A coupled approach to regional flood and land-use modelling to determine the impact of land-use-change and mitigation strategies on flood risk reduction

Eike Michael Hamers

B.SC. Civil & Environmental Engineering

M. SC. Civil Engineering

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The University of Adelaide
Faculty of Engineering, Computer and Mathematical Sciences
School of Civil, Environmental and Mining Engineering

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Abstract

Flooding is already one of the most devastating natural hazards when it comes to damage caused. A key factor for damage caused by flooding is the urbanization of floodplains. The high-density characteristic of urban development entails a high monetary value at risk. It also implies a high quantity of impervious areas furthering the intensity of occurring floods. With predicted future demographic and population growth these metropolitan areas are likely to increase. This will further negatively impact the potential flood loss. Estimations suggest an increase of up to US$ 63 Trillion of value at risk within the global 1 in 100-year floodplain by 2050. Climate change is adding further pressure on future flood risk by increasing the intensity and frequency of severe flood events.

Therefore, prudent flood risk management is vital to mitigate these future threats. This includes an increased importance of regional development planning in risk management. Technically, the implementation of land use planning as a mitigation strategy leads to a two-way interaction between flood and land use change models. In addition, the application of other mitigation choices is spatially limited to small areas within a region. To model and test the placement of such options an upscaling is necessary. Also, when dealing with future change, uncertainty needs to be considered. Local uncertainty is a problem in the results of standard land use models, dealt with by using statistical approaches to follow the allocation of different land use classes across the region of interest.

This thesis is organised in three publications dealing with the challenges of modelling regional flood risk in a distant future. The first paper introduces a computational framework to model the effect of land use planning as part of a mitigation strategy. This allows for the consideration of land use and climate change as drivers in future flood risk. The second paper investigates the use of portfolios of nature-based solutions (NBSs), as another land use-based mitigation option, in a regional planning application. For this purpose, rules of allocation to identify suitable locations were developed and tested to determine the trade-offs between portfolio size and corresponding effect on flood impact. In this case NBS portfolios are used to overcome the difference in spatial resolution in land use planning and the traditional modelling of NBSs. The final paper introduces a framework using a range of approaches to deal with uncertainty to investigate the impact of local uncertainty in land use change on future value at stake and the impact on future flood risk. The approaches include a baseline with uncertainty being not considered, a most likely, a most valuable, and a weighted average scenario.

The key findings of this thesis are the importance of using an integrated computational framework that considers plausible changes in the flood-land use nexus explicitly with the aid of linked, dynamic flood and land use models. It also provides a proof of concept of the consideration of portfolios of NBSs for flood risk reduction at the regional scale and highlights the value of and the necessity to include uncertainties in future land use as part of flood risk assessments.

Statement of originality

I certify that this work contains no material which has been accepted for the award of any other degree or diploma in my name, in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. In addition, I certify that no part of this work will, in the future, be used in a submission in my name, for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide and where applicable, any partner institution responsible for the joint award of this degree.

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Eike Michael Hamers Date

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Chapter 1: Introduction

Flooding is one of the most expensive natural hazards in the world (Hartmann et al., 2018, International Federation of Red Cross and Red Crescent Societies, 2018). In their latest report, the International Federation of Red Cross and Red Crescent Societies (2018) states that for the past 10 years, of 3,751 natural hazard events, 40.5% were floods. These floods caused roughly US$363 Billion of damage around the world (Guha-Sapir, 2018). According to the EM-DAT-database for natural disasters (Guha-Sapir, 2018), in this decade, the year 2011 on its own resulted in an estimated US$70 Billion of flood damage. The impact of flooding is likely to increase in the future due to climate change and urbanization, as well as a growth in population and developments and therefore a higher exposure of value (Tao et al., 2011, Beckers et al., 2013, Global Facility for Disaster and Recovery, 2014).

A common way to visualize risk is Crichton’s risk triangle (Crichton, 1999). Within this framing, risk is comprised of the three components of the hazard itself, the exposure of values at risk to the hazard, and the vulnerability of these exposed values to the hazard, each represented as a side of a triangle, where, pictorially, risk is conceived as the area of the triangle (Crichton, 1999). Different external drivers on each of the three sides therefor have direct influence on the shape and size of the triangle and on risk.

Land use change and climate change are both identified as main drivers in the change of future flood risk. Urbanization impacts the flood extent through a higher degree in sealing. With this leading to less infiltration and an increase in sealed surface area, runoff times are likely to decrease, which causes higher flood peaks in the river as runoff times will be faster than the river flow (Du et al., 2012, Miller et al., 2014). But the bigger contribution to the increase of flood risk is likely to be the increase in exposure through urbanization. This indirect impact on flood risk comes through the increase in building stock within the catchment (Jongman et al., 2012, Di Baldassarre et al., 2013, Zischg et al., 2018, Jafino et al., 2019). In contrast, climate change influences the hazard side of the risk triangle through increases in rainfall intensity. With the amount of rainfall increasing, river flooding will increase in severity (Dey and Mishra, 2017, Hodgkins et al., 2017).

1.1 Background (Challenges in future flood risk management on a regional scale)

The next subsections provide background and an overview of the work done to date on modelling of the flood-land use nexus in Section 1.1.1, the modelling of land use based mitigation strategies in Section 1.1.2, and the implementation of uncertainty for land use change in future flood risk assessment in Section 1.1.3.

1.1.1 Modelling of the Flood-Land Use Nexus in the Future

To understand, quantify, and mitigate the impact of flooding a nexus between flooding and land use is inevitable. This is because some land use characteristics (e.g. elevation, degree of imperviousness, slope, roughness etc.) have a significant impact on the transformation from rainfall to flooding (e.g. location, depth, velocity etc.) (Öztürk et al., 2013, Yan et al., 2013, Sanyal et al., 2014), whereas others (e.g. location of assets, such as buildings, critical infrastructure, areas of social and environmental value etc.) influence the transformation from flood levels and velocity to impact and damage. At the same time, flood impacts can have an effect on land use through policy interventions aimed at mitigating flood damage, such as zoning and buy-backs (Klijn et al., 2004). Consequently, the flood-land use nexus consists of the two-way interaction between land use impacts and flooding, and flooding impacts and land use (Zischg et al., 2018).

The flood-land use nexus is not static, with climate change impacting on rainfall amounts and intensity (Bouwer et al., 2010, Muis et al., 2015) and socio-economic development resulting in changes in land use, such as urbanisation and densification (Jongman et al., 2012, Löwe et al., 2017). The above changes are likely to increase the impact of future flood events, both as a result of an increase in flood extent and inundation levels caused by increases in rainfall intensities and impervious areas (GFDRR, 2016, IFRC, 2018), as well as an increase in the value of the assets exposed to flooding.

Given the dynamic nature of the flood-land use nexus, it is important to consider the two-way interaction between flooding and land use as part of the quantification of future flood risk, as well as the relative effectiveness of different long-term risk reduction strategies. However, existing studies generally only focus on a particular aspect of the change in this nexus. For example, a large number of studies have investigated the impact of climate change on rainfall intensity and flooding (Meehl et al., 2000, Booij, 2005, Dankers and Feyen, 2008, Guhathakurta et al., 2011, Guerreiro et al., 2018, Tabari, 2020), as well as at the impact of climate change on flood risk (Hallegatte et al., 2010, Ranger et al., 2011, Xu et al., 2019). While a number of studies investigate how historical land use change impacts flooding (El Idrissi et al., 2002, Du et al., 2012, Beckers et al., 2013), only a small number of studies investigate the impact of future development on flood risk (Shankman et al., 2009, Hounkpè et al., 2019) or correlate the impact of both land use and climate change on flood risk (Löwe et al., 2017, Gruhn et al., 2017).

While some studies have considered the two-way interaction between flooding and landuse in response to particular drivers of change (Hammond et al., 2018, Jafino et al., 2019), this has generally been done considering simplified modelling approaches and simplified representations of temporal dynamics. This is likely because there is currently no modelling framework that considers the flood-land use nexus in an integrated fashion in order to better understand, quantify and mitigate future flood risk.

1.1.2 Modelling the Relative Effectiveness of Land Use-Based Mitigation Strategies

The flood-land-use-nexus connects flood and land use with different drivers in climate change and socio-economic development. With an expected increase in flood risk, demands on flood mitigation are likely to increase in the future. However, given the lack of an integrated modelling framework for modelling the flood-land use nexus in the future, there has been a lack of consideration of the relative effectiveness of land use-based strategies for reducing future flood risk.

Although land use planning has been identified as one of the most potent means of reducing future flood risk (Klijn et al., 2004), the absence of an integrated flood-land use model has meant that previous studies that have considered the effectiveness of land use planning policy interventions on future flood risk have generally only considered current floods in conjunction with future land use (Klijn et al., 2004, Barredo and Engelen, 2010, Zischg, 2018). Consequently, there is currently a lack of understanding of some of the key issues affecting future flood risk, such as (i) the relative effectiveness of land use planning policies in reducing future flood risk and (ii) the importance of considering the two-way interaction between changes in land use due to socio-economic development on future flood risk and resulting changes in land use as part of policy interventions based on land use planning.

Similarly, despite the increasing interest in mitigating future flood risk by modifying land use characteristics via nature-based solutions (NBSs), which use natural elements to reduce water depths and flow speeds within a certain area by mimicking the effects of vegetation and soil characteristics on floods and their distribution (Castellar et al., 2021, Zölch et al., 2017, Kumar et al., 2021, Cameron et al., 2012, Whitford et al., 2001), the lack of an integrated modelling framework has prevented the consideration of NBSs as an option for potentially reducing flood risk at the regional scale. Instead, the effectiveness of NBSs has generally only been assessed at smaller, localised scales, such as street blocks or small suburbs (Zölch et al., 2017, Kumar et al., 2021, Vojinovic et al., 2021, Kim and Park, 2016, Zellner et al., 2016, Pappalardo et al., 2017), with assessments at larger scales rare (Fastenrath et al., 2020, Hankin et al., 2021, Chen et al., 2021). Given these localised assessment scales, previous studies have generally focussed on the detailed modelling of the effectiveness of individual NBS schemes at known locations, investigating the relative effectiveness of different types of NBSs under different rainfall regimes, including the impact of climate change (Zölch et al., 2017). However, the effectiveness of applying portfolios of NBSs at regional scales to complement, or act as potential alternatives to, more commonly used structural measures, has not been considered, despite the potential benefits this could provide in terms of increased adaptability and amenity, as well as reduced cost.

The consideration of the potential benefits of using portfolios of NBSs for flood mitigation at regional scales is neglected because of the lack of a formal approach to determining how many NBSs to use and where to locate them to achieve an appropriate trade-off between the number of NBSs (and hence their cost) and the corresponding reduction in flood impact. In addition, assessment of the relative effectiveness of different portfolios of NBSs requires a modelling approach that is suited to regional scale assessments, which is also not available at present. When considering regional scales, a coarser modelling resolution is likely to be more appropriate, as the focus is on the identification of the most suitable locations of NBSs, rather than the detailed modelling of individual schemes at a given location. Such a coarser resolution is likely to facilitate better integration with the land-use maps and models required for determining the suitability of different potential locations of NBSs and to enable different placement configurations to be modelled in a computationally efficient manner.

1.1.3 Consideration of Uncertainty in Land Use Models

The most commonly considered driver of future flood risk is climate change, which primarily affects the hazard side of the risk triangle through increases in rainfall intensity, and hence runoff (Hodgkins et al., 2017, Bao et al., 2017, Guerreiro et al., 2018). However, as mentioned above, urbanisation within floodplains and catchments is also a critical driver in the growth of future flood risk (Miller et al., 2014, Jongman et al., 2012). One mechanism of urbanisation increasing flood risk is that an increase in the sealed surface area (associated with urbanisation) decreases runoff times, which can overwhelm drainage systems, and lead to higher flood peaks within the catchment (Miller et al., 2014, Du et al., 2012). However, a second, and arguably more important, mechanism of urbanisation increasing flood risk is that urbanisation increases the quantity and value of assets within a catchment and a floodplain (Di Baldassarre et al., 2013, Zischg et al., 2018, Jafino et al., 2019, Jongman et al., 2012). This increase in value increases the exposure side of the risk triangle, resulting in an increase in expected flood damage, for a given flood event (Zischg, 2018). However, the quantification of future flood risk is highly uncertain due to uncertainties in modelling and drivers of change. These uncertainties can either be considered as “local” or “deep” (Maier et al., 2016).

Deep uncertainties are generally associated with assumptions around drivers of change, such as climate and land use change, potentially resulting in different plausible future flood risk trajectories. Different approaches to dealing with deep uncertainty have been developed across many different fields (Walker et al., 2012, de Moel and Aerts, 2010, Heuvelink, 1998), where one approach of interest is the use of scenarios (McPhail et al., 2020, Nakicenovic et al., 2000, Wack, 1985). In relation to the hazard side of the risk triangle, such scenarios generally involve consideration of different plausible climate futures, which are used to alter the rainfall inputs of flood models (Heal and Kriström, 2002, Jones, 2000). In relation to the exposure side of the risk triangle, scenarios represent a range of plausible socio-economic futures within a specific region and are typically constructed through participatory processes involving a broad array of regional and domain experts (Riddell et al., 2018, Riddell et al., 2017, Holman et al., 2017). Such scenarios then inform the social and economic growth projections used to simulate changes in land use, and hence exposure, throughout the area of interest (Riddell et al., 2018, Riddell et al., 2017).

Local uncertainty is generally concerned with natural variability or uncertainties associated with models (e.g. parameters, structure), given a particular future climate and/or socio-economic scenario (Maier et al., 2016, Ascough et al., 2008). Accounting for local uncertainty associated with the magnitude of a flood event is well established within flood and flood impact assessment (Wagenaar et al., 2016, Yu et al., 2012, Romanowicz et al., 2006, Bates et al., 2004, Aronica et al., 2002), and typically involves the consideration of a set of driving rainfall events across the range of annual exceedance probabilities of interest. For example, Yu et al. (2012) investigated the impact of uncertainty in flood inundation modelling on flood damage through adopting a Monte Carlo simulation (MCS) approach for the flood modelling. To estimate damage, MCS was used to determine the posterior probabilities for flood extent and inundation depth in a stochastic manner. Different return periods were used and modelled to determine the chance of inundation in particular cells. The resulting maps were then used in an impact assessment in combination with damage functions to determine the potential risk in the catchment.

However, while it is well-known that land use change models (e.g. SLEUTH (Clarke et al., 1997) and Metronamica (Van Delden and Hurkens, 2011b)) involve stochastic components associated with the time-varying allocation of land use throughout a simulation (e.g. Newland et al. (2018a)), the resulting impact of this source of local uncertainty is generally ignored in the assessment of uncertainty on future flood risk, with only de Moel and Aerts (2010) considering the combined influence of uncertainties in estimates of value at risk, damage curves and land use on flood impact. Consequently, given the significant impact land use change is likely to have on future flood risk, it is important to better understand the relative influence of deep and local uncertainty on future land use, and hence flood exposure and impact estimates.

1.2 Research objectives

In order to address the gaps in the integrated modelling of the future flood-land-use-nexus, the consideration of land use-based mitigation strategies, including land use planning (via zoning and buy-backs), and the consideration of the influence of uncertainties associated with land use modelling on future flood risk outlined above, the following research questions are answered:

1. What impact does the flood-land use nexus have on modelling future flood risk considering climate and socio-economic drivers?
2. How can nature-based solutions, as a land use based flood reduction method, be integrated in regional planning and flood risk modelling?
3. What is the impact of deep and local uncertainty in land use change models on future flood risk significant?

The corresponding objectives of this thesis are:

1.1. To develop a modelling framework that considers the flood-land use nexus in an integrated fashion by considering the impacts of climate and socio-economic drivers of change, as well as the impacts of policy interventions based on zoning, on future flood risk.

1.2. To apply the framework to a case study in Adelaide, South Australia, to better understand:

    a) The relative influence of climate change and socio-economic development on future flood inundation levels and damage

    b) The relative effectiveness of zoning policies in reducing future flood risk

    c) The importance of considering the two-way interaction between changes in land use due to socio-economic development on future flood risk and resulting changes inland use as part of policy interventions based on zoning

2.1. To develop a formal approach that is able to (i) identify suitable locations of portfolios of NBSs at regional scales, enabling trade-offs between portfolio size and the corresponding reduction in flood impact to be determined and (ii) model the flood reduction impact of portfolios of NBSs at regional scales at a resolution that enables the requisite analyses to be integrated with land use planning practises and to be conducted in a computationally efficient manner.

2.2. To illustrate the utility of the proposed approach and assess the degree to which portfolios of nature-based solutions can mitigate pluvial flooding at the catchment scale for a case study in Adelaide, South Australia.

3.1. To introduce a general framework that enables the relative influence of deep and local uncertainty on the exposure and impact of future flood risk to be estimated via the use of land use models.

3.2. To apply the framework to a case study in the Gawler River area in South Australia to assess:

    a. The relative influence of deep and local uncertainty and

    b. The impact of different methods of quantifying local uncertainty on estimates of future flood impact in terms of direct economic losses.

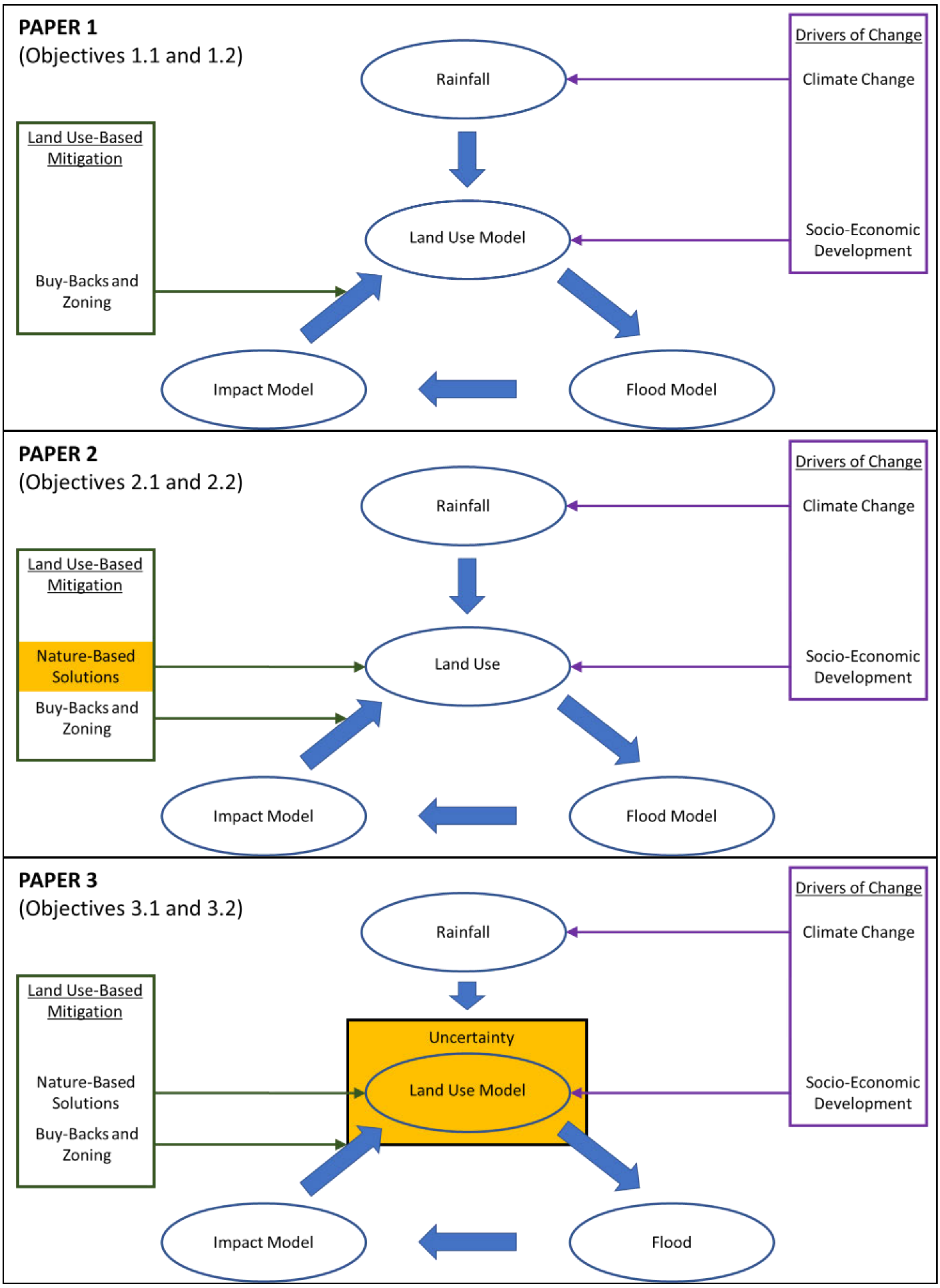

Figure 1 Overview of the organisation of the six aims into three papers

1.3 Thesis Organisation

This thesis consists of five chapters. Chapters 2 to 4 form the main body of this research and contain three papers connected to the research aims as shown in 1.3 . Chapter 2 (addressing Objectives 1 and 2) is going to be submitted to Environmental Modelling and Software, Chapter 3 (addressing Objectives 3 and 4) is going to be submitted to the Journal of Hydrology, while Chapter 4 (addressing Objectives 5 and 6) will be submitted to Natural Hazards and Earth System Sciences. Formatting and numbering of chapter, sections, figures, and tables have been adjusted to comply with university standards.

