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EXPLORING FUTURE DEVELOPMENT PATHWAYS AND ASSOCIATED DISASTER RISK

UNHaRMED scenarios for Greater and Peri-urban Melbourne

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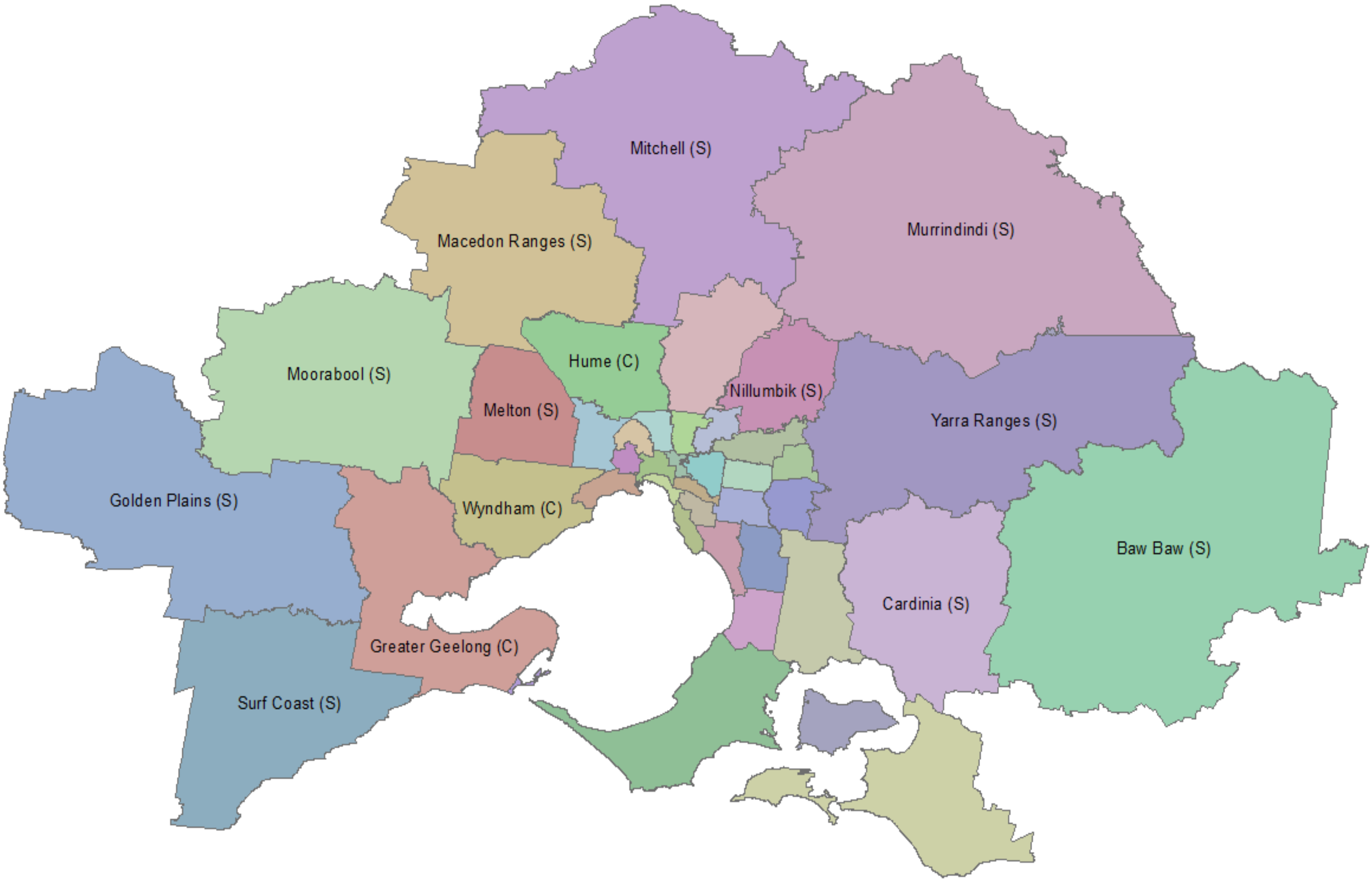

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1 INTRODUCTION

Australia is subject to significant impacts from natural hazards, the risk of which is increasing due to population growth and climate change (e.g. Newman et al., 2017).

The state of Victoria already has a long history of catastrophic bushfires, amongst which the Black Saturday bushfires of 2009 and the Black Summer bushfires of 2019-2020 stand out in terms of severity and impact in recent history. Expectations for the future are even worse with climate change resulting in a hotter and dryer climate with longer fire seasons. Likewise, climate change is expected to result in substantial sea level rise, putting communities on the coast at risk. In addition to the climate change impacts, the State is expecting a large increase in population, of which part is likely to live in the areas prone to bushfire and coastal inundation.

If we could, it would be cheaper, and cause less harm, to deal with some of these threats in advance to make our communities more resilient. The difficulty is knowing how to prioritize what to plan for, and how to make best use of available resources, which are generally scarce. This difficulty can be addressed by developing a risk reduction strategy, which requires a good understanding of current and future risks.

The projected increase in risk, together with the awareness of the complexity of the underlying dynamics affecting this risk, has led to the recognition that there is an urgent need to better understand the components of disaster risk and their dynamics. In response, over the past ten years, the University of Adelaide and the Research Institute for Knowledge Systems, supported and funded by the Bushfire & Natural Hazard Cooperative Research Centre (BNHCRC), have developed a decision support system (UNHaRMED - **U**nified **N**atural **Ha**zard **R**isk **M**itigation **E**xploratory **D**ecision Support System) to assist government agencies to better understand how risks arising from multiple natural hazards change over space and time under different plausible future conditions (e.g. climate change, population growth, economic development), as well as the relative effectiveness of different risk reduction strategies (e.g. structural measures, land use planning, land management, building code changes etc.). The development of UNHaRMED has been supported by the inputs of many stakeholders around Australia, including Victorian State Government agencies such as CFA, EMV and DELWP (now DEECA), shaping what the tool should be able to do and what it should look like.

This report demonstrates the use potential of UNHaRMED in a strategic risk assessment and risk reduction context, exemplified using the application developed for Greater and Peri-Urban Melbourne (GPUM), focusing on the following objectives:

1. To develop an approach for exploratory scenario risk assessment that combines narrative storylines with quantitative modelling from UNHaRMED.
2. To apply the approach to Greater and Peri-Urban Melbourne and develop a set of scenarios to obtain a better understanding of future risk

across multiple hazards, in particular bushfire and coastal inundation, under changing socio-economic and climate conditions.

3. To reflect on the role of UNHaRMED in supporting risk assessment and risk reduction.

This report first introduces the UNHaRMED system (Section 2), the study area (Section 3) and the application of UNHaRMED to the GPUM case study (Section 4), followed by the scenario risk assessment approach (Section 5) and the results obtained (Section 6). The report concludes with the main findings, lessons learnt and suggestions for further work (Section 7).

2 UNHARMED

UNHaRMED is a software tool developed by the University of Adelaide and RIKS as a spatial Decision Support System (DSS) for natural hazard risk reduction planning, funded by the BNHCRC. It consists of dynamic spatial exposure models (land use, assets) and multiple hazard models to consider how risk changes into the future, both spatially and temporally.

UNHaRMED was developed through an iterative, stakeholder-focused process to ensure the system is capable of providing the analyses required by policy and planning professionals in the planning, emergency management and risk assessment fields. The development process involved a series of interviews and workshops with potential end users across governmental and non-governmental organisations in South Australia, Tasmania, Victoria and Western Australia, aligning risk reduction options, policy relevant indicators and future uncertainties to be included, such that the system can sit within existing policy processes. This has resulted in a tool that considers how land use and values at stake change over time, how various hazards interact with these changes, and what the effectiveness of a variety of risk reduction measures is.

Land use changes are simulated based on a number of different drivers. These include external factors, such as population growth and projected increase of urban area, which determine the demand for different land uses. The land uses for every location are determined based on these demands and a set of socio-economic factors (e.g., will a business flourish in this location?), policy options (e.g., are there policy rules in effect that restrict new housing development in this location?) and biophysical factors (e.g., is the soil suited to agriculture here?). Different values at stake (e.g., buildings, infrastructure, agricultural production), as well as their vulnerability to different natural hazards, are then associated with the different land use classes. Natural hazards such as bushfire, earthquake, coastal inundation and riverine flooding can then interact with these land uses and values at stake. Each hazard is considered and modelled differently, depending on its underlying physical processes, as detailed in the UNHaRMED documentation (van Delden et al., 2022).

A simplified version of the system diagram developed for UNHaRMED is shown in Figure 1, which includes exposure, hazard risk and impact models, as well as the way they interact with the external drivers, risk reduction options and indicators. Socio-economic drivers affect land use, whereas climate drivers affect hazards such as bushfire and flooding (see e.g., Hamers et al., 2024). Risk reduction options can affect exposure (e.g. land use planning), hazard magnitude (e.g. the construction of levees can reduce flooding and prescribed burning can reduce bushfires) and vulnerability (e.g. building hardening and changes in building codes can affect infrastructure vulnerability).

UNHaRMED is developed in the Geonamica software environment (Hurkens et al., 2008) and comes as a stand-alone software application. The system comes with the Map Comparison Kit (MCK) for analysis of model results. UNHaRMED and the MCK use data formats that are compatible with standard GIS packages, such as ArcGIS.

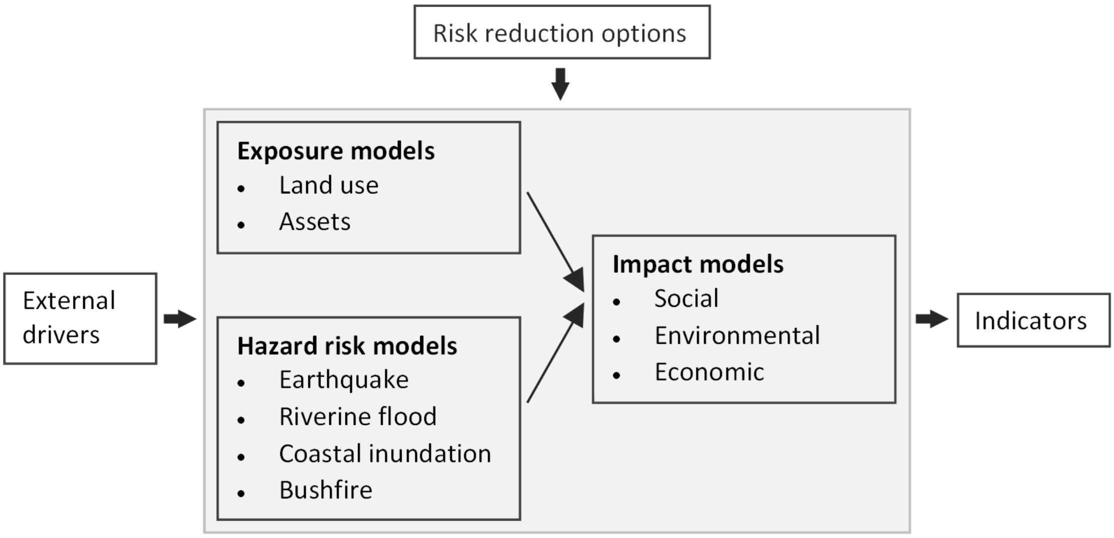


FIGURE 1: MODELLING COMPONENTS FOR INCLUSION WITHIN THE INTEGRATED MODELLING FRAMEWORK OF UNHARMED.

3 STUDY AREA

The study area considered is the Greater and Peri-Urban Melbourne (GPUM) region. Figure 2 shows the LGAs included in the model area and Figure 3 shows the land uses selected for the application of UNHaRMED for GPUM (Source Victorian Land Use Information System[1]).

FIGURE 2: GREATER AND PERI-URBAN MELBOURNE STUDY AREA WITH INCLUDED LOCAL GOVERNMENT AREAS.

