteria, or the broadest range of management options.

Given that there has been no prior use of the approach proposed here, Section 2 specifies a simulation-optimisation incorporating IAM for the management of natural hazard risk. Section 3 of this report will apply the proposed approach to a case study to verify its feasibility and worth.

2 A SIMLATION-OPTIMISATION FRAMEWORK FOR NATURAL HAZARD MANAGEMENT

The proposed framework for the complementary use of both optimisation and simulation, incorporating integrated assessment modelling, for natural hazard management is shown in Fig. 1, below. This framework (1) searches for the best-performing portfolios of management options, selecting from the (2) broadest range of management options, based on (3) a diverse set of risk and other non-risk economic, social and economic goals and constraints by means of an integrated multi-criteria assessment. In doing this, the framework also considers (4) uncertainty and (5) how risk changes through long-term planning horizons, for example due to climate change, population growth, and changes to demographics and development patterns. The framework achieves this while ensuring that the analysis of portfolios is (6) integrated within natural hazard management/planning processes via participatory approaches with stakeholders and decision makers. In doing this, the framework's purpose is to help decision makers and planners formulate natural hazard risk strategies that outline what types of options will be used to manage risk in a particular region to which the framework is applied. The way in which the framework achieves these goals is as follows:

In order to ensure that all plausible management options are considered, participatory problem scoping is used (Fig. 1 part c). With involvement of stakeholders, domain-knowledge experts and decision makers, scoping identifies what management options are plausible in the region and planning context (Fig. 1 part f). In a similar way, a diverse set of risk and other non-risk economic, social and economic goals and constraints is identified through scoping (Fig. 1 part g and h). Scoping also involves specifying how management options will be modelled and how goals, and constraints will be quantified (Fig. 1 part j, k ,l, respectively).

As mentioned, the framework embodies an integrated assessment approach to modelling through the construction of a model that is able to simulate the holistic effect of management options across a broad range of decision criteria and constraints. To do this, drivers and processes that cause risk and other decision criteria/constraints are identified during scoping (Fig 1 part i and m) and modelling components that incorporate these and that are able to model the effectiveness of management options are subsequently identified and integrated (Fig 1 part o and p).

In order to address the need to consider non-stationarity, the framework identifies those drivers and processes that will change in the future (as mentioned above, Fig 1 part i and m), and develops future scenarios around these (Fig 1 part q). These are then quantified (Fig 1 part r) and fed as inputs and parameters into the model (Fig 1 part x).

In addition to future uncertainty taken into account through scenarios, other forms of uncertainty also need considering and are therefore addressed in the framework. Uncertainty is considered either as a post analysis of identified best-performing portfolios (Fig 1 part aj); or within the search itself (Fig 1 part z). Using Monte-Carlo techniques, the uncertainty analysis runs the model multiple times

with different samplings of the uncertain parameters/values in order to calculate how robust a portfolio is with respect to its performance, as given by different realisations of these uncertainties.

In order to search for best-performing portfolios, optimisation is used to iteratively improve a set of management portfolios through automated and semi-automated routines.

In order to inform risk management processes and planning, post-optimisation appraisal is used. In order to maximise the value from the simulation-optimisation approach, techniques for the visualisation of results from the analysis are needed, in particular for informing decision makers and stakeholders on what management options were included by the optimisation in the portfolios, and how the combined effect of management options in portfolios performed in terms of decision criteria, across space and time.

To integrate the analytical approach presented here within risk management planning processes, participatory approaches to problem scoping and retrospective appraisal are included, as mentioned. However, continuous interaction with stakeholders and decision makers is needed during model development and application, for there will be requirements specified during scoping that will be incompatible or conflicting, as well as gaps and creep of the scope as planning processes evolve (Fig 1 part ak).

To illustrate the interconnectivity and complexity involved in applying the framework, consider how potential management portfolios propagate through the framework.

In the problem scoping phase, participatory approaches are used to elucidate what management options are feasible within the region, as mentioned above. Once elucidated, a low-level scoping exercise is required, wherein modellers and domain knowledge experts consider the key design and implementation details for each management option and identify factors that either have bearing on the feasibility of the option, or that significantly affect the objectives and constraints. For example, while detention storage may be identified as a management option during high-level participatory scoping, the potential locations and capacity constraints on this would need to be considered during low-level scoping. Modelling aspects also need to be kept in mind during scoping, to ensure that the decision/implementation options are at the correct level of detail, in that they can be represented in modelling approaches.

During the development of an analysis framework, an integrated model is specified that allows the quantification of how management options and their key design/implementation details affect the objectives and constraints. This analytical framework is dynamic, in that it simulates the effect of management options into the long-term future to consider non-stationarities — and thus the model needs to be capable of simulating when a management option is implemented, and how the effectiveness of the management option varies in time. Based on the key drivers of risk-causing processes that are affected by management options, modelling components that represent these drivers, and data that are needed for the inputs and parameters of these modelling components, are sought, acquired and/or developed, and integrated to form a

modelling system. Finally, the modelling system is connected to an optimisation module that searches for best performing management options.

Once the integrated model is calibrated, the simulation-optimisation is run, wherein management options are combined to form portfolios, and the combined effect of these is simulated. The combined effect of a portfolio is simulated rather than each option individually due to the non-additive effect of management options in terms of their effect on decision metrics. The simulation is potentially run multiple times across a number of plausible future scenarios so that the effect of uncertainties and non-stationarities on the performance of a management portfolio is characterised. The optimisation module iteratively develops better performing portfolios. In each iteration, machine learning techniques are used to further understand how choices on management options and their implementation details affect the objectives and constraints and use this information to develop better-performing portfolios for assessment in the next iteration.

Finally, in the post-optimisation appraisal phase, the performance of the Pareto-optimal management options in terms of their decision-metric values across time and space is visualised in a way that engenders understanding on how the best performing portfolios relate to each other in terms of what management options were included in them, and how the combined effect of these management options resulted in the spatial and temporal distribution of decision metrics, as calculated through the model. Through participatory processes, a number of portfolios may then be selected for further consideration by decision makers within the risk management process. Alternatively, other management options, objectives and/or constraints that were not identified during the initial scoping may be identified during the appraisal, in which case the process as just described is repeated with these included.

In the remainder of this section, the approach outlined here is further developed to draw out additional details on the complexities and interconnectivities of the framework, as follows:

In Section 2.1, how this processes is embodied within risk management processes is discussed.

In Section 2.2, problem scoping is discussed, describing the means of elucidating objectives, management options and constraints from stakeholders, and the relationships between high-level and low-level scoping. This section presents classifications for each of these aspects and provides guidelines for their selection. In addition, the required levels of integration/aggregation of risk variables over time and space are discussed for the development of decision metrics.

In Section 2.3, the specification of an analysis workbench is discussed, describing the key components of an integrated hazard, exposure and vulnerability risk assessment, the inclusion of uncertainty analysis, as well as the inclusion of temporal dynamics. In addition, the approach for searching for the best-performing management options to form optimal portfolios of management options is discussed, and guidance provided for the selection of an optimisation method.

In Section 2.4, the post-optimisation analysis, covering aspects of the visualisation and appraisal of best-performing management portfolios, is discussed.
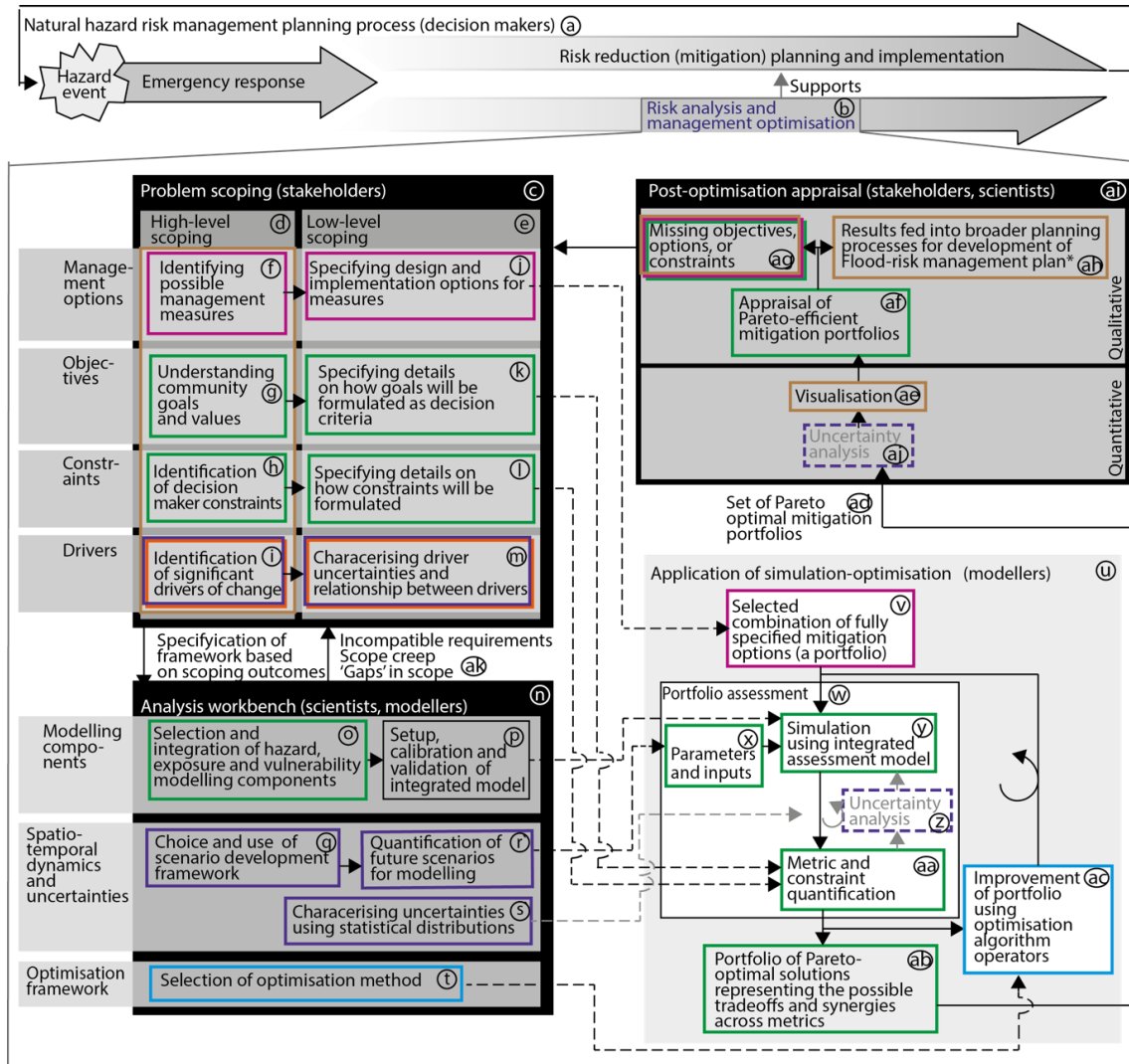
Key to coloured boxes, highlighting features of the framework
Sifting through and identifying best performing mitigation measures | Integrated multicriteria assessment | Considering uncertainty
A broad range of mitigation measures | Considering nonstationarity | Integration within flood management planning processes
Dashed lines represent a mapping of scoping and analysis workbench components to optimisation processes as the optimisation runs
Solid lines show dependencies between components of the simulation-optimisation development and use process

Fig. 1. Proposed high-level framework for a simulation-optimisation approach for temporally and spatially dynamic natural hazard risk assessment and planning. This framework uses optimisation to sift through the large number of potential portfolios of management options, carefully builds a model-chain to appropriately represent management options and calculate decision criteria, considers uncertainty and nonstationarity in risk drivers and processes, and selects appropriate modelling components and optimisation approaches that adequately balance the trade-off between simulation accuracy and computational cost, whilst being focussed on supplying useful information to enrich dialogue and decision making within risk management processes.

2.1 THE PLACE OF THE PROPOSED FRAMEWORK WITHIN A BROADER NATURAL HAZARD RISK MANAGEMENT PROCESS

The natural hazard risk management process is often considered as a cycle with four stages — planning, preparation, response and recovery (PPRR, Fig. 1 part a). During this cycle, the proposed framework has increased utility as management progresses from the recovery to planning phases of the cycle, as this is the stage

in the cycle where there are time and resources to develop and refine risk management strategies, and the framework is focussed on developing strategy and, in particular, planning. At the beginning of this stage, the framework is used to characterise the trade-off between risk management budgets and the level of risk reduction that can be achieved in order to help select the amount of funding for mitigation. Subsequently, the framework can be used to suggest what mitigation options to implement given a budget for this and to understand the trade-offs between risk reduction and other community goals. It is also worthy of note that the framework has utility during reconstruction, in the sense that damaged assets can be rebuilt with greater resiliency. In this case, the application of the framework can suggest the optimal balance between rebuilding to a higher standard ('build back better') and later mitigation activity. Finally, the framework has utility for response and recovery. By including the costs of response and recovery in the analysis and by including management options that improve preparation for response, the framework can also be used to help allocate funding across all phases of the emergency management cycle, and make each of these stages more efficacious. Consequently, the implementation of this framework within the planning phase provides information to optimise planning for how response, recovery and reconstruction should occur after the next natural hazard event.

As well as providing quantitative and transparent information on the current levels of risk, optimal portfolios of management options, and the trade-offs between risk reduction and other community goals, the framework also value-adds to the risk management process through social learning that occurs during its implementation. In particular, the framework can help raise awareness and deepen the understanding of decisions makers about the nature of risk, potentially triggering action and increasing the richness of dialogue between decisions makers and stakeholders. It also provides a scientific basis for this dialogue in that it takes stock of the social, environmental and economic processes that give rise to risk through scientifically calibrated and validated modelling components. In so doing, better decisions surrounding risk management can be made.

It is the interactions of modellers, scientists and IT specialists with decision makers and stakeholders that integrates the framework within risk management processes. These interactions concentrate during problem scoping (Fig. 1 part c), and post-optimisation appraisal (Fig. 1 part ai), as already mentioned. However, risk management processes continue to evolve while models are built, and optimisation problems are solved, and it is very likely that this will impact on the formulation of the optimisation problems that are solved by the framework and are of most help for decision making (in other words, the problem which is to be solved by the framework may well be a moving target). Consequently, continuous interaction with personnel involved within broader risk management combined with an agile model development strategy is essential and has as much importance as the formal interaction during scoping and the presentation of results.

2.2 PROBLEM SCOPING

The implementation of the framework starts with problem scoping. Problem scoping, as defined by the framework has two parts. First, high level scoping (Fig. 1 part d) is used to (1) identify potential management options that could be feasibly implemented within the case study region (Fig. 1 part f); (2) identify related community goals, which, as mentioned earlier, encompass more than natural hazard risk, but also other positive and negative side-effects of management options (Fig. 1 part g); (3) identify constraints to which management strategies must adhere (Fig. 1 part h), and (4) identify key drivers of risk that need to be considered (Fig. 1 part i). These four aspects form the context within which the framework is implemented, and elucidating this context involves engaging with decision makers, stakeholders and the community-at-large. Next, low-level scoping (Fig. 1 part e) is used to map the outcomes of the high-level scoping to aspects that relate to modelling and optimisation, so that the analytical approach can be specified and developed. This involves specifying decision variables relating to the selection and design/implementation of management options (Fig. 1 part j), mapping community goals and decision making constraints to quantifiable criteria (Fig. 1 part k and l), and specifying the key processes and their interlinkages that lead to risk and the side-effects of management options (Fig. 1 part m).