Chapter 2 (Research question 1) proposes a generic framework of the flood-land use nexus to consider future changes in flood and land use in a flood risk assessment (Paper 1 in Figure 1), corresponding to objective 1.1. The framework facilitates quantification of how drivers of socio-economic and climate change impact future flood depths and damage, as well as how zoning informed by knowledge of future flood levels and damage changes future land use. In this way, the proposed framework is able to represent the dynamics of the two-way interactions in the future flood-land use nexus. A key to being able to achieve this is the use of dynamic flood and land use models, which are able to represent the dynamic changes in land use and flooding in response to socio-economic and climate drivers explicitly.

To address objective 1.2, the framework is applied to the Gawler River region, South Australia, using Mike Flood from DHI as the dynamic flood model and Metronamica, a cellular automata land use model from the Dutch Research Institute of Knowledge Systems, as the dynamic land use model. Different computational experiments are conducted to determine the relative changes in future flood extent due to climate and land use change and the relative influence of considering the two-way interaction between land use planning for mitigating flood risk and flood extent.

To fulfil objectives 2.1 and 2.2, Chapter 3 (Research question 2) introduces and illustrates an approach that enables the utility of NBSs to be assessed at regional scales, including the ability to model the flood reduction benefits of NBSs at spatial resolutions that are commensurate with those commonly used in spatial planning studies (e.g. 50m x 50m to 500m x 500m) and the ability to identify the most suitable locations for placing portfolios of NBSs at regional scales. The approach is applied to the Gawler River region in South Australia, where the approach introduced in this paper is linked with the approach introduced in Paper 1 (see Figure 1). Using this combined approach, the most suitable locations for the placement of portfolios of NBSs in order to reduce flood risk are identified and the potential benefit of using portfolios of NBSs is assessed.

Chapter 4 (Research question 3) introduces a generic framework that enables the relative influence of deep and local uncertainty on the exposure and impact of future flood risk to be estimated via the use of land use models to meet objectives 3.1 and 3.2. By combining this local uncertainty framework with the integrated flood-land use nexus framework introduced in Paper 1 (Figure 1), the relative influence of local and deep uncertainty on future flood loss is assessed for the Gawler River case study. In addition, the influence of four different methods to quantify local uncertainty are also compared. These approaches differentiate between (i) a baseline which does not consider local uncertainty, (ii) a most likely approach choosing the value with highest probability for each cell, (iii) a most valuable approach choosing the highest possible value for each cell, and (iv) a weighted average using value and probability.

Chapter 5 provides a concluding summary of the development of the flood-land-use-nexus modelling framework and the additions to land use based mitigation and the integration of local uncertainty of land use change in flood risk assessment. The result gives an insight into the development and effectiveness of a modelling framework that considers the flood-land use nexus in an integrated fashion by considering the impacts of climate and socio-economic drivers of change, as well as the impacts of policy interventions based on zoning, on future flood risk. They also demonstrate the abilities of the developed approach to be able to (i) identify suitable locations of portfolios of NBSs at regional scales, enabling trade-offs between portfolio size and the corresponding reduction in flood impact to be determined and (ii) model the flood reduction impact of portfolios of NBSs at regional scales at a resolution that enables the requisite analyses to be integrated with land use planning practises, as well as the importance of a generic framework to include local uncertainty into risk assessment based on land use allocation probability. At the end of this chapter the limitations of this research provide an outlook on potential future research questions within the flood-land-use nexus framework.

Chapter 2: Integrated Framework for Considering the Flood – Land Use Nexus in the Assessment of Future Flood Risk

Eike Hamers, Holger R Maier, Aaron C Zecchin, Hedwig van Delden

To be submitted to Environmental Modelling and Software

Statement of Authorship

Title of Paper	Integrated Framework for Considering the Flood - Land Use Nexus in the Assessment of Future Flood Risk
Publication Status	☐ Published ☐ Accepted for Publication ☐ Submitted for Publication ☒ Unpublished and Unsubmitted work written in manuscript style
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Principal Author

Name of Principal Author (Candidate)	Eike M Hamers
Contribution to the Paper	Contributed to conceptualization of the framework, design and modelling of experiments, performing the analysis and interpretation of results, drafting of manuscript
Overall percentage (%)	70
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.
Signature	Date 01/07/2022

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);
ii. permission is granted for the candidate in include the publication in the thesis; and
iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

Name of Co-Author	Holger R Maier
Contribution to the Paper	Contributed to conceptualization of framework, analysis and interpretation of results, drafting of manuscript
Signature	Date 06/07/2022

Name of Co-Author	Aaron C Zecchin
Contribution to the Paper	Contributed to conceptualization of framework, analysis and interpretation of results
Signature	Date 06/07/2022

Name of Co-Author	Hedwig van Delden
Contribution to the Paper	Contributed to conceptualization of framework, analysis and interpretation of results
Signature	Date 04/07/2022

Abstract

Flood risk is expected to increase significantly around the globe, fuelled by the nexus between flooding and land use. This is because changes in land use due to socio-economic development increase runoff, as well as the “values-at-stake” exposed to flooding. At the same time, changes in flood extent and depth can impact land use via policy interventions aimed at reducing future flood risk, such as buy-backs and zoning. Existing approaches to flood risk assessment and mitigation have generally ignored this two-way interaction between flooding in land use. To address this shortcoming, an integrated framework for considering the dynamics of future changes in the flood-land use nexus is introduced and applied to the Gawler River region, South Australia. Results indicate that changes in land use due to socio-economic drivers can have a significantly greater impact on flood losses than climate change and that zoning can be an effective way of reducing future flood risk.

2.1 Introduction

Flooding is an issue in many parts of the world (Newman et al., 2017), causing US$363 Billion in damages worldwide over the last ten years alone (Guha-Sapir, 2018). A key to understanding, quantifying, and mitigating the impact of flooding is the nexus between flooding and land use. This is because some land use characteristics (e.g. elevation, degree of imperviousness, slope, roughness etc.) have a significant impact on the transformation from rainfall to flooding (e.g. location, depth, velocity etc.) (Öztürk et al., 2013, Yan et al., 2013, Sanyal et al., 2014) (Figure 2, A-B), whereas others (e.g. location of assets, such as buildings, critical infrastructure, areas of social and environmental value etc.) influence the transformation from flood levels and velocity to impact and damage (Figure 2, A-B-C). At the same time, flood impacts can have an effect on land use through policy interventions aimed at mitigating flood damage, such as zoning and buy-backs (Figure 2, C-D-G) (Klijn et al., 2004). Consequently, the flood-land use nexus consists of the two-way interaction between land use impacts and flooding, and flooding impacts and land use (Figure 2, B-C-D) (Zischg et al., 2018).

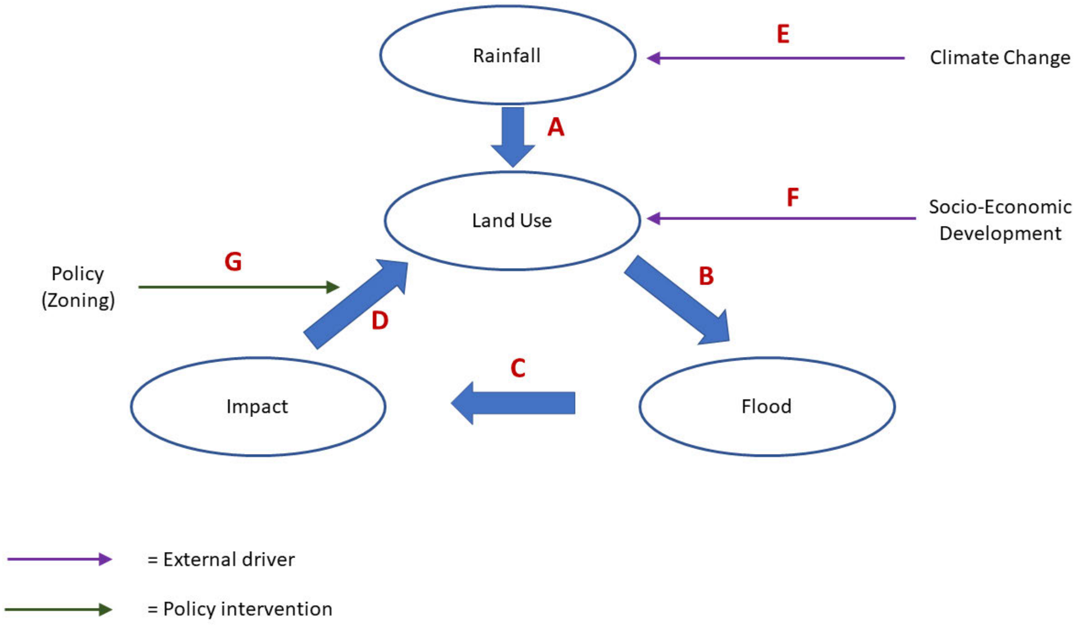

Figure 2 Conceptual representation of the nexus between flooding and land use and how the factors affecting this nexus change in the future in response to external drivers and policy interventions

As shown in Figure 2, the flood-land use nexus is not static, with climate change impacting on rainfall amounts and intensity (Bouwer et al., 2010, Muis et al., 2015) (Figure 2, E) and socio-economic development resulting in changes in land use, such as urbanisation and densification (Jongman et al., 2012, Löwe et al., 2017) (Figure 2, F). The above changes are likely to increase the impact of future flood events, both as a result of an increase in flood extent and inundation levels caused by increases in rainfall intensities and impervious areas (GFDRR, 2016, IFRC, 2018), as well as an increase in the value of the assets exposed to flooding, which is expected to increase based on land use growth from US$27 trillion to US$80 trillion for a 1 in 100-year flood event globally by 2050 (Jongman et al., 2012).

Given the dynamic nature of the flood-land use nexus, it is important to consider the two-way interaction between flooding and land use as part of the quantification of future flood risk, as well as the relative effectiveness of different long-term risk reduction strategies. However, existing studies generally only focus on a particular aspect of the change in this nexus. For example, a large number of studies have investigated the impact of climate change on rainfall intensity and flooding (Meehl et al., 2000, Booij, 2005, Dankers and Feyen, 2008, Guhathakurta et al., 2011, Guerreiro et al., 2018, Tabari, 2020) (Figure 2, E-A-B), as well as at the impact of climate change on flood risk (Hallegatte et al., 2010, Ranger et al., 2011, Xu et al., 2019) (Figure 2, E-A-B-C). While a number of studies investigate how historical land use change impacts flooding (El Idrissi et al., 2002, Du et al., 2012, Beckers et al., 2013), only a small number of studies investigate the impact of future development on flood risk (Shankman et al., 2009, Hounkpè et al., 2019) (Figure 2, F-A-B-C) or correlate the impact of both land use and climate change on flood risk (Löwe et al., 2017, Gruhn et al., 2017) (Figure 2, E-A-F-B-C). In addition, studies that have considered the effectiveness of policy interventions on future flood risk have generally only considered current floods in conjunction with future land use (Klijn et al., 2004, Barredo and Engelen, 2010, Zischg, 2018) (Figure 2, D-G).

While some studies have considered the two-way interaction between flooding and land use in response to particular drivers of change (Hammond et al., 2018, Jafino et al., 2019), this has generally been done considering simplified modelling approaches and simplified representations of temporal dynamics. This is likely because there is currently no modelling framework that considers the flood-land use nexus in an integrated fashion in order to better understand, quantify and mitigate future flood risk. As a result, there is a lack of understanding of some of the key issues affecting future flood risk, such as (I) the relative influence of climate change and socio-economic development on future flood risk, (ii) the relative effectiveness of zoning policies in reducing future flood risk and (iii) the importance of considering the two-way interaction between changes in land use due to socio-economic development on future flood risk and resulting changes in land use as part of policy interventions based on zoning. In order to address these gaps, the objectives of this paper are:

1. To develop a modelling framework that considers the flood-land use nexus in an integrated fashion by considering the impacts of climate and socio-economic drivers of change, as well as the impacts of policy interventions based on zoning, on future flood risk.
2. To apply the framework to a case study in Adelaide, South Australia, to better understand:
    i. The relative influence of climate change and socio-economic development on future flood inundation levels and damage
    ii. The relative effectiveness of zoning policies in reducing future flood risk
    iii. The importance of considering the two-way interaction between changes in land use due to socio-economic development on future flood risk and resulting changes in land use as part of policy interventions based on zoning

The remainder of this paper is organised as follows. Section 2.2 introduces the proposed integrated framework for considering the flood-land use nexus in the assessment and mitigation of future flood risk. The application of the framework to the case study is detailed in Section 2.3, followed by the presentation and discussion of the results in Section 2.4. Conclusions, limitations, and future research are presented in Section 2.5.

2.2 Proposed Integrated Framework for Considering the Flood-Land Use Nexus in Future Flood Risk

The proposed integrated framework for considering the flood-land use nexus in the assessment and mitigation of future flood risk, in this case a function of land use value and damage factor provided by a depth-damage curve, (Objective 1) is outlined in Figure 3. As can be seen, the framework facilitates quantification of how drivers of socio-economic and climate change impact future flood depths and damage, as well as how zoning informed by knowledge of future flood levels and damage changes future land use. In this way, the proposed framework is able to represent the dynamics of the two-way interactions in the future flood-land use nexus. A key to being able to achieve this is the use of dynamic flood and land use models, which are able to represent the dynamic changes in land use and flooding in response to socio-economic and climate drivers explicitly.

As part of the framework, changes in land use are caused by socio-economic drivers, such as population growth and economic development (Newland et al., 2018a). In order to translate these drivers of change into modelled changes in future land use, they are generally converted to annual time series of demands for different land use classes (e.g., residential, commercial, industrial, agricultural, public open space), which become inputs to a land use model. Cellular Automata models are commonly used for this purpose, as they are able to represent land use dynamics realistically, including the impact of zoning policies on modelled distributions of land use classes, and have been applied successfully to a range of environmental problems (Newland et al., 2018b, Newland et al., 2020). Examples of such Land-Use Cellular Automata (LUCA) models include SLEUTH (Clarke et al., 1997) and Metronamica (Van Delden and Hurkens, 2011b).

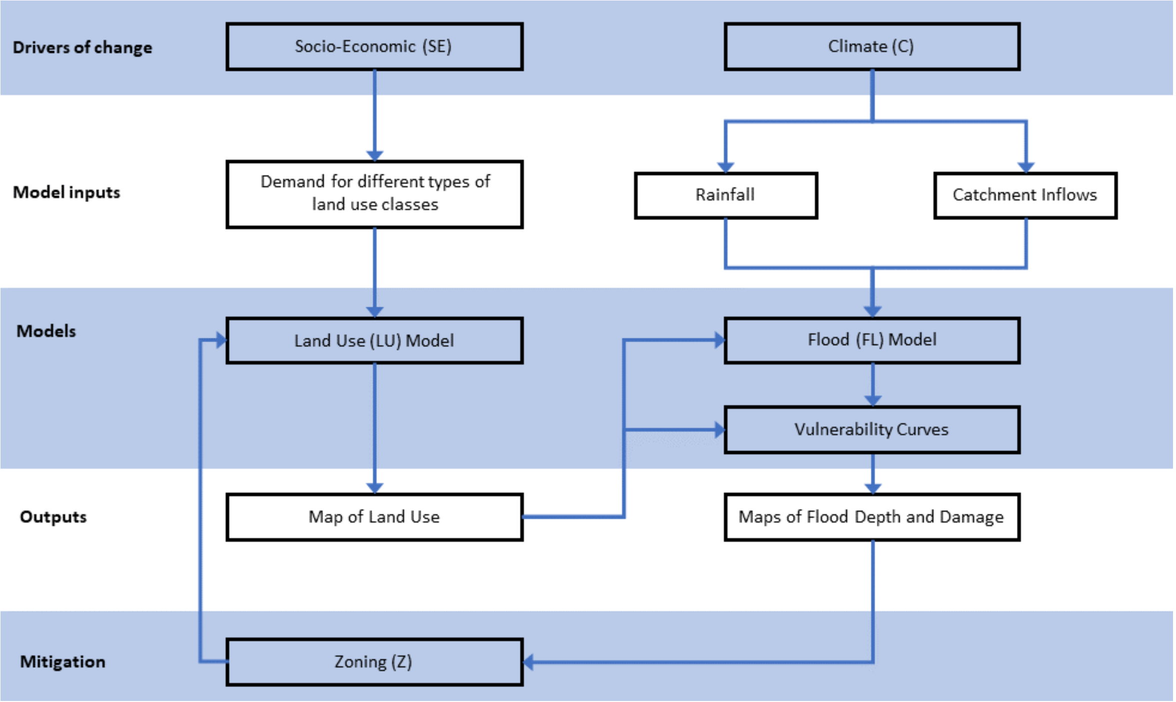

Figure 3 Proposed computational framework of the flood-land use nexus

The outputs of the land use model are spatially explicit maps that differentiate between the different land use classes considered. The attributes of these classes are used to determine the spatial distributions of surface roughness and infiltration coefficients, which are inputs to the 1D/2D hydrodynamic flood model used to estimate inundation extent, depth, and velocity (Figure 3). These land use maps also provide information on the spatial distribution of the assets exposed to flooding (e.g., buildings, critical infrastructure, agricultural areas), which is used to identify which vulnerability curves are most appropriate for the calculation of flood damage (Figure 3). Due to its dynamic nature, the land use model is able to quantify how distributions of the land use classes and assets change over time in response to the time series of demands for different land use classes and the zoning policies considered. These changes dynamically alter the corresponding distributions of the roughness and infiltration coefficients in the flood model, thereby enabling the two-way dynamics between changes in land use and flooding to be represented explicitly.