[1] http://vro.agriculture.vic.gov.au/dpi/vro/vrosite.nsf/pages/vluis

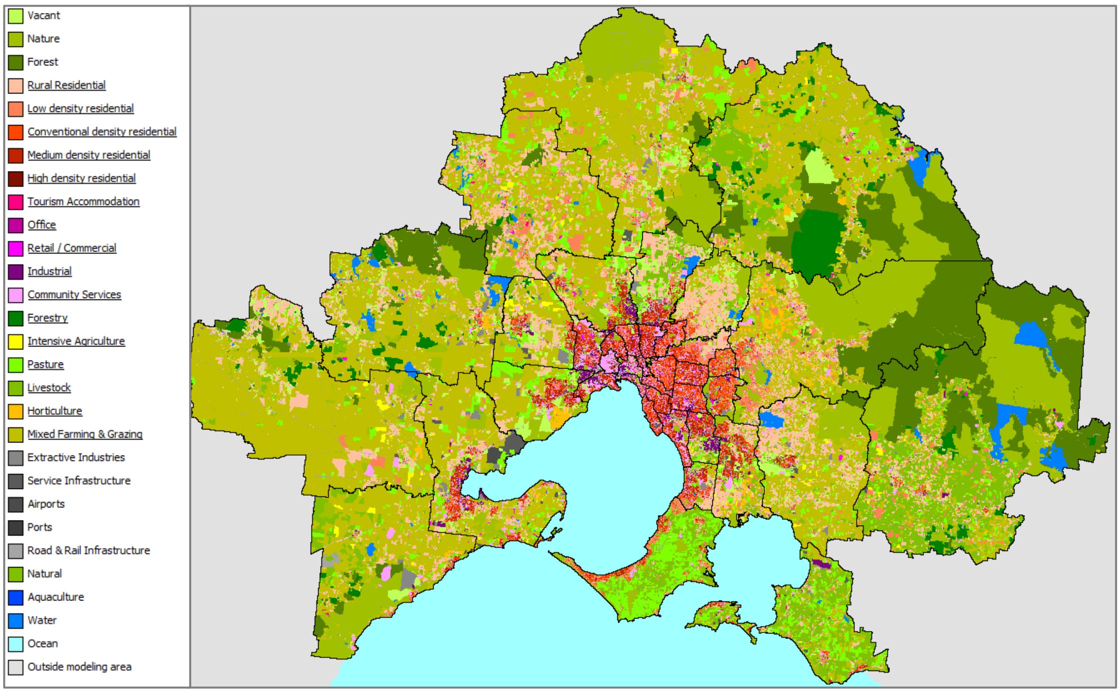


FIGURE 3: LAND USES SELECTED FOR THE GPUM APPLICATION.

In addition to the general land use classes, UNHaRMED includes a vegetation map with more details about the vegetation types, as vegetation type specific information is required for assessing bushfire risk. This map is shown in Figure 4 (source State of Victoria DELWP).

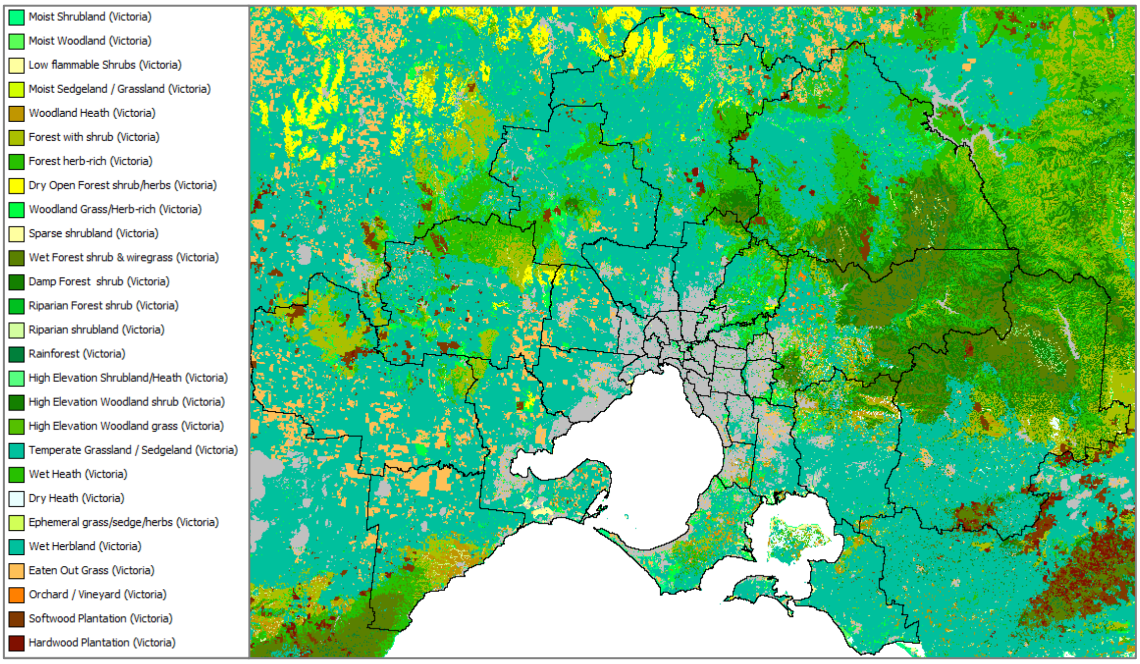


FIGURE 4: VEGETATION MAP OF THE GPUM APPLICATION. THE GREY REGIONS INDICATE NON-VEGETATED AREAS.

4 UNHARMED FOR GREATER AND PERI-URBAN MELBOURNE

4.1 MODEL CONFIGURATION

For this report, we make use of the components of UNHaRMED that are used in the calculation of coastal inundation and bushfire risk. Both calculate risk through the concepts of hazard, exposure and vulnerability, although details of each aspect vary per hazard.

Coastal inundation risk is calculated on an annual basis. For each year the *hazard* is represented through a set of inundation maps for different average recurrence intervals (ARIs). The *exposure* information is calculated based on the land use at each location as simulated by the land use model, and the related residential, commercial and industrial building stock and its monetary value, as determined by the building stock model. Agricultural value is assigned to the various agricultural classes simulated by the land use model. Using dedicated *vulnerability* curves for different types of agriculture, buildings and infrastructure, the expected risk is calculated based on the exposed assets and inundation levels for the various ARIs at each location (100x100 m cell). Inundation maps are calculated exogenously to UNHaRMED and can be included for different years (to simulate climate change impacts) and mitigation options.

In the calculation of bushfire risk, the bushfire *hazard* magnitude is provided through the bushfire likelihood map, which is calculated for each year and each location (100x100 m cell) as a function of fire behaviour – defined by fuel load and the rate-of-spread, ignition potential, and suppression capability. The *exposure* information is calculated based on the land use at each location as simulated by the land use model, and the related residential, commercial and industrial building stock and its monetary value, as determined by the building stock model – similar to the exposure information used in the calculation of coastal inundation. Using the Bushfire Attack Level (BAL) specific *vulnerability* of each building type to withstand a fire of a certain intensity, the bushfire likelihood and the value at stake at each location, the overall bushfire risk can be calculated, expressed as an average annual building damage for each 100x100 m cell.

Further details about the models included are given in the UNHaRMED technical specification document (Van Delden et al., 2022).

4.2 MODEL APPLICATION

This section provides an overview of the data, data processing and calibration of the GPUM application of UNHaRMED, structured along the main building blocks of the system used in this study: Land use (1), Building stock (2), Coastal inundation risk (3) and Bushfire risk (4).

The models included in UNHaRMED for calculating coastal inundation and bushfire risk make use of the following input maps:

- Land use map (1)
- Building stock map per NEXIS building type (2)
- Building stock map per BAL type (2)
- Coastal inundation hazard maps (3)
- *Vegetation map* (4)
- Slope map (1, 5)
- Time since last fire (TSLF) map (4)
- *Suppression capability map* (4)
- Prescribed burn map(s) and/or future burn map(s) (4)
- Climate maps (for different years and climate scenarios) (4):
    - Daily maximum temperature
    - Daily average relative humidity
    - Daily minimum winter temperature
    - Daily maximum wind speed

Key parameters used in the UNHARMED application for GPUM are:

- *Land use model parameters* (1)
- Future land use demands (1)
- *Building stock model parameters* (2)
- Vulnerability curves per NEXIS building type (3)
- Vulnerability curves per BAL type (4)
- *Ignition potential parameters* (4)
- *Parameters to calibrate the average annual damage* (4)
- Land use area per land use class from 2018 – 2050 (1)
- *Distribution of building types in newly developed urban areas* (2)

Information on the input for the exposure components of UNHaRMED is given in Section 4.2.1 for land use, and Section 4.2.2 for building stock. Information on inputs to the bushfire risk model are provided in Sections 4.2.3 Climate and 4.2.4. Fuel Age and information on the vulnerability curves for bushfire and coastal inundation is provided in 4.2.5 Vulnerability curves. In addition to the data preparation discussed in these sections, maps in italics in the list above were provided by the State of Victoria DELWP (now DEECA)[2]. Parameters listed in italics in the list above are set as part of the calibration.

[2] https://data.vic.gov.au

4.2.1 Land use

Inputs to the land use model are a set of maps: land use, infrastructure, base maps for zoning and base maps for suitability, together with land use demand projections, a set of interaction rules representing behavioural aspects and parameters to convert infrastructure maps and base maps for zoning and suitability into components contributing to the potential allocation of different land uses.

Land use maps were sourced from the Victorian Land Use Information System (VLUIS)[3].

Land use demand

Assumptions on future (area) demand for different socio-economic land uses were derived from the Victorian State Government population projections (State of Victoria DELWP, 2019), together with current densities of different urban land uses, which were derived from the current and historic land use maps and the current and historic population from the Australian Bureau of Statistics[4].

Human behaviour

Human behaviour (in terms of land use allocation actions) is analysed within the model using historical land use maps and considering the changes between them. This is used to calibrate the inertia of a land use to remain as is, its ease of conversion to other land uses and its relative attractiveness to other uses.

Accessibility

Accessibility typically relates to the infrastructure networks that enable an activity to meet its mobility and access needs from a cell.

For the Greater and peri-urban Melbourne model, six types of accessibility were considered as inputs to the model:

- Freeway and highways
- Local roads
- Primary routes
- Ramps
- Railway lines
- Railway stations

Transport networks were sourced from the Victorian State Government[5] and processed for the geographical extent of the model.

[3] http://vro.agriculture.vic.gov.au/dpi/vro/vrosite.nsf/pages/vluis
[4] Census | Australian Bureau of Statistics (abs.gov.au)
[5] https://discover.data.vic.gov.au

Suitability

Suitability relates to the physical characteristics of the land to support an activity in that cell.

Currently, slope is the only suitability factor included. Relevant data were sourced from DELWP (now DEECA). To ensure consistency in input data, the slope map from the land use model is also used in the bushfire likelihood component of the bushfire risk model.

Zoning

Several zoning plans are included within the model and determine, for a given location, whether a particular land use is actively stimulated, allowed, weakly restricted or strictly restricted in that location.

Two zoning strategies are included within the model in its current set up:

- Victorian Overlay Scheme
- Victorian Zone Scheme

Zoning data were selected in collaboration with DELWP, sourced from the Victorian State Government[6] and processed for the model extent.

4.2.2 Building stock

The NEXIS dataset provides information on building stock exposure (per building type) at an SA1 and SA2 Statistical Area level. To disaggregate building stock to a 100 m cell raster, the following process is applied: The Land use map from UNHaRMED is used to determine the number of cells to which the building stock Urban Land Use (ULU) types may be distributed within each Statistical Area (SA2 level for Residential and SA1 level for Commercial and Industrial). Within each statistical area the corresponding building stock(s) are evenly distributed amongst the relevant ULU cells. The total contents value and total structural value are handled using the same approach and disaggregated from SA level to cell level. The resulting total value at stake is the sum of the structural and content value of all buildings at each cell, as shown in Figure 5.

Next, the average structural value and average contents value within each LGA are calculated using the different building stock values and number of ULU cells by the relevant LGA areas.

The initial BAL ratings of the building stock at each cell, required for determining the vulnerability of buildings subject to a certain fire intensity[7], are determined by comparison against the Fire Intensity Potential map, and the age of the building stock at each cell. Buildings from pre-1980 are automatically assigned a BAL value 'Low'. All other buildings are assigned the lowest BAL value required to withstand the current Fire Intensity or Radiant Heat Flux Potential at the location. This Radiant Heat Flux Potential map (kW/m^2) is obtained by conversion from the Fire Behaviour Potential (kW/m)[8].

[6] https://discover.data.vic.gov.au
[7] Bushfire Attack Level – AS 3959
[8] A more detailed description of how this building stock map has been created, with the accompanying R code, may be provided on request.