A potential template for this engagement is given in Fig. 2. This template uses participatory approaches between stakeholders and scientists/domain knowledge experts, and the community-at-large for the high-level scoping (Fig. 2 part b) and between analysts and scientists for the low-level scoping (Fig. 2 part f). This process is governed by three key agreements that need to be made between those financing/resourcing the process with those managing the project. In the first of the agreements (Fig. 2 part a), the process by which scoping will occur needs to be agreed upon, as well as timelines and resource allocation for this. At this time, it is also beneficial to initially identify key stakeholders to include within scoping more broadly. The second agreement (Fig. 2 part e), involves endorsing the conclusions of the high level scoping, so that low-level scoping can commence. In the third agreement (Fig. 2 part g), the outcomes of the low-level scoping are endorsed so that the development and use of the simulation-optimisation analysis workbench can occur.
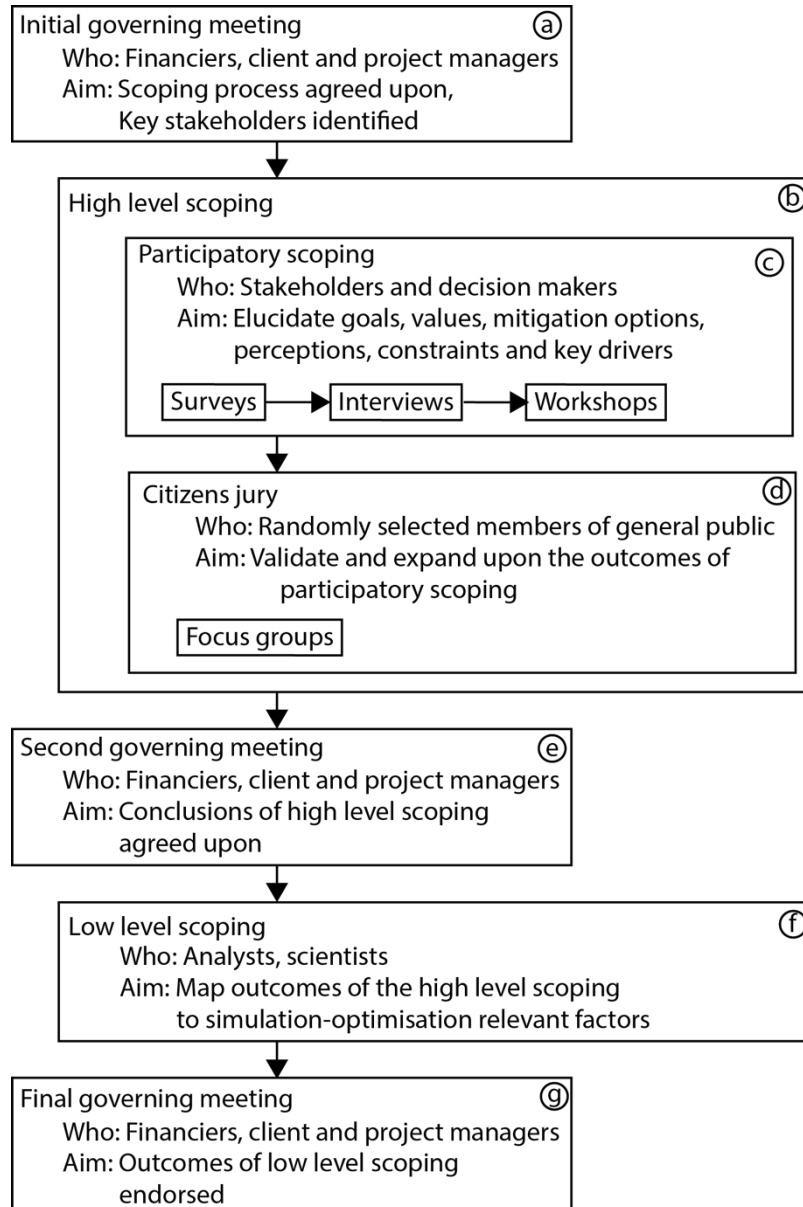
Fig. 2. Template process for specifying management options, community goals, constraints and key drivers to consider in the analysis, as part of scoping in part c of the overall framework presented in fig. 1

As mentioned, during the first governing meeting, an initial identification of stakeholders needs to occur. There will be multiple types of stakeholders to identify for the assessment, as natural hazards affect communities broadly and due to the public nature of natural hazard risk management. In the Australian context, key stakeholders to identify are: (1) decision makers, who tend to be government executives, and elected members of democratic governments; (2) domain knowledge experts, who tend to be scientists as well as professionals/officers working within government departments, non-government organisations, public utilities and consultants involved in the natural hazard risk management cycle; and (3) the public at large. There are a number of domains of knowledge that relate to risk management — including physical scientists, who can characterise the sources, propagation and response of assets to hazard; social scientists who understand the response of people to hazard and management options and the ultimate consequences of hazard and

management options on communities, and government officers, who understand the policy directions of government, the culture of communities and the characteristics of the region's built and natural environment. It is also important to recognise that analysts are also a type of stakeholder, in that the culture in which analysts work, and the choices they make in problem formulation, implementation and use of the proposed approach all affect the outcomes of the process (Wu et al., 2016). These 'brokers' ideally have a skill set that allows them to communicate within and across the cultures of stakeholders to facilitate communication and social learning, but who also are removed as far as practicable from the political motivations that operate within the study region, to reduce bias.

Once stakeholders are identified, the remainder of the scoping process can occur. For high level scoping, participatory techniques with domain knowledge experts and decision makers are used to elucidate their (1) goals and values, (2) potential management options and who has the power to implement them, (3) perceptions, both good and bad, of potential management options, (4) the constraints that decision makers work within, or that they place on others, and (5) key drivers that lead to risk and side effects of management options. This is then validated and expanded upon by using citizen juries, as explained later.

Mechanisms that can be used to elucidate information from domain knowledge experts and decision makers include surveys, interviews and workshops (Fig. 2 part c). For surveys, questions could relate to the following themes: individuals and their organisation's role and responsibilities within the risk management process, including their power and agenda/goals; the potential management options they would consider and their potential side effects; constraints, frameworks, regulations, policy documents, as well as previous studies/reports and press releases relating to risk management that they work to; drivers of risk and critical uncertainties; and other key stakeholders who should be included in scoping. When survey results are collated, there is value in identifying the synergies, conflicts and ambiguities in answers, as these aspects can then be clarified, for example, through the use of interviews. The value of workshops is that they are helpful for developing group consensus on factors affecting the feasibility, effectiveness and side-effects of management options, the relative importance of different types of uncertainties and drivers, as well as clustering and ranking the importance of community goals and constraints and mapping the processes that cause natural hazards and their impacts.

The use of both individual and workshop exercises may seem redundant, however, there is actually strong value in including both. Workshops are often biased by the voice of those who dominate the discussion, and therefore the results of the survey and interviews allows facilitators to draw the range of relevant elements into the discussion. Furthermore, group exercises and discussion help identify greater numbers of management options, drivers, uncertainties, constraints, and goals etc. and are better able to map the interrelationships between these than what would be obtained through individual responses alone.

Participatory techniques that are relevant for the workshops include brainstorming, as well as participatory pair-wise rankings for management options (López-Marrero and Tschakert, 2011), and mental-models to map the

causes and effects of natural hazards (Tschakert and Sagoe, 2009). To do the latter, using the source, pathway, receptor, consequence framework as a basis would be useful to ensure the entire system is captured that links causes of natural hazards to their effects. It is also important to consider processes resulting in the growth/decline of values-at-risk in the application region, as well as the movement and location of these values. A key result of mental-model activities is the development of influence diagrams (or decision networks, relevance diagrams), which are visual representations of the processes and therefore the flow of information required to evaluate risk and other community goals (Leonard et al., 2013). The development of such a diagram is invaluable to the process, in that it allows the holistic identification of the uncertainties, management options and future events/changes that would affect each element in the diagram (in that key uncertainties or future changes for each element of the diagram, and key actions that can be used to modify the effect of each element in the diagram, can be brainstormed during group exercises during the workshops).

Citizen juries (CJs) also have great value and could be involved (Kenyon, 2007) in scoping (Fig. 2 part d). CJs are groups of paid, randomly selected people representing a microcosm of their communities that together are asked to make public conclusions regarding pertinent issues based on public, rather than their own, interests. In the process of making these conclusions, deliberation occurs by jury members through discussions and interactions with domain experts, for example, through focus groups. Therefore, CJs allow informed input from the community-at-large. These juries should be well-focused on specific issues, well-structured and documented, as this has been shown to provide more robust and transparent outputs (Kenyon, 2007). In particular, the role of CJs during scoping is the ranking of management options in terms of their desirability and community goals. Furthermore, the role of CJs would also be to ensure all management options, community goals and drivers have been captured, particularly in terms of identifying grassroots measures and the impacts of natural hazards or management options that are very localised, as these are less likely to be captured in the workshops with domain knowledge experts who may have a broader geographical focus.

While the inclusion of CJs could be considered laborious, they do ensure active participation of the community in natural hazard risk strategy, and have the benefit of ensuring that management coincides with the needs and demands, interests and objectives of local communities, and may save time in the long-run in that the results of the analysis will be more accepted.

Finally, once the high-level scope of the analysis has been determined, analysts need to elucidate formulation-relevant factors from the workshops and CJs and synthesise them into a single problem formulation. As mentioned above, this is what occurs during the low-level scoping (Fig. 1 part e, Fig. 2 part f), and would normally be carried out by the analysts undertaking the study, based on what were considered to be the most significant/important factors through the workshops and CJs. It will often be the case that the power for decision making in risk management will be shared, leading to conflicts regarding what should be prioritised in the analysis. The process of elucidating decision criteria/constraints and potential management options from participatory approaches are described in the following subsections.

2.2.1 SELECTING MANAGEMENT OPTIONS FOR CONSIDERATION AND ELUCIDATING IMPLEMENTATION DETAILS FOR THESE

The proposed approach uses optimisation to build portfolios of management options that best meet community goals. This also involves elucidating details related to the implementation of each of the management options that were considered plausible during the high-level scoping that would significantly alter their performance, as these will also need to be included within the optimisation as decision variables (Fig. 1 part j).

There is a very broad range of management options that plausibly could be used to reduce risk. As shown for managing flood risk, Fig. 3, shows that risk management options range from structural options that modify hazard pathways to structural options that modify the response of assets to natural hazards (in other words their vulnerability/resilience). Governance options include aspects relating to land use, insurance, financial incentives and resourcing of response and hazard warning mechanisms, while so-called 'softer' options include education, which tend to increase community resilience and/or reduce vulnerability through shifts in behaviour.

The proposed participatory processes during the high-level scoping were designed to identify and assess what management options are feasible in the context of the assessment (and the taxonomy as proposed here should be used as part of this process to ensure that the brainstorming processes consider the full range of possible management mechanisms). All feasible options that decision makers would consider for implementation, as identified through the high-level scoping, should be included in the formulation, as often a mix of both structural and non-structural measures provides the best outcomes. Therefore, care should be taken not to disregard a measure a priori due to its perceived disadvantages, unless it is strictly infeasible; it is generally better to let the optimisation screen through and identify the best performing sets of options because it is difficult to fully understand the interplay between the effects of measures within a portfolio and the complexities of constraints put on a management plan without assistance from the simulation-optimisation approach, as proposed here.

It is also important to note that for each of these options that are included for consideration, there are a large number of details related to their implementation that will alter their performance, such as location, capacity and dimensions (as mentioned above). Using an example from flood management, in any given floodplain it would be usual to have hundreds of potential and existing levee sections (locations), where the performance of these sections is dependent on levee height (dimensioning), and failure probability, in addition to decision variables related to pumps, gates and barriers that form part of a levee defence system. Likewise, the effect of a reservoir will be dependent on its flood storage capacity, while the effect of channel works will be dependent on the cross-sectional shape, depth of the channel, and channel lining. Therefore, the specific decision variables included within the optimisation problem may correspond to (1) whether a particular management option is implemented at a specific location, (2) scheduling when the particular management option is implemented, and (3) specifying other key details related to how the option is implemented.

Decisions variables relating to the selection, location and scheduling of options are herein termed primary decision variables, while variables related to the other implementation details are termed supplementary decision variables. There are subjective decisions that need to be made on the level of detail that needs to be captured by the supplementary decision variables, which are related to the context and scope of the problem being addressed. It is important to bear in mind the purpose of the framework in making this judgement — that is, to identify well-performing management options, not detailed design. Consequently, as few implementation aspects as possible should be included in order to reduce the complexity required in modelling the risk-causing processes and computational demand of the modelling. In order to make this judgement, the use of the influence diagram developed during the workshops has great value, in that thought-experiments can be conducted to map out how changes in design variables propagate through the influence graph. Where these design variables map through elements that were identified as significant, then these should be included in the optimisation problem.

Fig. 3. A taxonomy of options that can be used for managing flood risk, showing the diversity of options available for consideration, as shown in part f of fig. 1 of the proposed framework. Although shown here for flood management, the general categories are applicable to other natural hazards as well. To obtain the best possible management outcomes, all of these options need to be considered jointly.

2.2.2 TRANSLATING STAKEHOLDER GOALS INTO QUANTIFIABLE OBJECTIVES AND SPECIFYING DETAILS OF THEIR EVALUATION

There are a number of steps that need to happen in translating stakeholder goals (as identified during the participatory approaches, described previously) to metrics that are minimised or maximised within a formal optimisation routine (Fig. 1 part k). To do this, we recommend the following process: First, clear statements of community goals need to be synthesised from stakeholder inputs. These are not necessarily mathematical, but need to be succinct and the set of goals ideally should capture the breadth of stakeholders' views. Second, the types of

values that are potentially impacted by hazard or management activities in terms of stakeholders' goals need to be identified. From this, indicators need to be developed that are mathematical relationships that calculate how values are impacted. Finally, these indicators need to be aggregated across time and space to form metrics that will be either minimised or maximised by the optimisation. The optimisation uses these metrics as objectives, and thus uses them to compare and rank different portfolios against each other so that it can direct the search toward good areas of the decision space.

Fig. 4 presents a taxonomy of the components involved in assessing the performance and side-effects of management options, taking into account the above steps. This highlights the complexity of this assessment due to the large number of aspects that can be considered and how they interact with each other.

There are many types of values that are impacted by hazards or the actual implementation of management options that all need to be considered for a comprehensive assessment (Fig. 4 part a). Also, specifying the values that are assessed is a key determinant of the choice of sub-modelling components and the temporal and spatial extent and resolution of modelling and therefore gives the analysis focus. Values to be assessed include aspects such as life or built assets, and metrics developed will quantify how much 'value' is lost or gained, either temporarily or permanently, when exposure to hazard occurs or from the side-effects of management options. There are also values that are not directly impacted by the hazard itself but are impacted by the flow-on effects of direct damages. For example, economic productivity is likely to be significantly impacted as a result of direct damages and losses can also be related to the environment, the social make-up of communities and the psychological impact to people. Often these impacts can be very significant (Hallegatte, 2008; Morris et al., 2008; Noy, 2009). Consequently, the analysis should extend beyond direct losses to also consider indirect costs both within and beyond the region directly affected by hazards (Fig. 4 part b).

The benefits and detrimental impacts of management options are not felt uniformly across a community and have different distributions in space and time (Fig. 4 part d). Therefore, it is important to consider whether objectives are calculated for a government, individuals, businesses or net over the entire community, and whether an emphasis is placed on vulnerable groups (such as the disabled, elderly or young) or specific regions where there is a disproportionate accumulation of value or those that have contributed larger amounts of funding to the management of hazards. Consequently, the indicators developed will need to be aggregated in multiple ways, to take stock of how impacts vary across different hazard events, long-term planning horizons, and across different value-types and community groups (Fig. 4 part e).

It should be noted that while aggregation is necessary to reduce the dimensionality of the objectives to be considered in the optimisation, they do not need to be aggregated into a single objective. Multi/Many objective algorithms, as discussed in a later section, are able to deal with competing objectives and constraints. The choice of aggregation will depend on what information decision

makers want, based on the nature of the goals of stakeholders, as elucidated during the high-level scoping. For example, decision makers may want information that presents an overall picture of risk that aggregates different types of criteria (e.g. environmental, social, economic) or disaggregates risk into specific aspects of a criterion (e.g. separate information for damage to buildings, transport and utility networks); presents risk for particular risk-owners (i.e. private, business, insurers, government); shows how specific risk types vary throughout time; or compares risk across different administrative regions or vulnerable social groups.

Furthermore, at this stage of the framework, the specific formulation of the metrics from stakeholder goals is not required to be fully resolved. The direction/focus of the metrics is needed and the specific formulation can occur side-by-side with model specification/development, as will be described in Section 2.3

Benefits and detrimental impacts of mitigation measures

Values that are considered (a)

Economic values
- Built environment (Often incorporated as direct losses in economic analysis)
  - Buildings (in general)
  - Critical infrastructure
    - Buildings (e.g. hospitals, evacuation centres)
    - Utilities (e.g. electricity, gas, water and wastewater)
    - Communication networks
    - Transport networks
  - Significant places
    - Heritage buildings
    - Museums and galleries
    - Other culturally significant places
  - Other
- Impact on economic productivity (Dollar values *may* be placed on intangibles and incorporated within econmic analysis, and/or may be considered as separate indicators)
  - Primary productivity
  - Manufacturing
  - Service

Environmental values
- Terrestrial ecology
- Aquatic / marine ecology
- Groundwater system
- Aesthetics and recreation
- Landscape and river geomorphology
- Greenhouse gas emissions
- Other environmental impacts

Social values
- Fatalities
- Casualties
- People requiring assistance
  - Short term
  - Long term
- Public security
- Political implications
- Psychological impacts
- Loss of cultural values
- Other

Components of analysis

Benefits/costs arising from hazard events (b)
- Within region directly affected
  - Direct losses (e.g. physical damage)
  - Indirect costs (e.g. business interruption)
- Outside region directly affected
  - Indirect costs (e.g. interrupted supply chain)
- Indirect benefits (e.g. stimulate construction industry)

Benefits/costs from implementing measures (c)
- Direct cost (e.g. design, construct, operate)
- Opportunity cost (could spend mitigation dollars to meet other community goals)
- Other costs/benefits of measure (side-effects, e.g. reduced accessibility)

Values to whom/what (d)

Net across all of society, or emphasis on vulnerable groups
- Individuals
- Businesses
- Public purse / government
- Others

Methodological considerations (e)

- Annual expected benefits/cost (exceedance likelihood weighted) *or* benefit/cost of a small number of specific events
- Temporal-spatial aggregation
  - Planning horizon
  - Discounting scheme/rate
  - Whether equal weighting applied across all areas of study region
- Whether aggregated across the types of values that are considered
- Whether insured losses are included
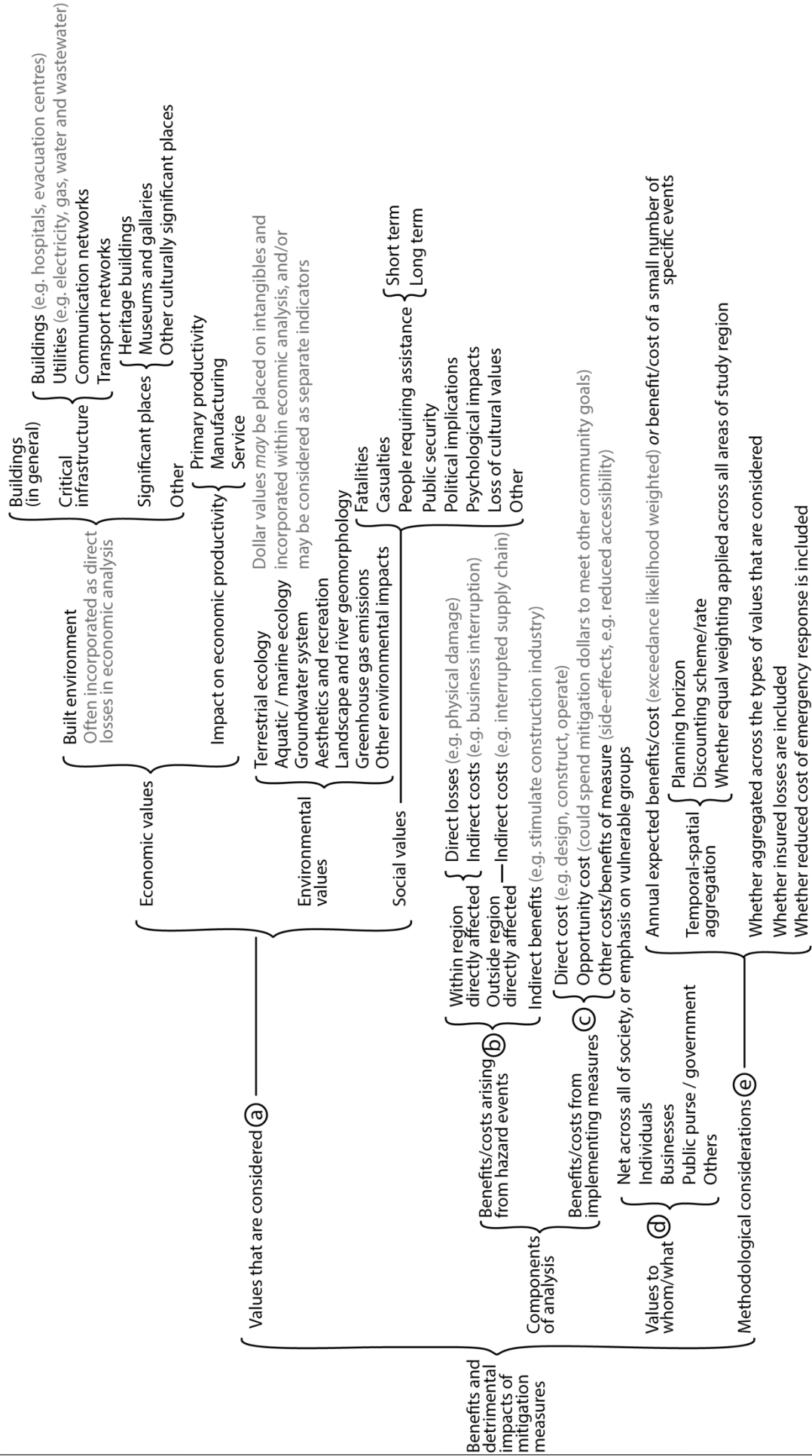- Whether reduced cost of emergency response is included

Fig. 4. A taxonomy of aspects that should be considered in the development of metrics that indicate the benefits and detrimental impacts of management options. Corresponds to part o of the overall framework presented in fig. 1.