In addition to changes in land use (see above), changes in flooding and corresponding damage are also caused by the effect of climate change on rainfall and catchment inflows (Figure 3), which can be quantified using a range of top-down or bottom-up methods (e.g. Guo et al. (2018), Bennett et al. (2021), Culley et al. (2021)). The resulting climate-perturbed times series of rainfall and catchment inflows become inputs to the flood model. 1D/2D hydrodynamic models are commonly used for this purpose as they are able to provide realistic representations of flood dynamics and hence estimates of inundation extent, depth and velocities (Frank et al., 2001, Dutta et al., 2007). Examples of such models include Mike-Flood (Kjelds and Rungo, 2002, Rungo and Olesen, 2003), HEC-RAS (Brunner, 2002), TUFLOW (Syme, 2001), and Sobek (Verwey, 2001, Dhondia and Stelling, 2002).

The outputs of the flood model are spatially explicit maps of inundation extent, depth and velocity that can be combined with maps of asset classes from the land use model and corresponding vulnerability curves to obtain spatially explicit maps of flood damage (Figure 3). Such vulnerability curves generally relate inundation depth and/or velocity to a damage factor (i.e., percentage of asset damage), which is multiplied by the asset value to obtain an estimate of damage. Such vulnerability curves are widely available for typical asset classes (Messner, 2007, Huizinga et al., 2017, Wehner et al., 2017), but can also be tailored to particular applications, if sufficient information is available (Smith, 1994, Dale et al., 2004, Pistrika et al., 2014, Nasiri et al., 2016). The maps of flood depth and damage change over time in response to changes in rainfall and catchment inflows due to climate change and changes in land use due to socio-economic changes (Figure 3), ensuring the dynamics of future changes in the flood-land use nexus are captured.

The maps of flood depth and damage can be used to inform zoning policies designed to reduce future flood damage (Figure 3). For example, zoning policies can be designed to exclude any future development from areas with a projected inundation depth above a certain threshold (e.g., above stipulated floor levels of buildings) or to instigate buy-backs to reduce flood damage caused by existing assets. By incorporating these zoning policies into the land use model (Figure 3), the impact of these policies on future spatial distributions of land use and assets can be obtained, which have an influence on flooding and damage. In this way, the proposed framework is able to fully represent the two-way interactions between flooding and land use in a dynamic fashion under drivers of climate and socio-economic change, including the impact of land use change on the transformation of rainfall to runoff and the impact of flood extent and damage on land use via zoning policies designed to reduce damage (Figure 3).

2.3 Case Study

The following subsections provide an overview over the case study used to test the framework of the flood-land use nexus. Section 2.3.1 gives an overview of the Gawler River region used for this case study, while Section 2.3.2 describes the implementation of the flood-land use nexus modelling framework.

2.3.1 Background

The case study area is the Gawler River region located to the North of Adelaide, Australia, which covers an area of 683.22km^2 and spans seven different Local Government Areas (Figure 4). The majority of the region is considered to be rural, mostly consisting of agri- and horticultural- development and low-density rural residential areas (Tonkin Consulting, 2018). However, there are also urban areas, with high-density development, especially around the township of Gawler (Figure 4).

This area has been selected for the case study as it is affected by flooding on a regular basis, with significant events occurring approximately once every 10 years in the recent past. For example, the most recent flood in 2016 resulted in $50 million in damage (Fisher et al., 2017, Tonkin Consulting, 2018). In addition, significant growth is expected in the area due to socio-economic development (DPTI, 2010, DPTI, 2019), which, in combination with the impacts of climate change on rainfall intensity, is expected to increase flood risk in the future. Consequently, this region provides an excellent case study for illustrating the proposed integrated framework for considering the flood – land use nexus in the assessment and mitigation of future flood risk introduced in Section 2.

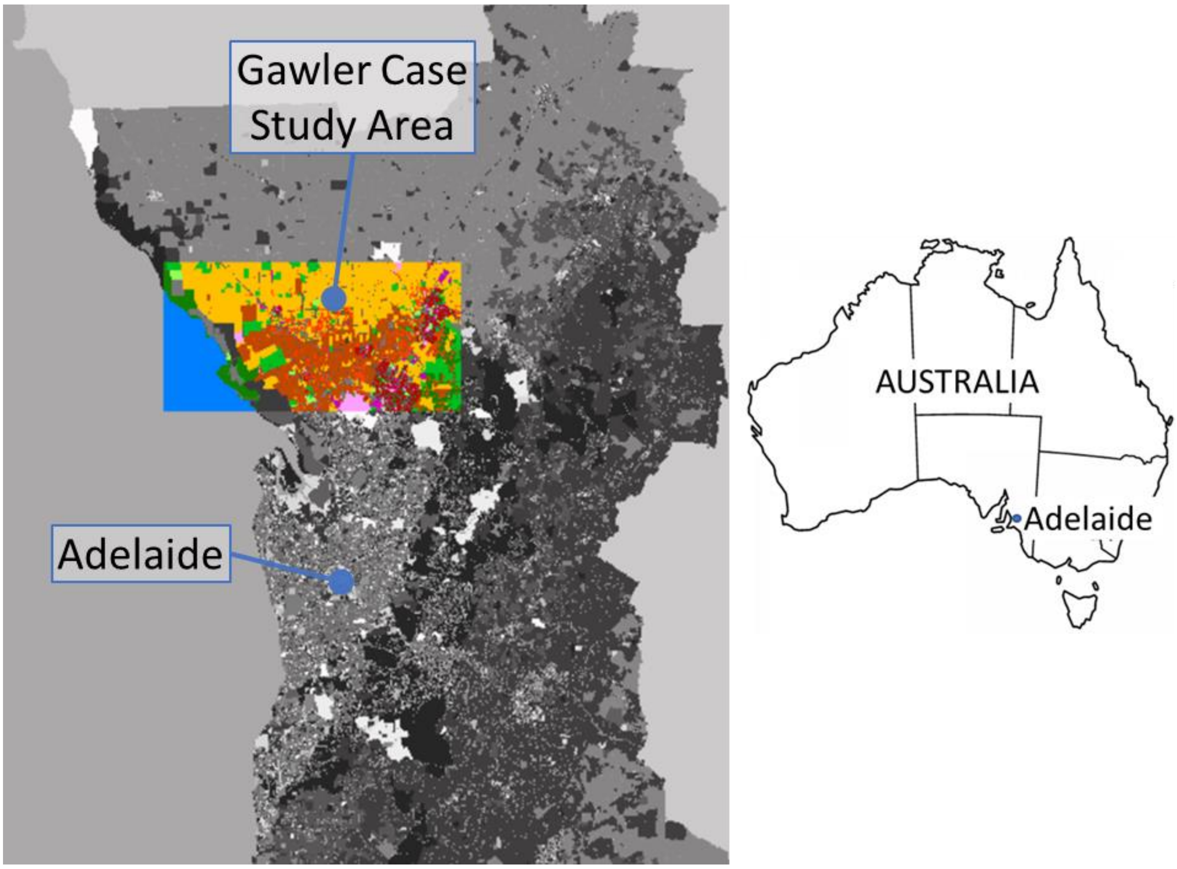

Figure 4 Gawler Case study area to the North of the Greater Adelaide region

2.3.2 Implementation of flood-land use nexus framework

An overview of the application of the proposed flood-land use nexus framework to the Gawler case study is given in Figure 5 with details of the different steps in the framework given below.

2.3.2.1 Drivers of change and model inputs

The two drivers of change considered include socio-economic development and climate change, which were modelled at an annual time step from 2018 to 2100. The "business as usual" socio-economic scenario for the greater Adelaide region developed by Riddell et al. (2017) was used, with the corresponding growth rates for the different land use classes considered shown in Figure 5. The worst case climate-change scenario based on the State of the Climate 2020 report for Australia (BOM and CISRO, 2020) was used, with corresponding increases in catchment rainfall and inflows shown in Figure 5.

2.3.2.2 Models

Land use change was modelled using Metronamica (Van Delden and Hurkens, 2011a), which is a spatially explicit LUCA model simulating land use change in the future. As mentioned previously, changes in selected land use classes were modelled at an annual time step in response to demands for different land use classes (see Figure 5), as well as the application of different zoning policies (see Sections 2.3.2.3 and 2.3.3). An existing calibrated and validated Metronamica model for the greater Adelaide area (Riddell et al., 2017), which works at a resolution of 100m x 100m, was adapted to the extent of the case study area considered.

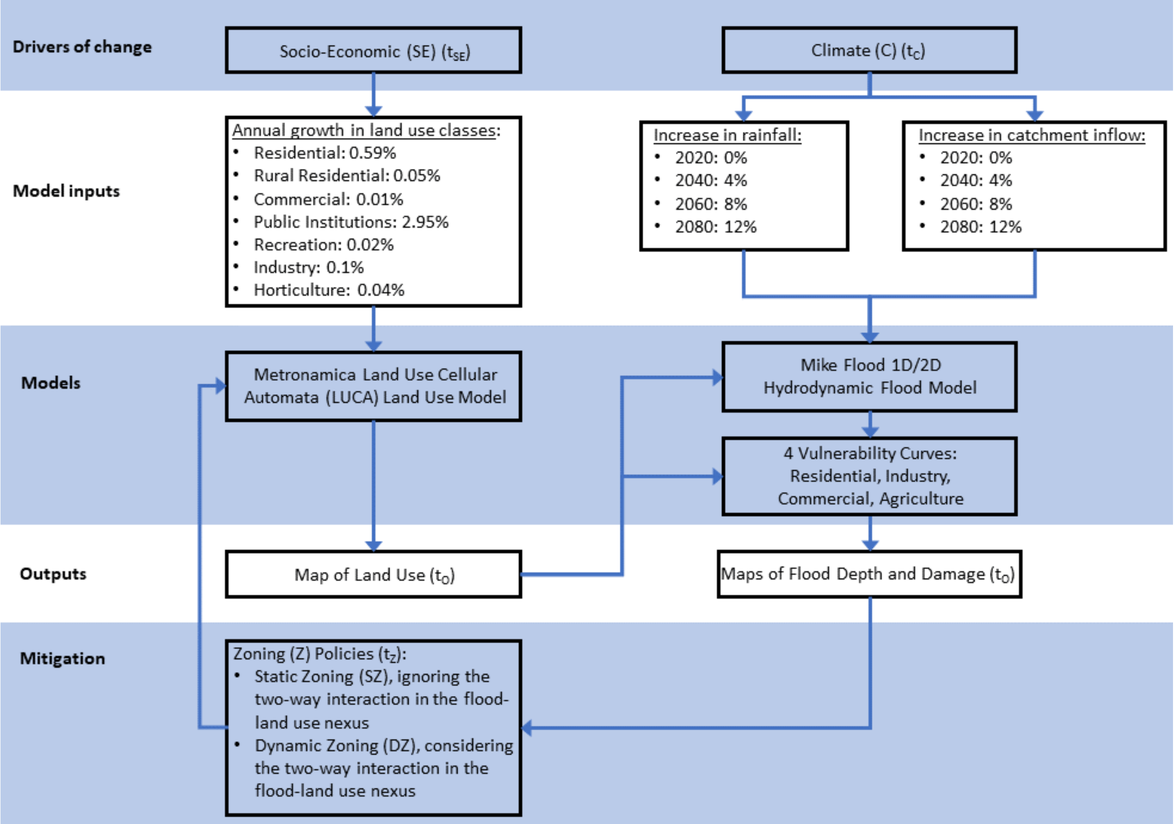

Figure 5 Modelling framework for a flood-land-use-nexus

Flood extent and depths were modelled using Mike Flood (DHI, 2017), which is a coupled 1D/2D hydrodynamic flood model. Flow in the main watercourses in the catchment was modelled using a 1-D Mike-Hydro river model. This model was used to route 1 in 100-year flood event hydrographs from two upstream entry points, corresponding to inflows from the Para North and Para South river tributaries, through the catchment. These were chosen due to availability from a previous study (Tonkin Consulting, 2018). Overland flow was modelled in 2-D using Mike 21 FM, including fluvial flooding resulting from spills from the river channel and in addition pluvial flooding resulting from a 1 in 100-year, 30-minute rainfall event. While the primary source of flooding is the channel flow from outside of the study area, the rainfall event was chosen as additional stress to the area. As the study conducted is a proof-of-concept, only one flood and rainfall event were chosen. Digital elevation was represented in the Mike 21 FM model via a flexible mesh with a maximum area of 225m^2 and a maximum angle of 25°. Infiltration, roughness, and rainfall were grid-based input values at a 15x15m resolution. The infiltration rate was set at 2mm/h for areas defined as rural and 0mm/h for urban areas. These are relatively low infiltration rates, as saturation due to heavy rainfall prior to the flood event can be expected (Tonkin Consulting, 2018). The interaction between the 1D representations of channels and the 2D representation of the floodplain was modelled using Mike Flood. The model was calibrated and validated by comparing modelled results with those of a model used in a study conducted by Tonkin Consulting (2018) for a 1 in 100 year event.

The vulnerability curves used to convert inundation levels to a damage index were taken from van Delden et al. (2022) based on Wehner et al. (2017) and Huizinga et al. (2017). Different curves were used for different land use classes, representing different types of asset classes. Total damage for each 100m x 100m cell was obtained by multiplying the damage index obtained from the relevant vulnerability curve by the average value in each cell obtained from van Delden et al. (2022). Details of the vulnerability curves and land use class values used can be found in Appendix D.2.

2.3.2.3 Outputs

The outputs obtained include annual maps of land use, value at stake, flood extent and flood depth from 2018 to 2100. In order to obtain results that enable objectives 2(i), 2(ii) and 2(iii) to be addressed, values of loss and inundation depth were aggregated spatially and compared at four different time periods (2020, 2040, 2060, 2080).

2.3.2.4 Mitigation options

Different types of zoning policies were considered as mitigation strategies, including buy-back options. These policies were applied to land use classes that were considered high-risk, including those of urban character with residential, commercial, and industrial development. The areas in these land use classes to which the zoning polices were applied were based on inundation levels obtained from the Mike flood model as follows:

- No zoning was applied to areas with inundation depths below 250mm, as this level of inundation was assumed to cause little damage and to be able to be mitigated relatively easily through other options (e.g., structural options, nature-based solutions)

- Slightly restricted zoning was applied to areas with inundation depths between 250mm and 500mm, which means that some development is allowed, but only if no alternative can be found
- Strictly restricted zoning (i.e., no future development and removal of existing development via buybacks) was applied to areas with inundation depths above 500mm, as this level of inundation was assumed to result in significant damage

The zoning plans resulting from applying the above criteria were used as inputs to the Metronamica land use model (Figure 5). These zoning plans were either static or dynamic. As part of static zoning, a zoning and buy-back scheme was developed for the 2020 flood conditions and then used throughout the entire simulation period until 2080. Consequently, static zoning ignores the two-way interaction in the flood-land use nexus. As part of dynamic zoning, the zoning maps were updated every 20 years based on changes in the flood maps resulting from climate change, socio-economic development, and the influence of zoning strategies at previous time steps. Consequently, dynamic zoning considers the two-way interaction in the flood-land use nexus.

2.3.3 Computational experiments

Details of the computational experiments conducted in order to address Objectives 2(i), 2(ii) and 2(iii) are summarised in Table 1. The purpose of Experiment 1 was to establish a baseline of current inundation levels and damage against which the results from the other Experiments could be compared and does therefore not consider any drivers of change or mitigation strategies. The purpose of Experiments 2 to 4 was to assess the relative influence of climate change and socio-economic development on future flood inundation levels and damage (Objective 2(i)). This was achieved by considering experiments that consider (i) changes in climate while keeping socio-economic drivers constant (Experiment 2), (ii) changes in socio-economic drivers while keeping climate constant (Experiment 3) and (iii) combined changes in both climate and socio-economic drivers (Experiment 4).

The purpose of Experiments 5 to 8 was to assess (i) the relative effectiveness of zoning policies in reducing future flood risk (Objective 2(ii)) and (ii) the importance of considering the two-way interaction between changes in land use due to socio-economic development on future flood risk and resulting changes in land use as part of policy interventions based on zoning (Objective 2(iii)). With regard to Objective 2(ii), Experiments 5 to 8 provide a comparison of the effectiveness of zoning policy interventions for reducing future losses due to flooding when considering socio-economic drivers of change only (Experiments 5 and 7) and when considering both socio-economic and climate drivers of change (Experiments 6 and 8). With regard to Objective 2(iii), Experiments 5 to 8 provide a comparison of the effectiveness of zoning policy interventions for reducing future losses due to flooding when ignoring the two-way interaction in the flood-land use nexus by using static zoning policies (Experiments 5 and 6) and considering the two-way interaction in the flood-land use nexus by using dynamic zoning policies (Experiments 7 and 8) (see Section 2.3.2.3).

Table 1 Details of computational experiments, showing (i) the different scenarios considered (i.e. consideration of different drivers of change, including climate (C) and socio-economic (SE), and different zoning policies (Z), including static zoning (SZ) and dynamic zoning (DZ)) and (ii) the years for which inputs into the flood model used to obtain corresponding flood maps in different output years (i.e. 2020, 2040, 2060, 2080) were used, including land use affected by socio-economic drivers (t_{SE}), rainfall / catchment inflow affected by climate change (t_C) and land use affected by zoning policies (t_Z). Details of how these maps were obtained are given in Figure 5.

Exp	Scenario				Output Year (t_O)											
	Driver of Change		Zoning Policy		2020			2040			2060			2080		
	C	SE	SZ	DZ	t_{SE}	t_C	t_Z	t_{SE}	t_C	t_Z	t_{SE}	t_C	t_Z	t_{SE}	t_C	t_Z
1					2020	2020	N/A	2020	2020	N/A	2020	2020	N/A	2020	2020	N/A
2	X				2020	2020	N/A	2020	2040	N/A	2020	2060	N/A	2020	2080	N/A
3		X			2020	2020	N/A	2040	2020	N/A	2060	2020	N/A	2080	2020	N/A
4	X	X			2020	2020	N/A	2040	2040	N/A	2060	2060	N/A	2080	2080	N/A
5		X	X		2020	2020	N/A	2040	2020	2020	2060	2020	2020	2080	2020	2020
6	X	X	X		2020	2020	N/A	2040	2040	2020	2060	2060	2020	2080	2080	2020
7		X		X	2020	2020	N/A	2040	2020	2020	2060	2020	2040	2080	2020	2060
8	X	X		X	2020	2020	N/A	2040	2040	2020	2060	2060	2040	2080	2080	2060

N/A = Not Applicable

For Experiments 2 to 8, flood and damage maps were obtained for 2040, 2060 and 2080 with the aid of the Mike 1D/2D hydrodynamic flood model. However, the inputs into the flood model varied between experiments, depending on the purpose of the experiment (see Table 1). For Experiments 2, 4, 6 and 8, the rainfall and catchment inflow inputs to the Mike flood model in 2040, 2060 and 2080 were modified in response to climate change, as detailed in Figure 5. For Experiments 3 to 8, the land use inputs to the Mike flood model in 2040, 2060 and 2080 were those obtained from the Metronamica LUCA model. In all of these experiments, land use was changed in response to socio-economic drivers of change, as expressed via increased demands for different land use classes (see Figure 5). In Experiments 5 to 8, the land use maps produced by the Metronamica model were also modified in response to the consideration of zoning policies. In Experiments 5 and 6, these policies were developed based on inundation extents and levels in 2020 and were not changed in future years (i.e., static zoning). In Experiments 7 and 8, the 2020 policies used in Experiments 5 and 6 were updated in 2060 and 2080 based on inundation levels in 2040 and 2060, respectively, enabling the two-way interaction between changes in land use and flooding to be considered dynamically (i.e., dynamic zoning).