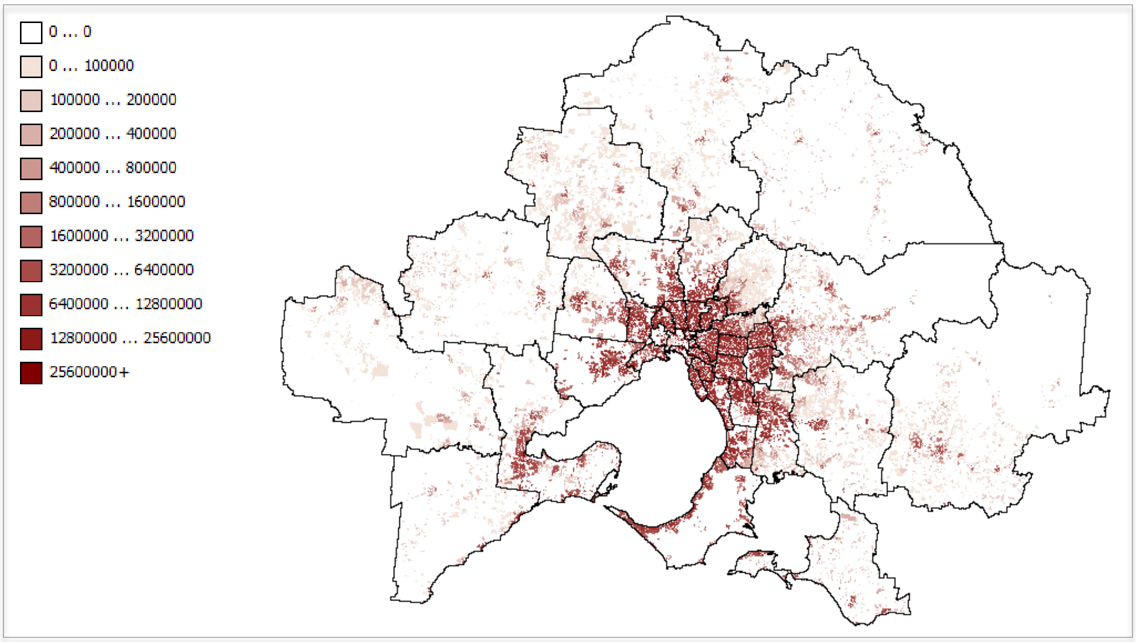


FIGURE 5: VALUES AT STAKE OF RESIDENTIAL, COMMERCIAL, AND INDUSTRIAL BUILDINGS IN 2018 ($).

4.2.3 Climate

The current climate (i.e., not future projected) data have been sourced from DELWP (now DEECA). Information on future climate projections was sourced from the CSIRO Climate Change Australia website[9]. This website provides climate model data from 47 global climate models (GCMs), which have been assessed for Australia for four IPCC greenhouse gas emissions scenarios (RCP 2.6, 4.5, 6.0, and 8.5).

Use was made of projected changes in climate relative to the IPCC 1986-2005 baseline. Annual, seasonal, and monthly data are available at 20-year time slices centred on 2030, 2050, 2070 and 2090. These data are presented as projected ranges of change (in %) based on the 10-90th percentile of the model range and for individual models. For any given region, time period, and emissions scenario, these models can be used to represent "best case", "worst case" and "maximum consensus" scenarios.

The pre-processing of the future climate projection data for inclusion in the Bushfire Model Block can be divided into 3 steps.

<u>Step 1: Identify the most relevant global climate model</u>
The Projection Builder tool[10] was used to identify which climate model would be the most relevant for each UNHaRMED application region (worst-case conditions). The Bushfire Model Block calculates fire behaviour over the summer months, so the season considered for future climate projections was set to December - February (DJF). The climate variables of interest were: Maximum Daily Temperature, Minimum Daily Temperature, Humidity, and Wind Speed. As

[9] https://www.climatechangeinaustralia.gov.au/en/
[10] https://www.climatechangeinaustralia.gov.au/en/projections-tools/climate-futures-tool/projections-builder/

the Projection Builder offers the possibility to identify the "best case", "worst case", and "maximum consensus" scenario models, the following parameters were selected to define these scenarios:
Best case:

- Little change in December - February (DJF) Wind Speed
- Small increase in December - February (DJF) Maximum Daily Temperature
- Little change in December - February (DJF) Humidity

Worst case:

- Increase in December - February (DJF) Wind Speed
- Large increase in December - February (DJF) Maximum Daily Temperature
- Decrease in December - February (DJF) Humidity

This process was repeated for each time slice and emissions scenario of interest. Once all the queries had been submitted, a summary of the "worst case" and "maximum consensus" scenario models was created to identify the most appropriate climate model for the time-slices considered.

Step 2: Download the gridded change datasets for each climate variable
The relative gridded change datasets for each of the four climate variables and time slices of interest were downloaded from the Climate Change Australia archive. These gridded datasets are available in NetCDF format and cover the entire globe. A description of the files and information contained within each grid can be accessed through the website[11].

Step 3: Re-process the gridded change datasets to the GPUM extent and format required by UNHaRMED
The relative gridded change datasets were re-projected and resampled to the resolution and extent of the case-study area and re-processed to actual change datasets to be combined with the current climate input maps (baseline). As a result, new climate maps were produced for each time slice and emissions scenario of interest.

4.2.4 Fuel age

Fuel age, in combination with the vegetation type, is an important factor in determining fuel load.

The initial fuel age map was determined based on historic fires in the modelled region[12] using the following approach:

1. Load the historical fire scar map (use both planned burns and bushfire records).
2. Identify the maximum fuel age as the longest time since any fire has occurred in the region (this will become the background value if no fires occurred on a given cell).

[11] https://www.climatechangeinaustralia.gov.au/en/projections-tools/climate-futures-tool/projections-builder/
[12] https://discover.data.vic.gov.au/dataset/fire-history-records-of-fires-primarily-on-public-land-showing-the-fire-scars

3. For each record, calculate the interval (in years) between the fire ignition date and the desired simulation date (e.g., 2022).
4. Convert the modified shapefile to a raster layer (select the column that contains the fuel age value calculated in Step 3) and apply the background value calculated in Step 2 to all other cells.

4.2.5 Vulnerability curves

Vulnerability, or damage, curves are set per building type for calculating coastal inundation risk and per BAL type for bushfire risk. Annex I provides an overview of the vulnerability curves applied in the risk calculation of coastal inundation and bushfire.

5 SCENARIO RISK ASSESSMENT APPROACH

To meet the objectives of the report, we developed an approach to improve disaster risk reduction planning that integrates different types of knowledge and assessments, both qualitative and quantitative, through exploratory scenarios to consider extended planning horizons in a dynamic manner (Riddell et al., 2019). This allows for the characterisation of risk against time for various scenarios that incorporate challenging and relevant assumptions on uncertain and complex factors and interactions influencing risk. This process enables decision makers to better consider the impact of different factors on risk, allows for an understanding of the impact on current decisions and policy on future risk and enables a collaborative approach to be undertaken to better plan for a less risky future.

The implementation of the approach is shown in Figure 6 across nine distinct steps, which can be grouped into four stages, including problem formulation, qualitative scenario development, quantitative scenario development and future risk assessment. The feedbacks between the different steps and stages are also shown. To enable the desired outcomes from the approach to be achieved, its implementation is focussed on integrating participatory and qualitative information with quantitative modelling and analysis to enable the exploration of risk profiles. For further information on the approach, please see Riddell et al. (2019).

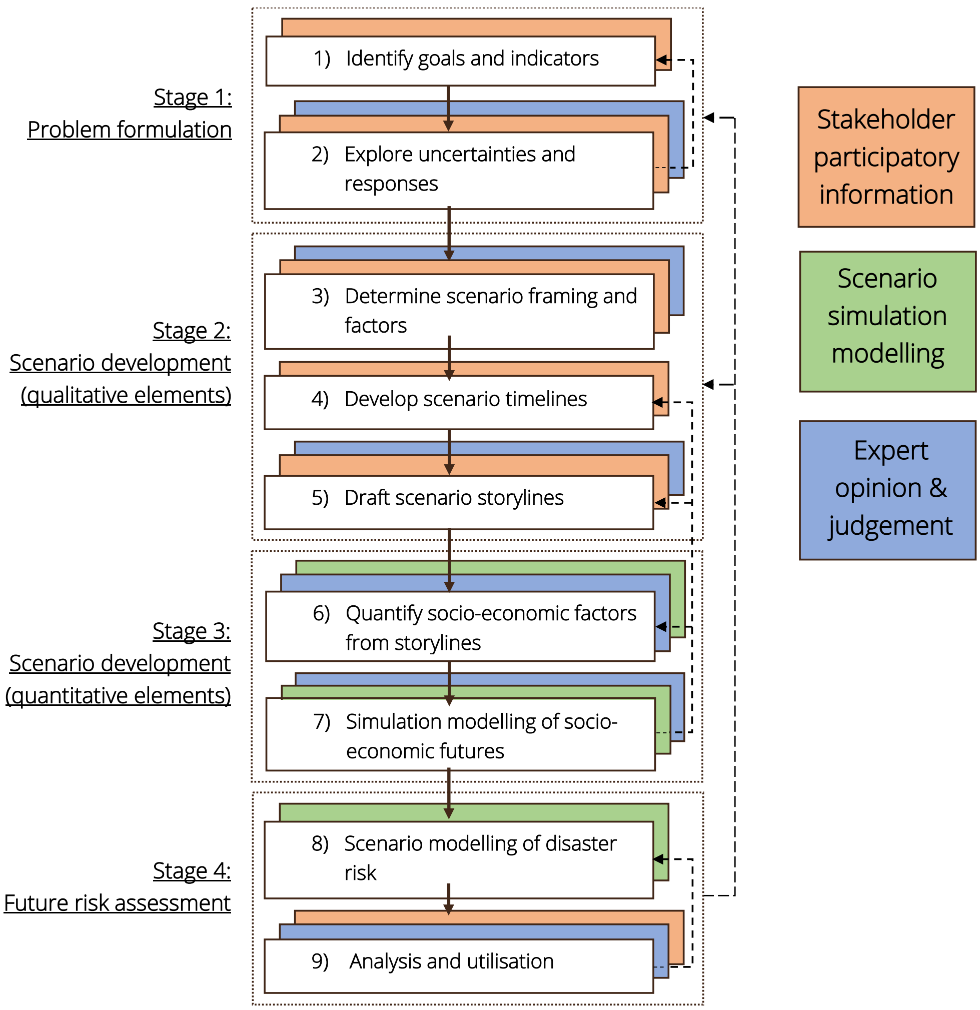


FIGURE 6: OVERVIEW OF THE APPROACH TO DEVELOP AND USE EXPLORATORY SCENARIOS IN DISASTER RISK ASSESSMENTS. COLOURED BOXES INDICATE THE SOURCES OF INFORMATION USED IN EACH STEP (RIDDELL ET AL., 2019).

As part of the GPUM case study application, the following activities have been carried out in the different stages:

Stage 1: Problem formulation: Questionnaires, interviews and a workshop were conducted to scope the exercise and introduce UNHaRMED and the exploratory scenario approach for risk assessment to stakeholders across different government organisations, including CFA, DELWP (now DEECA) and EMV.

Stage 2: Scenario development (qualitative elements): A workshop with stakeholders from Victoria was conducted to decide on the key drivers and uncertainties for the future of Greater and Peri-Urban Melbourne. Participants were asked to work within a giving scenario framing and think about futures for the region with low and high challenges to government intervention and resilience (Figure 7, Riddell et al. (2019)). For each of the four quadrants presented in Figure 7, scenario timelines were developed, which were complemented by a literature review and turned into storylines by the project team. Draft storylines were presented and discussed in a follow-up workshop and adapted based on feedback from participants.

Stage 3: Scenario development (quantitative elements): Quantitative elements of scenarios consist of the external drivers, parameters and possibly model structures used to temporally simulate the qualitative narrative elements. The quantification of factors from the storylines, Step 6, typically is undertaken by expert opinion and judgment of the modellers who look for elements from the storylines that can be used to inform elements of the model to be modified. This follows the identification of clues, indicators and impacts that inform the parameterization of the model. This approach follows the storyline and simulation approach as outlined in Alcamo (2008) and uses the CI2 methodology outlined in Van Delden and Hagen-Zanker (2009). The pathways corresponding to the different storylines were simulated using the land use and building stock models incorporated in UNHaRMED, resulting in a set of future land use and value-at-stake maps for each of the four narrative storylines.