2.2.3 QUANTIFYING DECISION MAKER CONSTRAINTS

Constraints as identified during the high-level scoping also need to be formulated as quantifiable criteria. In particular, as mentioned above, governments may assign budgets for management over a number of years; or a budget ceiling may be assumed based on the perceived willingness of governments to invest in mitigation. Apart from this, there may be legal, physical, social and environmental constraints (such as specified in legislation) which need to be considered in order for the optimisation approach to yield feasible portfolios. In formulating constraints, only hard constraints should be included, as soft constraints are better formulated as objectives.

2.3 SPECIFYING AN ANALYSIS FRAMEWORK FOR ASSESSING AND OPTIMISING MITIGATION OPTIONS IN TERMS OF THE OBJECTIVES AND CONSTRAINTS

Once the optimisation problem has been formulated through scoping, the approach for calculating the effect of management options in terms of the objectives and constraints needs to be specified. This is done through an integrated assessment modelling framework, wherein a model is constructed that simulates how management options perform over the long term and across a landscape. The model does this by considering all elements of risk in an integrated fashion, being the spatial and temporal distribution of: (1) the severity of the hazard itself, (2) the location and density of values-at-risk across the landscape that are potentially exposed to hazards, and (3) the response of these values to hazards and management activity in general. These three aspects — hazard, exposure and vulnerability, respectively — are the components of risk as conceptualised by the risk triangle (see Fig. 5 part a, b and c), and by integrating models for each of these components, a model-chain is developed that is capable of producing maps of risk and other metrics across the landscape and into the future (see Fig. 1 part p and q and Fig. 5 part d). A framework for the specification of this model chain is presented in Section 2.3.1. To drive the simulation, future projections of climate, population, economic conditions and other pertinent drivers of change need to be formed into scenarios (as shown in Fig. 1 part t), and this is described in Section 2.3.2. Finally, the method used for optimising management portfolios needs to be specified as shown in Fig. 1 part y. Guidance for this given in Section 2.3.3.

2.3.1 SPECIFYING AN INTEGRATED MODELLING FRAMEWORK FOR ASSESSING MANAGEMENT OPTIONS IN TERMS OF THE OBJECTIVES AND CONSTRAINTS

The model chain for the quantification of metrics being optimised is shown in Fig. 5. These metrics are calculated through the aggregation of indicators that reflect stakeholders' goals across space and time, as mentioned in Section 2.2.2. The spatially and temporally distributed indicators, themselves, are calculated through modelling the impact of a set of management options (Fig. 5 part e) and a set of hazard events (Fig. 5 part f). The impact of a hazard event within the framework is calculated through vulnerability models (Fig. 5 part p and ab/ac) that link the impact of hazard to (1) variables that describe the hazard (Fig. 5 part g, h, and i) and (2) the location, characteristics and density of values-at-risk (such as the building stock and populations) across a landscape (Fig. 5 part j, k, and l). In turn, hazard variables, as well as the distribution of values-at-risk across the landscape, are characterised using modelling components.

Fig. 5. The modelling chain for integrated assessment, to be specified during the development of the analysis framework as shown in fig. 1 part p and q.

2.3.1.1 MODELLING HAZARD

The purpose of hazard modelling is the development of maps showing the extent and severity of hazard (Fig. 5 part i), as influenced by a set of modelled management options (Fig. 5 part e) and key drivers and conditions (Fig. 5 part g). Many of these factors are non-stationary with strong dependencies between them and it is important to characterise these in the scenarios developed (as will be discussed in Section 2.3.1.1).

As previously mentioned, the hazard model simulates a number of hazard events, either using a Monte-Carlo approach as is often done for earthquake and bushfire modelling, or with associated exceedance probabilities as is often done for flood modelling (Fig. 5 part f). These events should be carefully chosen, such that the set of events has the ability to sufficiently characterise the overall nature of hazard in the region of interest.

There are interdependencies between hazards and the location and characteristics of values at risk that need to be included in the modelling chain (as represented by the link between parts h and k in Fig. 5). For example, when considering pluvial flood risk, the development of previously pervious areas into impervious (which occurs during urbanisation of rural or natural areas by the construction of civil infrastructure) not only increases the number of exposed values, but also is well known to increase flood risk due to changed hydrology (as the volume of overland flow increases according to the reduction in subsurface flow).

In terms of the modelling components required to generate the hazard maps (Fig. 5 part h), this itself usually requires a modelling chain comprising of models that describe the source of the hazard, and how it propagates through the landscape. Therefore, spatial modelling (1d, 2d or even 3d) of hazards will generally be required.

Using the developed model chain, each hazard event needs to be simulated at certain points into the long-term future, for the framework accounts for how risk changes over time, due to non-stationary processes.

2.3.1.2 MODELLING THE LOCATION, CHARACTERISTICS AND DENSITY OF VALUES

To track the location, movement and change in the characteristics of values in the landscape (Fig. 5 part l), temporally and spatially dynamic models are needed (Fig. 5 part k) that are able to simulate the effect of increased economic and urban development, as well as population growth (Fig. 5 part j). Therefore, demographic and economic projections will also be needed in the scenarios developed (see Section 2.3.1.2).

Just as hazard was dependent on the location and characteristics of urbanisation, the way in which urban areas expand is dependent on hazard (for people may not be inclined to place values within risky areas), and so this interdependency will also need to be included in the modelling (as represented by the link between parts h and k in Fig. 5). For example, land use plans and other government policies may well prevent further development within hazard zones.

A number of modelling approaches could be used for tracking the location, characteristics and density of values in a landscape, depending on what values-at-risk are being tracked over time. These approaches include the use of cellular automata land use models, agent-based models and Markov-Chain models.

Using this model chain, the iterative change in the spatial distributions of the values-at-risk is characterised across long-term planning periods. At time-steps where the hazard model chain is also run, geographic operations are used in the framework to identify which values are exposed to hazards (Fig. 5 part m and n).

2.3.1.3 MODELLING THE VULNERABILITY OF THE VALUES TO FLOOD HAZARD

As mentioned above, the purpose of the vulnerability models is to link the impact of hazards to variables that describe the nature of a hazard and the number and characteristics of the exposed values in the landscape. To do this, vulnerability functions are used (Fig. 5 part p). These vulnerability functions are simple mathematical expressions relating the impact that could be, on average, expected when the values-at-risk are exposed. These functions take into account key characteristics such as the spatial extent, severity, duration and frequency of hazard events (as given by the input (Fig. 5 part n) to the loss calculation (Fig. 5 part q). If the relationships given by these functions are non-stationary, then additional parameters quantifying the non-stationary aspects also need to be incorporated (Fig. 5 part o). More sophisticated modelling approaches can also be used (Fig. 5 part s) but would not be preferred unless there is a compelling reason for such additional level of detail.

The end result of the vulnerability modelling is the generation of maps of risk indicators at each time step that the hazard modelling chain is run at (Fig. 5 part r). From this, the metrics to be optimised are calculated through aggregation, as previously explained (Fig. 5 part t), thus concluding the risk modelling chain.

2.3.2 UNCERTAINTY AND SCENARIOS

As stated in the introduction, there are a number of uncertainties in natural hazard risk assessment that are significant enough to mean that optimal portfolios for risk reduction are indeterminate for the (unknown) future that will take place. Therefore, considering and addressing this uncertainty within the modelling chain is critical when attempting to optimise management portfolios.

The simulation framework proposed here accounts for uncertainty through two different approaches: Monte Carlo-type simulation of variables for which distributions of uncertain variables are known or assumed, and scenario analysis. Scenario analysis accounts primarily for epistemic Knightian uncertainties which are extremely difficult, or impossible, to characterise using probability distributions or for which it is extremely difficult or impossible to describe the processes leading to these uncertainties within an analytical/computational modelling framework.

Scenarios for risk management typically combine several trends across the sources of uncertainty to make a coherent and plausible storyline into the planning horizon used to test the effectiveness of management options across multiple future pathways. Subsequently, variables reflecting the trends within each scenario would be quantified and be used for parameter values and inputs within the modelling (as drivers of the hazard, exposure or vulnerability modelling, as described previously in Fig. 5 part g, j, and o). As an example, uncertainty regarding future climate, population, the density of residential development or defence failure pathways would often be incorporated using scenario analysis. For the first example, two future trends could be used to explore what would happen to flood risk if policies and/or cultural drift resulted in rapid high density or slower paced low-density development. Consequently, the set of scenarios span the range of conditions that we cannot describe using probability distributions, that risk management options will need to function under (1 part aa). When management options function well across all scenarios, they are said to be robust options.

For uncertainties that are quantifiable in the sense that they can be described by probability distributions, Monte Carlo-type simulations can be used. In these approaches, results from multiple simulations of the models with inputs/parameters strategically sampled from these probability distributions are pooled to characterise the model output uncertainty.

With regard to linking uncertainty analysis as incorporated within the simulation (as described above) with optimisation, different techniques are required for the two approaches.

For Monte Carlo-type approaches as described above, we recommend that distributions formed around the metrics are summarised using appropriate statistical measures (such as the mean and the use of one-sided variability measures taking into account upside and downside risk, such as the minimax ratio), and these be used as the objectives within the optimisation (instead of the metric values, themselves). In this case, uncertainty is characterised by the portfolio assessment process, as seen in Fig. 1 part aj.

For scenario-based approaches, a two-stage process is best. Initially, separate optimisation problems are solved for each scenario, forming optimally scheduled mitigation portfolios for each scenario. Then, these scheduled portfolios are analysed to elicit a compromise solution that best meets community goals. This is done by comparing optimal portfolios of mitigation measures across the scenarios, wherein measures that are included across the scenarios are regarded as more robust choices if they perform well across a number of alternative scenarios/futures. The benefit of using a two-stage approach is that this approach does not make a priori assumptions regarding the probability that a particular scenario ensues (this is consistent with the theoretic basis of scenario analysis), and is computationally more efficient, as uncertainty is characterised and accounted for after the application of simulation-optimisation as shown in Fig. 1 part aj

Not all sources of uncertainty need to be incorporated in the analysis; only those that have a significant bearing on the relative ranking of different mitigation portfolios. In other words, as the size of uncertainty will vary for different sources,

only those that dominate should be included. Sensitivity analysis (such as the Sobol method) can be used to identify what uncertainties to include.

2.3.3 OPTIMISATION TECHNIQUE

At this point in the approach, an optimisation problem has been formulated, in which mitigation options for consideration have been identified, together with their potential locations and design/implementation characteristics; and quantitative metrics that assess their performance and side-effects, and constraints that need to be met, have been specified, as well as an integrated modelling chain for their quantification.

Now, an optimisation technique is used to solve this problem. Multi-objective techniques are required for this. These solvers find multiple (as opposed to single) 'optimal' portfolios that cannot be said to be better or worse than each other. By way of explanation, consider Fig. 6, which shows the performance of various portfolios in regard to their cost of implementation (to be minimised) and their expected risk reduction (to be maximised). In this figure, design (a) cannot be said to be fundamentally better than design (b); while design (a) may have lower cost, it also has a higher residual risk. The portfolios that cannot be said to be better than each other (i.e. those shown in black) are called Pareto optimal designs. Multiple Pareto optimal designs form a Pareto front, and the aim of multi-objective optimisation methods is to find this Pareto front. Therefore, there is great utility in this approach for identifying optimal trade-offs in decision criteria.
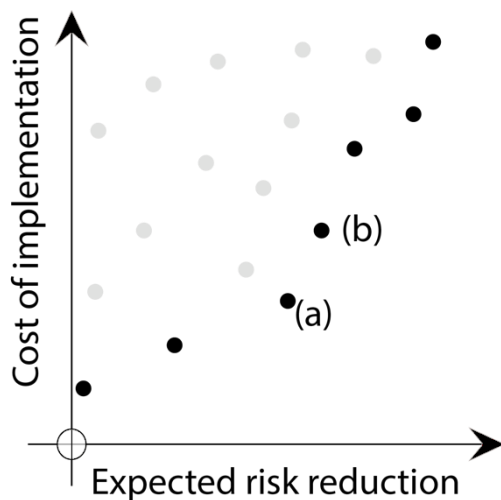

Fig. 6. A hypothetical pareto front showing how there are trade-offs in metrics across optimal portfolios in multidimensional objective space. Each marker plots the cost of implementation and the expected risk reduction of a candidate mitigation portfolio. The pareto front is given by the darker markers. The purpose of the optimisation as shown in fig. 7 part y is to characterise this pareto front.

When choosing an optimisation technique, the choice of solver needs to be robust with respect to the objectives, which will be characterised by nonlinearities, saliency and multimodality. The recommended choice of technique for solving the optimisation problems posed through following this framework, taking into account the above factors, is shown in Fig. 8, and needs to take into account the computational cost of evaluating the metrics using the integrated assessment model as well as the size of the decision space.

For formulations where there are few feasible mitigation options, it will be possible to evaluate every possible portfolio; in other words, a complete enumeration of all possible solutions to the optimisation problem will be possible (Fig. 8 part a). Once done, it is simple to rank the portfolios based on a Pareto sorting routine.

However, it will generally be impractical to assess all plausible portfolios because of the combined effect of the (1) computational burden associated with calculating the metrics and constraints, and (2) the large number of potential portfolios that need evaluating. In this case, formal optimisation routines should be used (Fig. 8 part b). The advantage of formal optimisation routines is that they search for best performing portfolios while only evaluating a subset of the entire decision space. Multi-objective, population-based metaheuristic routines, such as evolutionary algorithms, are suitable solvers for such optimisation problems.

In application to the mitigation planning framework proposed here, population-based metaheuristics iteratively improve mitigation portfolios through deriving information about what choices of mitigation options result in better-performing metrics through comparing metric values and mitigation choices across a set (population) of candidate portfolios (Fig. 1 part af). The means of deriving information about what mitigation measures work best with each other in this comparison is through applying a set of simple and very general heuristics (computationally efficient rules). The derived information on what mitigation options perform best is then used to generate another set of candidate portfolios that are likely to have superior metric values. By iteratively applying these heuristics, the quality of the portfolios within the generated sets improves as the optimisation process progresses. The key advantage of these optimisation approaches (solvers) is that they require no knowledge regarding the mathematical characteristics of the metrics or constraints, derive information about what mitigation options work best by only comparing the metric values obtained from the simulation, and simultaneously use information obtained from a population of solutions which span across proportions of the decision space, rather than from a single location only. This also means they are not easily trapped in local minima when the span of the population in the solution space is larger than the span of local minima, and also because heuristics that randomly perturb mitigation portfolios allow escape from local minima. Finally, they have been shown to be robust techniques used in a variety of problem domains, including some recent applications to flood management.