2.4 Results and Discussion

The results addressing Objectives 2(i), 2(ii) and 2(iii) are outlined and discussed in Sections 2.4.1, 2.4.2 and 2.4.3, respectively.

2.4.1 Relative influence of climate change and socio-economic development on future flood inundation levels and damage

The results of Experiments 2 to 4 clearly show that, for the case study and future scenarios considered, the influence of socio-economic drivers of change on future flood damage far outweighs the influence of climate change (Figure 6). As can be seen, when climate change is considered, but socio-economic development is ignored (Experiment 2), losses increase by about 5%, 5% and 7.5% in 2040, 2060 and 2080, respectively, compared with the 2020 baseline (Experiment 1). However, when socio-economic development is considered, but climate change is ignored (Experiment 3), these losses increase by about 12%, 32% and 44% in 2040, 2060 and 2080, respectively. The significantly greater influence of socio-economic development on losses compared with that of climate change is also highlighted by the relatively small increase in losses (~2%) when climate drivers are added to socio-economic drivers of change (i.e., comparing the results of Experiments 3 and 4).

The primary reason for the greater losses resulting from the consideration of socio-economic development, rather than the consideration of climate change, is the addition of significant "values-at-stake" in the floodplain when the former driver of change is considered. As can be seen in Figure 6, which compares the relative changes in the spatial extent and depth of inundation levels for Experiment 2 and the relative changes in the spatial extent and type of "values-at-stake" for Experiment 3, socio-economic development results in the expansion of "values-at-stake" into the floodplain, exposing more vulnerable assets to flood damage. However, this is not the case when the impacts of climate change are considered in isolation. While there is an increase in losses due to increased inundation levels when climate change impacts are considered, this is confined to existing "values-at-stake". Consequently, the case study results suggest that the impact of exposing new assets to flooding exceeds the incremental impact on existing exposed assets due to the effects of climate change.

While the relative influence of climate change and socio-economic development on future flood losses is likely to be case study dependent, as it is a function of a number if interrelated factors, the results obtained in this study highlight the importance of considering socio-economic development, in addition to climate change, in assessments of future flood risk. This emphasises the value of using a computational framework that considers changes in the flood-land use nexus by modelling changes in both flooding and land use explicitly and dynamically.

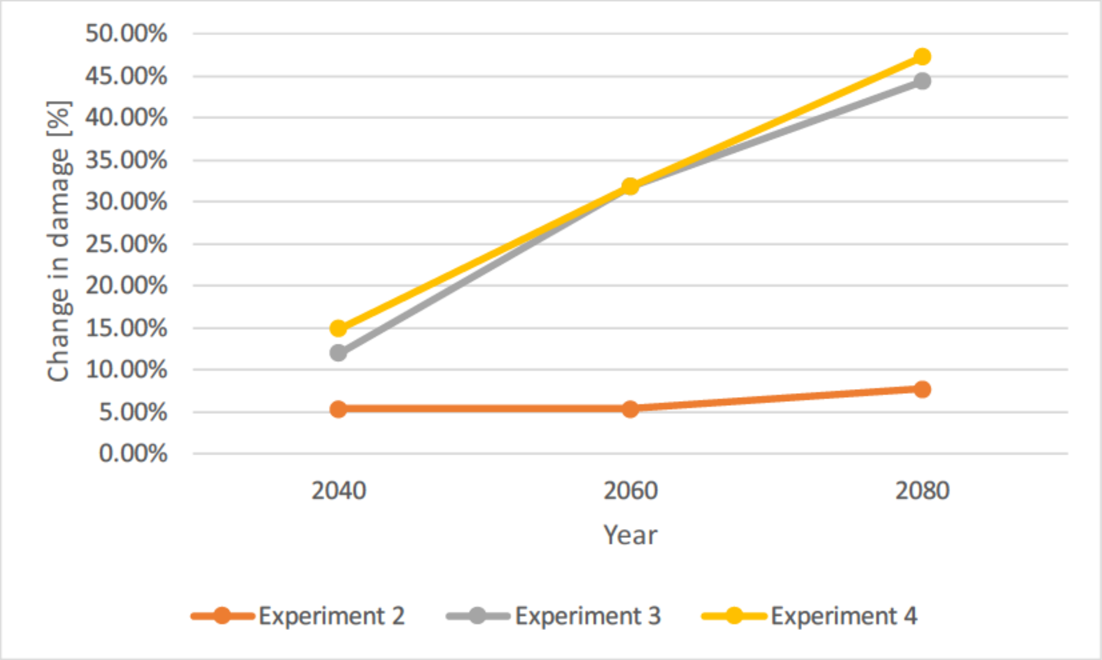

Figure 6 Relative impact of climate change (Experiment 2), socio-economic development (Experiment 3) and their combined impact (Experiment 4) on changes in future damage compared with 2020 baseline conditions (Experiment 1)

2.4.2 Relative effectiveness of zoning policies in reducing flood risk

The case study results show that the implementation of zoning policies results in significant reductions in loss (between 65% to 72%, Figure 8), highlighting the effectiveness of zoning as means of reducing future flood losses. This is not surprising, given that the results of Experiments 2 to 4 indicate that the vast majority of future losses are due to the expansion of “values-at-stake” into flood prone areas in response to socio-economic drivers of change (see Section 4.1), which is prevented by the implementation of zoning policies. This can be seen clearly in Figure 9, which enables land use maps with and without zoning to be compared.

When socio-economic drivers of change are considered in isolation (Experiments 5 and 7), changes in the reduction in losses over time are relatively constant, as the expansion of “values-at-stake” into flood prone areas is virtually non-existent (Maps for Experiments 5, 7 and 8 can be found in Appendix A). When the impacts of climate change are considered in addition to those due to socio-economic development (Experiments 6 and 8), there is a slight reduction in the benefits of zoning by between 2% and 6% (Figure 8). This is primarily because the zoning policies adopted do not remove existing “values-at-stake” from, or prevent future development in, areas with low levels of inundation (see Section 2.3.2.3), which are likely to increase due to the impacts of climate change, resulting in some losses. In addition, when static zoning is used (Experiment 6), zoning policies are not updated in response to increased inundation extents and levels due to climate change, making it possible for future development to expand into areas that become inundated in the future as a result of climate change (see Section 2.4.3).

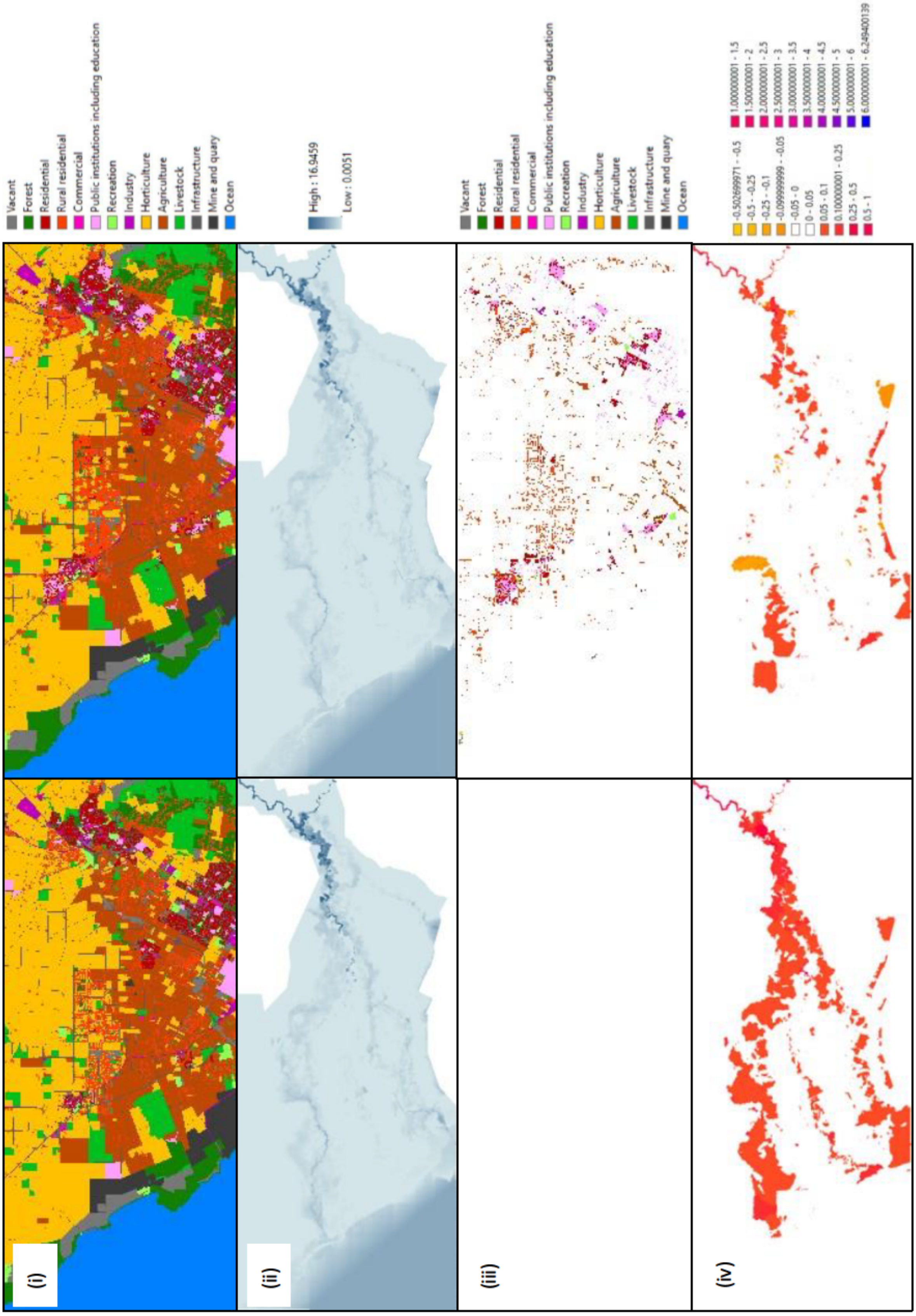

Figure 7 Comparison between Experiments 2 (left) and 3 (right) with (i) land use maps in 2080, (ii) flood maps in 2080, (iii) land use change in 2080, and (iv) change in inundation depth from 2020 to 2080 above 5cm. Details can be found in Appendix A.

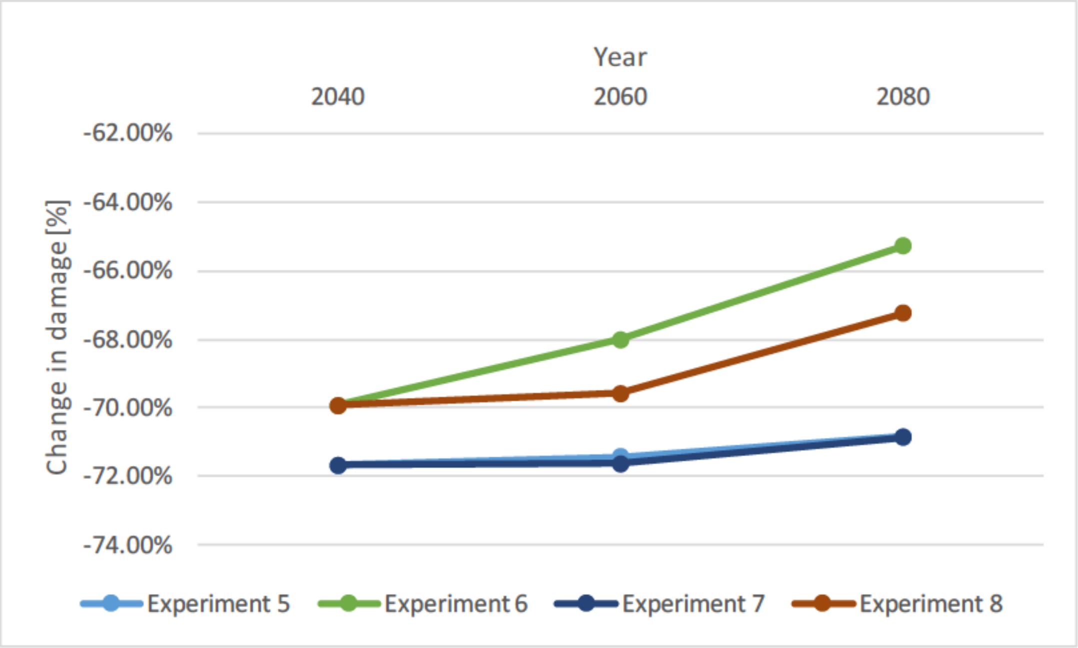

Figure 8 Comparison of the effectiveness of zoning policy interventions for reducing future damage due to flooding (i) when considering socio-economic drivers of change only (Experiments 5 and 7) and when considering both socio-economic and climate drivers of change (Experiments 6 and 8) and (ii) when ignoring the two-way interaction in the flood-land use nexus by using static zoning policies (Experiments 5 and 6) and considering the two-way interaction in the flood-land use nexus by using dynamic zoning policies (Experiments 7 and 8) compared with 2020 baseline conditions (Experiment 1)

As was the case for the relative impact of climate and socio-economic drivers on future flood risk (Section 2.4.1), the relative effectiveness of zoning policies is likely to be case study dependent, as it depends on a number of site- and context- specific factors. However, the results obtained highlight the potential of zoning for reducing future flood risk and the importance of using an integrated computational framework that considers plausible changes in the flood-land use nexus explicitly with the aid of linked, dynamic flood and land use models.

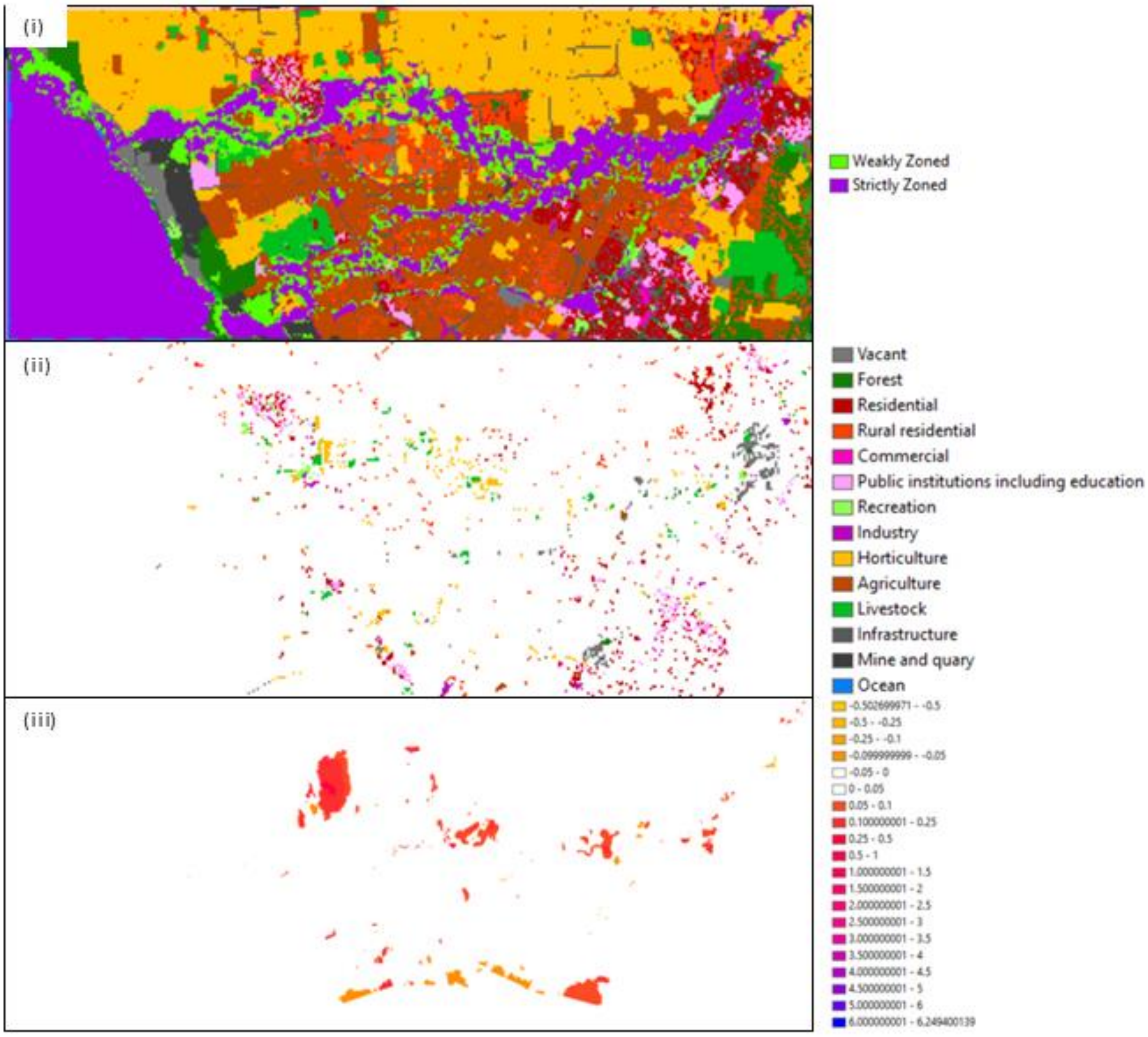

Figure 9 Comparison between Experiments 6 and 4 (i) the zoning in 2020 for experiment 6 (ii) difference in land use for Experiment 6 in 2080, (iii) difference in inundation depth in Experiment 6 in 2080 above 5cm. Details can be found in Appendix A.

2.4.3 Importance of consideration of two-way interaction in the flood-land use nexus when estimating future flood risk

The results in Figure 8 indicate that consideration of the two-way interaction in the flood-land use nexus (i.e., the use of dynamic zoning) does not have a significant impact when socio-economic drivers of change are considered in isolation (Experiments 5 and 7). However, this is not the case when considering both climate and socio-economic drivers of change (Experiments 6 and 8). This is as expected, as dynamic zoning allows zoning policies to be adjusted over time in response to changes in flood maps. When the effects of climate change are ignored, there are only likely to be minor changes in inundation levels and extents, resulting from changes in the degree of imperviousness due to urbanisation, which are unlikely to result in changes in zoning policy. However, when the effects of climate change are considered, there are likely to be marked changes in future flood maps, to which dynamic zoning policies are able to respond (Figure 10). In this instance, the ability to adjust zoning policies dynamically (Experiment 8) resulted in a 2% reduction in loss in 2080 compared with the case where static zoning was used (Experiment 6). While this change is relatively small for the case study considered, these changes could be much larger in cases where the impacts of climate change are more pronounced or urban expansion is more rapid, adding further weight to the importance of considering the two-way interactions between flooding and land use using frameworks such as the one introduced in this paper.