Stage 4: Future risk assessment: The socio-economic futures simulated in Stage 3 were used to drive the quantitative risk assessment under two different climate scenarios: RCP 4.5 and RCP 8.5. Dynamic risk assessment was undertaken for two of the hazards incorporated in UNHaRMED: bushfire and coastal inundation. For each of the hazards, the risk was simulated from 2020 until 2050 on an annual basis. To be able to compare risk values across different hazards, average annual damage (AAD) was selected as the relevant risk metric.

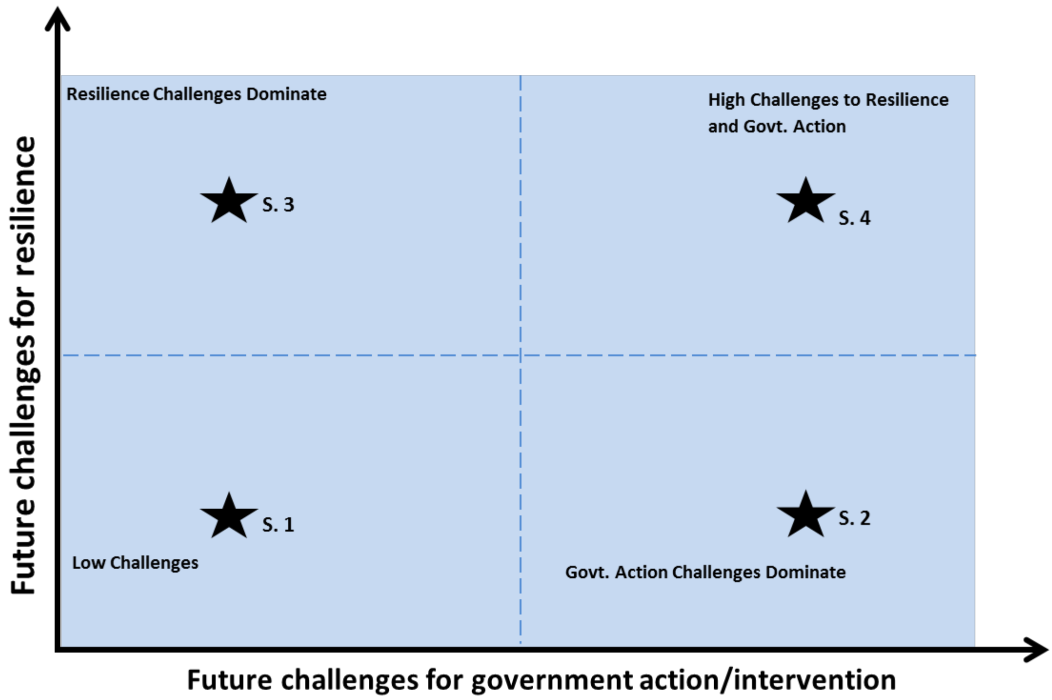


FIGURE 7: SCENARIO FRAMING APPLIED TO DEVELOP FUTURE PATHWAYS FOR GREATER AND PERI-URBAN MELBOURNE (RIDDELL ET AL., 2019).

Results of the implementation of the approach are presented and discussed in the next section.

6 RESULTS AND DISCUSSION

Using the scenario framework presented in Section 5, a set of four scenarios has been developed using the scenario logic presented in Figure 7. The following sections first present the scenario narratives that have been developed (Section 6.1), followed by their quantification into model inputs (Section 6.2), the socio-economic model results (Section 6.3) and the risk assessment (Section 6.4).

6.1 FOUR PATHWAYS FOR GREATER AND PERI-URBAN MELBOURNE

S.1 – Living with Nature

Low challenges to resilience. Low challenges to government action and intervention – A vision for Greater & Peri-urban Melbourne

Population and urbanisation: Population and migration policies are designed to continually enable the economic growth desired by the public and State. Immigration is driven by the desirability of Melbourne, and the opportunity to engage in a technology-driven economy but be surrounded by nature. This places an emphasis on 'living with nature' and planning schemes that create distance between natural and built-up areas and integrates nature into urban planning. This also includes restricting development in areas with unacceptable risk, agreed on by the community, and an emphasis on mixed use developments, creating spaces where people come together. This results in a densification of the urban core and rural development around existing centres, providing centres of mixed land uses and diverse residential developments with ample services. This urban/nature separation enables the natural environment to perform its natural function, where possible, with minimal human intervention and increased ecosystem services. This split, however, is not at the expense of integration of nature and urban areas with increasing consideration of urban greenery.

Community Profile: A growing social conscious, driven by a community desire to prosper despite increased global threats and challenges, sees the region value diversity and equality over all else. This inclusive society feels enabled to engage in decision-making and influence change with access to the knowledge required to do so. An open government engages in processes of co-development with local communities to develop sustainable, resilient communities, where the risks are known and appropriately communicated, understanding the nuances of local values and incorporating these in overall strategic planning. Although increased flexibility and technology enable people to work from home, the creative economy develops local community working hubs, encouraging social engagement and innovation for local challenges.

Economy & Lifestyle: Increasing access to open information and data, along with improved education outcomes, sees a high-tech economy flourish. This is supported by migration from current global technology hubs for Melbourne's liveability, especially in comparison to increasing tension in more traditional centres. Australia, and in particular Victoria, is seen as a safe investment centre with good access to growing Asian markets. This changing economy is supported by a regulatory framework that encourages and supports innovation with appropriate safety nets, along with continued investment in higher education and science, with a long-term strategic vision of making Melbourne the education centre of the Asia-Pacific region. Changes to the economy's structure to less traditional industries are supported by government investment in re-training programs and facilities, along with supporting small scale high-tech industrial developments. Workplace engagement is also high, with a diverse economy providing flexible opportunities for all sectors of society to participate. This flexibility allows a slower entrance to retirement and lessens the burden on social services. These changes in lifestyle result in a growing appreciation of cultural and arts precincts, with growing investment in social and environmental values supporting a connected and engaged populous. This investment is supported by government, but also increasing levels of philanthropy and corporate social responsibility actions.

Politics & Institutions: An increasingly educated and engaged general populous, as well as political parties, see advantages in embracing deep community engagement and co-development in the policy process. Flexible and fulfilling employment allows citizens to become more active in the direction the region takes and increasing tech solutions allow community engagement and citizen juries to become simpler and more efficient. This high level of community engagement is also enabled by a stronger public service, with public servants empowered and encouraged by the public and politicians to offer solutions to systemic, long-term challenges that fall outside the effective influence of political cycles. A strong public service is evident across levels of government, with strategic collaboration and development between State and Local governments. This facilitates a balanced approach to meeting state-wide objectives and local needs through place-based planning.

Technology & Infrastructure: The economic shift to technology in the region sees innovation being applied across all sectors of society. This results in new technology, such as drones, being used to reduce risk and improve efficiency via remote management and inspection and the provision of early warning systems. Infrastructure planning and provision of services is done in a coordinated manner to enable development. This results in the connection of residential areas with integrated transport networks of bike lanes, public transport and on-demand services. Construction methods are also improved, reducing the vulnerability of structures to hazards, along with community support for high standards in line with other countries' response to climate adaptation and mitigation. In addition, an increasing appreciation of a broader set of values, rather than those focused on financial factors, sees buildings retrofitted to improve safety and resilience.

S.2 – Local and Lovin' it

Low challenges to resilience. High challenges to government action and intervention.

Population and urbanisation: Lower levels of migration to the region due to Federal policies result in slower than anticipated population growth, although migration rates remain sufficiently high for Melbourne to be one of the fastest growing regions in Australia. The lower-than-anticipated migration rate causes a slight ageing in the demographic profile and results in a community that prefers a stable and traditional base, is knowledgeable about the land they live on and is able to deal with small scale hazards that occur reasonably frequently. The community has an inward-looking focus, with a dislike for government interference, especially in relation to large-scale projects requiring significant resources and dealing with long-term development, as they feel entitled to being able to maintain the status quo, regardless of longer-term impacts.

Community Profile: The demand of older generations seeking a more rural lifestyle results in an increased local understanding of nature, its values and its risks, which is supported by increased access to information via technology from private providers due to increasing satellite technologies. This leads to resilient, local communities, capable of dealing with their own small, local risks. However, a lack of diversity and inability to consider changing risks sees communities more exposed and vulnerable to large-scale disasters. There is a strong sense of community, both in the rural areas as well as the inner city, with active inner city and rural networks. However, due to their limited exposure to hazards, urban communities have not built up much understanding about them. The strong sense of community empowers the population and makes people more resilient and confident in being able to handle hazards. A limited understanding of large-scale and long-term developments, however, puts limitations on the actual capability to deal with more extreme and cascading events. Along with the feeling of empowerment and entitlement is a distrust of government intervention and public research and information due to a series of failings at an institutional level at both a State and Federal level.

Economy & Lifestyle: The emphasis on small government and reduced regulation result in industrial innovation growth and increasing privatisation of smaller government services. This is driven by a community distrust of government, due to their perception of inefficiency, resulting in a preference for private companies to run public services. The State does hold on to larger assets, as large-scale investment into the State is not forthcoming, with national policies not favouring foreign investment. Along with restricting foreign investment via protectionist trade policies, there are few State government incentives to attract large national or foreign industrial/tech firms. There is growth in small scale, boutique agriculture with a community preference for locally grown, organic produce. The same protectionist trade policies restricting industrial investment result in a focus on agriculture and food security in Australia, and allows Victoria to position itself as one of the nation's and region's most prosperous food bowls.

Politics & Institutions: Institutional failings lead to large community distrust in government and, as a result, more and more public services become privatised at the will of the public. A stripped back public service struggles to catch up with new technology and its adoption, as well as associated legislation and regulation. This offers short-term benefits in innovation in a world of limited regulation, but also poses new risks that government is not equipped to deal with. Short-termism creeps in and initial gains in innovation are not sustained without government support, both financially and institutionally. There is also pressure on the three tiers of government, with State and Local government merged. This sees a lack of local level engagement and understanding, further exacerbating local communities' angst at the lack of understanding by government.

Technology & Infrastructure: There is a slow privatisation of assets, especially in the energy sector, which results in new and existing development shift away from badly maintained and increasingly costly centralised energy grids to localised micro-grids, managed by a suite of local companies. Empowered businesses and a small government puts a halt to long-term investment in infrastructure, with local businesses, due to their need to be competitive, under pressure to focus on short term gains. This results in local developments that are designed to cater to currently known risks that are considered likely, but larger and cascading risks are not considered.

S.3 – Brittle Balance

Low challenges to government action and intervention. High challenges to resilience.

Population and urbanisation: Australia develops its social and immigration policies to encourage migration from climate impacted and other vulnerable areas of the world. This, however, is not matched by a Federal housing affordability plan and results in metropolitan regions, such as Melbourne, increasingly opening land on the urban fringes and in rural areas to facilitate the development of new housing estates. Government believes its role is to facilitate such development so as to decrease pressure on urban areas. This development in regional areas is reinforced by policies focused on rebalancing growth between regions and the city, with a particular focus on housing affordability, resulting in Victorians (encouraged by government policies) seeking property further from the city. State government policies to stimulate such development, however, result in disjointed efforts, with a lack of integration of residential and other land uses leading to reduced accessibility to services. This re-balancing of the regions and the city also results in stark contrasts between dense and sparse urban patterns. With increasing restrictions on Greater Melbourne's land supply, there is a resulting increase in high density living, while, at the same time, new developments in regional areas consist of large blocks of land to encourage uptake, resulting in low density residential developments.

Community Profile: The trends of urbanisation and regional development result in growing numbers of new migrants and lower income families living in areas of high hazard risk, who have little understanding of their exposure and vulnerabilities. Due to their disconnect from activity centres and jobs, commuting times are long, allowing little opportunity to develop a sense of community. This lack of community (along with poor communication due to a lack of effective integration programs) produces cultural and demographic tensions that place stress on the cohesiveness of society. As a result of the promoted urban form of high-density inner city living and regional disconnected suburbs, an elderly section of the community (isolated in traditional suburbs of Greater Melbourne) is left with large properties to maintain or required to downsize and move to inner city communities, where they have few connections.

Economy & Lifestyle: Effective top-down government intervention and timely stimulus programs and tax breaks for foreign investment see Victoria return to the prime manufacturing centre of the nation. New manufacturing hubs from foreign companies are developing, with an emphasis on just-in-time production, reducing production lag and increasing efficiency, allowing Australian manufacturing to compete globally based on cost. The gains seen in the manufacturing industry result in growing economic output, but not always in growing employment, and the economic successes in manufacturing are not replicated in other sectors that have a higher level of reliance on local companies. This results in reduced employment opportunities for new migrants. However, government supported safety nets exist to provide financial support to all who require it, although this increases dependence on government support. Global manufacturing giants manipulate profits out of Australia and there is little transfer of knowledge, with much of the expertise coming from overseas. Lack of public and private investment in non-manufacturing sectors results in compressed markets and a lack of innovation.