Despite the advantages of evolutionary algorithms, their use is potentially computationally expensive; while the heuristics used to drive their search are computationally efficient, these heuristics require information obtained from evaluating tens of thousands of alternative solutions/portfolios (i.e., sets of decision variable values, which in this case are portfolios of management options) before they converge on the Pareto front. Therefore, if the runtime of the simulation model that is used to evaluate portfolios is not sufficiently short, then the use of evolutionary algorithms may be computationally intractable within commonly used computational budgets. In this case, a range of options including metamodelling (including simplifying the underlying modelling), making use of expert knowledge to help direct the search, and parallel

processing are all available to make the approach tractable (Fig. $N#figure:optimisation> part c).
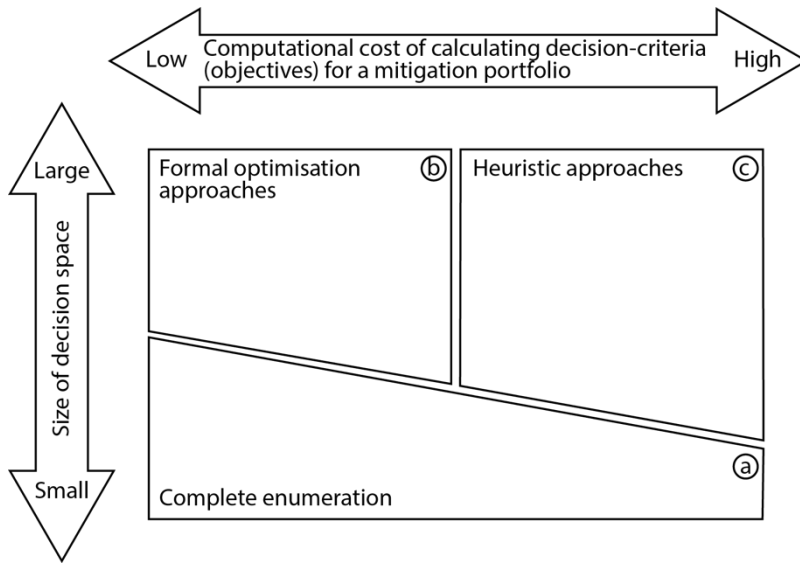

Fig. 8. Classification of optimisation approaches for use in the framework, based on the size of the decision space and the computational cost of evaluating the metrics that are optimised, to provide guidance for selection as shown in part y of fig. 1.

2.4 POST OPTIMISATION ANALYSIS

Once optimisation has been applied, a number of candidate portfolios of management options have been constructed that display optimal trade-offs in the decision criteria (Fig. 1 part ad). Now, the best performing portfolios can be presented to stakeholders and decision makers for additional evaluation, ideally through participatory activities (Fig. 1 part ai). In this way, the results of the analysis are used as a vehicle for discussion and social learning, rather than seen as the solution itself. To enable this, visualisation techniques are critical and may include interaction with the simulation model through graphical user interfaces (Fig. 1 part ae). Interface design would ideally allow users to both overview the analysis and also dynamically zoom into particular details of the solution and decision spaces, in ways that tracked the discussion, or indeed in ways that focussed and moved the discussion forward. To this end, the ability to refine and test mitigation portfolios, potentially during a model run, within group discussions would also be beneficial.

The discussion serves two purposes. First, it identifies missing objectives, mitigation options or constraints (Fig. 1 part ag). These are elucidated as stakeholders (1) realise they do not have all the information they would like to, in order to properly assess the benefits and consequences of particular portfolios, (2) reject particular portfolios due to their infeasibility/undesirable characteristics, or (3) come up with novel management solutions as they better understand the problem. This then serves to refine the scope, and additional time and funding may be decided upon to improve the analysis to better tailor it to the planning process. Second, the discussion adds a richness of information to help decision makers select what (if any) portfolios to include in strategic management plans (Fig. 1 part ah).

The particular techniques used for the post-optimisation analysis mirror those used during the scoping. Citizen juries should be used to rank portfolios of options, potentially using pair-wise ranking techniques, given the potentially large number of alternative portfolios that are developed by the optimisation. In addition, brain storming the benefits and consequences of portfolios not captured in the metrics could be used to identify gaps in the problem formulation, as well as participatory modelling and refinement of the management portfolios identified. These same techniques could also be used amongst the stakeholders. In addition, multi-criteria decision analysis, with weights for each optimisation metric elucidated from the citizen juries in the scoping phase, would help decision makers select the best trade-offs between community goals. Furthermore, as stated in Section 2.2, power for decision making will likely be shared, leading to conflicts regarding what mitigation options should be prioritised, and therefore polycentric governance techniques would also be appropriate here. Such techniques build up a rich body of transparent knowledge which then aids decision makers in the selection and implementation of mitigation options for the development of risk reduction plans.

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3 APPLYING THE SIMULATION-OPTIMISATION APPROACH TO A CASE STUDY WITHIN THE GREATER ADELAIDE REGION

In this section, we report on the application of the framework to a case study. We do this to demonstrate the utility of the proposed simulation-optimisation approach. Specifically, we will report on the technical aspects of the application, in particular the modelling and optimisation. The integration of the modelling and optimisation within broader planning processes is reported elsewhere as part of this BNHCRC research project, as given in Table 2.

The region to which the framework was applied is Greater Adelaide, South Australia, as shown in Fig. 9. While there are a number of significant natural hazards that threaten this region, the case study here is limited to coastal flooding to demonstrate the approach. There are no limitations that would prevent it, however, from being applied to other hazards or across several hazards, although this would likely increase its computational cost.

Greater Adelaide has significant coastal flooding risk, which is expected to increase, if left unmitigated, into the future. Historically, coastal flooding has occurred multiple times across the coast, which has resulted in severe and widespread damage (see for example photographs of flooding from 1919, 1923 and 2016 in Fig. 10). In recent years, coastal surge during storm events have threatened the coastline, with the May 9 event in 2016 causing the Port River to spill over its banks with inundation stretching two blocks from the River. In particular, the North-Western end of the coastline is the most susceptible to coastal flooding, and the combined effect of land subsidence and sea level rise is more pronounced in the North-West also. In the study region, land subsidence is known to be occurring at a rate of approximately 2.1 mm/year and sea level could plausibly rise by 800 mm over the next century.

Fig. 9 the modelling domain of the case study application of the proposed framework, in grey, representing the greater adelaide region

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Fig. 10 photograph of flooding caused by coastal inundation at port adelaide, c. 1919 and 1922 and may 9 2016, respectively. Image sources: searcy collection at the state library of south australia (https://collections.slsa.sa.gov.au/resource/prg+280/1/9/397, https://collections.slsa.sa.gov.au/resource/prg+280/1/39/481) and port adelaide environment and heritage wiki (http://www.portadelaidewiki.org.au/index.php/file:birkenhead_street_flooding_1,_2016.jpg)

3.1 PROBLEM SCOPING

As mentioned in the framework chapter of this report, the aim of problem scoping is to identify potential mitigation options, community goals, constraints and key drivers of risk, which are necessary for formulating an optimisation problem and the development of an IAM for use in solving it. These factors were elucidated through workshop activities as part of this BNHCRC project, as well as through meetings with key State Government personnel working in the coastal and natural hazard space. As mentioned, the outcomes of these participatory approaches for the Greater Adelaide case study are reported elsewhere, as given in Table 2; here, the outcomes of this process in terms of the specific constraints and mitigation options that were chosen is reported on.

The remainder of this section is structured according to the proposed framework. As such, we first report on the high level scoping, and subsequently on the low level scoping.

Table 2 Reports relating to the participatory approach taken to developing and using an IAM for natural hazard management across Greater Adelaide, which has influenced the formulation of the optimisation problem solved here.

Report	Description
"Natural Hazard Mitigation Decision Support System Framework Report" (van Delden et al., 2015)	Framework report detailing the development and use of decision support systems for natural hazard risk reduction
" Futures Greater Adelaide 2050: An exploration of disaster risk and the future" (Riddell et al., 2017)	Report on future scenarios developed for Greater Adelaide for the purpose of natural hazard risk management and planning
"Enhancing the policy relevance of exploratory scenarios: Generic approach and application to disaster risk reduction" (Riddell et al., 2018)	A paper on how to pose the scenario development problem for natural hazard risk management and planning
"Greater Adelaide Multi-hazard Mitigation Planning : Stakeholder problem formulation" (Riddell et al, 2017)	Report on risk reduction context detailing the enduser engagement process used and the objectives and management options of interest to endusers

3.1.1 HIGH-LEVEL SCOPING

The purpose of the high-level scoping is to identify the general types of management options, constraints and drivers of change. As mentioned above, these were elucidated through participatory processes with natural hazard risk experts involved in this project. Through this process, the management options identified as plausible within the region included zonal policy, building codes, and sea wall defences, although the analysis here is limited to zonal policy, as this was a management option of significant interest to end users. With regard to objectives, much analysis in South Australia is currently limited to direct losses from building stock, and this was adopted here also. Finally, key drivers of change that were identified for coastal flooding risk in Greater Adelaide are changes in the state of the economy, development patterns (which was identified to be affected by culture, policy, technology and population growth), as well as sea level rise.

3.1.2 LOW LEVEL SCOPING

The purpose of low level scoping is synthesising the high level scoping into a single problem formulation by specifying the general mathematical and computational template for quantifying the objectives and constraints and using this to consider the requirements of the modelling chain. The outcomes of the low-level scoping are reported in this section.

3.1.2.1 MANAGEMENT OPTION CONSIDERED — ZONAL POLICY

The management option that this case study investigated was zonal policy. A key goal amongst end users in the workshops was steering the geographical growth of Greater Adelaide toward low risk areas. Given that the Northern Adelaide plains along the coastline are low-lying and therefore susceptible to coastal flooding, and are not yet urbanised but have been earmarked for further residential development, does mean that good zonal policy in this region may be critical for good risk management. In addition, the 2015 Productivity Commission Report into Natural Hazard Risk endorsed the consideration of land use planning for natural hazard management, finding that it is "perhaps the most potent policy lever for influencing the level of future natural disaster risk" (Australian Government Productivity Commission, 2015).

In particular, the management option considered is a zonal exclusion policy that prevents the urbanisation of land. That is, the exclusion policy prevents the development of residential, commercial, and industrial areas, or public institutions (including schooling), within the policy region.

The decision variables related to this option (that is, the supplementary decision variables, using the terminology introduced in the framework) are which subregions of Greater Adelaide will be included in the zonal policy. In more detail, the optimisation builds up the region wherein the zonal policy operates by selecting from a number of subregions for inclusion within the policy. The subregions to select from were delineated from within the region affected by the 1% annual exceedance probability (AEP) flood (as projected in 2050 under the RCP 8.5 scenario, which is presenting in Section 3.2.1.1 and Fig. 14), based on hazard contours for the 1% AEP flood as well as local government area boundaries. In total, 204 subregions were delineated by this process, as shown

in Fig. 11, creating a decision space characterised by 2.6 × 1061 different zonal exclusion policies that needed sifting through.

The zonal exclusion region optimised in this study is not modelled to forcefully remove development that may already exist in each of the subregions included. That is, it is not a policy for the buy-back of land. Rather, it prevents further development. For example, if a residential land use occurs within a subregion included in the policy, this residential land use is permitted to continue. However, conversion to a commercial or industrial land use is not permitted. Saying that, conversion to a natural or recreational land use is permitted, as the coastal flood risk that results from these land uses tend to be lower; but this conversion is not forced as in a buy-back scheme, but rather is an organic movement away from more vulnerable land use types in specific locations, as these locations become less desirable or suitable, or other locations become more desirable or suitable due to changes in the makeup of the urban landscape over time.
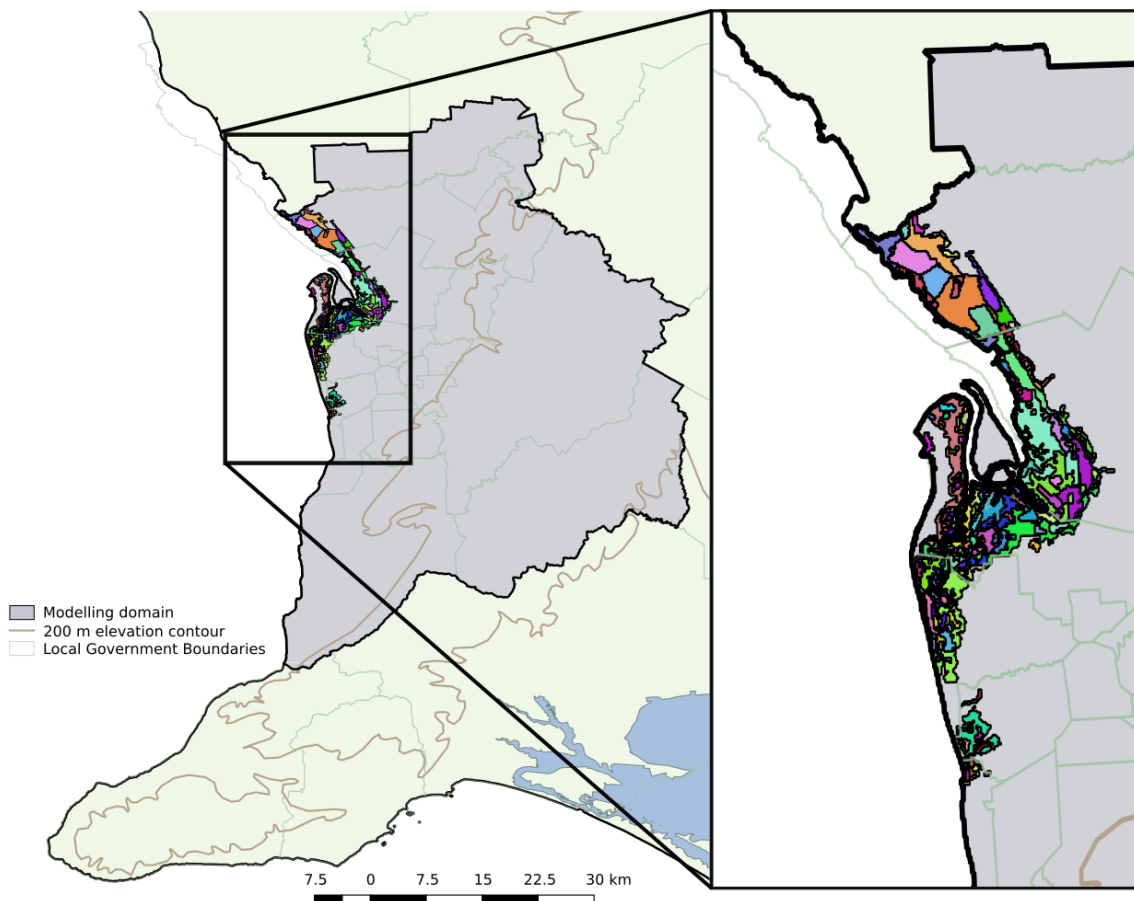
Fig. 11. Zonal subregions included in the analysis from which the optimisation builds a zonal exclusion layer.

3.1.2.2 CRITERIA TO ASSESS THE PERFORMANCE OF MANAGEMENT OPTIONS

As stated in the framework, in applying optimisation to build mitigation portfolios, quantifiable criteria that measure the performance of mitigation need to be developed; and these criteria should reflect the goals and outcomes desired by communities impacted by coastal flooding and the

proposed potential management activity. The optimisation uses the sets of criteria developed in order to compare and rank different portfolios of management options against each other, so that it can direct the search toward good combinations of management options.

The criteria used in this study were developed based on end-user input through a series of workshops. In the workshops, end-users developed a vision for the management of natural hazard risk. End-users envisaged management that supported communities that were relationally interconnected and characterised by equity, that were also safe, healthy, prosperous, and in good harmony with the environment. Therefore, the goal of coastal surge management includes risk minimisation, but in a way that fosters community resilience and environmental protection, and that allows for, or potentially stimulates, economic growth.

Based on the end user input, above, the criteria that were developed for the optimisation included:

Direct losses to building stock

The direct losses to building stock due to inundation was included as a minimisation objective. This criterion is included as based on an annual expected loss, or in other words, what the long-term average loss on an annual basis would be.

The average annual loss (AAL) is estimated in this study from a number of flood events with different exceedance probability, in order to reflect the range of flood events and damages that could occur. These flood events, and the associated losses that are estimated for them, are used to generate a damage-probability curve, as shown in Figure 12, from which the AAL is calculated as the area under the curve using numerical integration (The Trapezoidal method was used in this study).
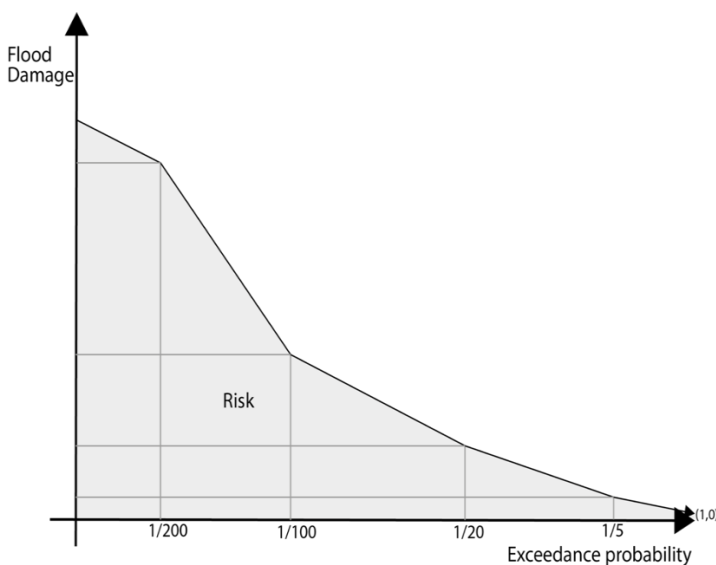

Fig 12. Damage-probability curve for calculating risk

The cost of coastal surge management

The net costs of implementing management options across the entire community (public and private) was included as a minimisation objective. In this case study, this was limited to the costs of the zonal exclusion policy.

There are a number of costs involved with zonal policy. To government, there is the cost of specifying and enacting the policy, as well as managing/enforcing the policy. There is also a very significant opportunity cost to the public, in that restriction means that land that could be put to a more valuable use may not be allowed, and in its place, a lower valued land use occurs. Costings for these are difficult to obtain, but it would be expected to be proportional to the size of the zonal restriction policy. Therefore, in this study, we use this area as an indicator of cost. This indicator is calculated as the sum of the areas of the subregions which were chosen for inclusion within the restriction zone.

At this point in the problem scoping, we have defined the objectives — minimising the cost of zonal policy and minimising direct losses to buildings. These were minimised through optimising what subregions are included within a zonal exclusion policy. Therefore, the unit of the risk assessment is the individual building, and consequently the modelling chain needs to identify how many buildings are exposed to flood events of different AEPs. In addition, the modelling chain needs to be dynamic in order to account for key drivers of change. As mentioned earlier, these were identified by end users as changes in the state of the economy, development patterns, as well as sea level rise. Sea level rise was included as a driver of inundation depth for the flood events included in the assessment, while the state of the economy and development patterns were accounted for through inputs into an integrated land use-building stock modelling chain that accounted for exposure. Details on the modelling chain is now presented in the following section.