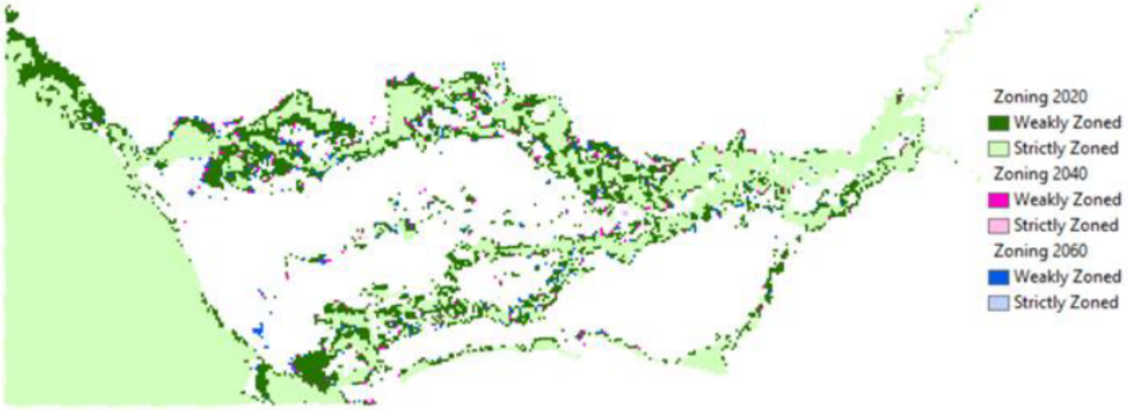

Figure 10 Experiment 8 zoning plans for 2020, 2040, and 2060 as used in Metronamica. Details can be found in Appendix A.9.

2.5 Summary and Conclusions

While the global impacts of flooding are already significant, they are expected to increase in the future as a result of climate change and socio-economic development. Quantifying changes in the nexus between flooding and land use is critical to our ability to better understand, quantify and mitigate this future risk. This is because changes in land use due to socio-economic development increase runoff and the "values-at-stake" exposed to flooding, increasing flood-related losses. At the same time, changes in flood extent and depth can change land use via policy measures aimed at reducing losses due to flooding, such as buy-backs and zoning policies. In order to enable this two-way interaction to be taken into account, a modelling framework is introduced in this paper that enables changes in the flood-land use nexus to be modelled dynamically by linking the inputs and outputs of spatially and temporally explicit flood and land use models.

The framework was applied to the Gawler River region in South Australia to assess (i) the relative importance of climate and socio-economic drivers of change, (ii) the relative effectiveness of zoning policies and (iii) the impact of considering the two-way nexus between impacts of land use on flooding and the impacts of flooding on land use. Results indicate that socio-economic drivers had a significantly greater impact on flood damage than climate drivers, highlighting the importance of considering the impacts of socio-economic drivers of change on future flood risk. In addition, zoning policies and buy-backs resulted in significant reductions in flood damage, as they were able to remove “values-at-stake” from, and curtail future development in, flood-prone areas. Finally, consideration of the two-way interaction between flooding and land use made a noticeable difference when considering both climate and socio-economic drivers, as this enabled zoning policies to be adapted in response to increased flood extents and depths caused by climate change.

While the proposed framework is generally applicable, the findings from the analysis are specific to the case study and scenarios considered, including the relative importance of climate and socio-economic drivers, the effectiveness of zoning and the impact of the consideration of the two-way interaction between flooding on the quantification of future risk. Consequently, there is a need to apply the proposed framework to a wider range of case studies with different characteristics. However, the case study results obtained in this paper demonstrate the importance of considering changes in future land use, zoning and the two-way interaction between flooding and land use in the assessment and mitigation of future flood risk. This highlights the value of using an integrated computational framework that considers plausible changes in the flood-land use nexus explicitly with the aid of linked, dynamic flood and land use models, such as the one introduced in this paper.

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Chapter 3: Effectiveness of Nature-Based Solutions for Mitigating the Impact of Pluvial Flooding at the Regional Scale

Eike Hamers, Holger R Maier, Aaron C Zecchin, Hedwig van Delden

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By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);

ii. permission is granted for the candidate in include the publication in the thesis; and

iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

Name of Co-Author	Holger R Maier		
Contribution to the Paper	Contributed to conceptualization of framework, analysis and interpretation of results, drafting of manuscript		
Signature		Date	06/07/2022

Name of Co-Author	Aaron C Zecchin		
Contribution to the Paper	Contributed to conceptualization of framework, analysis and interpretation of results		
Signature		Date	06/07/2022

Name of Co-Author	Hedwig van Delden		
Contribution to the Paper	Contributed to conceptualization of framework, analysis and interpretation of results		
Signature		Date	04/07/2022

Abstract

Pluvial flooding causes significant damage in urban areas globally. The most commonly used approaches to mitigating these impacts at regional scales include structural measures such as dams, levees and floodways. More recently, the use of nature-based solutions (NBS) is receiving increasing attention, as such approaches are more adaptive than structural measures and have a number of potential co-benefits (e.g., improvements in water quality and amenity). However, as NBSs are generally applied at house- or block-scales, their potential for reducing the impacts of flooding at the regional scale are unknown. In this paper, we introduce an approach that enables the potential of using portfolios of NBSs to reduce the impact of flooding to be assessed at the regional scale. The approach enables the most suitable locations for such portfolios of NBSs to be identified, as well as their effectiveness to be modelled at spatial resolutions that are commonly used for regional planning studies. The approach is applied to the Gawler River region in South Australia, which is subject to frequent flooding causing millions of dollars of damage. Results obtained suggest that there is significant potential for using strategically placed portfolios of NBSs to reduce the impact of pluvial flooding at the regional scale. For example, by placing portfolios of NBSs on 0.2% of the catchment, the resulting damage to building stock was reduced by 20% for a 1:10 year event and 14% for a 1:50 year event. These reductions in building stock damage increase to around 32% for the 1:10 year event and 27% for a 1:50 year event if the area covered is 1%.

3.1 Introduction

With more than 1,500 documented flood events worldwide classified as catastrophic from 2010 to 2020, resulting in overall damage of US$363 Billion, flooding is one of the costliest natural hazards today (Guha-Sapir, 2018, IFRC, 2018). The causes of these floods can be quite different, but often heavy rainfall is a key factor in the emergence of a flood. Extreme rainfall events on a catchment cause stress on the river network downstream and a significant rise in overland flow within the affected region (Miller et al., 2014, Jha et al., 2012, GFDRR, 2014).

With an increase in urbanization around the world, the risk of severe flooding caused by heavy rainfall is increasing significantly as a result of an increase in impervious areas. These newly built areas also have a significantly higher monetary value than rural regions. Consequently, there is also a significant increase in flood risk due to increases in exposure (Crichton, 1999, GFDRR, 2014). This trend is likely to increase in the future. For example, if urbanization rates continue without change, in 2050, the expected increase in sealed surfaces in urban areas of up to 15,000km^2 will lead to even larger runoff and, therefore, even greater flood extents and higher water depths. At the same time, globally, US$53 trillion of value is expected to be added to the 1 in 100-year floodplain by 2050, which would lead to an accumulated value of US$80 trillion (Jongman et al., 2012, Miller et al., 2014). In addition, rainfall events are also likely to become more intense due to the impacts of climate change (Bao et al., 2017, Guerreiro et al., 2018), further increasing flood risk.

With the expected increases in flood risk outlined above, demands on flood mitigation are also likely to increase int the future. Structural mitigation strategies, such as dams and levees, belong to the class of grey infrastructure and are arguably the most widely used mitigation option at present (White, 1942, Birkland et al., 2003, Thampapillai and Musgrave, 1985, IFRC, 2018). They are able to direct the flow paths of floods away from areas of higher value towards areas of lower value (White, 1942) and can be effective over large areas, enabling flood risk to be reduced at regional scales. However, despite their proven effectiveness, structural measures also have some disadvantages, including (i) they are generally expensive to construct and maintain (Thampapillai and Musgrave, 1985, Birkland et al., 2003) and (ii) they are generally not well suited to adaptation once constructed, making them less able to respond to unknown changes in future conditions (Thampapillai and Musgrave, 1985).

In response, there has been increasing interest in the development of more adaptive flood mitigation options (Dey and Mishra, 2017, Di Matteo et al., 2019a, Liang et al., 2019, Hodgkins et al., 2017, van Herk et al., 2015, Zevenbergen et al., 2013, Vergouwe, 2016, Kabisch et al., 2017, Dawson et al., 2011). In contrast to structural measures, many of these adaptive options belong to the class of green and blue infrastructure, or nature-based solutions (NBSs), which use natural elements to reduce water depths and flow speeds within a certain area by mimicking the effects of vegetation and soil characteristics on floods and their distribution (Castellar et al., 2021, Zölch et al., 2017, Kumar et al., 2021, Cameron et al., 2012, Whitford et al., 2001). This is achieved by increasing surface roughness and permeability, thereby reducing the impact of localised flooding by reducing flow velocities and increasing infiltration rates. Examples of NBSs include rain gardens, green roofs, retention basins, wetlands and re-naturalized river systems, and they are often used in conjunction with some sort of storage facility to further reduce flood peaks (Dawson et al., 2011, Liang et al., 2021, Australian Institute for Disaster Resilience, 2017, Chen et al., 2021, Huang et al., 2020). In addition to mitigating flood risk, NBSs are also able to increase amenities in urban areas (Kabisch et al., 2017, Whitford et al., 2001).

In contrast to structural mitigation options, the effectiveness of NBSs has generally only been assessed at smaller, localised scales, such as street blocks or small suburbs (Zölch et al., 2017, Kumar et al., 2021, Vojinovic et al., 2021, Kim and Park, 2016, Zellner et al., 2016, Pappalardo et al., 2017), with assessments at larger scales rare (Fastenrath et al., 2020, Hankin et al., 2021, Chen et al., 2021). Given these localised assessment scales, previous studies have generally focussed on the detailed modelling of the effectiveness of individual NBS schemes at known locations, investigating the relative effectiveness of different types of NBSs under different rainfall regimes, including the impact of climate change (Zölch et al., 2017). However, the effectiveness of applying portfolios of NBSs at regional scales to complement, or act as potential alternatives to, structural measures, has not been considered, despite the potential benefits this could provide in terms of increased adaptability and amenity, as well as reduced cost.

A likely reason for the lack of consideration of the potential benefits of using portfolios of NBSs for flood mitigation at regional scales is that there is currently no formal approach to determining how many NBSs to use and where to locate them to achieve an appropriate trade-off between the number of NBSs (and hence their cost) and the corresponding reduction in flood impact. In addition, assessment of the relative effectiveness of different portfolios of NBSs requires a modelling approach that is suited to regional scale assessments, which is also not available at present. When considering regional scales, a coarser modelling resolution is likely to be more appropriate, as the focus is on the identification of the most suitable locations of NBSs, rather than the detailed modelling of individual schemes at a given location. Such a coarser resolution is likely to facilitate better integration with the land-use maps and models required for determining the suitability of different potential locations of NBSs and to enable different placement configurations to be modelled in a computationally efficient manner.

In order to address the above limitations, the objectives of this paper are:

To develop a formal approach that is able to (i) identify suitable locations of portfolios of NBSs at regional scales, enabling trade-offs between portfolio size and the corresponding reduction in flood impact to be determined and (ii) model the flood reduction impact of portfolios of NBSs at regional scales at a resolution that enables the requisite analyses to be integrated with land use planning practises and to be conducted in a computationally efficient manner.

To illustrate the utility of the proposed approach and assess the degree to which portfolios of nature-based solutions can mitigate pluvial flooding at the catchment scale for a case study in Adelaide, South Australia.

The remainder of this paper is organised as follows. The proposed methodology for identifying and modelling the most suitable locations of portfolios of NBSs at the regional scale is introduced in Section 3.2, followed by the case study application in Section 3.3. The results are presented and discussed in Section 3.4 and the conclusions are provided in Section 3.5.

3.2 Methodology

In this section, the proposed approach for including portfolios of NBSs as potential options in regional flood reduction studies is introduced. This includes (i) identification of where portfolios of NBSs should be placed throughout a region (Objective 1(i) – see Section 3.2.1) and (ii) how to best model the impact of NBSs at regional, rather than street or small-suburb, scales (Objective 1(ii) – see Section 3.2.2).

3.2.1 Placement of Portfolios of NBSs at Regional Scales

The formal approach to identifying feasible locations for portfolios of NBSs at regional scales to enable trade-offs between portfolio size and the corresponding reduction in flood impact to be determined is outlined in Figure 11. As can be seen, the proposed framework consists of four main steps, including determination of potential locations for NBSs (Step 1, Figure 11), determination of feasible locations for NBSs (Step 2, Figure 11), determination of the placement of NBSs (Step 3, Figure 11) and determination of the effectiveness of the NBSs placed as part of Step 3 (Step 4, Figure 11). Knowledge of the relative effectiveness of the placement of NBSs in different regions of the catchment can potentially be used to refine the placement of NBSs to achieve better trade-offs between the number of NBSs and the corresponding reduction in flood risk as part of an iterative formal or informal optimisation process (Maier et al., 2019).

For each of the four steps mentioned above, an outline of the choices that have to be made by users of the framework, what tools and data are required, and the outcomes obtained are also given in Figure 11. Details of each of the four steps are given in subsequent paragraphs.

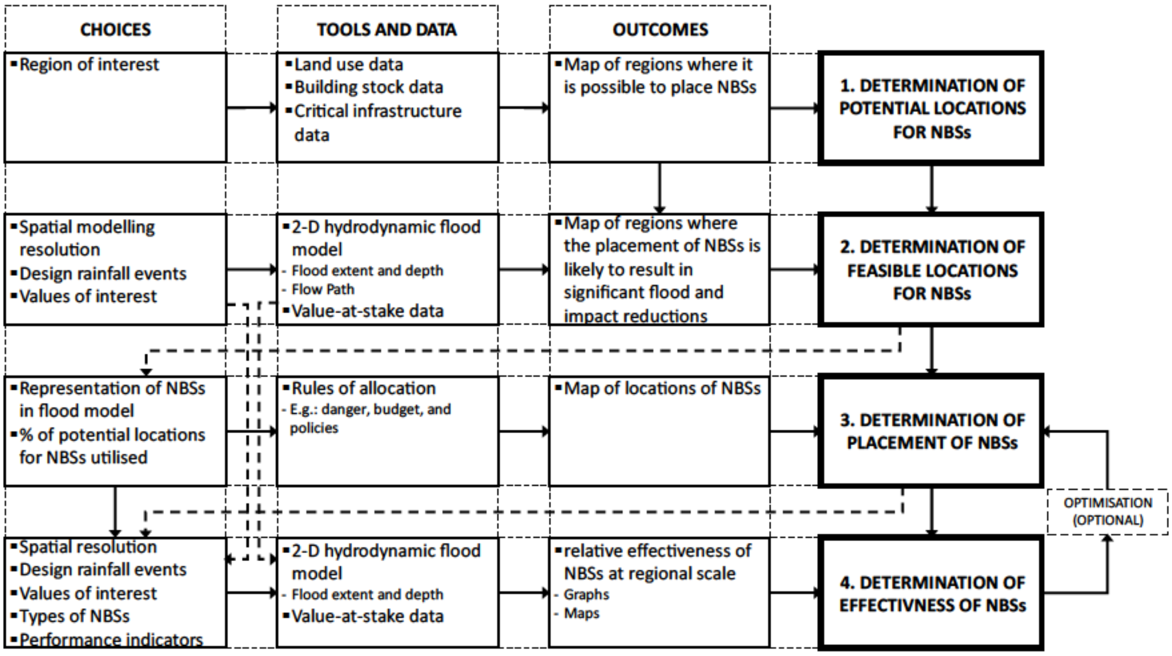

Figure 11 Generic framework of placing nature-based solutions throughout a catchment in a regional planning setting

In order to identify potential locations for the placement of portfolios of NBSs (Step 1, Figure 11), the region for which there is interest in determining the potential of using portfolios of NBSs to reduce flood risk has to be defined, along with areas where it is possible to locate NBSs. The latter requires information on the spatial distribution of different land use classes, as well as the location of building stock and critical infrastructure. Other local, context-specific information (e.g. local regulations, social factors etc.) should also be considered. The outcome of this step is a map of regions where it is possible to place NBSs.

As part of the next step (Step 2, Figure 11), regions where the placement of portfolios of NBSs is likely to result in a significant reduction in flood levels and impacts are identified. This is achieved by examining the coincidence of the potential locations of portfolios of NBSs identified in Step 1 with flood extent and depth and value-at-stake data (i.e. values of buildings, critical infrastructure, ecological assets etc.). Choices to be made in this step include the design rainfall events against which the effectiveness of nature-based solutions is going to be tested, as well as the values of interest to be included (e.g. economic, social, environmental etc.). The flood maps that correspond to the selected rainfall events can either be obtained from previous studies or with the aid of an appropriate model (e.g. 1-D/2-D hydrodynamic flood model) and should contain information such as flood depth, flood extent and flow velocity. The outcome of this step is a map of the relative feasibility of potential locations of NBSs in terms of flood risk reduction.

As part of the third step (Step 3, Figure 11), locations where portfolios of NBSs should be placed are determined. This is done with the aid of rules of allocation that consider a combination of factors, such as the map of the relative feasibility of potential locations of NBSs obtained as part of Step 2, the types of NBSs to be considered, available budget / number of NBSs / fraction of feasible locations to be utilised, local policies / plans / restrictions etc. These rules are case study specific and need to be predetermined. As part of high-level planning exercises, such an approach could be automated based on numerical criteria (e.g. inundation level thresholds), although in practice would most likely also include stakeholder engagement processes (see Di Matteo et al. (2017), Di Matteo et al. (2019b), Wu et al. (2016)). The outcome of this step is a map of the locations of portfolios of NBSs to be considered.

The fourth step (Step 4, Figure 11) involves determination of the effectiveness of the configuration of NBSs selected in Step 3 in terms of the performance indicators of interest, such as reduction in flood depth and extent and / or reduction in flood damage. This is done with the aid of a flood model that enables the impact of the selected configuration of NBSs on the selected performance indicators to be assessed (e.g. 1-D/2-D hydrodynamic model). If these indicators go beyond purely hydraulic factors (e.g. damage to building stock), additional information translating hydraulic variables to the required impact metrics is also required (e.g. which buildings are inundated, the values of these buildings and the vulnerability curves translating inundation levels to degree of building damage).

When developing the hydraulic model used to assess the effectiveness of the selected configuration of NBSs, it is critical that an appropriate spatial modelling resolution is used. The resolution that is most appropriate depends on a number of factors, such as the spatial extent of the area to be modelled, the modelling approach used, the available computational resources, the scale of the NBSs considered and the spatial resolution at which planning studies are conducted. Given that the spatial modelling resolution is likely to be significantly larger than the spatial extent of individual NBSs (see Section 1), a key issue that needs to be addressed is how to best represent portfolios of NBSs in the flood model so that the impact of the addition of portfolios of NBSs at the regional scale can be assessed with an appropriate level of accuracy and computational efficiency (Objective 1(ii)). The proposed approach for achieving this is outlined in Section 3.2.2.

In practice, it is unlikely that only a single configuration of portfolios of NBSs is assessed. For example, there might be interest in repeating Steps 3 and 4 for different numbers of portfolios of NBSs / percentage utilisation of feasible locations (and hence cost), enabling trade-offs between the number of NBSs and corresponding performance indicators to be determined. Alternatively, formal optimisation algorithms could be used to determine the configurations of portfolios of NBSs that result in the optimal trade-offs between number of NBSs considered (and hence cost) and flood risk reduction (as measured by the selected performance indicators) (e.g., see Di Matteo et al. (2019b)). Consequently, potential outcomes of this step include graphs of (optimal) trade-offs between the number of NBSs and flood risk reduction and / or maps of the relative flood risk reduction resulting from different configurations of NBSs.