Politics & Institutions: A burgeoning public service results in the institutionalisation of many systems, but little opportunity to innovate and a lack of flexibility to respond to complex, emerging challenges. The continuous promotion of increasing numbers of government studies creates a sense in the community that all is well, and that the State is well-placed to protect its citizens, regardless of the severity of a hazard event. There is, however, little contingency planning on behalf of the government and private industry if things do go catastrophically wrong. Emergency management services are functional and are well supported through appropriate budget allocations, providing sufficient response capabilities and resulting in the development and implementation of effective building regulations. However, Government policies also embrace a 'one size fits all' philosophy, which creates tension in some parts of society and results in a growth of single-issue political parties. Diversity is managed more than embraced, and as such, there is a lack of development of social cohesion between different community sectors.

Technology & Infrastructure: Strong systems of assessment result in a focus on rigid infrastructure. This focus, however, also results in inflexibility to changing demands and pressures. A lack of long-term vision and planning results in infrastructure operating at or over capacity, with little flexibility to adapt to growth. Infrastructure planning is also characterised by siloed thinking, with a lack of consideration of broader impacts or co-benefits in decision-making processes. The emphasis on 'just-in-time' results in little redundancy and resilience in networks and little contingency planning in the case of loss of essential services. New technologies, like driverless cars, are effectively adopted and integrated within current networks. However, the efficiency of their integration has not been coupled with any contingency planning.

S.4 – Polarised Prosperity

High challenges to resilience. High challenges to government action and intervention.

Population and urbanisation: Migration rates remain on trend, however, the continued ageing of the population, change in economic structure and shift in the desirability of Melbourne has resulted in migration requirements shifting from skilled labour to services for the elderly. The impact of an ageing population is exacerbated by the economic divide of the region between those forced into early retirement due to a lack of accessible employment, and those looking to enjoy their retirement in Victoria's natural beauty. Emigration of skilled migrants increases with the globalisation and casualisation of the workforce, resulting in those enabled and engaged with global workflows moving away in search of different markets.

Community Profile: The increasing disconnect between those needing services and those providing them, and those profiting from privatisation of governments services and those left vulnerable without them, incites polarisation of social views. At an inner-city level, this results in rising civil unrest, driven by increasing frustration at growing poverty and political disenfranchisement. People increasingly rely on outsourced services in all aspects of their lives, because access to them is easy and quick. Additionally, people's limited time availability (caused by unstable employment requiring more time devoted to working) drives them to those services. This increased reliance on outsourcing decreases the ability to self-sustain. Cost-of-living pressures are particularly severe for the increasingly elderly population, with decreased government services requiring increased self-reliance. This results in older generations shifting from the city in search of cheaper accommodation, and aged-care residences developing increasingly in rural areas. It also results in tensions between generations, with savings and investments used to support retirement, instead of being passed on to future generations. Another response to these pressures is the increase of multi-generational households on the urban fringe, or property exchanges between generations. Changes to work practices impact on the development outcomes of younger generations, with less parental care and support due to the need to generate income. This has flow-on impacts to educational attainment and an increase in youth crime rates.

Economy & Lifestyle: Working styles become increasingly transient at both local and global levels. This transience is linked with the casualisation of work and the need to travel to secure employment. At a regional level, the decline in government investment in transport infrastructure and public transport results in people renting closer to their workplaces. However, with these becoming less permanent, many sections of society find themselves moving around the region frequently. At a global level, the workforce is more fluid, with skilled, and globally oriented workers finding themselves based on project work, taking them to various corners of the world. This results in a flux of workers moving in and out of the region for varying periods of time, causing a lack of local understanding and the application of global solutions to sometimes more local problems. Companies are focused on short-term projects and profit-making and capitalise on a slow global uptake of climate policies to exploit fossil-fuel based products. This sees Victoria's economy remaining heavily reliant on these resources - with little planning for transition, as private organisations with vested interests increasingly impose their will on government, which, with more public-private partnerships (PPP) has weakened institutional influence. This focus exposes economic vulnerability when global markets move away from imports of materials in a response to tackle climate change. Large scale agriculture is a key component of the economy but with a preference on cash crops and monocultures to feed the globe, rather than local farmers living on and understanding the land.

Politics & Institutions: Reduced tax revenue from declining economic prosperity of the State and strong industries flexing influence to negotiate tax concessions, along with the more flexible working styles of taxpayers allowing them to more easily avoid paying tax, results in a government with a declining public service and fewer investment options. This smaller government leads to reduced services provided, increasing privatisation of service provision, and selling off assets. When investment is undertaken by government it is often through PPP. The government increasingly becomes a contract and project manager, tendering out risk. This privatisation results in growing knowledge inequality, with a reduced focus on open government and data. Strong central planning is decreased, as there is a continual need to demonstrate private benefits to ensure PPPs are realised. This results in vested interests driving change, as opposed to societal needs.

Technology & Infrastructure: With more focus on on-demand services, there is a growing reliance on technology and the internet. Contingency planning is lacking, which becomes especially apparent in out-of-the-ordinary situations such as hazard events. There is inequality in service provision and infrastructure maintenance, with assets that are now privately owned being well maintained through the revenue they generate, while public services and assets fall behind. Decreased planning and the prioritisation of profit over social good results in the creation of new homogenous developments with little provision of services.

6.2 TRANSLATING STORYLINES INTO MODEL INPUTS

The starting point for translating the storylines in Section 6.1 into model inputs was the identification of the scenarios across key factors (Table 1). Information from Table 1 was subsequently elaborated upon in deriving a set of inputs and parameters for modelling the corresponding socio-economic futures. Table 2 shows which settings have been selected for each scenario for the model input types listed on the left-hand side of the table.

TABLE 1: SCENARIO IDENTIFICATION ACROSS KEY FACTORS.

TABLE 2: MODEL SETTINGS FOR EACH SCENARIO.

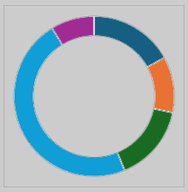
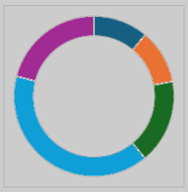
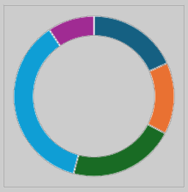
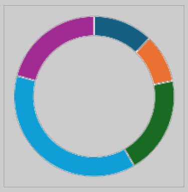
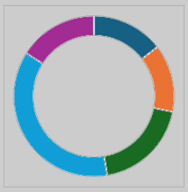
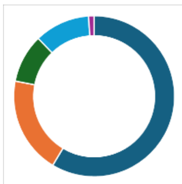
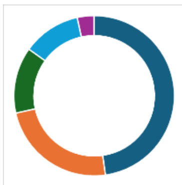
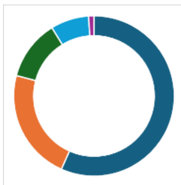
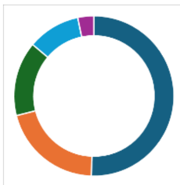
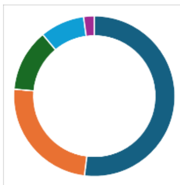
Model input or parameter	Living with Nature	Local and Lovin' it	Brittle Balance	Polarised Prosperity
Population	10 M	8.5 M	12 M	10 M
Urban land use developments (interaction rules, accessibility parameters)	Integration of nature in urban areas, mixed use developments	Limited growth of urban areas	Development of peri-urban areas and increase in density in urban core	Expansion into urban fringe
Rural land use developments (interaction rules, accessibility parameters)	Distance between nature and urban areas, no uncontrolled urban sprawl in natural areas	Increase in agriculture, mix of residential development and agriculture, industrial innovation with some growth expected	Large-scale, low density residential development in rural and regional areas, with limited access to services	Focus on agriculture - cash crops, residential development in rural areas next to existing development
Building resilience (vulnerability curves[13])	Adapted vulnerability curves for bushfire and coastal inundation risk to reflect more resilient buildings in new developments	Adapted vulnerability curves for bushfire and coastal inundation risk to reflect more resilient buildings in new developments	Adapted vulnerability curves for bushfire and coastal inundation risk to reflect more resilient buildings in new developments	Standard vulnerability curves
Land use planning (zoning to restrict development in hazard-prone areas)	Zoning to restrict new urban development in locations prone to coastal inundation or bushfires	No restrictions to develop in hazard-prone areas	No restrictions to develop in hazard-prone areas	No restrictions to develop in hazard-prone areas
Structural mitigation (seawalls implemented in inundation maps)	Seawalls implemented to protect assets against a 1/100-year event	No structural mitigation implemented	Seawalls implemented to protect assets against a 1/100-year event	No structural mitigation implemented

An important distinction between the scenarios is the future allocation of total area per land use type. To decide on the land area for different land use types, we first distributed the population over the different land use classes and next assessed the demand for each residential land use class based on the population and the land use specific density. Results for both are provided in Table 3.

[13] See Annex I for adapted vulnerability curves applied.

Economic land use demands were set based on the population developments, in combination with specific scenario drivers (e.g., more focus on agriculture in S2-Local and Lovin' it, and more focus on industry in S3-Brittle Balance). An overview of the numeric values for land use demands for all dynamic land use classes (land uses that evolve during the simulation) is provided in Table 4. Figures 8 and 9 show a graphic representation of the land area for 2020 and for each scenario (2050). The distinct features of the scenarios are represented in the calculated land use demands: the small urban footprint of S1-Living with Nature, the rural focus of S2-Local and Lovin' it, with a large increase in rural residential and a focus on agriculture, the high population growth of S3-Brittle Balance resulting in a high overall growth of the urban uses and an increase in industrial areas at the cost of agriculture, and S4-Polarised Prosperity with an increasing area of low residential development on the outskirts of the city and the countryside.

TABLE 3: POPULATION AND LAND USE FOR INITIAL YEAR (2020) AND SCENARIOS (2050).

	2020	**Living with Nature**	**Local and Lovin' it**	**Brittle Balance**	**Polarised Prosperity**
Population					
Land use					

■ Rural Residential ■ Low density residential
■ Conventional density residential ■ Medium density residential
■ High density residential

TABLE 4: OVERVIEW OF LAND USE DEMANDS (HA) IN 2020 AND THE DIFFERENT FUTURE SCENARIOS (2050).

Urban land use type	2020	Living with Nature	Local and Lovin' it	Brittle Balance	Polarised Prosperity
High density residential	5,333	19,585	7,477	23,364	14,932
Medium density residential	52,293	67,797	52,542	76,271	62,166
Conventional density residential	45,843	77,273	82,851	107,875	87,396
Low density residential	91,517	137,500	153,450	147,197	170,322
Rural residential	276,097	276,097	387,420	362,295	362,295
Tourism accommodation	2,079	3,198	2,718	2,885	2,398
Community services	53,332	82,037	69,731	98,444	61,528
Office	559	1,290	731	1,032	860
Retail / Commercial	6,074	14,015	7,942	11,212	9,343
Industrial	18,450	18,450	24,123	34,056	21,285
Intensive agriculture	12,072	10,725	13,279	10,725	13,279
Horticulture	22,081	19,618	24,289	19,618	24,289
Pasture	135,496	119,032	113,998	106,660	116,699
Livestock	170,852	151,787	153,454	154,026	163,123
Mixed farming & grazing	966,019	858,223	884,990	796,430	831,820
Forestry	67,536	67,536	67,536	67,536	67,536
Forest	336,389	337,029	333,178	335,824	336,297
Nature	449,664	511,194	403,421	432,520	438,179
Shrub & vacant	90,718	30,018	19,274	14,434	18,657