3.2 SPECIFICATION OF THE ANALYSIS FRAMEWORK

As specified in the framework, the analysis requires an integrated hazard, exposure and vulnerability modelling chain that can simulate the effect of the management options and from which the objectives can be calculated, as well as an optimisation routine. In this section, these modelling components are specified.

3.2.1 SPECIFICATION OF AN INTEGRATED HAZARD, EXPOSURE AND VULNERABILITY MODEL

With regard to the simulation, the Unified Natural Hazard and Risk Mitigation Exploratory Decision Support System (UNHaRMED) was used, which is a decision support shell that contains an IAM suitable for this study.   The purpose of this report is not to specify the UNHaRMED in full, as this can be found elsewhere (See Table 2). Rather, the modelling chain directly involved in the calculation of the objectives is described. With regard to this modelling chain, a planar surface model outputting an inundation depth was used for coastal hazard, a coupled land use and building stock model outputting the number of different building types occupying land was used for exposure modelling, and

damage curves for different building types outputting the expected loss were used for vulnerability.

3.2.1.1 HAZARD MODELLING USING A PLANAR SURFACE INUNDATION MODEL

A planar surface inundation model was used to map the location and depth of inundation across the Greater Adelaide coast, based primarily on the topography of the land surface at the coast, the expected tidal and coastal surge heights and also the extent of sea-level-rise. This modelling approach was chosen for its computational expediency as well as being a commonly used method in Australia for characterising coastal inundation across large geographical regions.

Conceptually, inundation depth and extent are calculated in this model based on an analogy of a 'bathtub'. This model calculates flooding by applying a planer water surface across the topography based on surge height. In other words, it identifies all raster cells with elevations lower than the specified surge elevation that are adjacent to the ocean or to other inundated cells. The model does this iteratively as the coastal surge propagates landward, as shown in Fig. 13.
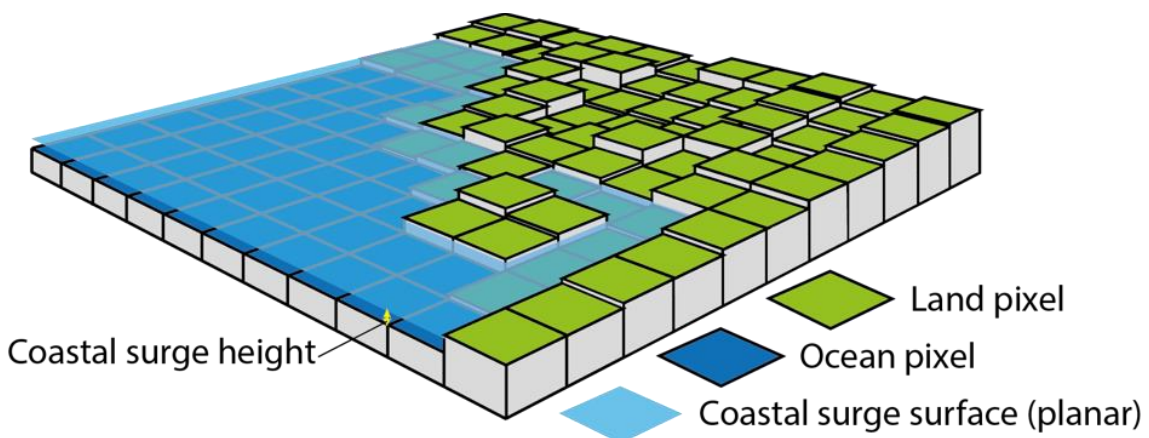

Fig. 13 coastal flood modelling concept based on a planar surface, or bathtub process.

In order to represent the topography of the Adelaide coastline, two digital elevation models were merged. First, a Lidar-derived 1m horizontal resolution DEM was obtained from Geoscience Australia as part of a nationwide elevation survey of coastlines with relatively higher population densities. The vertical accuracy of this dataset is at least 0.3m. This was the preferred source of elevation where available. Second, a hydrologically enforced digital elevation model derived from the Shuttle Radar Topography Mission (SRTM) data was used. This dataset has a horizontal resolution of approximately 30m, and has been processed by Geoscience Australia to impose drainage lines and elevation smoothing using the ANUDEM interpolation software. In merging the datasets, the SRTM data were interpolated to a 3m horizontal resolution; likewise, the Lidar data were aggregated to a 3m resolution on a consistent grid using a neighbourhood mean approach.

The coastal surge heights that were mapped using the planar surface model were derived by Flinders University (of South Australia) for the Port Adelaide

Seawater Stormwater Flooding study (Tonkin Consulting, 2005), as given in Table 3. These surge heights were calculated from historical analysis.

AEP	Surge height (m AHD)
1%	2.325
2%	2.248
5%	2.138
9.5%	2.047
18.1%	1.948
39.4%	1.787

Table 3 annual exceedance probability for surge height exceedance

In addition, an allowance of 0.4m was made to account for wave setup and wave run-up, which is consistent with that used by the South Australian Coastal Protection Board.

Furthermore, to account for climate change, the following increase in mean sea level were applied to the surge heights, based on the outputs of the Climate Change in Australia project (CSIRO and Bureau of Meteorology, 2015). These increases, which were applied as a delta-change, are given in Table 4.

Year	Surge height (m AHD)	
	RCP4.5	RCP8.5
2015	0.053	0.057
2031	0.13	0.14
2047	0.22	0.26

Table 3 annual exceedance probability for surge height exceedance

Using this process, inundation maps were developed, as illustrated in Fig. 14 for an indicative 1% AEP flood event across the Adelaide coastline.
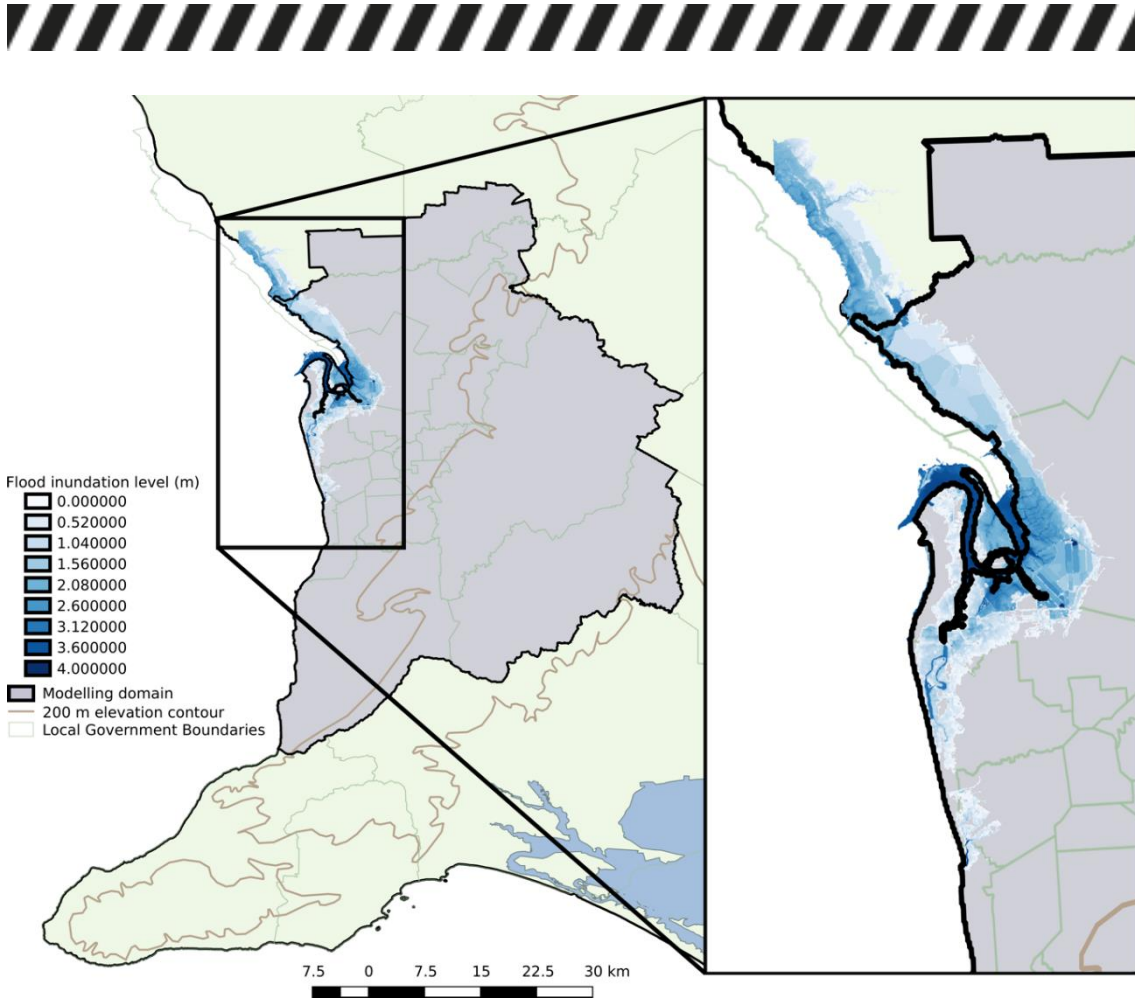
Fig. 14. Indicative flood inundation extent and depth calculated using the planar-surface model at the 1% aep level in 2047, based on an rcp 8.5 scenario

3.2.1.2 EXPOSURE MODELLING USING A COUPLED LAND USE AND BUILDING STOCK MODEL

To account for the number of buildings that are potentially exposed to flooding, a coupled land use and building stock model were used. For land use, a cellular automata approach was used to simulate where residential, commercial, and industrial and other functions were likely to occur through time, while the building stock model allocated the number of buildings existing across the modelling domain for a number of residential, commercial and industrial building types. This allocation was based on the land use existing at a location, as well as building stock renewal rates, which also took into account population growth.

3.2.1.2.1 SPECIFICATION OF THE LAND USE MODEL

To simulate land use change, the Metronamica model was used. Metronamica was chosen as it has a strong track-record across the globe in helping explore and social, economic and environmental systems, in order to develop informed management actions and policies. For example, it has been used to develop long-term natural resource management plans in New Zealand (Rutledge et al., 2008), impact assessments of agricultural policies (OXLEY et al., 2004) and river basin management (de Kok et al., 2008; van Delden et al., 2007) in Europe and improved cultivation practises in Sri Lanka (Wickramasuriya et al., 2009).

As previously mentioned, Metronamica is a cellular automata land use change model that dynamically simulates how land use changes over time (van Delden and Hurkens, 2011). The cellular automata represent the urban fabric as a raster map of land use, whereby each raster cell is assigned a land use type, such as commercial, industrial, residential, agriculture, forestry, vegetation, green space, etc. At each timestep in the model, the cellular automata attempt to satisfy the demand for land for each land use type. As illustrated in Fig 15, this allocation is performed by calculating a transition potential metric. This metric indicates the likelihood for a certain land use type to exist at a location based on the locations' accessibility, suitability, land use zoning and what other land uses are occurring in the vicinity.
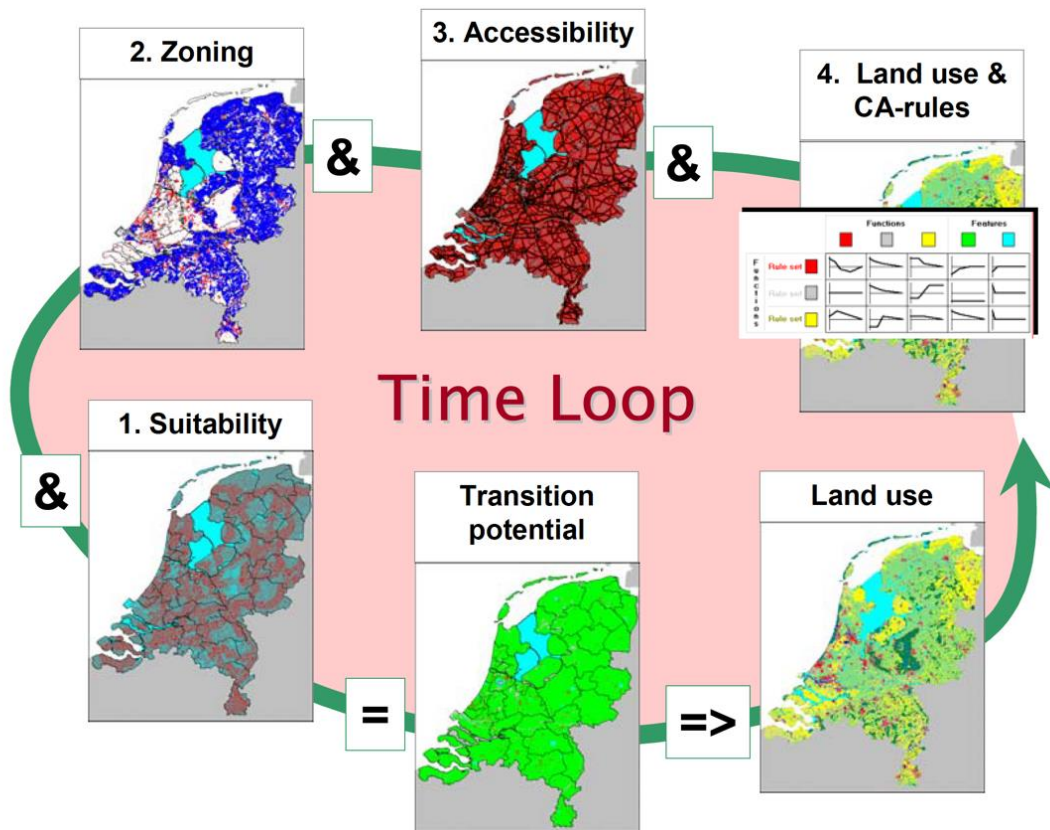
Fig. 15. Illustration of how land use is allocated according to a transition potential metric, which itself is allocated based on land use and ca-rules related to land uses in the vicinity of a location, as well as accessibility, zoning and suitability maps.

For this case study, the land use model was calibrated on a 100m raster to run on a two-year time step, in that land use was dynamically recalculated every two years between 2015 and 2047. The modelled scenario was based on a moderate increase in population and economic development, with land use development patterns consistent with historical patterns. The demand for various types of land uses, which quantitatively defines this scenario, are given in Fig 16.
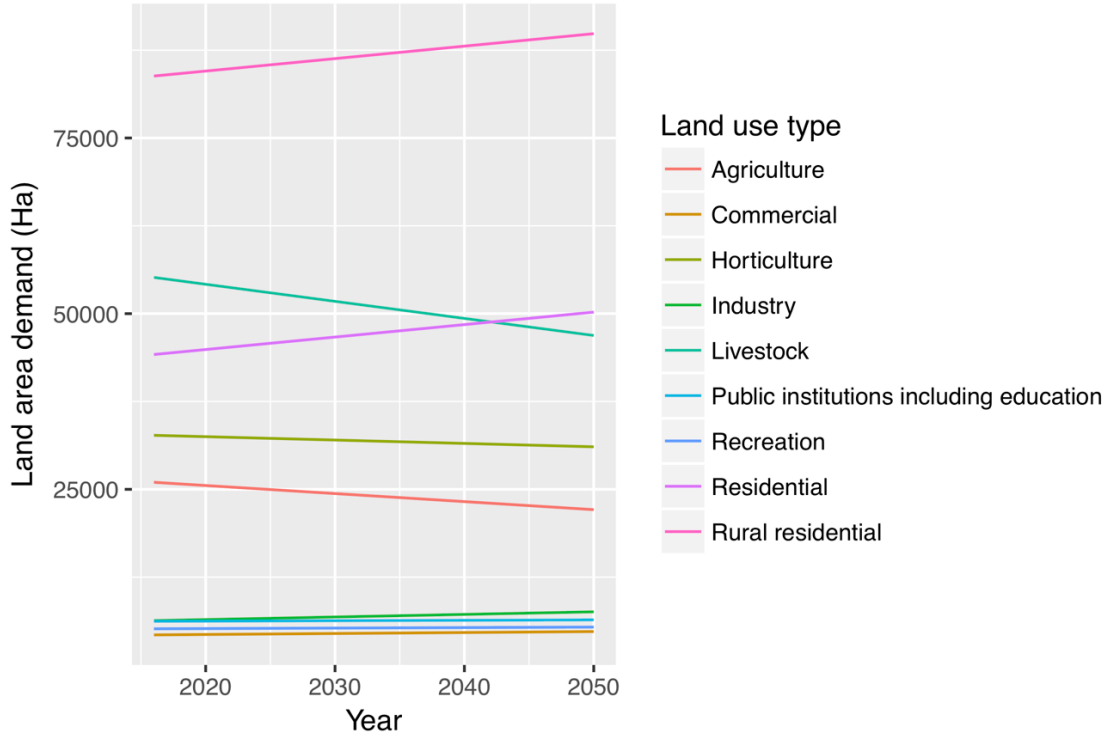
Fig. 16. Demands for land use, based on economic and social trajectories for greater adelaide, used for the modelling in this report.