3.2.2 Modelling of Impact of NBSs at Regional Scales

As mentioned in Section 1, in previous studies, the effectiveness of NBSs has been assessed by modelling the impact of a particular type of NBS at a particular location, rather than modelling the impact of a portfolio of NBSs at regional scales. In order to achieve the latter, the modelling resolution (i) has to be commensurate with that used in regional land use planning studies (e.g. Newland et al. (2020), Newland et al. (2018a)) and (ii) result in a model that is sufficiently computationally efficient to enable the relative effectiveness of different portfolios of NBSs to be assessed in a reasonable timeframe.

In order to achieve this, it is proposed to (i) adopt a spatial resolution that is appropriate for the case study under consideration, considering factors such as the spatial extent of the area to be modelled, the modelling approach used, the available computational resources, the scale of the NBSs considered and the spatial resolution at which planning studies are commonly conducted (e.g. from 50m x 50m to 500m x 500m) (see Section 2.1) and (ii) use an equivalent uniform infiltration rate for each of these spatial areas, which is a function of the number, type and extent of NBSs on this area, rather than modelling each scheme individually. The uniform infiltration rate simplifies the otherwise complex modelling of NBSs to allow for an automated allocation in larger regions.

To determine an appropriate uniform infiltration rate for the selected spatial modelling resolution and the types of NBSs considered, the "calibration" approach depicted in Figure 12 is proposed. As part of the approach, typical numbers of building- (e.g. green roofs, rain gardens – Scheme A, Figure 12) and block- size (e.g. wetlands – Scheme B, Figure 12) measures are selected for a single spatial modelling unit. The runoff hydrographs resulting from different spatial configurations of these portfolios of NBSs are then obtained at a number of locations within this spatial unit with the aid of the selected flood simulation model. These runoff hydrographs are compared with the hydrographs obtained by applying an "equivalent" uniform infiltration rate over the same spatial modelling unit, which is adjusted in an iterative fashion until a satisfactory match is obtained between the hydrographs obtained by modelling individual portfolios of NBSs and those obtained by applying an equivalent uniform infiltration rate (Figure 12).

How well these two sets of hydrographs match can be assessed using visual inspection or in a more quantitative fashion using a range of performance metrics (see Bennett et al. (2013)). The process of iteratively adjusting the equivalent infiltration rate can be done manually or using more formal optimisation methods (see Maier et al. (2019)). The convergence of this iterative process is likely to increase by starting the iterative process with a value that is informed by an understanding of the underlying processes (e.g., see Newland et al. (2020); Bi et al. (2016)), such as using the area-weighted average of the infiltration values of the individual members of the portfolio of NBSs considered.

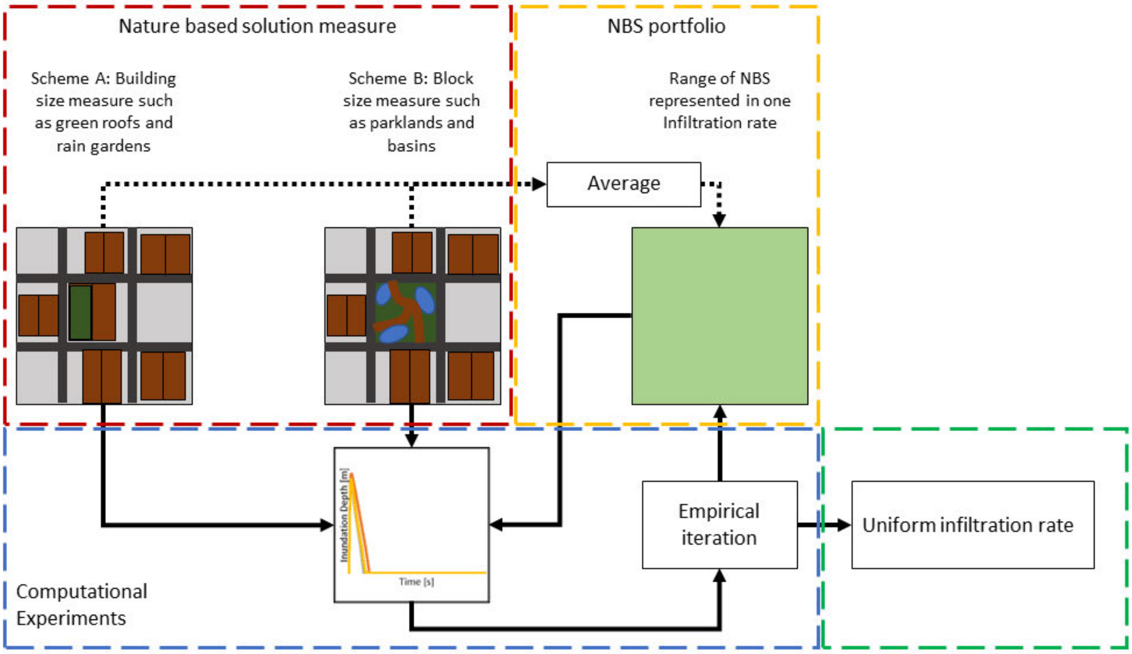

Figure 12 Methodology to determine uniform infiltration rate for NBS portfolio

3.3 Case Study

In this section, the methodology used to (i) illustrate the utility of the approach introduced in Section 2 and (ii) assess the degree to which different portfolios of nature-based solutions can mitigate pluvial flooding at the catchment scale is outlined for a case study in Adelaide, South Australia (Objective 2). The choices made, tools / data used, and outcomes achieved for each of the four steps of the proposed methodology for the case study are summarised in Figure 14 and detailed in the following sub-sections.

3.3.1 Determination of Potential Locations for NBSs

The Gawler River region to the north of Adelaide, South Australia, was selected as the case study area (Figure 13). The region covers an area of 683.22km^2 and spans seven different Local Government Areas. The majority of the region is considered to be rural, mostly consisting of agri- and horticultural- development and low density rural residential areas (Tonkin Consulting, 2018). However, there are also urban areas, with high density development, especially around the township of Gawler.

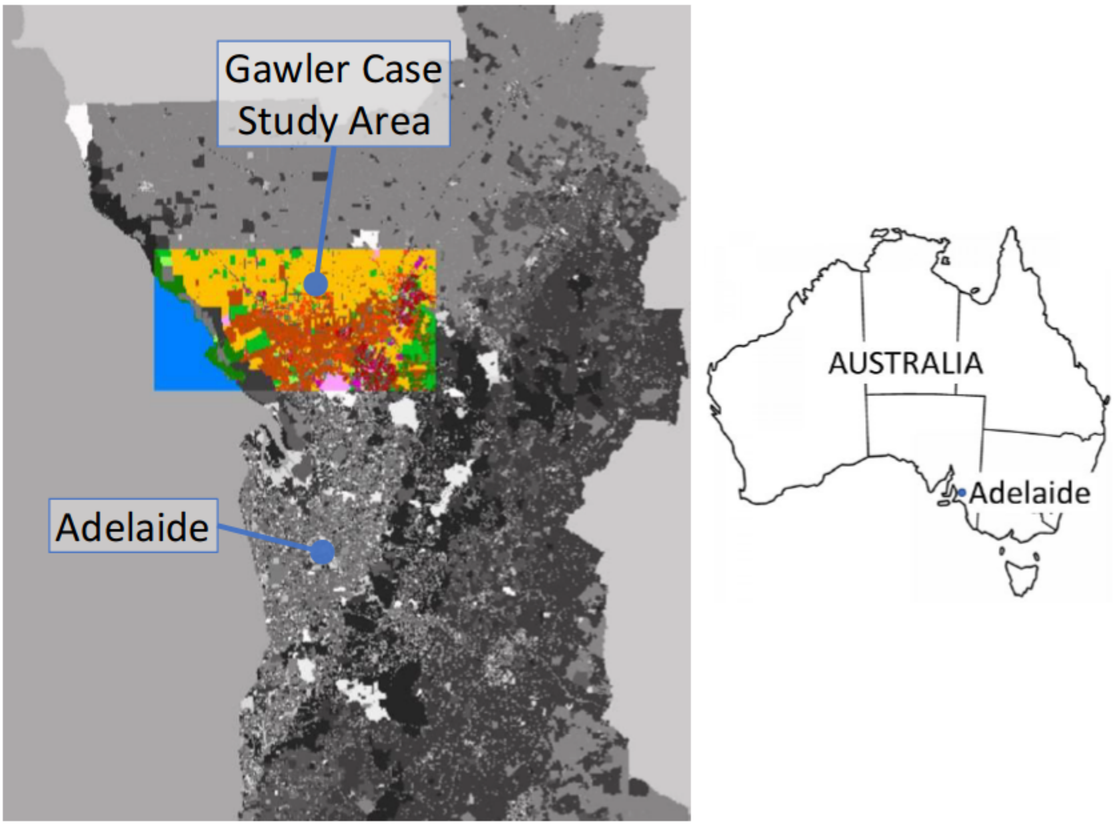

Figure 13 Gawler Case study area in the North of the Greater Adelaide region

The region is affected by significant flooding. The most recent major event in 2016 caused AU$50 million in damage and resulted in the formation of the Gawler River Floodplain Management Authority, as well as planning for a floodway along the river to protect the most vulnerable areas (Tonkin Consulting, 2018, Fisher et al., 2017). However, there has been no consideration of using NBSs at the regional scale to reduce flood risk.

Land use and building stock maps were available at a 100m x 100m resolution and were used to identify potential locations for NBSs, which corresponded to residential, commercial and industry land use classes (Figure 14, Step 1, Tools and Data). This resulted in a map of regions where it would be possible to place NBSs (Figure 14, Step 1, Outcomes, red areas). As can be seen, these regions are primarily distributed in the eastern part of the catchment, with smaller pockets of potential locations for NBSs distributed throughout the remainder of the area. Overall, the potential areas for the placement of NBSs cover an area of 38.69 km^2, which corresponds to 6.66% of the total area considered. Details of the land use map and the map of potential locations are given in Appendix B.1 and B.3.

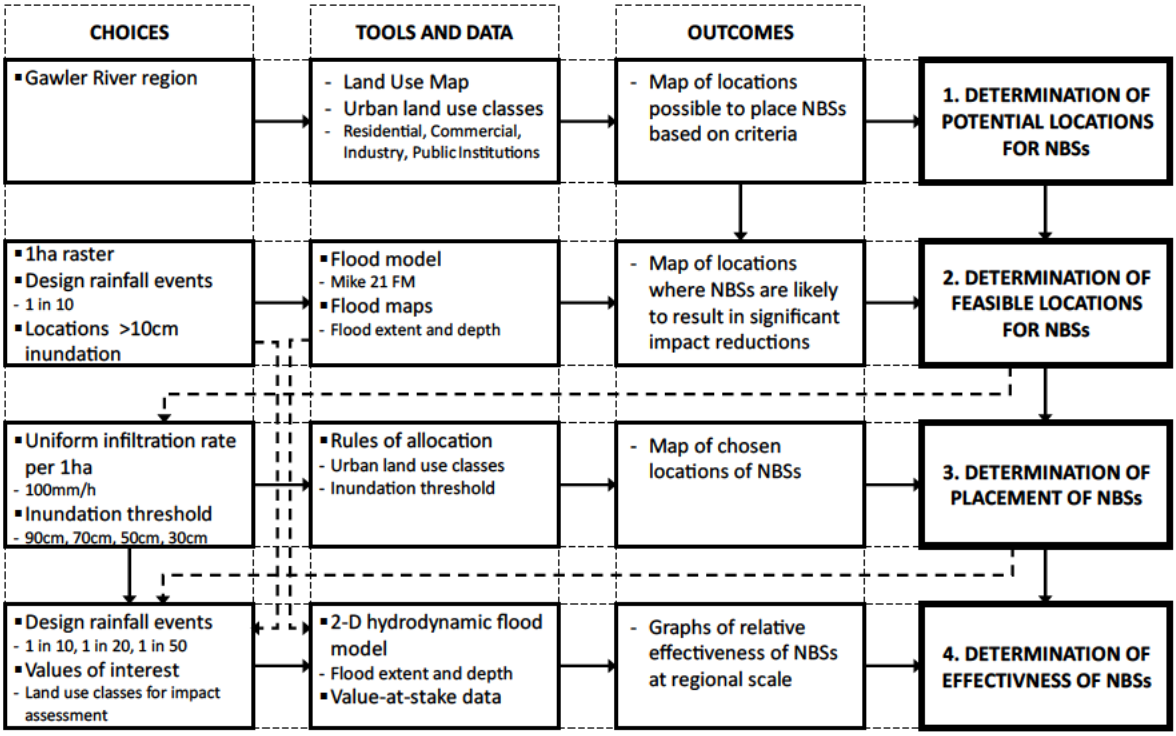

Figure 14 Case study specific framework of placing nature-based solutions throughout the Gawler River region

3.3.2 Determination of Feasible Locations for NBSs

In order to identify the feasible locations for NBSs, the map of potential locations for NBSs obtained in Section 3.3.1 was overlayed with the flood map for the 1:10 year pluvial flood event. Any potential locations that exceeded an inundation threshold (i.e. depth in excess of a particular value) of 100mm were selected as feasible locations for NBSs. A return period of 10 years was selected as this is a common return period when using NBSs (Water Sensitive SA, 2010) and an inundation threshold of 100mm was used because this is the starting water depth for the depth-damage-curves. This resulted in a map of feasible locations for placing NBSs (Figure 14, Step 2, Outcomes, green areas). As can be seen, these areas form a small subset of the potential areas, covering an area of 1.17 km^2, which corresponds to 3.02% of the Potential Area identified in Section 3.3.1 and 0.20% of the total area considered. Details of the map of potential locations, the 1:10 year inundation map and the map of feasible locations are given in Appendix B.2 and B.3.

The inundation map was obtained with the aid of a 2-D hydrodynamic flood model of the catchment developed using Mike Flood 21 FM of DHI (DHI, 2017). The model was implemented using a flexible mesh and Digital Elevation Model (DEM) to simulate flood extent and flow throughout the catchment. The flexible mesh reduces computational time significantly compared with using a standard grid, as this enables the use of graphics processing units (GPUs). A maximum area of 225m^2 and an angel of 25° were used to create the mesh. However, it should be noted that input data on infiltration, roughness, and rainfall can be entered in a regular grid format, which was selected to be 15m x 15m to be commensurate with the grid sizes used for the detailed assessment of individual NBSs (e.g. Huang et al. (2020), Meshram et al. (2021), Vojinovic et al. (2021), Zölch et al. (2017)). Both infiltration rate and rainfall rate are expressed in mm/h, and while the infiltration rate is spatially explicit, the rainfall rate is uniform throughout the area of interest.

Overland flow was modelled in Mike 21 FM, a 2D flood model using flexible mesh. Infiltration rates were set to 1mm/h and 2mm/h for urban and rural land use classes, respectively. This is because a reduction in infiltration across the catchment is assumed caused by extensive rainfall prior to the flood event in accordance with Tonkin Consulting (2018). In addition, the infiltration rates for cells corresponding to high degrees of surface sealing, such as those occupied by infrastructure, were set to 0mm/h.

The model was calibrated and validated by comparing results with those of a model used in a study conducted by Tonkin Consulting (2018) for a 1 in 100 year event. The model is capable of simulating fluvial and pluvial flooding. Further details of the calibration and validation process are given in Appendix D.1.

3.3.3 Determination of Placement of NBSs

The rules of allocation used to determine in which sub-areas of the feasible regions identified in Section 3.3.2 to place portfolios of NBSs was based on different inundation thresholds, including 300mm, 500mm, 700mm and 900mm. This was done for illustration purposes, as it enabled different regions and extents where NBSs are placed to be identified (see Table 2), enabling trade-offs between different numbers of NBSs (and hence costs) and the corresponding flood risk to be investigated. The impact of using an additional sub-region consisting only of urban residential land use classes (Restricted Potential, Table 2) was also investigated to narrow the gap between potential and feasible location coverages. As mentioned in Section 3.2.1, in practice, the allocation process would most likely also involve consideration of a range of other factors, such as local regulations and input from relevant stakeholders.

As can be seen from Table 2, the Restricted Potential area covers just over half the area of the Potential area, whereas the Feasible area only covers 3.02% of the Potential area. As the required inundation threshold increases from 30cm to 90cm, the percentage of the Potential area where portfolios of NBSs are placed in accordance with the rules of allocation used reduces from1.81% to 0.08%, which correspond to 59.9% and 2.48% coverage of the Feasible region, respectively. This enables the importance of placing NBSs at strategic locations at the regional scale, and hence the potential utility of the proposed approach, to be assessed.

The outcome of the allocation process is the development of maps showing the location of NBSs for the different inundation thresholds considered (Figure 14, Step 3, Outcomes, pink areas), details of which are given in Appendix B.3.

Table 2 Placement choices, area covered in NBS, and utilisation based on different thresholds

Chosen Thresholds [cm]	**90**	**70**	**50**	**30**	**Feasible**	**Restricted Potential**	**Potential**
Area [km^2]	0.03	0.18	0.40	0.70	1.17	19.38	38.69
Utilisation of catchment	0.005%	0.03%	0.07%	0.12%	0.20%	3.34%	6.66%
Utilisation of potential	0.08%	0.48%	1.03%	1.81%	3.02%	50.1%	100%
Utilisation of feasible	2.48%	15.8%	34.1%	59.9%	100%	-	-

3.3.4 Determination of Effectiveness of NBSs

In order to determine the effectiveness of the different placements of NBSs selected in Section 3.3.3 to be assessed, the impact of the NBSs on inundation depth and extent was modelled using the 2-D hydrodynamic flood model developed for the Gawler River catchment (see Section 3.3.2). Effectiveness was assessed using the total reduction in the level of inundation and the total reduction in the damage to building stock. The latter was determined with the aid of vulnerability curves that determine the percentage destruction of a building based on inundation level. This percentage is multiplied by the value of the building to determine the damage. By performing this calculation using inundation levels with and without the presence of regional portfolios of NBSs, the reduction in damage in building stock was determined. The value of the building stock was determined from a report for the Gawler River UN Mitigation Project (van Delden et al., 2022), as were the vulnerability curves for the different building types.

The effective uniform infiltration rate that best represents the impact of the addition of different portfolios of NBSs for the selected 100m x 100m modelling resolution was determined using the approach outlined in Section 3.2.2. Different configurations of NBSs within these 100m x 200m areas were considered for building- and block- size measures, as summarised in Figure 12. For building size measures (Scheme A, Figure 12), one spatial configuration of ten measures with a size of 15mx30m and an infiltration rate of 400mm/h across the 100x200m area was considered. For block size measures (Scheme B, Figure 12), one spatial configuration of two measures with a size of 75mx90m and different infiltration rates ranging from of 10 mm/h to 500mm/h was considered. These sizes and infiltration rates were considered because of examples given in Water Sensitive SA (2010).

A manual calibration process was used, iteratively adjusting the uniform infiltration rate over the 100m x 200m cell until the runoff hydrographs from the different configurations of building- and block-size measures closely matched those obtained when the uniform infiltration rate was used. These hydrographs were compared at nine random locations within the 100m x 200m cell using visual inspection.

In order to assess the suitability of using portfolios of NBSs at regional scales, the computational experiments summarised in Figure 15 were conducted (see also Figure 14). As can be seen, the effectiveness of the different portfolios of NBSs considered was assessed for flood events of different return periods, including 1:10 (average intensity of 24.5mm/h), 1:20 (average intensity of 29.7mm/h) and 1:50 (average intensity of 37.3mm/h) year events for a 60min duration. An expected damage was not used in this case study to obtain understanding of the behaviour of the concept under different circumstances. For each of these events, the effectiveness of two different configurations of NBSs was assessed, corresponding to NBS placement locations determined using the different inundation thresholds considered (see Table 2 and Figure 14). As mentioned previously, effectiveness was assessed both in terms of reduction in inundation depth and reduction in damage to building stock. Consequently, the output of this step is a set of trade-off curves relating different degrees of coverage of the Feasible region with NBSs and corresponding reduction in inundation level and building damage (Figure 14, Step 4, Outcomes).