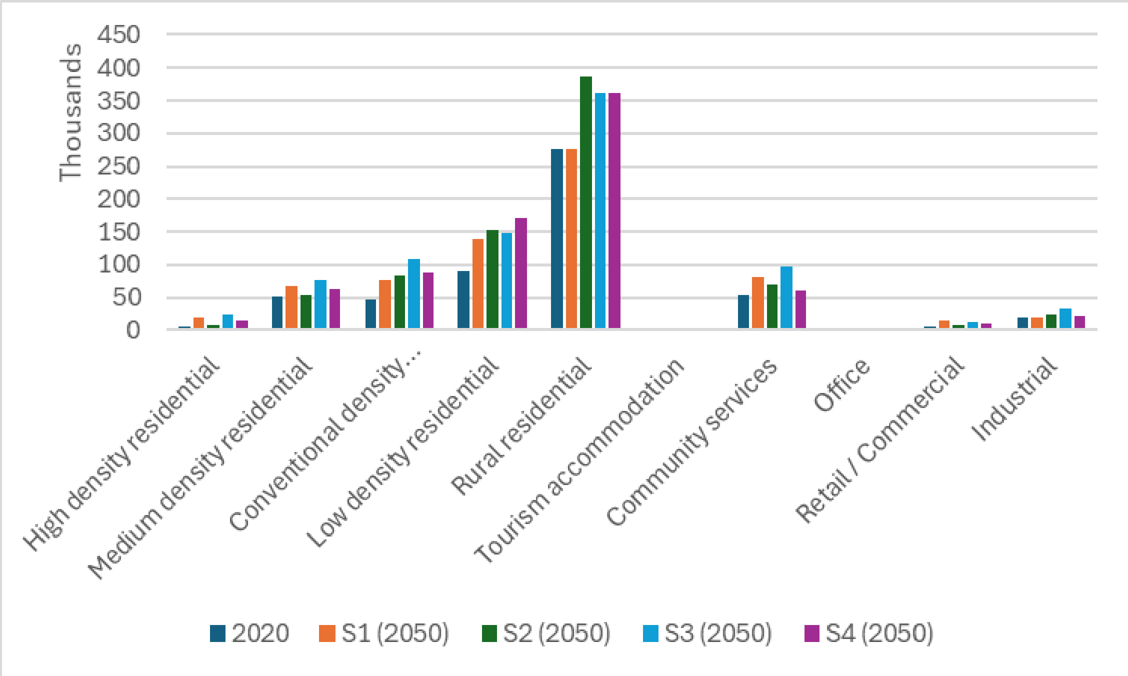


FIGURE 9: TOTAL AREA (HA X1000) PER URBAN LAND USE TYPE IN 2020 AND FOR EACH OF THE SCENARIOS (2050).

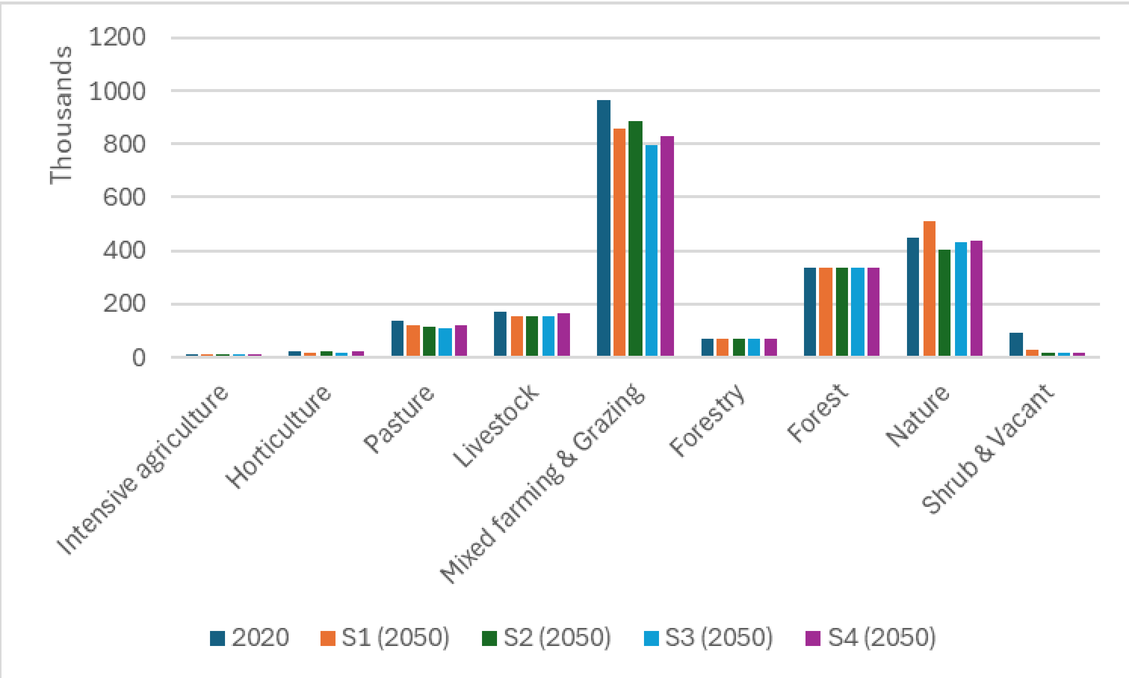


FIGURE 8: TOTAL AREA (HA X1000) PER AGRICULTURAL AND NATURAL LAND USE TYPE IN 2020 AND FOR EACH OF THE SCENARIOS (2050).

6.3 SOCIO-ECONOMIC PATHWAYS IMPACTING ON EXPOSURE

The simulated scenarios show distinct land use developments over time (2020-2050). **S1-Living with Nature** has the smallest urban footprint, and little new development into the rural areas. New developments that emerge in the rural areas are clustered and next to existing development. The mixed-use development and the integration of nature into the urban core is shown in the map inset in Figure 10.

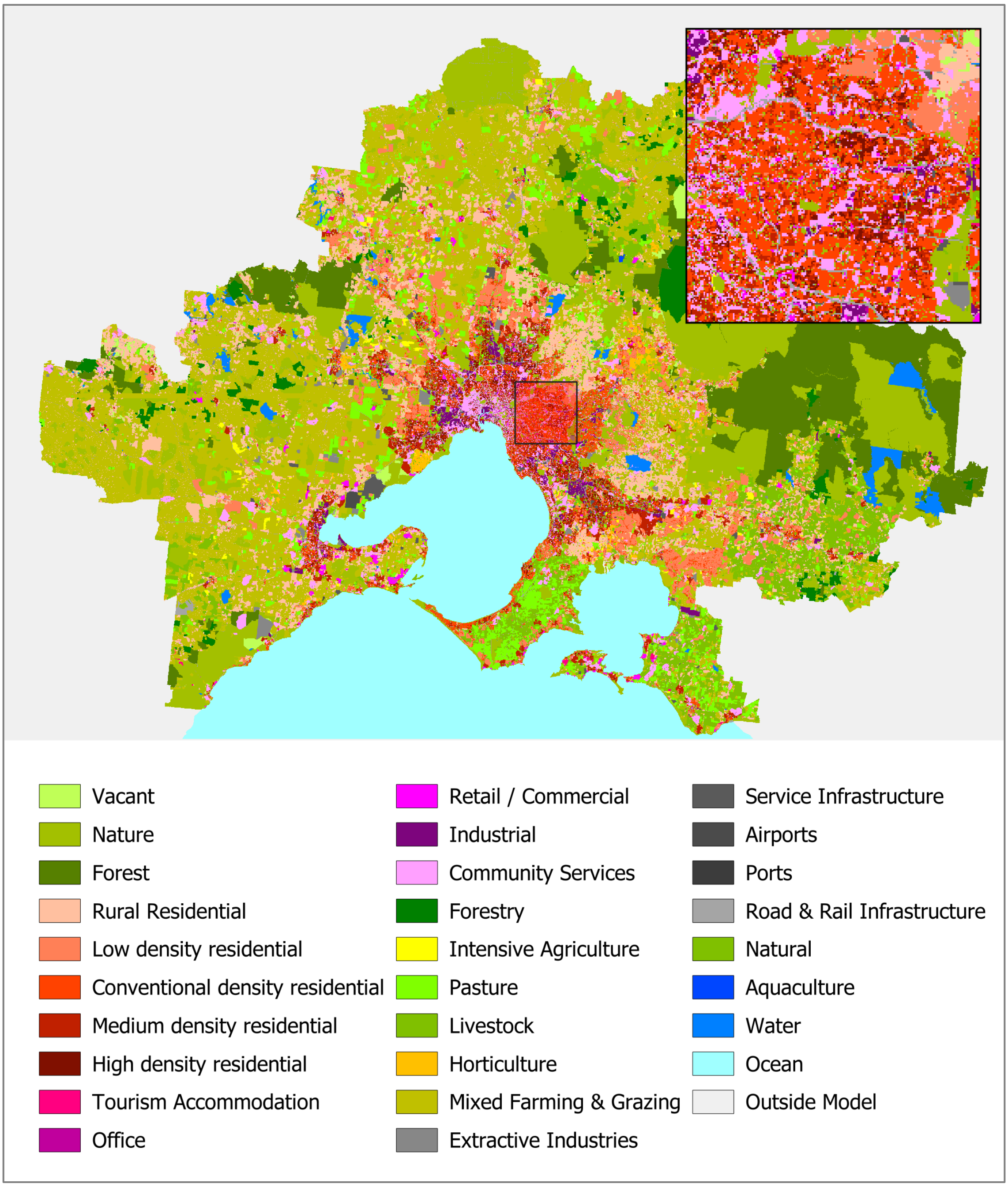


FIGURE 10: SCENARIO S1 - LIVING WITH NATURE: SIMULATED LAND USE MAP FOR 2050. THE MAP INSET SHOWS A MIXED URBAN DEVELOPMENT WITH NATURE INTEGRATED IN THE BUILT-UP AREAS.

Although **S2-Local and Lovin' it** has the lowest socio-economic growth, the increase in rural development is substantial (Figure 11). With a focus on agriculture, and limited protection of nature, new rural residential developments emerge within nature areas, as indicated by the example in the blue circle on the map.

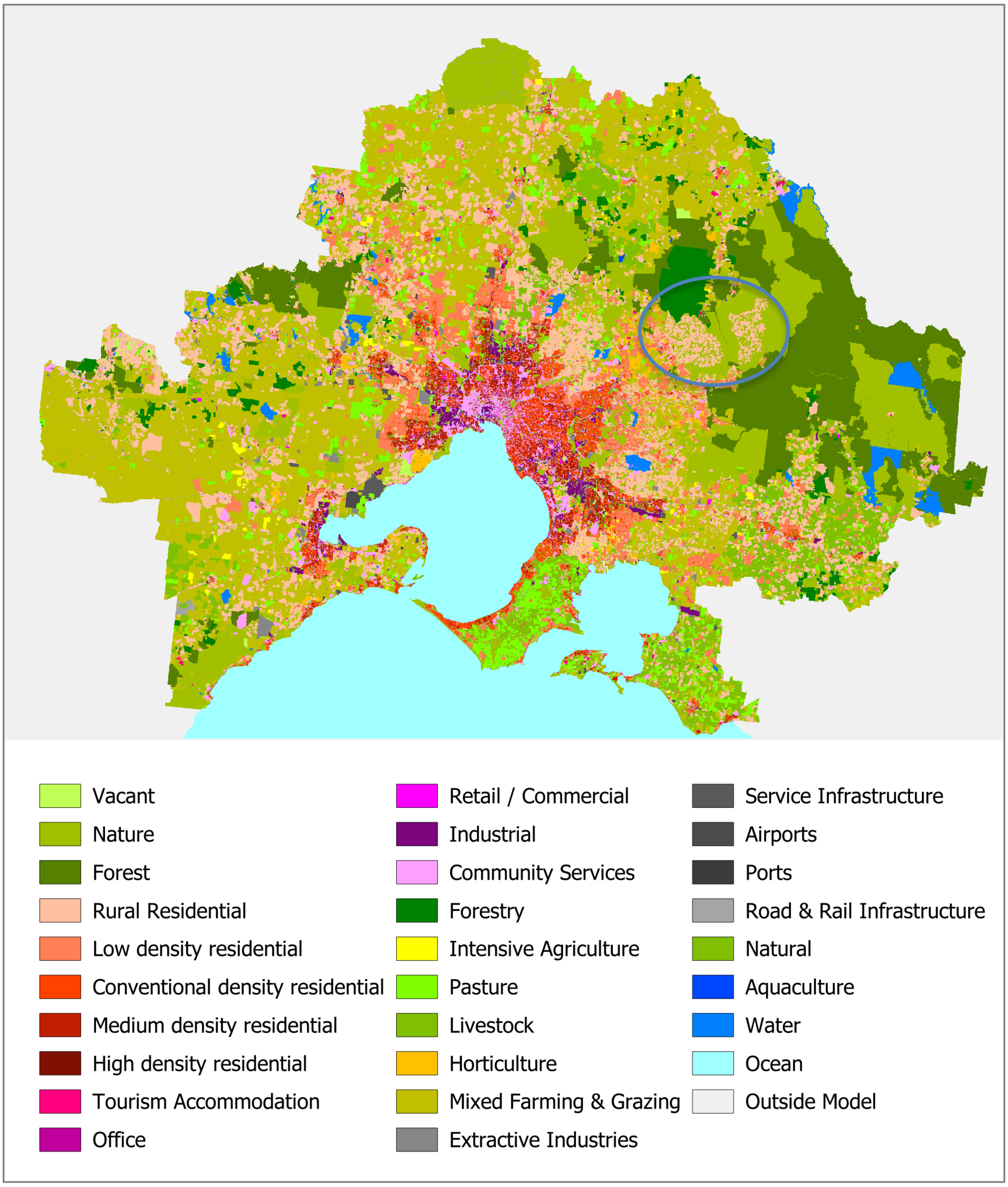


FIGURE 11: SCENARIO S2 – LOCAL AND LOVIN' IT: SIMULATED LAND USE MAP FOR 2050.