Land use maps across the modelled land use classes can be seen within the user interface of UNHaRMED in Fig. 17, assuming no management options were implemented.
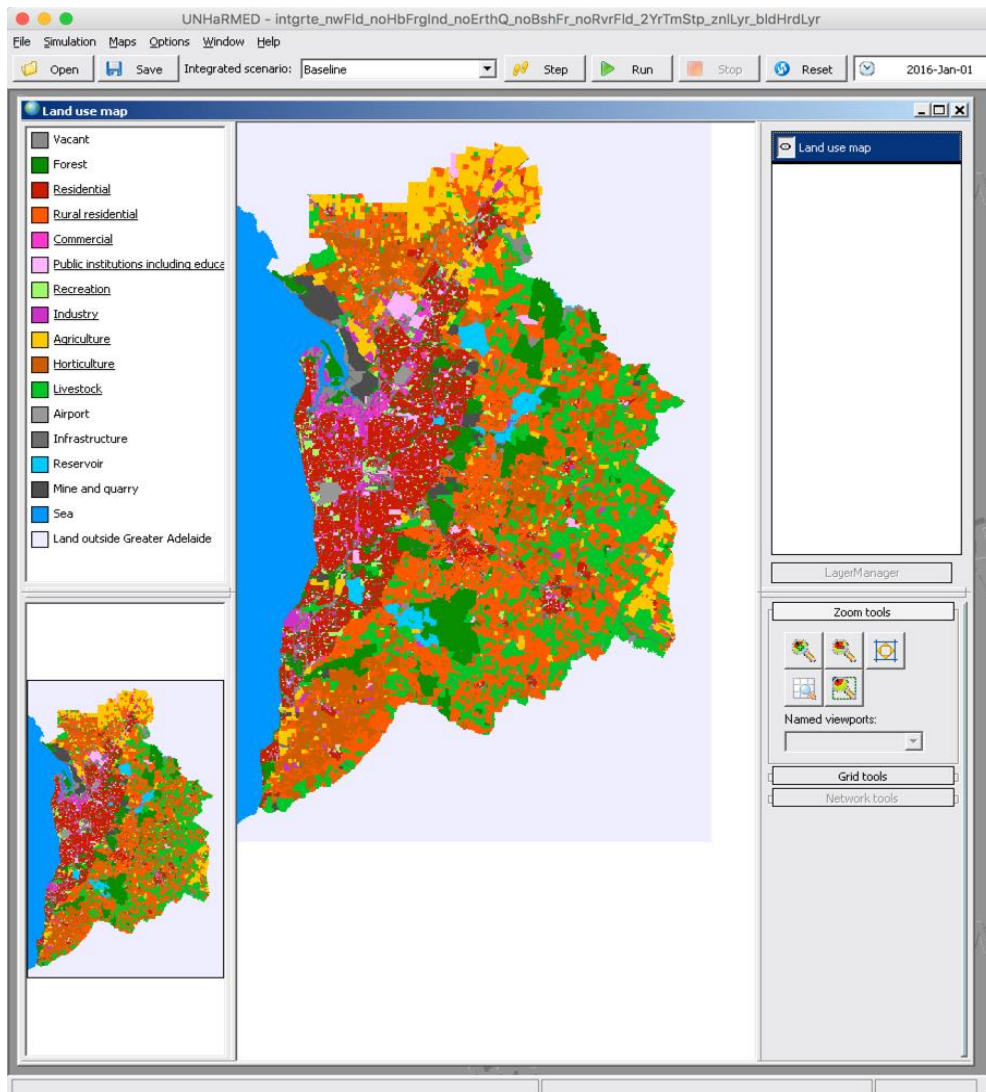
Fig. 17. Land use allocation map developed by the metronamica model, a component of the unharmed dss.

3.2.1.2.2 SPECIFICATION OF THE BUILDING STOCK MODEL

As mentioned previously, the building stock model provides information regarding the mix of construction types and associated asset values.

The building stock model works on the level of local government areas (LGAs), and disaggregates the information it produces across the 100 m grid on which the land use model runs. For each LGA, initial building stock is derived from the National Exposure Information System (NEXIS), and the simulated change in building stock is based on a two-step process. First, the amount of renewal, that is the number of buildings that are demolished in each timestep, is calculated based on renewal rate parameters. These buildings are then assumed to be rebuilt. The type of building that is rebuilt is based on a ratio as given by model parameters. The natural growth in the number of buildings (which is occurring in Adelaide, for example, from population growth and changing demographics), is simulated by using ratios of new buildings being built having a sum greater than 1 from across the building types.

Building stock changes are also simulated to occur when land use transitions occur. In this case, the building stock in the transitioned raster cell is based on the average building density for each building type in the LGA in which the cell is situated.

3.2.1.3 VULNERABILITY MODELLING USING DAMAGE CURVES

At this stage of the modelling chain, we have inundation depth data as well building stock data. These data are spatially distributed across the modelling domain such that for each cell in the raster the number of buildings of each building type is known, as well as the inundation depth to which it is exposed. Now, these data are used to calculate damage to the building stock.

To calculate the damage sustained to each building type, damage curves were used which relate a damage index (percentage of building value lost) to inundation depth. Consequently, net damage to building stock for a particular building type is the damage index multiplied by the net value of the building stock for this building type. The net building value at stake was derived from the NEXIS database (Australia's National Exposure Information System), and a set of 6 damage curves was used across 31 building types, as given in Appendix B.

In order to calculate the direct losses as specified in Section ??, the inundation depth that was computed from the planar-surface model (Section 3.2.1.1) at a 3m horizontal resolution was aggregated to a 100m grid aligned to the land use and building stock information coming from the exposure modelling chain. From this, damage was calculated, according to the description above. Consequently, damage was calculated individually for each raster cell. The AAL is then calculated across the flood events according the description in Section ??, and aggregated across the entire modelling domain by summing the damages spatially and at three points of time — 2016, 2032, and 2048. Future damages were adjusted to their present value in 2016 using a discount rate of 6%, which is consistent with that used by Government for planning purposes in South Australia. At the end of this process, a three-time-step discounted annual average loss has been calculated.
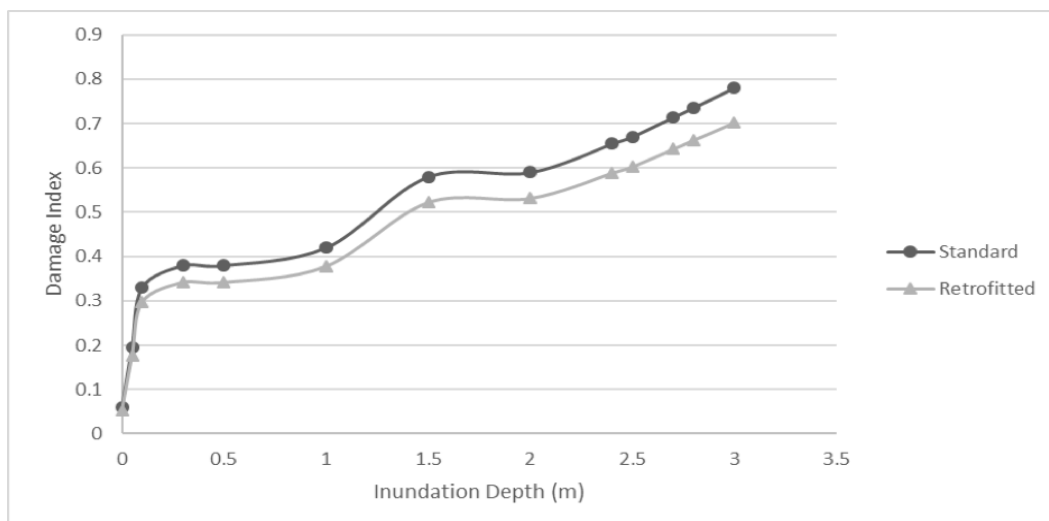

Fig. 18. Example of vulnerability curves.

3.2.2 OPTIMISATION USING EVOLUTIONARY ALGORITHMS

The purpose of the optimisation is to screen through and identify which portfolios of management options result in optimal trade-offs between the objectives. For this purpose, the Non-dominated Sorting Genetic Algorithm II (NSGAII) was used in this case study (Deb, 2002). This is a population-based Multi-Objective Genetic Algorithm (MOGA) regarded as an industry standard (Wang et al., 2015).

MOGAs repeatedly use simple heuristics (computationally efficient rules) across a number of 'generations', to derive information about which management options result in better objective values, and use this information to generate the next (child) generation of portfolios, some of which are likely to have superior objective values. The heuristics mimic those of 'survival of the fittest,' and are referred to as selection, cross-over and mutation.

Selection is used to promote better performing management options within the portfolios constructed in subsequent generations, by comparing different portfolios and selecting, by some mechanism, those which perform better. Cross-over takes a subset of management options from a pair of portfolios and randomly recombines them to form new portfolios. The purpose is to select management options that have been shown to perform well, and to trial them in different combinations. This is because better performing management options, when combined differently, may result in "children" with superior objective values. Mutation makes small, random changes to a portfolio, the purpose of which is to diversify the search to explore a wider possible range of management options, which might lead to superior objective values.

The specific MOGA operators employed by the NSGA-II, as well as the additional features that distinguish it from other MOGAs, are illustrated in Fig 19. As shown, NSGA-II begins with an initialisation step, where an initial population of solutions with randomly generated decision variable values is created. The associated objective function values are then calculated. Next, the standard genetic operators previously discussed (selection, cross-over, mutation) are used to generate a child population from the existing parent population. This implementation of NSGA-II uses tournament selection, one-point crossover, and uniform mutation, according to the specification originally proposed by Deb et al. (2002), because the optimisation problem solved in this case study uses integer-value decision variables (there is a discrete choice between inclusion or exclusion within the zonal policy for each of the subregions).
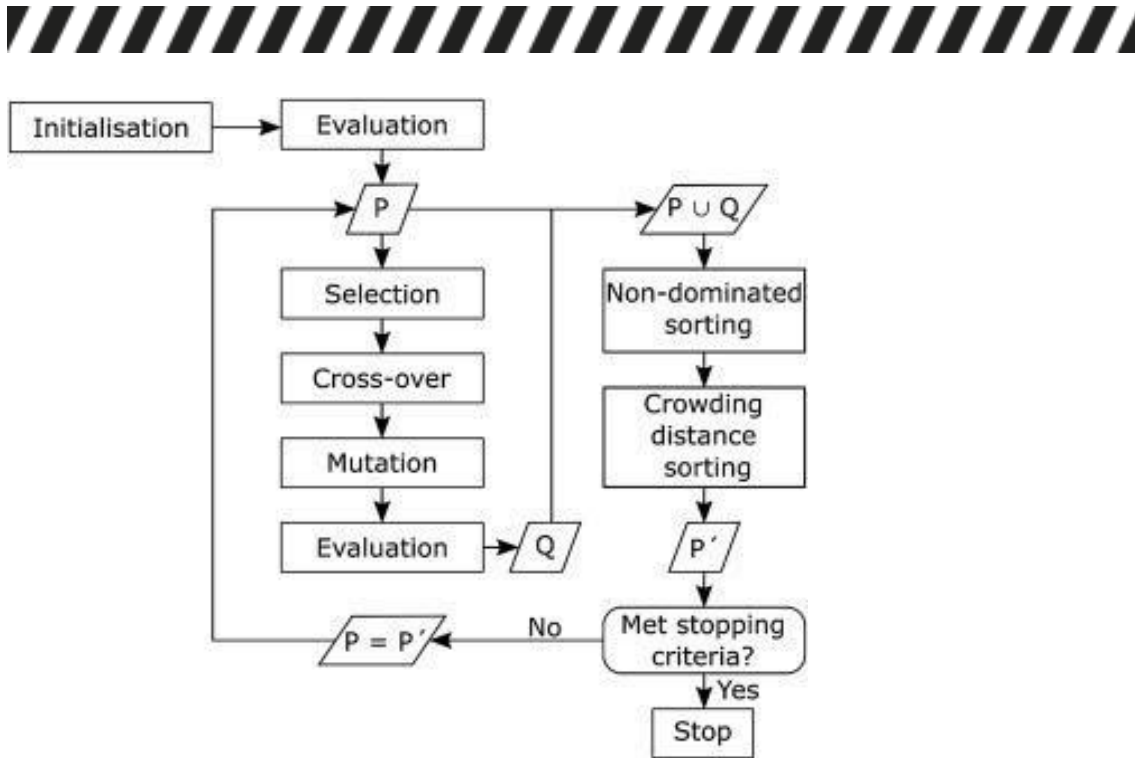
Fig 19 optimisation process performed by nsga-ii, the parent population (p) is modified to generate a child population (q), which is then recombined and modified further to produce the parent population (p') of the next generation.

The key performance advantage of using NSGA-II is achieved via the additional operators implemented in the algorithm, which preserve non-dominated (i.e. the best performing) solutions from generation to generation. As shown in Fig. 19, NSGA-II recombines the parent (P) and child (Q) populations, and ranks the combined population in order of non-dominated fronts that occur, which are a series of Pareto fronts. From this, a new parent population (P') is formed, by iteratively selecting the solutions belonging to the best fronts. If only a subset of solutions from a front can be included, crowding distance sorting is used, which aims to select the most diverse set of solutions from the final front that is included. This process is repeated until the stopping criteria are met.

Although it is generally recommended to fine tune the parameters controlling the searching behaviour of the optimisation algorithm, such as the population size, the probability of mutation and probability of cross-over, via sensitivity analysis before application, for large problems such as addressed here, this is extremely computationally expensive and therefore impractical (Wang et al., 2015). Therefore, recommended NSGA-II parameter values are adopted (Newland et al., 2018; Wang et al., 2015; Zheng et al., 2016), namely a probability of crossover of 0.9 and a probability of mutation equalling the inverse of the number of decision variables. The selection of population size, which corresponds to how many chromosomes would be included per generation, is also informed by the work of Wang et al. (2015) and Newland et al. (2018) into optimisation problems with many decision variables. Their results show that the population size for large problems must be greater than the number of problem decision variables to find non-dominated solutions. Hence, this research uses a population size of 209.

The stopping criterion, which determines when the search process is halted, is based on solution convergence, and reaching a certain number of generations. The required number of generations used is 500 (i.e. G = 500), after

which the hyper volume metric, which measures the size of the Pareto Front, did not improve significantly. Convergence implies that, for the given optimisation algorithm configuration, negligible improvement is obtained in the objective values with continued optimisation. There are numerous metrics for measuring convergence (Maier et al., 2014). This research uses the hyper-volume metric (Zitzler, 1999), a commonly employed metric of multi-objective performance (Hadka and Reed, 2012; Reed et al., 2013) that captures convergence and diversity of the objective space.

For the proposed case-study, running UNHaRMED on an Intel Core i7-3770 through the 'wine' emulator took 145 seconds, while post processing UNHaRMED output to calculate objective values (the criteria) took 1 second. Extrapolating this out to a complete optimisation run, the total computational time would be approximately $P \times G \times R = 209 \times 500 \times 146 = 177$ days. Hence, to make the optimisation process feasible from a practical perspective, a parallelised version of NSGA-II is implemented, to decrease the wall-time required to complete an optimisation run. This uses the Phoenix cluster, a high-performance computing facility operated by Research Services at the University of Adelaide. The separate optimisation runs are parallelised by distributing the evaluations, one for each member of the population, over 210 CPU processing cores across 35 computational nodes. For the Phoenix cluster, each computational node consists of 2 Xeon E5-2698v3, chipsets each containing 16 cores. To control the parallelisation, a master/slave model of computation is implemented, wherein 209 slave processes running on separate CPU cores are used in parallel to evaluate the objective functions for separate members of the population, and the 210th is the master process that coordinates the search and runs the recombination (that is the selection, crossover, mutation, non-dominated sorting and crowding distance operators). Parallelisation is achieved using the Message Passing Interface (MPI) using asynchronous communication to improve algorithm efficiency. Using MPI, the master process passes messages containing a set of decision variable values (a management portfolio) to each of the slaves. Upon receiving this message, the slave runs the UNHaRMED IAM through a command line interface, evaluates the decision criteria, and passes a message back to the master containing these values. Through this allocation, near linear speedup is achieved (as communication time is orders of magnitude lower than time taken to evaluate the calibration objectives) with the NSGA-II completing 500 generations within 48 h. Code, in C++, for this implementation of the NSGA-II is fully open sourced and available as per the details in Appendix A.

3.3 RESULTS

This section presents the results of applying the simulation-optimisation framework to the Greater Adelaide case study, and discusses these results in four parts. First, the Pareto-efficient zonal policies are presented, to understand the trade-offs between the amount of area excluded from further development and resultant risk reduction. Second, the spatial patterning of the zonal exclusion areas are presented, in order to understand where zonal exclusion is most effective along the Adelaide coast. Third, the spatial patterning of risk given the Pareto-efficient zonal exclusion areas are presented, to understand where risk and risk reduction occur along the Adelaide coast.

Finally, the way in which risk changes through time are presented, to discuss the importance of considering temporal change.