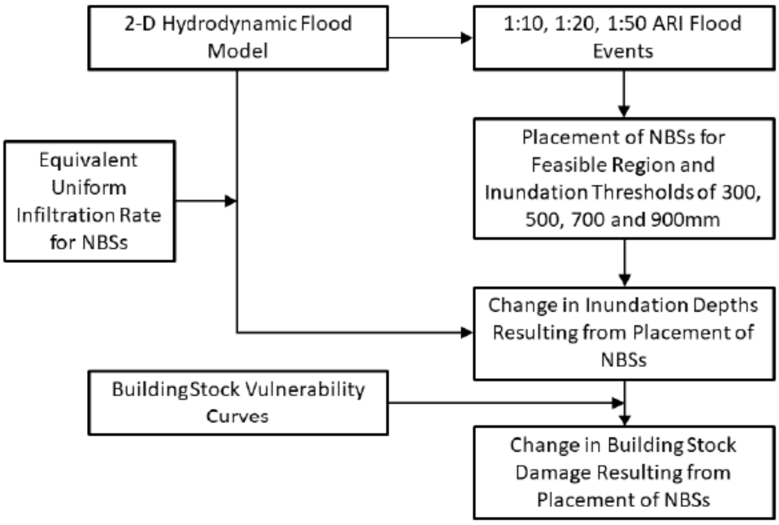

Figure 15 Overview of computationals expirements

3.4 Results and Discussion

In this section, the results of the computational experiments outlined in Section 3.3.4 are presented and discussed. First, the results of the calibration process used to determine the equivalent uniform infiltration rate that enables portfolios of NBSs to be modelled at coarser spatial scales for the purposes of regional planning (Objective 1(ii)) are presented and discussed (Section 3.4.1). Next, the results of the computational experiments designed to assess the degree to which portfolios of nature-based solutions can mitigate pluvial flooding at the catchment scale for a case study in Adelaide, South Australia (Objective 2), are presented and discussed (Section 3.4.2).

3.4.1 Determination of Equivalent Infiltration Rate

As part of the calibration process, a uniform infiltration rate of 100mm/h was found to give good results, as shown in Figure 16. In the Figure, representative modelled runoff hydrographs obtained at four of the nine random locations within the 100m x 200m spatial units considered are shown for the two detailed sets of configurations of NBSs (building size measures (Scheme A, Figure 12) and block size measures (Scheme B, Figure 12)), as well as when a uniform infiltration rate of 100mm/h was used over the entire 100m x 200m spatial unit. As can be seen, use of an equivalent uniform infiltration rate results in very similar runoff hydrographs than when the different configurations of NBSs are modelled in more detail. Although there is a better match to the building size measures, the discrepancy in hydrograph peak and timing when compared with the block size measures is minimal when an equivalent uniform infiltration rate is used. Similar results were obtained for the other five locations (see Appendix B.4).

The above results suggest that the proposed approach is suitable for determining an equivalent uniform infiltration rate that enables portfolios of NBSs to be modelled at coarser spatial scales for the purposes of regional planning. The results also suggest that it is possible to adopt a relatively coarse spatial modelling resolution, such as 100m x 100m, for the purposes of approximating the potential impact of portfolios of NBSs that are distributed throughout a region as part of preliminary assessment studies. However, once suitable locations of portfolios of NBSs have been identified, a more finely resolved modelling approach is likely required for the preliminary and detailed design of individual NBSs.

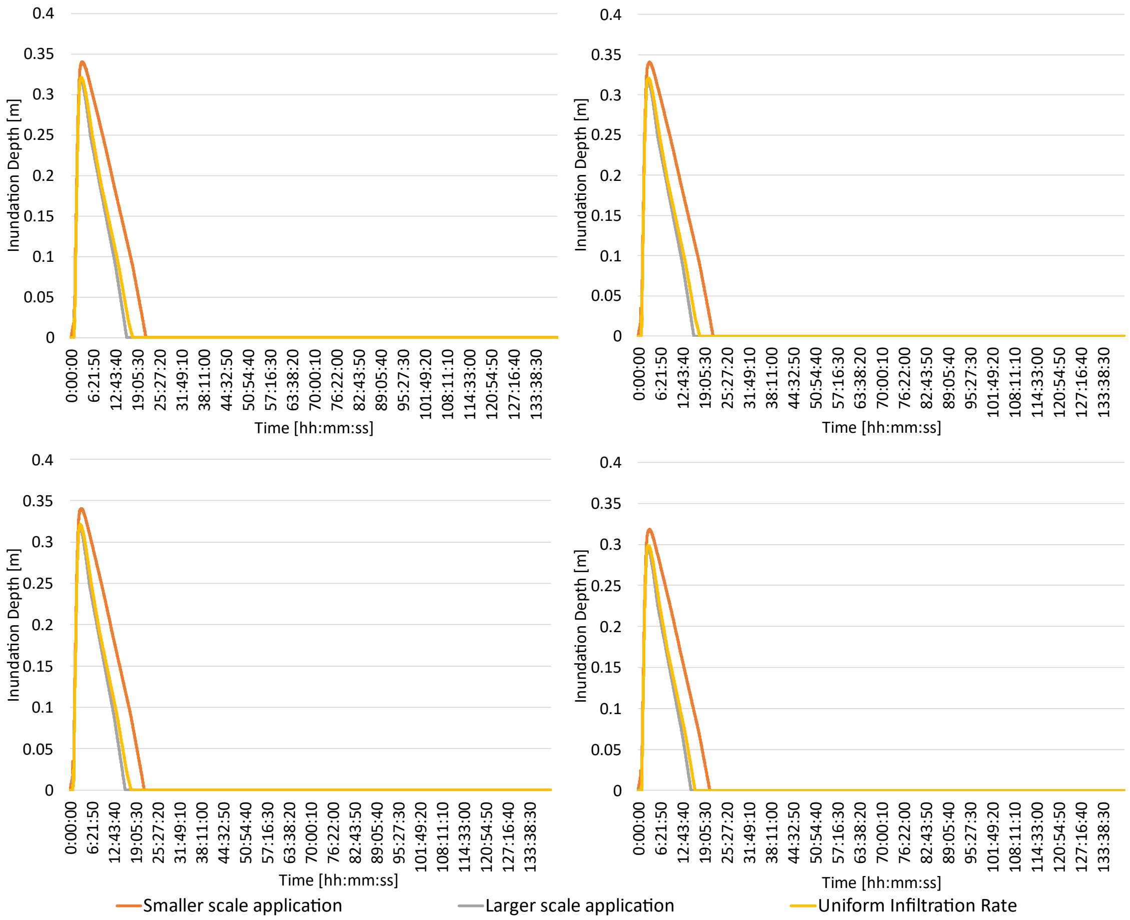

Figure 16 Comparison of inundation depths of different detailed nature-based solutions and the uniform infiltration rate over time in four spatial varying locations

3.4.2 Determination of Trade-Off between Number of NBSs and Effectiveness

The trade-offs between using a larger number of strategically placed NBSs, as represented by different utilisation rates of the total Feasible region, and their flood risk reduction effectiveness, as represented by the reduction in damage to building stock and the reduction in flood inundation level, for different return period events (i.e. 1:10, 1:20 and 1:50) are shown in Figure 17 and Figure 18, respectively. As can be seen from Figure 17, the strategic placement of NBSs throughout the Gawler region has the potential to reduce damage to building stock significantly. For example, for a 1:10 year event, by placing portfolios of NBSs on 0.2% of the area under consideration, the resulting damage can be reduced by 20%. This number increases to around 32% if the area covered is 1%. However, the marginal increase in the effectiveness NBSs decreases rapidly as the area covered by NBSs increases, as shown by the highly non-linear nature of the plots in Figure 17, where the biggest marginal increase in effectiveness occurs for percentages of less than 0.15% and almost reaches zero for percentages in excess of 3.5%. This highlights the effectiveness of the approach proposed in Section 3.2 in terms of being able to identify locations where NBSs should be placed to achieve the biggest returns for investment.

The shape of the trade-off curves between the number of NBSs and percentage reduction in building stock damage is very similar for events with different return periods (Figure 17). However, as expected, for the same configuration of NBSs, there is a reduction in effectiveness as the return period of the flood event increases. For example, the damage reduction associated with a 0.2% coverage of the area under consideration with NBSs decreases from 20% for a 1:10 year event to around 14% for a 1:50 year event and from around 32% to around 27% when the coverage is 1%. However, overall, the results obtained indicate that the use of strategically-placed portfolios of NBSs still appears to be a potentially successful strategy for reducing the damage to building stock caused by flooding at the regional scale for higher return periods, such as 1:50 year events.

Although the placement of portfolios of NBSs at the regional scale resulted in significant reductions in building stock damage (Figure 17), they did not result in significant reductions in inundation level (Figure 18). For example, for a 1:10 year event, by placing portfolios of NBSs on 0.2% of the area under consideration, the resulting inundation level was only reduced by about 0.16%, whereas the corresponding damage was reduced by 20%. Similarly, when the percentage coverage of NBSs was 3.34% and 6.66%, the corresponding reductions in inundation levels were only 1.1% and 1.8%, respectively, whereas the associated reductions in damage were around 69% and 76%. These results highlight the non-linearity in the relationship between inundation level and damage, especially the relationship between the effect of floor level height on damage (i.e. zero damage occurs if inundation levels are below floor level and potentially significant damage occurs once inundation levels exceed floor levels). However, it also confirms the ability of the approach introduced in Section 2 to identify the most promising locations for the placement of portfolios of NBSs at the regional scale in terms of damage reduction.

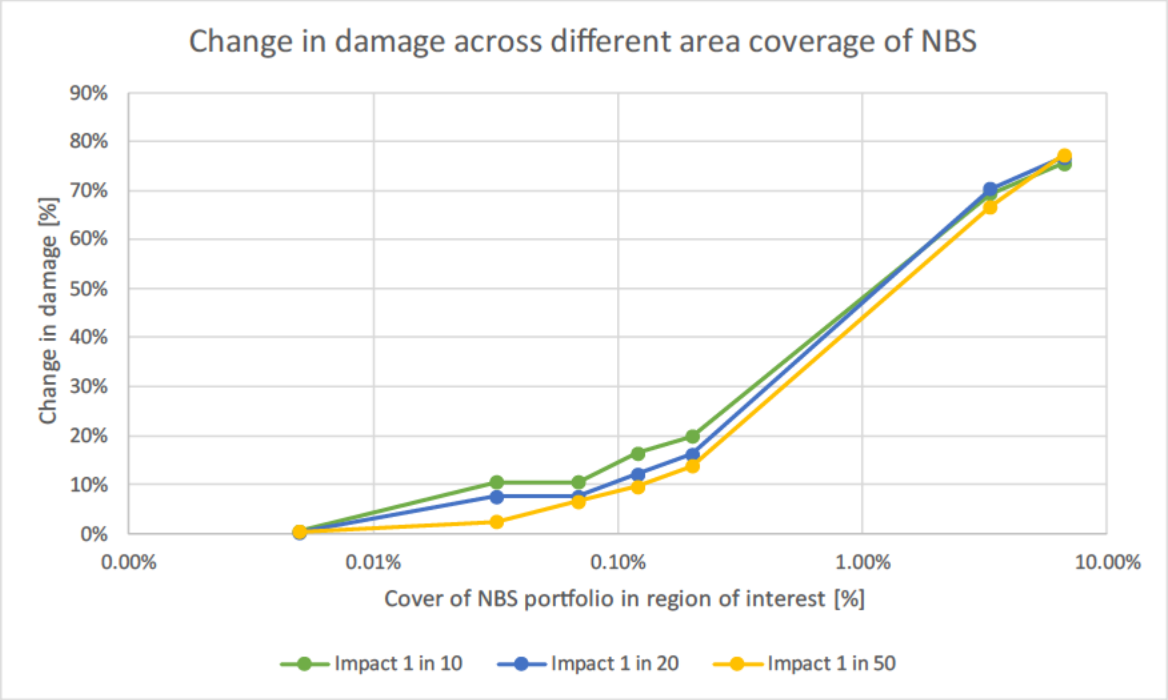

Figure 17 Reduction in loss for each return period and coverage in nature-based solutions

As was the case for the shape of the trade-off curves between the number of NBSs and the percentage of reduction in building stock damage (Figure 17), the shape of the trade-off curves between the number of NBSs and the percentage reduction in inundation level is very similar for events with different return periods (Figure 18). However, contrary to a percentage change in building stock damage, the percentage changes in inundation level increase with an increase in return period. This is because of the increase in intensity of the rainfall events. However, as discussed above, this increased percentage reduction does not translate into an increased percentage reduction in losses as the effectiveness of the NBS portfolio reduces.

Although the shapes of the trade-off curves in Figure 17 and Figure 18 are both non-linear in the lower ranges of NBS coverage (~0% to 0.2%), this is not the case for higher ranges. While the marginal benefit of adding a larger number of NBSs decreases as the number of NBSs increases with regard to percentage reduction in building stock damage (Figure 17), as discussed above, the same is not the case for percentage reduction in inundation levels, which continues to increase with an increase in the size of the area covered with NBSs as a result of the increase in infiltration rate (Figure 18). However, if there is no building stock in these areas, there is no further reduction in building stock damage, even though there is a reduction in inundation level. This further highlights the importance of an algorithm that enables the most beneficial locations of NBSs to be identified at the regional scale.

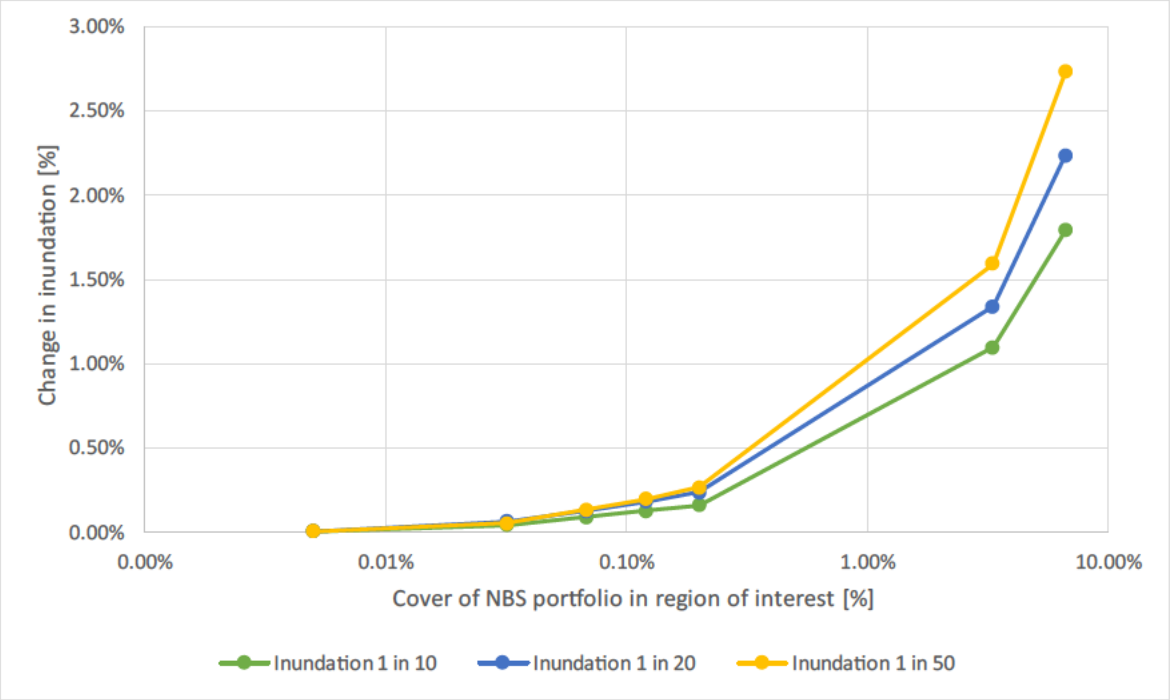

Figure 18 Reduction in total inundation depth for each return period and coverage in nature-based solutions

3.5 Conclusion

Flooding causes significant damage world-wide. Structural options are often used to mitigate flood risk at regional scales. While the use of nature-based solutions (NBSs) is becoming increasingly popular as a potential alternative to structural measures due to their adaptability and co-benefits, such as improved water quality and increased urban amenity, their application has only been considered at building- or block-scales. In this paper, we introduce and illustrate an approach that enables the utility of NBSs to be assessed at regional scales, including the ability to model the flood reduction benefits of NBSs at spatial resolutions that are commensurate with those commonly used in spatial planning studies (e.g. 50m x 50m to 500m x 500m) and the ability to identify the most suitable locations for placing portfolios of NBSs at regional scales.

The proposed approach was applied to the Gawler River region in South Australia, which is prone to flooding that has the potential to cause significant damage. The most suitable locations for the placement of portfolios of NBSs in order to reduce flood risk were identified and the potential benefit of using portfolios of NBSs was assessed. Results indicate that the strategic placement of portfolios of NBSs has the potential to reduce regional flood risk significantly. For the case study considered, by placing portfolios of NBSs on 0.2% of the area under consideration, the resulting damage to building stock can be reduced by 20% for a 1:10 year event, 16% for a 1:20 year event and 14% for a 1:50 year event. These reductions in building stock damage increase to around 32% for the 1:10 year event, 30% for a 1:20 year event and 27% for a 1:50 year event if the area covered is 1%.

While the case study considered has demonstrated the potential of using portfolios of NBSs to reduce flood risk at regional scales, application of the proposed approach to a wider range of case studies is needed to better understand the conditions under which such an approach might provide potentially viable alternatives to more commonly used structural mitigation strategies. In addition, it should be noted that risk reduction is only one of the criteria determining the viability of such an approach. For example, there is a need to consider a range of economic, social and environmental criteria as part of a multi-criterion assessment to ascertain which approach to regional flood risk reduction is most appropriate in a given decision context. This includes consideration of the feasibility and acceptance of placing portfolios of NBSs over larger urban areas, which will most likely require significant stakeholder engagement. Consequently, the proposed approach and case study results presented in this paper only provide the first step towards the consideration of portfolios of NBSs for flood risk reduction at the regional scale. However, it does open the door to the consideration of an alternative approach to reducing regional flood risk that is adaptive and has the potential to result in a range of co-benefits, such as improved water quality and amenity.