With the highest population growth, **S3-Brittle Balance** shows clear urbanisation patterns, with new urban areas emerging close to the urban core and in the peri-urban space as indicated by the blue circles (Figure 12). As the coastline is not protected from urban development, denser urban land uses can be found here as well. The additional growth in industry compared with the other scenarios can mainly be found close to original industrial developments (for example, as indicated by the purple circle).

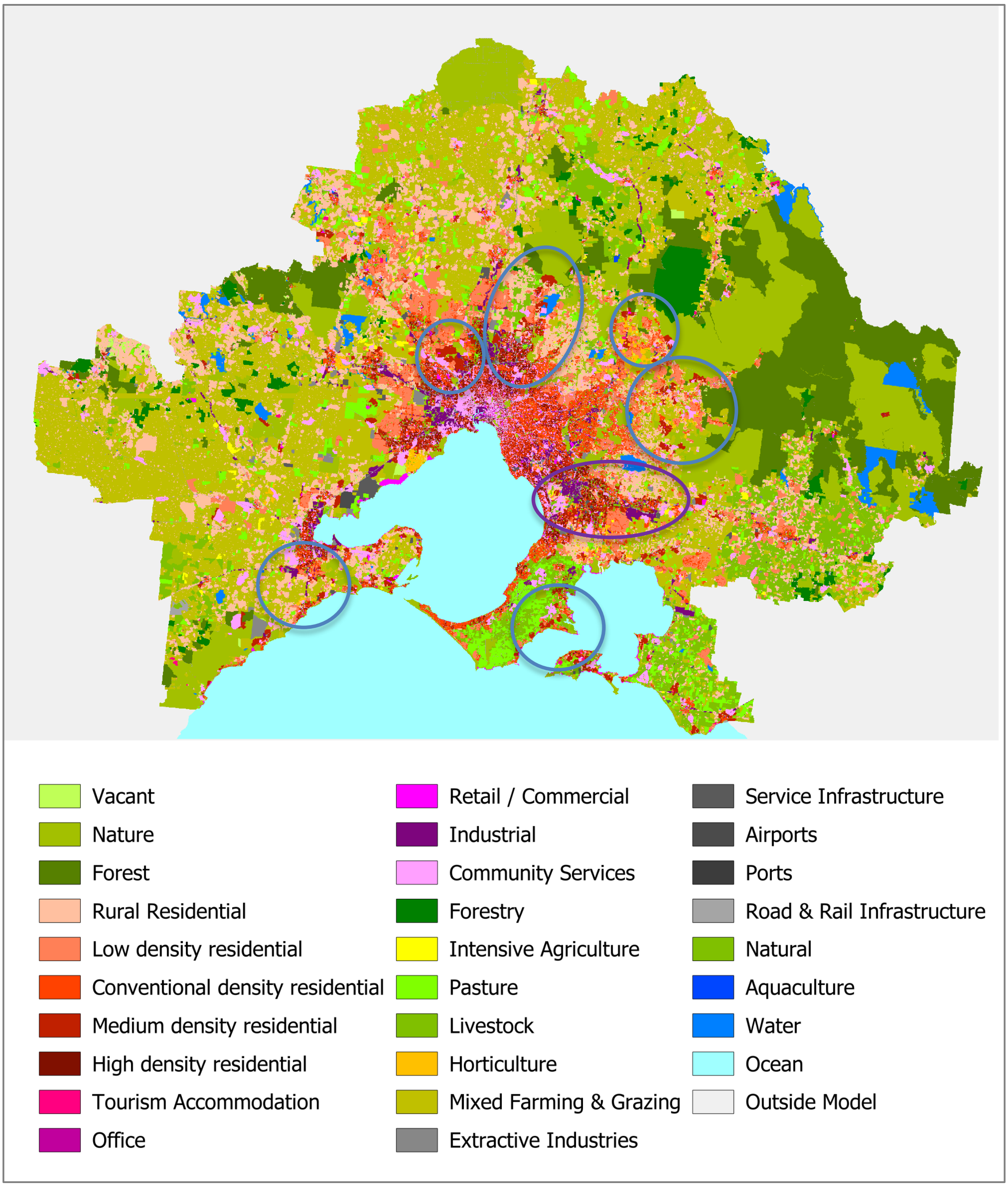


FIGURE 12: SCENARIO S3 – BRITTLE BALANACE: SIMULATED LAND USE MAP FOR 2050.

S4-Polarised Prosperity follows ongoing land use development trends and is least distinct in its growth pattern (Figure 13). It resembles S2: Local and Lovin' it, although results in urban development within the agricultural areas instead of the nature areas, and has slightly denser developments (more low density developments compared with rural residential development) due to the requirement for better accessibility in this scenario.

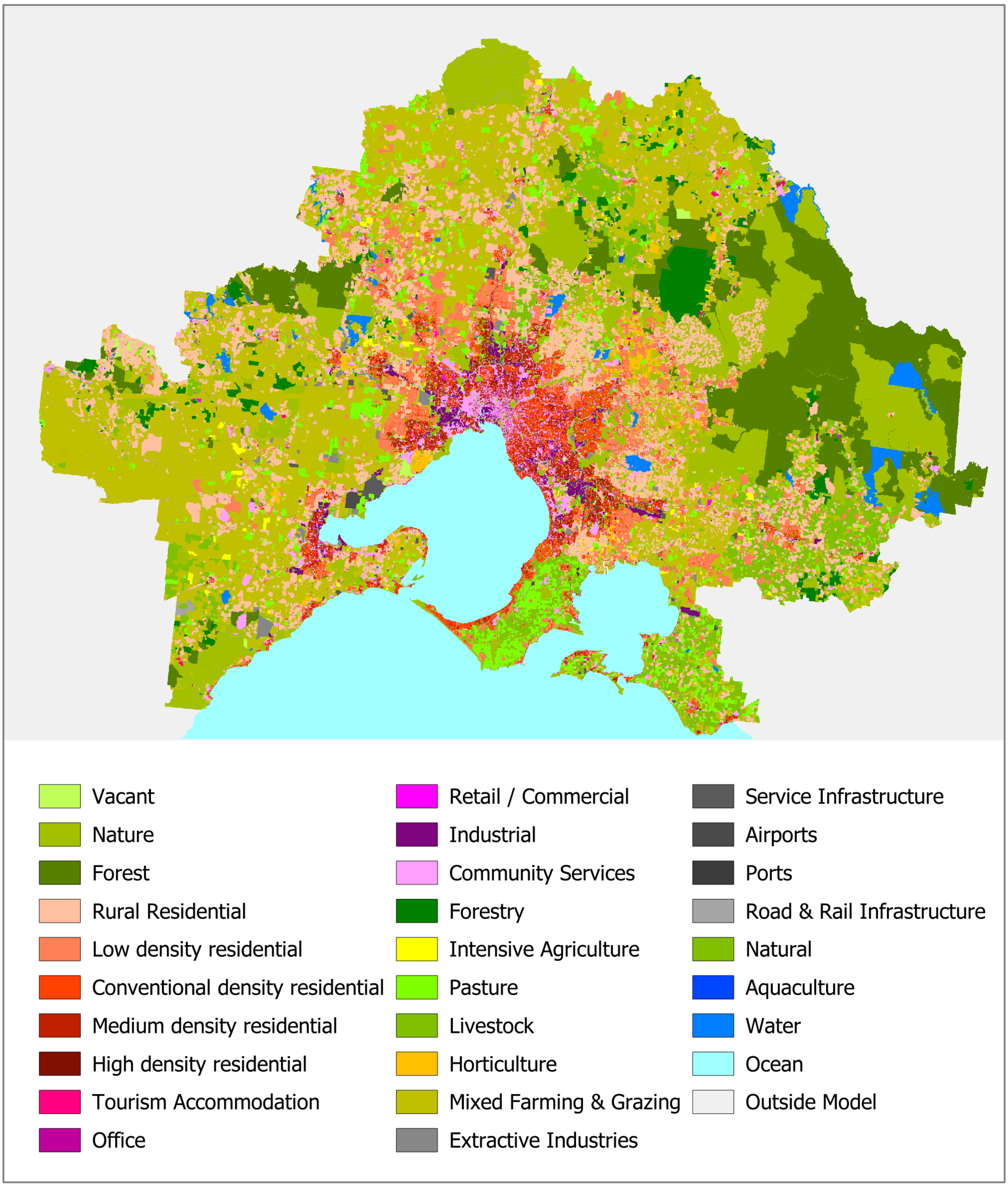


FIGURE 13: SCENARIO S4 – POLARISED PROSPERITY: SIMULATED LAND USE MAP FOR 2050.

6.4 QUANTIFYING FUTURE RISK PROFILES

Bushfire and coastal inundation risks, expressed as average annual damage (AAD), was assessed for the initial year (2020) and for each of the socio-economic pathways for two climate scenarios: RCP 4.5 and RCP 8.5. Results are provided as change compared to the initial year.

With regard to coastal inundation, Figure 14 shows that future risk in S1-Living with Nature is assessed as being the lowest, while future risk in S4-Polarised Prosperity is assessed as being the highest. This is in line with expectations according to the scenario framing, with S1 resembling a vision for the region and S4 assuming the worst in terms of resilience and government action. The low risk in S1 (i.e., an expected decrease of 39% from the 2020 risk for RCP 4.5 and an expected decrease of 28% from the 2020 risk for RCP 8.5) can be explained by the implementation of the seawalls, the restriction to build in areas most prone to coastal inundation and improved building resilience for new developments. The largest contributor to S1's lower risk profile relative to the initial year is that S1 has seawalls implemented and the initial situation has not. Over the simulation period, the AAD in S1 does increase, especially due to sea level rise, but not to the extent that it exceeds the risk for 2020. With no risk reduction options implemented, S4 has the highest risk (i.e., 575% of the 2020 risk for RCP 4.5 and 612% of the 2020 risk for RCP 8.5). This increase of approximately a factor 6 is due to new developments located along the coast, without any improvements to the building standards, nor any implementation of structural measures.

Scenarios S2-Local and Lovin' it and S3-Brittle Balance show some interesting results. While S3 has the highest population increase (and related urban development on the coast) and S2 the lowest, their future coastal inundation risk is very similar (i.e., 365% and 337% of the 2020 risk for S2 and S3 respectively for RCP 4.5, and 387% and 360% of the 2020 risk for S2 and S3, respectively for RCP 8.5). This can be explained by the seawalls implemented in S3 limiting the inundation, hence decreasing risk. The improved building standards in both scenarios are the cause of the lower AAD compared to S4.

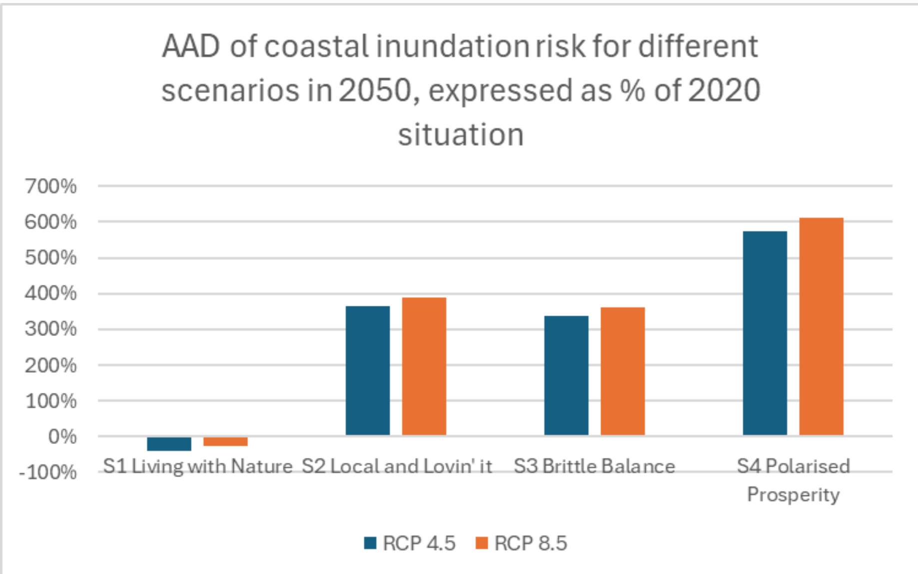


FIGURE 14: COASTAL INUNDATION RISK 2050 ACROSS SCENARIOS. AAD VALUES AS % OF THE INITIAL SITUATION (2020).