3.3.1 PARETO OPTIMAL ZONAL EXCLUSION POLICIES

The effectiveness of Pareto-optimal zonal policies with regard to coastal flooding risk and the area of the zonal exclusion needed to achieve this, are shown in Fig. 6 part i. In total, 209 Pareto optimal policies were developed by the optimisation, each corresponding to different combinations of subregions selected to be part of the exclusion zone. The identified optimal zonal policies ranged from those where there was no exclusion, marked (f) in Fig. 6 (wherein the annual average loss across the entire modelling domain was $3.32 billion AUD), to excluding further development across the entire region affected by the 1% AEP flood as marked by (a) in Fig. 6, (wherein the annual average loss across the entire modelling domain was $3.02 billion AUD). As solution (f) had no areas where development was excluded (or in other words, allowed development across the entire region affected by coastal flooding), this solution acts as a baseline against which to compare the effect of different zonal policies as identified by the optimisation across the Pareto front. Consequently, an indication of the potential for coastal exclusion policies for reducing flood risk can be determined through comparing the two solutions at the extremes of the Pareto front; that is, comparing the solution wherein further development was excluded across the entire 1% AEP flood zone to the baseline solution. Accordingly, these results indicate that exclusion zones could potentially reduce coastal flood risk in Greater Adelaide by up to 10% in 2048.
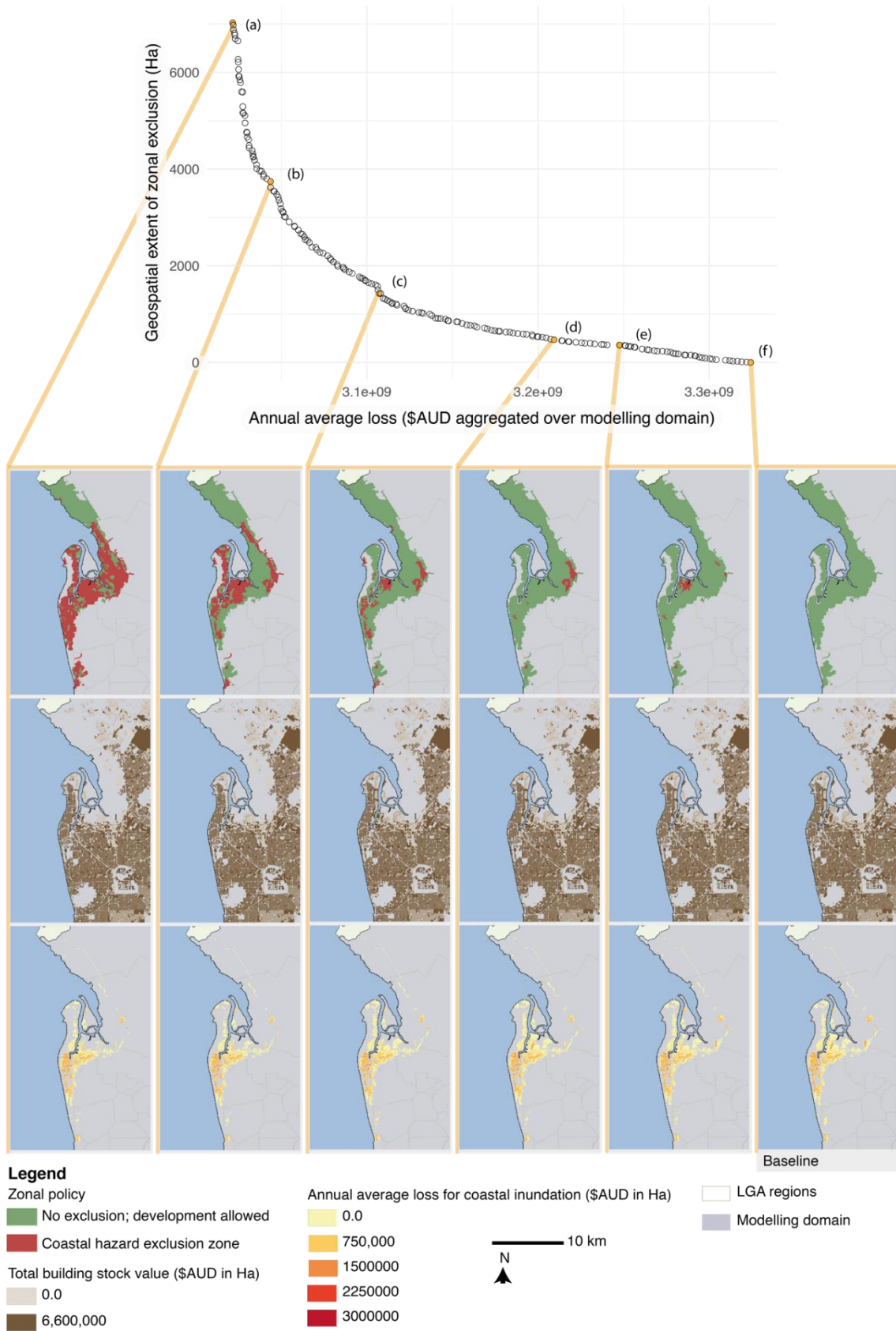
Fig. 6 pareto front displaying trade-off between the extent of zonal exclusion and the resulting risk (i). For six of the zonal exclusion policies developed by the optimisation, labelled (a) to (f), maps showing the area in which the exclusion policy operates (ii), the value of the building stock in 2048 (iii) and the annual average loss for 2048 (iv) are shown.

3.3.2 SPATIAL PATTERNING OF ZONAL EXCLUSION AREAS ACROSS THE PARETO FRONT

In this section, the spatial patterning of exclusion areas as they change across the Pareto front is described. As mentioned previously, moving in a direction from solution (f) to solution (a) in Fig. 6, the optimisation builds successively larger exclusion zones, from an area of 0 at (f) to 7028 Ha at (a). Regarding which regions are preferentially selected for being part of the exclusion zone, the optimisation tends to select subregions with the greatest growth in risk levels (as based on a baseline scenario where no development exclusion occurred). As shown in Fig. 21, the greatest growth in risk in the baseline simulation occurs in the urban fringe along the north-west coast region, and regions around the Port River. Accordingly, these same subregions are preferentially selected for exclusion as shown in Fig. 6.

In Fig. 20 we explore the relationship between the frequency in which subregions are selected for exclusion (part a) with the characteristics of these subregions (part b and c). As can be seen, the relationships are not simple. While there is a tendency for the optimisation to select with greater frequency subregions where the growth in risk is greatest in the baseline scenario, subregions where there is little (or no) growth in risk are also selected. It needs to be remembered that in Fig. 20, what is plotted in part b is the growth of risk in the baseline scenario, and this hides the more complex interactions between where development is excluded and the effect this has on development patterns and by implication the spatial distribution of risk. For example, excluding development from occurring in one subregion where it was observed to occur in the baseline simulation may result in greater development elsewhere that did not occur in the baseline simulation but which still has significant inundation likelihood; therefore, effective zonal policy for reducing risk would need to restrict development in both these subregions. In addition, for each point along the Pareto front, the optimisation effectively needs to select a number of subregions wherein the combined area is less than the value at that point on the front, and therefore may need to choose regions where risk is not reduced as much in order to satisfy this constraint. It is for this reason that we also observe, in Fig. 20, the greater frequency with which smaller subregions are selected for development exclusions.
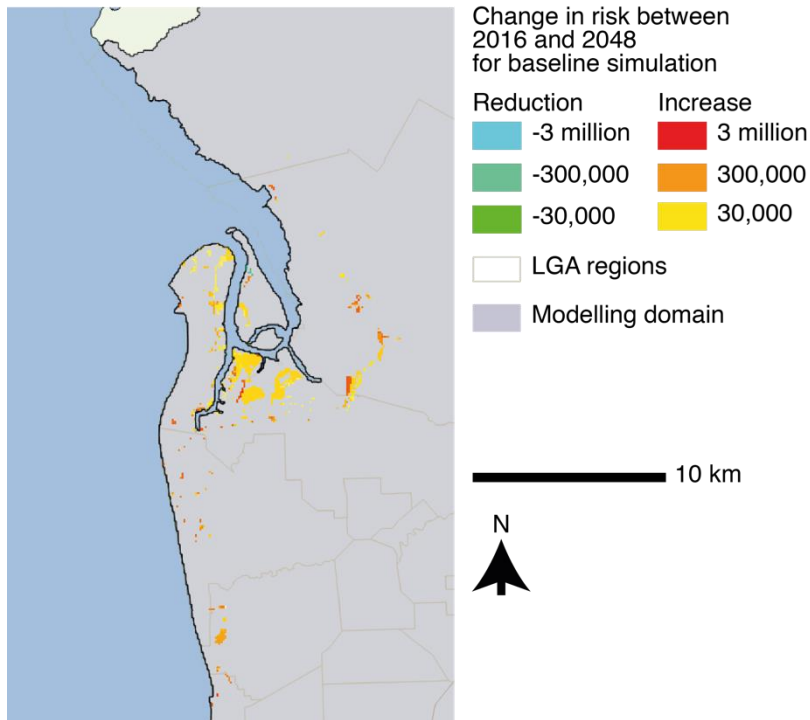
Fig. 21 change in risk between 2016 and 2048 due to development and sea level rise along the greater adelaide coastline, for the baseline simulation where no exclusion zone was included in the modelling.
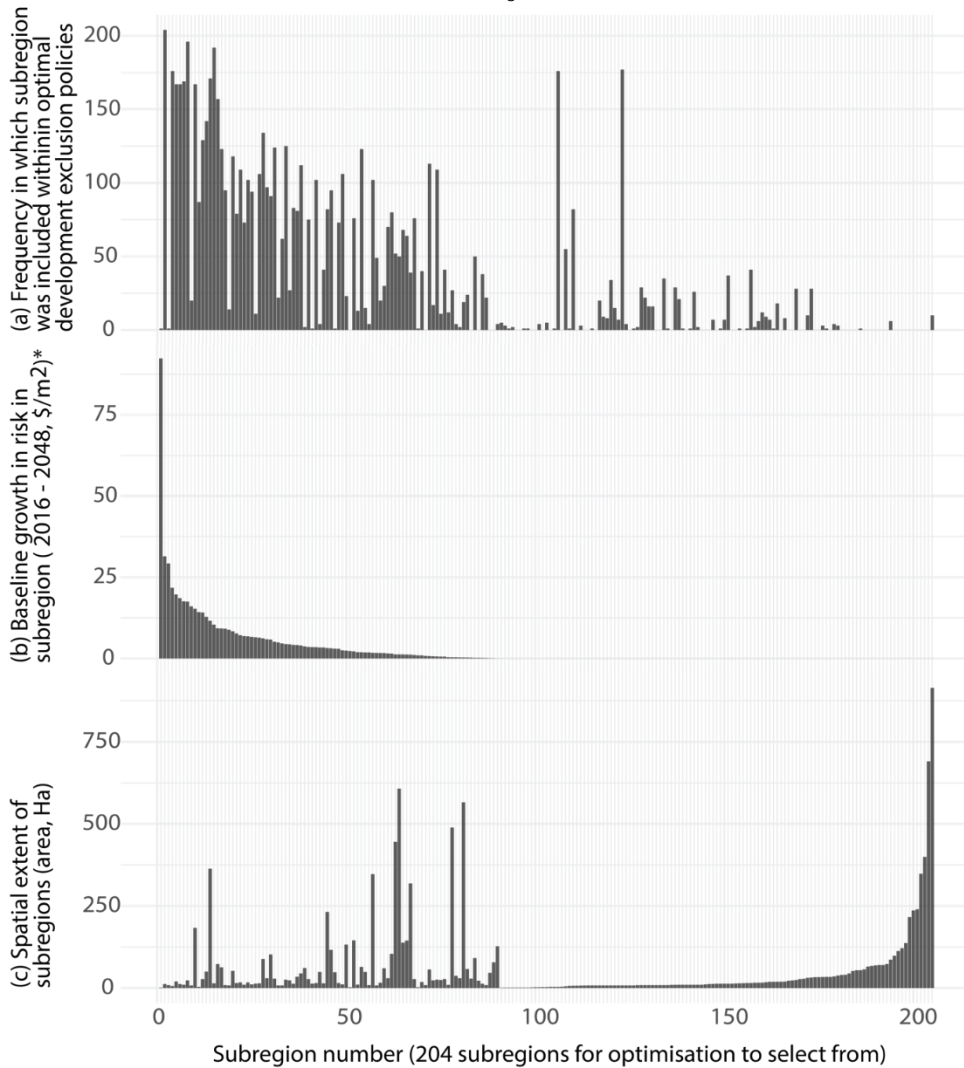
Fig. 20. Characteristics of the subregions from which the optimisation selected from to develop zonal development exclusion policies: (a) the frequency by which each subregion was included within the pareto optimal policies, (b) the baseline growth in risk (* calculated as the change in the spatial density of annual average loss in the baseline simulation on a subregion-by-subregion basis), (c) the geospatial area of each subregion.

With regard to the effect of zonal exclusion and the ensuing development patterns, Fig 22 shows the difference in land use type and building stock values as simulated for 2048 comparing three Pareto efficient policies (marked as a, e and f in Fig. 6) with the baseline. Excluding development along the coast means that land use that would have arisen there needs to move elsewhere, and as can be seen in Fig. 22, this development tends to move across the urban-rural fringe surrounding Adelaide to the North, East and South, generally. This is particularly the case for residential land use. Furthermore, there is a significant reduction in industry in the Port region under zonal exclusion policies, and the majority of this was moved by the land use model into the Northern Adelaide plains (see Fig. 22).

Fig. 22. Comparison between three pareto optimal zonal exclusion policies — solutions (a), (c), and (e) as referenced in fig. 6 — with the baseline simulation in terms of land use and building stock value

3.3.3 SPATIAL PATTERN OF RISK ACROSS THE PARETO FRONT

Even under the most extensive zonal exclusion areas developed by the optimisation, risk is still high along the Port River region, the regions that were historically wetlands where the Torrens drained into the Port River region (including West Lakes), and near the Patawalonga mouth. This is because the optimisation developed exclusion policies that prevented additional development, but allowed currently existing development to remain; these regions are currently heavily developed (see Fig 23), with relatively low-lying coastal topography. This also explains why exclusion zones were only able to reduce flood risk by around 10% in 2048, and also highlights, in hind-sight, the importance of considering coastal flood hazard in long-term land use planning, and the potential utility of the proposed approach.

3.3.4 TEMPORAL CHANGE IN RISK ACROSS THE PARETO FRONT

As just mentioned, coastal flood risk is already high in many places along the Adelaide coastline, and will remain so even with the implementation of exclusion policies, as investigated in this report. However, without exclusion policies, coastal risk will continue to grow, increasing by 20% if unabated by 2048, as shown by the baseline solution, marked (f) in Fig. 23. However, as also shown in Fig. 23, the growth of risk could be almost halted through land use planning measures — as indicated by solution (a), wherein the entire 1% AEP flood zone was placed under a development exclusion policy.
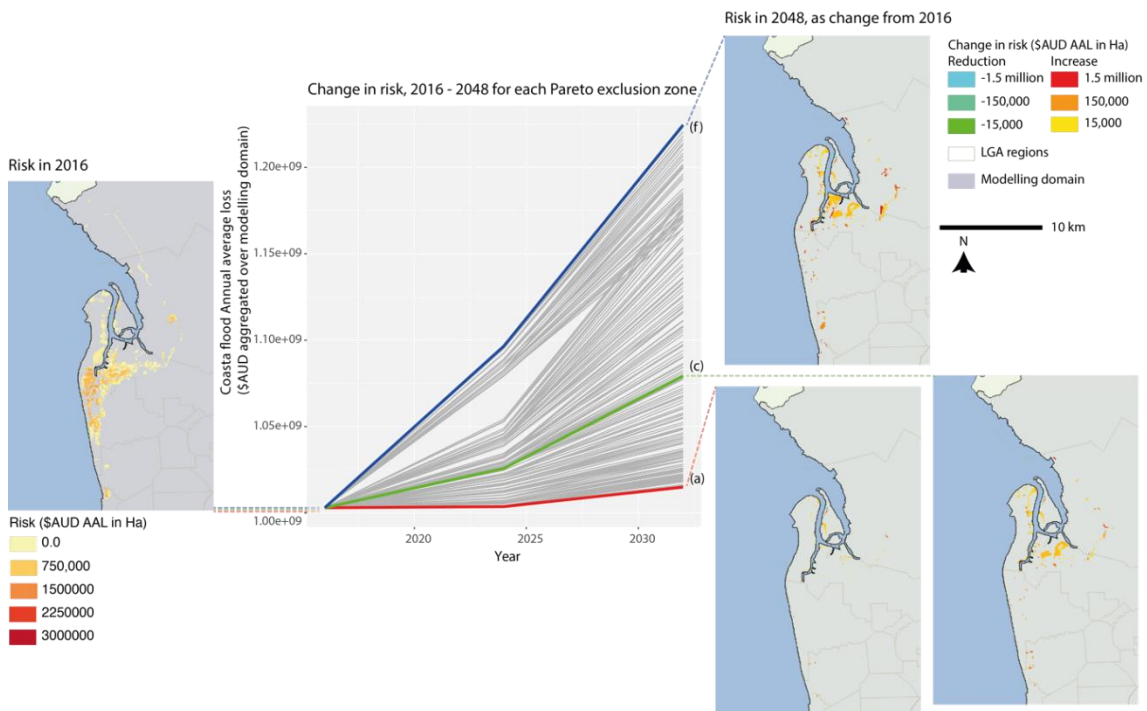

Fig. 23 change in risk over time for three solutions on the pareto front.

4 DISCUSSION ON THE CASE STUDY RESULTS AND UTILITY OF THE FRAMEWORK

In this section we first consider the results obtained from the optimisation process, critically assessing the effectiveness of zonal policy as a management option and identifying valuable improvements to the problem scope and analysis workbench developed for it. Then the discussion broadens to consider the utility of the proposed framework, in light of the case study application.

4.1 THE EFFECTIVENESS OF LAND USE POLICY FOR RISK MANAGEMENT

In 2016, the Commonwealth of Australia productivity commission into natural hazard losses stated that land use planning was perhaps the most potent policy lever for influencing the level of future natural disaster risk. The results here add further evidence to this statement, with the simulation showing only very marginal increases in risk into the future when very strong development restrictions were applied. On the other hand, coastal flooding risk arising from existing development in Adelaide is already very significant and land use planning measures as investigated in this report only act on the risk that arises from potential new development, which accounts for only 20% of the total risk profile in 2048. Therefore, other management options not addressed in this report will be important in managing coastal flood risk in this region. This highlights the importance of the relative extensiveness and patterning of current and future development, including the mix and location of green-field, brownfield and renovation development, when assessing how effective land use planning could be as a management option in a particular region.

4.2 FURTHER WORK OF VALUE WITH REGARD TO CASE STUDY SCOPING AND ANALYSIS WORKBENCH

In a way, the goal of the proposed framework is an elusive one — in the sense that the aim of the approach is to incorporate all critical drivers of risk across the social, environmental, policy aspects related to hazard, exposure and vulnerability, and in practice this needs to be done within limited time and budgets, which makes the approach challenging. This highlights the importance of the iterative improvement strategy as proposed by the framework, wherein it is better to first develop a simplified problem and scope and analysis workbench and then subsequently build upon this. Consequently, we offer the following recommendations for further development of the case study initially developed for this report.