It should be noted that the differences in future coastal inundation risk due to different climate change scenarios are very small for all scenarios.

With regard to bushfire, Figure 15 shows that S1-Living with Nature results in the lowest future risk amongst the scenarios, while S2-Local and Lovin' it is expected to have the highest future risk. The lower risk of S1 (i.e., 105% of the 2020 risk for RCP 4.5 and 106% of the 2020 risk for RCP 8.5) can be explained by the zoning regulations to restrict urban development in the most bushfire-prone areas and the increasing resilience of the building stock due to new developments having higher fire resistance and people maintaining their property better. Although the same building resilience is applied to S2, its positive effect is overshadowed by the vast rural, low density residential developments in bushfire prone areas, resulting in significantly greater increases in risk in this scenario (i.e., 136% of the 2020 risk for RCP 4.5 and 139% of the 2020 risk for RCP 8.5).

Scenarios S3-Brittle Balance and S4-Polarised Prosperity have a similar future risk profile (i.e., 117% and 121% of the 2020 risk for S2 and S3 respectively for RCP 4.5, and 119% and 123% of the 2020 risk for S2 and S3 respectively for RCP 8.5). Although S3 has a much higher population growth, development is mostly in the denser residential areas and due to the building standards in place in this scenario, the building stock in the fire-prone areas is more resilient. S4 has more low-density development in bushfire prone areas and does not assume improved building standards or appropriate property management, making the risk profile similar to that of S3.

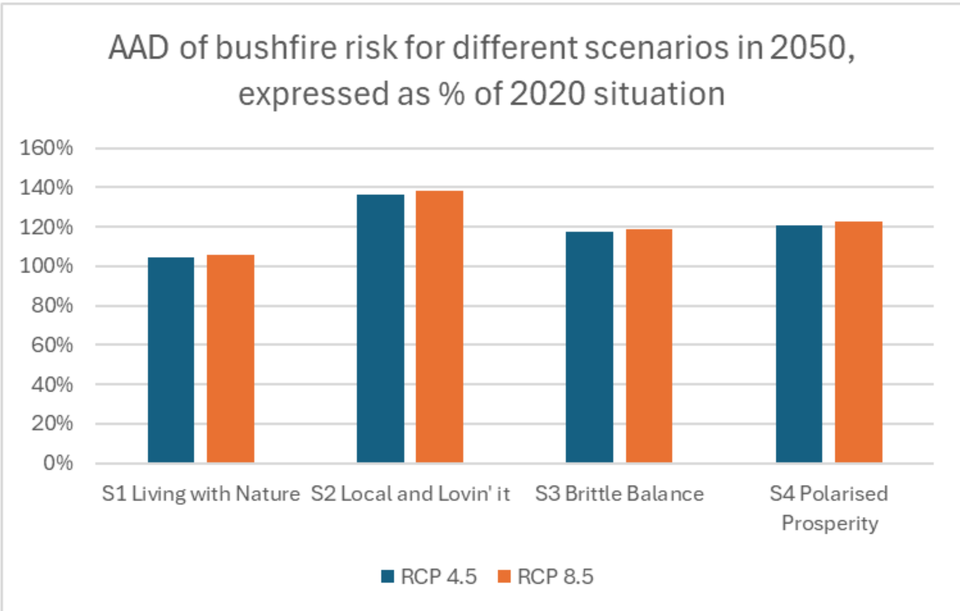


FIGURE 15: BUSHFIRE RISK 2050 ACROSS SCENARIOS. AAD VALUES AS % OF THE INITIAL SITUATION (2020).

Comparing the coastal inundation and the bushfire risk profiles across the various scenarios, we see that the range of coastal inundation risk (AAD) is much larger than that of bushfire risk. The best-case scenario for coastal inundation has an expected decrease of 39% from the 2020 risk, while the worst-case scenario sees an increase in risk of 612% of the 2020 risk. In contrast, the best-case scenario for bushfire risk has an expected increase in risk of 105% of the 2020 risk, while the worst-case scenario sees an increase in risk of 139%. The large difference in risk in the coastal inundation scenario can be explained by both the expected impact of sea level rise on the hazard and the new urban development in the hazard prone locations. Furthermore, the mitigation options for this hazard can be very effective, as both the implementation of seawalls and not having any further exposure in the hazard prone areas can result in vast decreases in risk.

7 CONCLUSIONS AND LESSONS LEARNT

This study has shown a potential use of UNHaRMED for understanding future risk and assessing the impact of risk reduction under various future scenarios. It has shown how storylines can be combined with quantitative modeling to better understand future uncertainties regarding socio-economic developments and related risk profiles.

Results show that socio-economic growth does not necessarily have to result in an increase in risk, if appropriate risk reduction strategies can be put in place. Restricting development in hazard-prone areas, structural mitigation options such as seawalls, and making the building stock more resilient, all contribute to reducing the risk. Likewise, without any measures put in place, a large part of society will be exposed to risk and this risk will only increase into the future.

The application of UNHaRMED to Greater and Peri-Urban Melbourne has demonstrated that:

- The use of integrated modelling approaches, coupled with qualitative scenarios analysis, is vital for enhancing understanding of future risk.
- Changes in future risk are non-linear, both spatially and temporally, highlighting the importance of quantifying the spatio-temporal dynamics of future risk explicitly.
- It is vital to consider changes in both population growth and socio-economic development (affecting future exposure) and climate change (affecting future hazard) in the assessment of future risk.
- The data requirements for UNHaRMED are significant, and the uncertainty present in the modelling results is dependent on the quality of the input data. In the absence of accurate data, reasonable assumptions can be made, but it is important to evaluate the modelling results in light of these assumptions.
- Decision support systems like UNHaRMED need to be tailored to specific decision contexts with the aid of stakeholder input. A joint participatory and modelling approach strengthens the modelling and facilitates its understanding, relevance and uptake amongst stakeholders. Moreover, it enables the incorporation of important aspects relevant to the decision-making process that cannot be modelled.
- While the application of UNHaRMED offers significant flexibility, it is likely that changes to the software are required in order to meet specific end-user needs in different decision contexts.

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ANNEX I – VULNERABILITY CURVES

VULNERABILITY CURVES FOR BUSHFIRE RISK

All buildings with the same BAL type are expected to have a similar damage when confronted with a fire of a similar intensity expressed as radiant heat flux (RHF).

Bushfire vulnerability curves are defined based on the standards for the different BAL types, as shown in Table A-1. Adapted bushfire vulnerability curves for scenarios with increased building resilience have been obtained by moving the RHF value a building type can withstand 25% into the direction of the RHF value of the next, more fire-resistant, building type. The RHF value of the highest category has been raised by 10%.

TABLE A-1: BUSHFIRE VULNERABILITY CURVES FOR DIFFERENT BAL TYPES. A VALUE 0 RESEMBLES A DAMAGE INDEX OF 0, OR NO DAMAGE, A VALUE OF 1 RESEMBLES A DAMAGE INDEX OF 1, OR TOTAL DESTRUCTION. CURVES ARE LINEARLY INTERPOLATED BETWEEN DAMAGE INDEX VALUES.

Radiant Heat Flux (kW/m²)	BAL Low	BAL 12.5	BAL 19	BAL 29	BAL 40	BAL Flame Zone
0	0	0	0	0	0	0
6	1	0	0	0	0	0
12.5	1	1	0	0	0	0
19.5	1	1	1	0	0	0
29	1	1	1	1	0	0
40	1	1	1	1	1	0
60	1	1	1	1	1	1

TABLE A-2: ADAPTED BUSHFIRE VULNERABILITY CURVES FOR DIFFERENT BAL TYPES FOR SCENARIOS WITH INCREASED BUILDING RESILIENCE. A VALUE 0 RESEMBLES A DAMAGE INDEX OF 0, OR NO DAMAGE, A VALUE OF 1 RESEMBLES A DAMAGE INDEX OF 1, OR TOTAL DESTRUCTION. CURVES ARE LINEARLY INTERPOLATED BETWEEN DAMAGE INDEX VALUES.

Radiant Heat Flux (kW/m²)	BAL Low	BAL 12.5	BAL 19	BAL 29	BAL 40	BAL Flame Zone
0	0	0	0	0	0	0
7.2	1	0	0	0	0	0
14.3	1	1	0	0	0	0
20.5	1	1	1	0	0	0
31.8	1	1	1	1	0	0
45	1	1	1	1	1	0
66	1	1	1	1	1	1

VULNERABILITY CURVES FOR COASTAL INUNDATION RISK

The coastal inundation vulnerability curves used in this study built on the damage functions developed by the European Union Joint Research Centre (Huizinga et al., 2017). These functions are provided for different global regions, including Oceania. To align with the Australian and Victorian context, the functions for buildings have been adapted to reflect expected damage for low inundation depths. All damage functions for existing buildings therefore start to calculate damage from an inundation depth of 15cm (see e.g. Table A-3).

Vulnerability functions for different crop types have been adapted more drastically based on expert judgement from stakeholders across Australia.

Adapted vulnerability curves for scenarios with more resilience building types have been created by raising the curve 30 cm (see e.g. Table A-4).

TABLE A-3: VULNERABILITY FUNCTION FOR RESIDENTIAL BUILDINGS

Water depth (m)	Damage factor
0	0
0.15	0
0.5	0.48
1	0.64
1.5	0.71
2	0.79
3	0.93
4	1

TABLE A-4: ADAPTED VULNERABILITY FUNCTION FOR RESIDENTIAL BUILDINGS

Water depth (m)	Damage factor
0	0
0.45	0
0.8	0.48
1.3	0.64
1.8	0.71
2.3	0.79
3.3	0.93
4.3	1

TABLE A-5: VULNERABILITY FUNCTION FOR COMMERCIAL BUILDINGS 1-3 STORIES

Water depth (m)	Damage factor
0	0
0.15	0
0.5	0.24
1	0.48
1.5	0.67
2	0.86
3	1

TABLE A-6: ADAPTED VULNERABILITY FUNCTION FOR COMMERCIAL BUILDINGS 1-3 STORIES

Water depth (m)	Damage factor
0	0
0.45	0
0.8	0.24
1.3	0.48
1.8	0.67
2.3	0.86
3.3	1

TABLE A-7: VULNERABILITY FUNCTION FOR COMMERCIAL BUILDINGS 4-7 STORIES

Water depth (m)	Damage factor
0	0
0.15	0
2	0.24
4	0.48
6	0.67

TABLE A-8: ADAPTED VULNERABILITY FUNCTION FOR COMMERCIAL BUILDINGS 4-7 STORIES

Water depth (m)	Damage factor
0	0
0.45	0
2.3	0.24
4.3	0.48
6.3	0.67

TABLE A-9: VULNERABILITY FUNCTION FOR COMMERCIAL BUILDINGS 8+ STORIES

Water depth (m)	Damage factor
0	0
0.15	0
6.0	0.24

TABLE A-10: ADAPTED VULNERABILITY FUNCTION FOR COMMERCIAL BUILDINGS 8+ STORIES

Water depth (m)	Damage factor
0	0
0.45	0
6.3	0.24

TABLE A-11: VULNERABILITY FUNCTION FOR INDUSTRIAL BUILDINGS

Water depth (m)	Damage factor
0	0
0.15	0
0.5	0.31
1	0.48
1.5	0.61
2	0.71
3	0.84
4	0.93
5	0.98
6	1

TABLE A-12: VULNERABILITY FUNCTION FOR INDUSTRIAL BUILDINGS

Water depth (m)	Damage factor
0	0
0.45	0
0.8	0.31
1.3	0.48
1.8	0.61
2.3	0.71
3.3	0.84
4.3	0.93
5.3	0.98
6.3	1