UnHARMED currently focusses on direct losses to building stock, and that was the focus of this case study. However, it is noted that there is a wide range of values-at-risk for which loss can be calculated. Beyond building stock, damages to transport and communication networks, as well as utilities and equipment have been very significant in previous floods and natural hazard events within the studies region. In addition, commerce and trade could be impacted as a result of direct damage, particularly given the importance of the Port Adelaide region for the movement of goods in and out of South

Australia. Furthermore, as mentioned in Section 2.2.2, losses can also be related to the environment, the social make-up of communities and the psychological impact to people. Therefore, it is desirable to extend the analysis here to include indirect and other losses of significance.

There are also other benefits and costs arising from zonal exclusion policies that have not been accounted for in this analysis. For example, excluding land use development will likely impact the overall commute times for people in the region as they travel for work, recreation, social, commerce, and educational activities, etc. Likewise, it may cause greater habitat fragmentation, particularly as development is pushed to the urban fringes to the North, East and South of Adelaide. On the other hand, the removal of development along the coast line allows for greater environmental amenity and recreational function of this space. Quantifying these aspects as criteria as part of the problem scope would be beneficial to understand the trade-offs between these benefits and costs.

There are costs arising from the implementation and management of zonal exclusion areas that have only been included in a simple fashion in the current analysis by assuming proportionality to the area in which an exclusion policy is acting. This hides complexities including who the costs apply to, the proportion between upfront and ongoing cost, and how this cost may compare to other management options. With regard to whom the cost applies, the brunt of the costs apply to the general public and private enterprise, who lose opportunity to carry out various activity/uses of land in the exclusion zone. This opportunity cost could be difficult to predict, but estimating it is plausible: for example, the land use model, in allocating land to various uses, calculates a metric that indicates the potential for each land use class that is simulated to exist in each of the raster cell. It would be expected that this metric has strong correlation with the economic value of land and therefore an opportunity cost could be derived from this relationship.

While land use planning may be one of the most potent options for risk management, it is by no means the only option available in Greater Adelaide. Therefore, the analysis should be extended to also consider other options that have been identified as plausible by practitioners in Adelaide, including in particular, the effectiveness of dry and wet-proofing and/or elevating (in other words, means of increasing flood resilience on a building-by-building level), or through hardening coastal defence mechanisms such as enhancing or extending the series of sea walls that already exist along the coast.

Finally, as we observed in the results in this report, excluding development along the coast resulted in increased development across the urban-rural fringe, which typically has higher bushfire risk in the case study region. Consequently, it would be important to take a multi hazard approach that also considers bushfire as well as other risks included in UNHaRMED, such as river flooding and earthquake.

There is one more limitation in the modelling that is worth mentioning, and that is the way imminent development is represented in the model. There are subregions in the modelling domain, for example the 40 Ha Port Adelaide renewal project to be completed in 2027, wherein development will occur

imminently, but which is not yet reflected in the base land use patterning from which the modelling commences. Therefore, applying a development restriction to this area will result in no development of this site, but this is not a realistic simulation output, as halting development now in this area is unlikely. This is not a limitation of the model per se, but highlights the importance of working with end users in specifying what areas of a modelled region could feasibly have a zonal policy applied to them, and ensuring a model calibration that realistically simulates imminent development.

The UNHaRMED DSS offers a flexible architecture for further enhancement with these capabilities, due to its development on a generic IAM core, being Geonamica. In addition, the optimisation software developed for this report is also built around a flexible module system and can be used with any Geonamica based IAM. As the concerns above are known to be significant and generic across many regions, it would be strategic to further develop UNHaRMED and the optimisation in this direction.

4.3 THE UTILITY OF THE PROPOSED APPROACH

As mentioned, the purpose of this section is to broaden the discussion to highlight the benefits and limitations of the proposed framework, particularly those aspects brought to light through its application to the Greater Adelaide case study. These are discussed below.

4.3.1 A VALUABLE LINE OF EVIDENCE FOR INFORMED DECISION MAKING

The framework is valuable as it provides a transparent, modelling based approach to help inform risk management. Thus, it provides a line of evidence, which amongst other qualitative information, supports decision makers in planning how to manage risk in an area. This is evidenced in the case study through the development of a large number of different zonal policies with different geospatial extensiveness and patterning, which are all Pareto-optimal. Developing such a diversity of zonal policies, and providing information on their effectiveness through performance criteria, could help decision makers understand how development restrictions can be specifically targeted in different locations along the coastline, and how effective these are in reducing future risk.

4.3.2 DEVELOPMENT OF RISK MANAGEMENT STRATEGY

In developing a large number portfolios, the framework is able to compare management portfolios that are vastly different, yet all Pareto-optimal. This is very helpful for the development of management strategy, in that it likely results in the selection of a better strategy and a better implementation of that strategy. In contrast to manual assessment approaches, wherein only a few management options could be assessed across a handful of portfolios, the use of optimisation means that a broader range of management options can be assessed that effectively considers all possible portfolios of these options.

In the case study application, the analysis was limited to considering zonal exclusion strategy. However, through broadening the scope of the analysis to consider more management options and hazard types, broader hazard management strategies could be explored. In addition, despite the analysis here aiding the understanding of the general effectiveness of zonal policy, it provided no support on the specific design of zonal policy. This is because the regular spatial grid on which the simulation was based is a limitation in terms of picking up appropriate features of the landscape and urban form, which are important for exact delineations of zonal regions. However, the same framework, but with a narrower scope and a more spatially resolved analysis workbench, could be developed for the purpose of supporting the design of zonal policy. For example, this would be possible if the loss calculation components of the IAM and the delineation of potential zonal exclusion subregions were based on irregular shaped land-parcels that picked up appropriate spatial features. Consequently, it would be ideal to have a toolbox consisting of a number of accurate simulation-optimisation tools that implement this framework, but with different precisions and tailoring for different parts of the risk management processes.

4.3.3 ROLE OF OPTIMISATION IN INCREASING THE EFFECTIVENESS OF IAM TECHNIQUES

One of the challenges in using IAMs is that while an IAM allows transparent and rigorous assessment of a very broad range of management options, this is limited by the time available for model users to explore different options in a manual trial-and-error approach. Such manual approaches are laborious and despite best efforts, may miss the identification of the best performing combinations of management options. Optimisation, on the other hand, is a semi-automated (or automated) procedure that, when well specified, can effectively sift through and identify feasible, best-performing management options. In addition to making the process more efficient, optimisation can also help reduce bias in the identification of best-performing management options, as it treats all options that are being considered based only on their assessed performance, as given by the model. This means the amount of attention/focus given to options is on an equal footing.

It should be noted that the use of optimisation in this approach is for helping explore what management options work best. The results of the optimisation are not designed to be prescriptive, but to help improve understanding of how options, when used in combination, could best be used to manage risk, in addition to making the process of sifting through options more efficient and effective. This is because models will be limited, in that other, non-modelled, criteria may be important when making a decision, and contain uncertainty, which must be also considered and judgements made about. What this framework does is provide information by which to make these judgements, and techniques, such as multi criteria analysis may be helpful in balancing the different criteria by which to develop risk management plans.

4.3.4 DEALING WITH THE COMPUTATIONAL COST

One of the key challenges in applying the framework is the computational requirement of running the simulation-optimisation, although the ever increasing availability of computing power has made it possible to apply the framework to a case application reported here through use of high performance computing facilities. Currently, the framework could be run in cloud computing environments such as Amazon AWS / Microsoft Azure and that offered by Google. In time, it is expected that the computational demands of the framework could be managed by workstations (currently, on a single cutting-edge workstations, the workload for a single simulation would take around 2 months).

5 CONCLUSIONS

As greater demands are put on planners to effectively manage natural hazard risk, whether from politicians or from the public who have an increasingly reduced appetite for hazard losses, there is a need for analytic frameworks for exploring how to best manage risk. This report presented a framework for exploring how best-performing management options reduce risk through coupling integrated assessment modelling (IAM) practices with optimisation techniques. This framework addressed several needs that practitioners have with regard to risk and adaptation assessment. Specifically, it is designed to explore management strategy, and does so by simulating the effectiveness of management options over long-term planning horizons. This is important, for management options may have long lead-in-times, and/or may have long lifetimes, are not easily/readily changed, and so need to be effective over a broad range of plausible future conditions, which likely include larger populations, increased economic development and climate change. In addition, the framework emphasises holistic assessment, wherein the IAM simulates the effect of management options across a number of criteria, therefore allowing practitioners to explore the trade-offs between risk reduction with other community goals, including environmental, social and economic.

Through application to a case study, this report showed how the framework is able to increase the effectiveness and efficiency by which IAM can be applied to natural hazard risk management. The role of the optimisation was seen not to be prescriptive, but to enable better exploration of risk management options. The framework was therefore able to provide rich information on the effectiveness of management portfolios by which better risk management plans could be formed.

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APPENDICES

APPENDIX A. AN OPEN-SOURCE AND GENERIC OPTIMISER FOR GEONAMICA-BASED DECISION SUPPORT SYSTEMS

In this appendix, the availability of the open-source software packages used in this report are specified. The software used in this report enables the use of multiobjective genetic algorithms with Geonamica-based decision support systems. Geonamica-based decision support systems are an integrated assessment model composed of a set of interlinked (coupled) modelling components, which is made available to users either through a command-line model-runner, or through a graphical user interface that is tailored to the decision-making processes and decision-options available for a particular decision-making context. On the other hand, multiobjective genetic algorithms are a type of optimisation routine that can be used to search for and locate values of decision variables that exhibit Pareto-optimal tradeoffs across many objectives, which have been repeatedly shown to search for optimal combinations of decision variable values in a robust manner, even under difficult problem characteristics, including multimodality in objective space and saliency in decision variable space. When used in conjunction, Geonamica-based integrated assessment models and genetic algorithms implement a simulation-optimisation approach, and have applicability to a wide range of environmental and natural resource management problems. In particular, the use of optimisation aids the use of model-based decision support systems by helping to provide focus on well-performing decision variable values (i.e. the best sets of management options) when used for making management plans. It is also of note that the use of optimisation and the presented software have utility for the calibration — and specifically, the parameterisation — of integrated assessment models (Newland et al., 2018).

The genetic algorithm chosen for implementation within this optimisation package is an adapted implementation of the non-dominated sorting genetic algorithm, first introduced by Deb et al (Deb, 2002). This genetic algorithm uses an elitist and multi objective strategy and is regarded as an industry standard with a proven track-record in application to environmental and natural resource management problems and model calibration. A significant challenge in the application of simulation-optimisation approaches with integrated assessment models is the typically long runtimes of such models, and the software introduced overcomes this difficulty through parallelisation of the search. The software is able to run on Windows, linux or macintosh desktop computers or on high-performance computing clusters. As Geonamica-based DSSs are Windows specific applications, the use of the optimisation on non-Windows systems has been tested using the Wine emulator.

A.1 Software and data availability

The software used in this report is composed of two parts. First, there is a backend optimisation package, which implements the non-dominated genetic algorithm (NSGAII), called 'Parallel NSGA-II Backend'. Second, there is a frontend that includes a graphical user interface, in which an optimisation

problem can be specified with reference to a Geonamica-based integrated assessment model; this front end solves the optimisation problem through compiling with and running the 'Parallel NSGA-II Backend'.

Name of tool: Parallel NSGA-II Backend

Developers: Jeffrey Newman

Hardware required: Hardware requirements are case study dependent and largely depends on the requirements of the simulation model (e.g. Geonamica-based IAM) that is used to quantify the optimisation problem's objectives and constraints

Software required: Software dependencies include the Boost C++ libraries, which are a free, open-sourced, mature and peer reviewed collection of C++ code that implements a number of commonly used programming data types and routines.

Programming languages: Standard C++; compilable under the cross-platform and open source gnu and clang compiler chains, as well as Microsoft's visual C++.

Program size: approx. 50mb (makes extensive use of inline functions which creates faster executables at the expense of program size).

Availability and cost: Free open sourced code licensed under the GNU General Public License v2.0. Project is hosted on GitHub at https://github.com/jeffrey-newman/parallel-nsgaII-backend.

Year first available: 2016

Name of tool: Geonamica-Optimisation

Developers: Jeffrey Newman

Hardware required: Hardware requirements are case study dependent and largely depends on the requirements of the Geonamica IAM that is is used to quantify the optimisation problem's objectives and constraints.

Software required: Software dependencies include the Boost, GDAL, pugixml and OpenCV C++ libraries, which are free, open-sourced, and mature C++ codes. The software is also built upon a folked version of Alex Hagen-Zanker's open-source raster input/output library ('Pronto|raster').

Programming languages: Standard C++; compilable under the cross-platform and open source gnu and clang compiler chains, as well as Microsoft's visual C++.

Program size: approx. 50mb (makes extensive use of inline functions which creates faster executables at the expense of program size).

Availability and cost: Free open sourced code licensed under the GNU

General Public License v2.0. Project is hosted on GitHub at https://github.com/jeffrey-newman/Geonamica-Optimisation.

Year first available: 2016

APPENDIX B. DEPTH-DAMAGE CURVES USED FOR ESTIMATING LOSS FOR BUILDING STOCK EXPOSED TO COASTAL FLOOD EVENTS

Hazard maps for coastal inundation and riverine flood were produced externally from the UNHaRMED DSS and losses from these events were calculated within UNHaRMED, according to the simulated building stock at each time step, using empirical depth-damage functions.

The use of depth damage curves has a basis in the literature and other studies. In particular, we based the depth-damage curves used in this study on Wehner (2012). For this, the building types simulated in UNHaRMED needed to be linked to the building types included within Wehner (2012), as given in Table B1 and B2, respectively for residential and industrial land use types. All commercial building types in UNHaRMED are assumed to have losses characterised by the same ACFS_4 curve (showroom/office, 2 storey, without basement).

UNHaRMED Building Type Name	Wehner et al. (2012) depth-damage Curve Name	Depth-damage curve Description
WALLS AAC	FCM_10	1 storey, slab on grade, cavity masonry, no garage
WALLS REINFORCED CONCRETE MASONRY	FCM_10	1 storey, slab on grade, cavity masonry, no garage
WALLS CAVITY AND SOLID MASONRY	FCM_10	1 storey, slab on grade, cavity masonry, no garage
WALLS VENEER MASONRY	FCM_7	1 storey, slab-on-grade, masonry veneer, plaster board lining, integral garage
WALLS PRECAST CONCRETE	FCM_10	1 storey, slab on grade, cavity masonry, no garage
WALLS TIMBER	FCM_1	1 storey, raised floor, weatherboard cladding, plaster board lining, no integral garage
WALLS METAL SHEETING	FCM_1	1 storey, raised floor, weatherboard cladding, plaster board lining, no integral garage
WALLS FIBRE CEMENT	FCM_1	1 storey, raised floor, weatherboard cladding, plaster board lining, no integral garage
WALLS MUDBRICK OR RAMMED EARTH	FCM_7	1 storey, slab-on-grade, masonry veneer, plaster board lining, integral garage

WALLS SYNTHETIC	FCM_1	1 storey, raised floor, weatherboard cladding, plaster board lining, no integral garage

Table B1 Residential building types in UNHaRMED, linked to depth-damage curves developed by Wehner (2012).

UNHaRMED Building Type Name	Wehner et al. (2012) depth-damage Curve Name	Depth-damage curve Description
ISS_URM_S	ACFS_6	Factory, 1 storey, without basement
ISS_URM_PS	ACFS_6	Factory, 1 storey, without basement
ISS_RM_S	ACFS_6	Factory, 1 storey, without basement
ISS_SS_S	ACFS_6	Factory, 1 storey, without basement
ISS_SSURM_S	ACFS_6	Factory, 1 storey, without basement
ISS_SSPC_S	ACFS_6	Factory, 1 storey, without basement
ISS_SPC_S	ACFS_6	Factory, 1 storey, without basement
ISS_PC_S	ACFS_6	Factory, 1 storey, without basement
IDS_CSURM_S	ACFS_5	Warehouse/garage, 2 storey, without basement
IDS_CSPC_S	ACFS_5	Warehouse/garage, 2 storey, without basement
IDS_CURM_S	ACFS_5	Warehouse/garage, 2 storey, without basement
ISSB_CSPC_S	ACFS_5	Warehouse/garage, 2 storey, without basement
ISSB_SSS_S	ACFS_5	Warehouse/garage, 2 storey, without basement

Table B2 Industrial building types in UNHaRMED, linked to depth-damage curves developed by Wehner (2012).

The depth-damage curves used for each of these building types in the case study reported here are shown below, in Table B3. These curves express damage as a fraction of total building value, and include both insured and uninsured, as well as structural and content losses.

Inundation depth (above ground level)	FCM_10	FCM_7	FCM_1	ACFS_4	ACFS_5	ACFS_6
0.3	0.02	0.03	0.06	0.01	0.02	0.01
0.35	0.165	0.21	0.195	0.02	0.05	0.06
0.4	0.31	0.39	0.33	0.03	0.07	0.07
0.6	0.35	0.43	0.38	0.05	0.07	0.07
0.8	0.35	0.43	0.38	0.05	0.07	0.07
1.3	0.39	0.47	0.42	0.06	0.07	0.07
1.8	0.45	0.63	0.58	0.06	0.09	0.08
2.3	0.47	0.66	0.59	0.086667	0.131667	0.083333
2.7	0.566	0.772	0.654	0.108	0.165	0.086
2.8	0.59	0.8	0.67	0.113333	0.173333	0.086667
3	0.626	0.828	0.714	0.124	0.19	0.088
3.1	0.644	0.842	0.736	0.129333	0.196667	0.088667
3.3	0.68	0.87	0.78	0.14	0.21	0.09
3.4				0.142727	0.216667	0.092308
3.6				0.148182	0.23	0.096923
3.8				0.153636	0.24	0.101538
4.3				0.167273		0.113077
4.4				0.17		0.115385
4.6				0.18		0.12
5.4						0.138462
5.7						0.145385
5.9						0.15
6.6						0.157
6.9						0.16