Acknowledgments

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Chapter 4: Probabilistic land use models for characterising spatial uncertainty in future flood risk

Eike Hamers, Holger R Maier, Aaron C Zecchin, Hedwig van Delden

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Principal Author

Name of Principal Author (Candidate)	Eike M Hamers		
Contribution to the Paper	Contributed to conceptualization of the framework, design and modelling of experiments, performing the analysis and interpretation of results, drafting of manuscript		
Overall percentage (%)	70		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature		Date	01/07/2022

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);

ii. permission is granted for the candidate in include the publication in the thesis; and

iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

Name of Co-Author	Aaron C Zecchin		
Contribution to the Paper	Contributed to conceptualization of framework, analysis and interpretation of results, drafting of manuscript		
Signature		Date	06/07/2022

Name of Co-Author	Holger R Maier		
Contribution to the Paper	Contributed to conceptualization of framework, analysis and interpretation of results		
Signature		Date	06/07/2022

Name of Co-Author	Hedwig van Delden		
Contribution to the Paper	Contributed to conceptualization of framework, analysis and interpretation of results		
Signature		Date	04/07/2022

Abstract

The impacts of flooding are likely to increase around the globe as a result of urbanisation and socio-economic development. Estimation of future flood loss as a result of these changes requires the use of land use models to enable estimates of plausible future distributions of land use classes and values at stake to be obtained. However, these models are subject to deep uncertainty resulting from uncertainties in socio-economic development driving changes in land use and local uncertainty resulting from the stochasticity of the land use allocation processes used in these models to meet projected future demand in different land use classes. In order to enable the impact of these uncertainties on future flood loss to be assessed in a systematic fashion, a general framework for achieving this is introduced in this paper and applied to a case study in the Gawler River region in South Australia. Case study results indicate that when deep- and local- uncertainty were considered in isolation, the corresponding variation on estimates of future flood loss was up to 30% and 25%, respectively. The combined effect of local and deep uncertainty was even more pronounced, with variations in future losses resulting from the consideration of different methods of dealing with local uncertainty ranging from around 45% to 105% for low- and high- socio-economic development scenarios, respectively. Overall, the results highlight the importance of considering both deep- and local- uncertainty in land use modelling in the estimation of future flood loss, as both can have a significant impact on loss estimates.

4.1 Introduction

Flooding is one of the most costly natural hazards worldwide (Hartmann et al., 2018, IFRC, 2018). In their latest report (IFRC, 2018), the International Federation of the Red Cross, Red Crescent Societies (IFRCS), stated that for the 10-year interval from 2008 to 2018, 40.5% of the 3,751 natural hazard events recorded were floods. This decade of floods caused roughly US$363 billion in damages globally (Guha-Sapir, 2018). According to the International Disaster Database (Guha-Sapir, 2018), in the aforementioned decade, the year 2011 alone resulted in an estimated US$70 billion of flood damage. The impact of flooding is likely to increase in the future due to the compounding factors of climate change and urbanisation, leading to more extreme events, and increasing value of exposed assets (Tao et al., 2011, Beckers et al., 2013, GFDRR, 2014, Miller et al., 2014). Within one study (Jongman et al., 2012), it was estimated that the values at risk will triple from 2010 to 2050 within the global 1 in 100 year floodplains, demonstrating the importance of capturing land use change in future impact assessment.

A common way to understand risk is via Crichton’s risk triangle (Crichton, 1999). Within this framing, risk is comprised of three components, including the hazard itself, the exposure of values at risk to the hazard, and the vulnerability of these exposed values to the hazard, each represented as a side of a triangle, where, pictorially, risk is conceived as the area of the triangle (Crichton, 1999, GFDRR, 2014). If any side of the triangle changes, overall risk also changes. In case of flood risk, these components consist of: hazard in the form of a flood map (inundation depth distributed across space); exposure as the spatially distributed land use classes (e.g. residential or commercial) within the flooded region; and vulnerability, as a functional map of the transformation from inundation depth to potential damage, in form of vulnerability curves (GFDRR, 2014, Englhardt et al., 2019).

The most commonly considered driver of future flood risk is climate change, which primarily affects the hazard side of the risk triangle through increases in rainfall intensity, and hence runoff (Hodgkins et al., 2017, Bao et al., 2017, Guerreiro et al., 2018). However, as mentioned above, urbanisation within floodplains and catchments is also a critical driver in the growth of future flood risk (Miller et al., 2014, Jongman et al., 2012). One mechanism of urbanisation increasing flood risk is that an increase in the sealed surface area (associated with urbanisation) decreases runoff times, which can overwhelm drainage systems, and lead to higher flood peaks within the catchment (Miller et al., 2014, Du et al., 2012). However, a second, and arguably more important, mechanism of urbanisation increasing flood risk is that urbanisation increases the quantity and value of assets within a catchment and a floodplain (Di Baldassarre et al., 2013, Zischg et al., 2018, Jafino et al., 2019, Jongman et al., 2012). This increase in value increases the exposure side of the risk triangle, resulting in an increase in expected flood damage, for a given flood event (Zischg, 2018). However, the quantification of future flood risk is highly uncertain due to uncertainties in modelling and drivers of change. These uncertainties can either be considered as “local” or “deep” (Maier et al., 2016).

Deep uncertainties are generally associated with assumptions around drivers of change, such as climate and land use change, potentially resulting in different plausible future flood risk trajectories. Different approaches to dealing with deep uncertainty have been developed across many different fields (Walker et al., 2012, de Moel and Aerts, 2010, Heuvelink, 1998), where one approach of interest is the use of scenarios (McPhail et al., 2020, Nakicenovic et al., 2000, Wack, 1985). In relation to the hazard side of the risk triangle, such scenarios generally involve consideration of different plausible climate futures, which are used to alter the rainfall inputs of flood models (Heal and Kriström, 2002, Jones, 2000). In relation to the exposure side of the risk triangle, scenarios represent a range of plausible socio-economic futures within a specific region and are typically constructed through participatory processes involving a broad array of regional and domain experts (Riddell et al., 2018, Riddell et al., 2017, Holman et al., 2017). Such scenarios then inform the social and economic growth projections used to simulate changes in land use, and hence exposure, throughout the area of interest (Riddell et al., 2018, Riddell et al., 2017).

Local uncertainty is generally concerned with natural variability or uncertainties associated with models (e.g. parameters, structure), given a particular future climate and/or socio-economic scenario (Maier et al., 2016, Ascough et al., 2008). Accounting for local uncertainty associated with the magnitude of a flood event is well established within flood and flood impact assessment (Wagenaar et al., 2016, Yu et al., 2012, Romanowicz et al., 2006, Bates et al., 2004, Aronica et al., 2002), and typically involves the consideration of a set of driving rainfall events across the range of annual exceedance probabilities of interest. For example, Yu et al. (2012) investigated the impact of uncertainty in flood inundation modelling on flood damage through adopting a Monte Carlo simulation (MCS) approach for the flood modelling. To estimate damage, MCS was used to determine the posterior probabilities for flood extent and inundation depth in a stochastic manner. Different return periods were used and modelled to determine the chance of inundation in particular cells.

The resulting maps were then used in an impact assessment in combination with damage functions to determine the potential risk in the catchment.

However, while it is well-known that land use change models (e.g. SLEUTH (Clarke et al., 1997) and Metronamica (Van Delden and Hurkens, 2011b)) involve stochastic components associated with the time-varying allocation of land use throughout a simulation (e.g. Newland et al. (2018a)), the resulting impact of this source of local uncertainty is generally ignored in the assessment of uncertainty on future flood risk, with only de Moel and Aerts (2010) considering the combined influence of uncertainties in estimates of value at risk, damage curves and land use on flood impact. Consequently, given the significant impact land use change is likely to have on future flood risk, it is important to better understand the relative influence of deep and local uncertainty on future land use, and hence flood exposure and impact estimates.

In order to address the shortcomings in existing literature identified above, the objectives of this paper are (1) to introduce a general framework that enables the relative influence of deep and local uncertainty on the exposure and impact of future flood risk to be estimated via the use of land use models and (2) to apply the framework to a case study in the Gawler River area in South Australia to assess (a) the influence of deep and local uncertainty and (b) the impact of different methods of quantifying local uncertainty on estimates of future flood impact in terms of direct economic losses.

The remainder of this paper is organised as follows. Section 4.2 introduces the general framework that enables the influence of deep and local uncertainty on the exposure and impact of future flood risk to be estimated. Section 4.3 provides information on the case study to which the framework is applied, including details of how the framework is implemented in a modelling environment and of the different computational experiments conducted to address Objective 2. Section 4.4 presents the results for Objectives 2 a) and b), while Section 4.5 offers conclusions on the effectiveness and impact of the proposed framework.

4.2 Framework for Considering Uncertainty in Exposure in Future Flood Impact Assessment

The proposed framework that enables the influence of deep and local uncertainty on the exposure and impact of future flood risk to be estimated (Objective 1) is outlined in Figure 19. As can be seen, the framework facilitates quantification of the influence of deep and local uncertainty on estimates of future land use classes via the use of land use models. Knowledge of these land use classes enables corresponding estimates of values at stake to be obtained for different types of assets, which are converted to estimates of impact in the form of direct economic loss via vulnerability curves. Different land use classes require different vulnerability curves in the form of depth-damage functions (GFDRR, 2014). These functions provide a damage factor based on inundation depth, according to the given land use class. The damage factor is then multiplied with the building stock value to determine potential loss (GFDRR, 2014). In accordance with the idea of the risk triangle introduced by (Crichton, 1999), the impact assessment determines loss through hazard in the form of inundation depth, exposure through flood extent and asset value, and vulnerability in form of vulnerability curves.

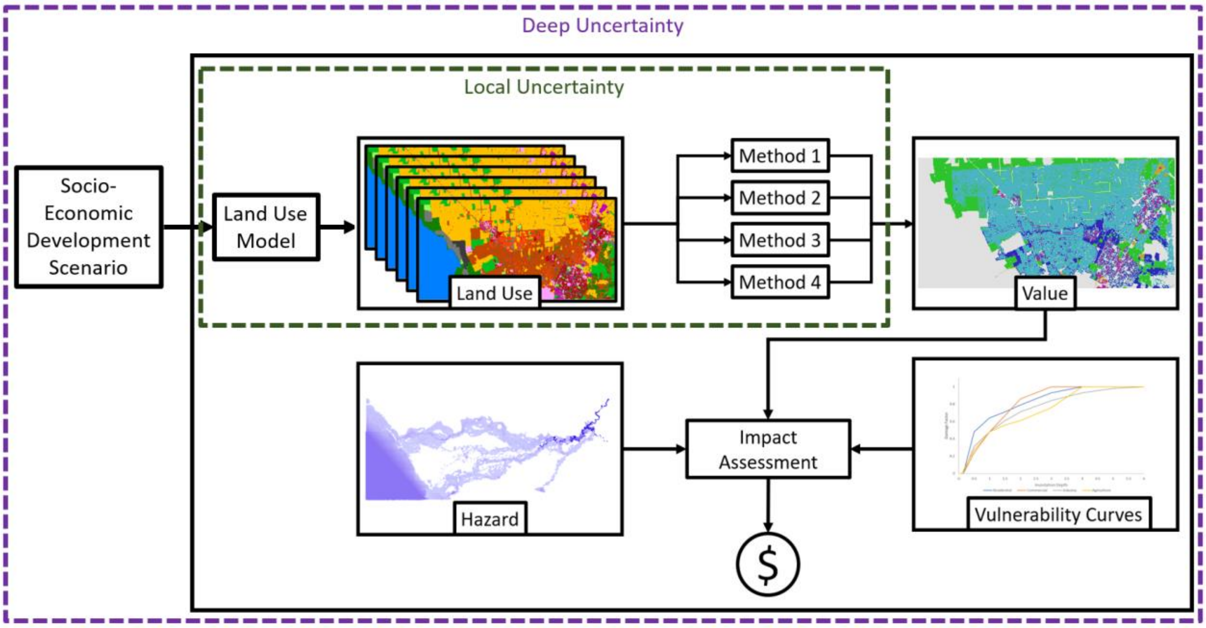

Figure 19 Proposed framework for considering local and deep uncertainty in exposure in future flood impact assessments

Deep uncertainty is taken into account via different socio-economic development scenarios resulting in different demands for various land-use classes. These demands are used as inputs into the land use model, resulting in a modelled land use map for a particular scenario at a particular time in the future. Local uncertainty is taken into account via the stochastic component of the land use model by running the land use model repeatedly with different stochastic realisations, resulting in different land use maps for a particular socio-economic development scenario at a given future time period, as shown by the different instances of land use maps shown in Figure 19. These maps can be combined in different ways in order to determine the probability that each land use class occupies a given cell, thereby enabling the construction of individual probability maps for each land use class, which can be converted to individual maps of values at stake. The value at stake in this case is defined by the average value of each land use class within the area of interest. As part of the proposed framework, four different methods of achieving this are considered (Figure 19). Further details of selected components of the framework are given in the subsequent sections.

4.2.1 Flood (Hazard) Modelling

Hydrodynamic flood models are the most common tool used to model flood events based on different return periods. They use maps of ground properties, such as slope, infiltration and hydraulic resistance, as an input to simulate flooding over time and space. Besides flood extent and inundation depth, hydrodynamic flood models are also able to provide more detailed physical characteristics, such as velocity, as an output (World Bank, 2014). Commonly used hydrodynamic models include HEC-RAS (Brunner, 2002), TUFLOW (Syme, 2001) and Mike Flood by DHI (DHI, 2017).

4.2.2 Land Use (Exposure) Modelling

Land use models, such as Metronamica (Van Delden et al., 2005), are typically cellular automata-based models[1] used to simulate the change in land use cover over time, based on a set of calibrated heuristic rules. These rules can take the form of attraction and repulsion of different neighbouring land use types, as well as suitability of a location for a specific use, for example, ground slope or the accessibility of infrastructure. Land use models uses mechanisms to induce stochasticity into the simulation (i.e. to capture the non-determinacy

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[1] Other examples of land use models are agent based, economic based, or Markov chain models SCHROJENSTEIN LANTMAN, J. V., VERBURG, P. H., BREGT, A. & GEERTMAN, S. 2011. Core principles and concepts in land-use modelling: A literature review. *Land-use modelling in planning practice,* 35-57.

of real-world land use change), for example, in the case of Metronamica a stochastic factor is used to perturb the land use allocation process (Van Delden et al., 2005). Given that land use simulators involve stochastic processes, the correct way to model the land use allocation process is through the use of MCS. For this purpose, the model is run multiple times to determine the probability of a land use class occupying a certain cell at a given point in time. These cellular probability distributions characterise the local uncertainty.

4.2.3 Methods for Dealing with Local Uncertainty

An overview of the four methods used for dealing with local uncertainty in the land use model is given in Figure 20. These approaches include: (1) Baseline; (2) Most Valuable; (3) Most Likely; and (4) Expected Value. An overview of the methods can be seen in Figure 20, and is explained in the following. The red box in Figure 20 is the overview of the framework presented in Figure 19 with the different methods explained in the green boxes.

Method 1 (No uncertainty): Unlike the other three approaches represented in Figure 20, Method 1 does not include uncertainty across a range of simulations, but only deals with a small set of simulations. A land use map is used to compute potential loss for the start and end time of the timeline of interest. To determine a spatially explicit value map, the individual land use class, represented by LU(*n*) in Figure 20, has an allocated value, which is placed in each cell throughout the land use map.

Method 2 (Most valuable): The second approach in Figure 20 deals with uncertainty by determining the most valuable possible land use map on a cell-by-cell basis. This approach uses the probability maps for each land use class to allocate the given value to each cell if their probability of allocation is greater than zero. For example, as in Figure 20, the probability map for any land use class determines the allocation of the value on a cell-by-cell basis throughout the area of interest, with each land use class having its individual value. This is done for each probability map for all the land use classes. Following this, a comparison between the resulting maps determines the highest value in each cell which is used to create the value map for the impact assessment.

Method 3 (Most likely): To determine the most likely allocation of a land use class, a comparison of the different probability maps for each land use class enables the determination of the land use class with highest probability, as depicted in Figure 20. This land use map is then used to allocate a value on a cell-by-cell basis. The resulting value map can then be used in the impact assessment.

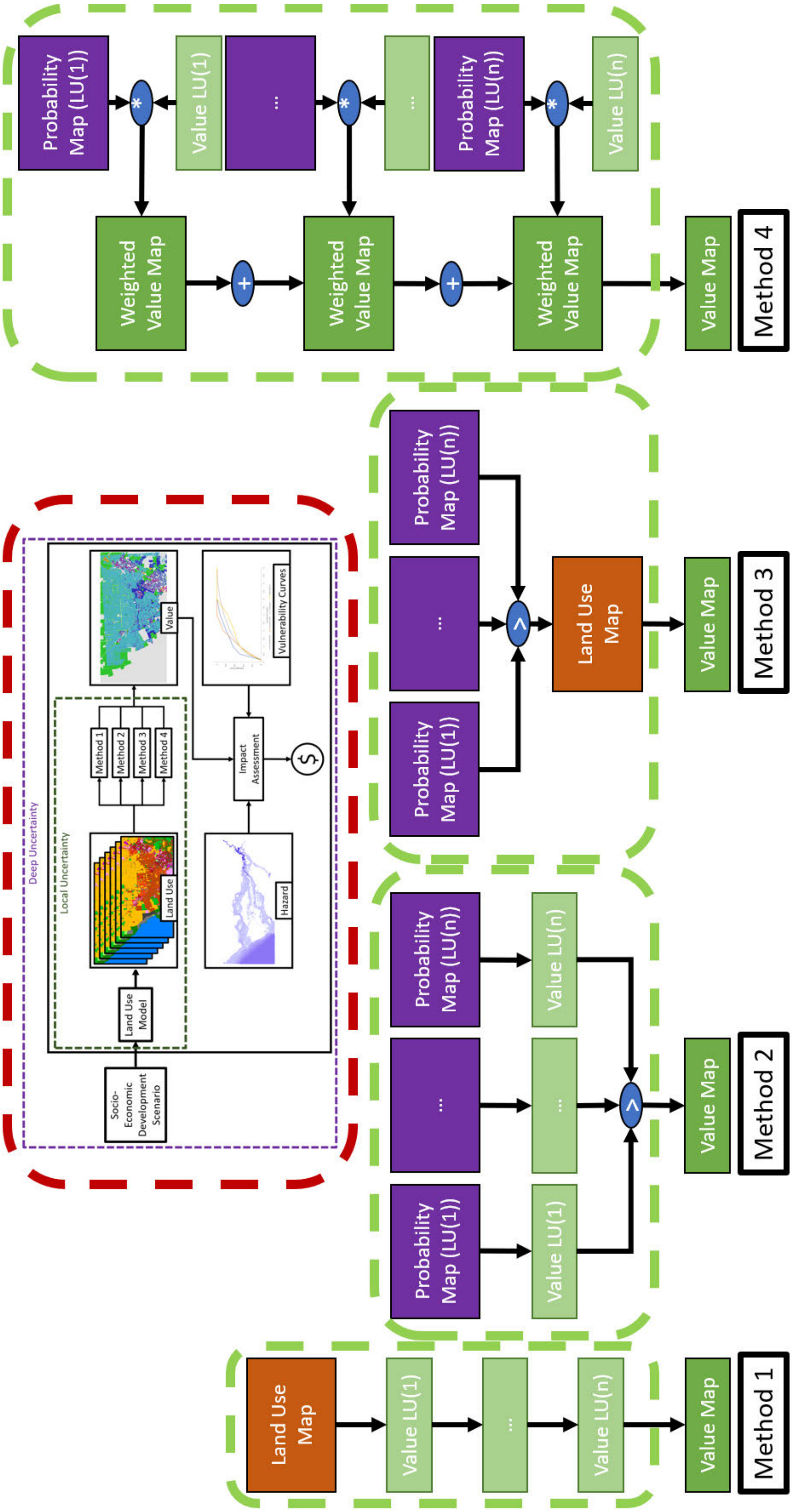

Figure 20 Framework of methods to deal with uncertainty in estimating the value of future land use development for a flood risk assessment, with LU(n) representing a specific land use class and n representing the number of different land use classes

Method 4 (Expected Value): The final approach in Figure 20 involves computing the expected value across all land use classes to determine the value in each cell. In every cell, the probability for all land use classes is multiplied by the allocated value for the land use class and then summed across all classes to yield the expected value. This provides the value in relation to the likelihood of a land use class occupying the cell.

4.3 Case Study

Details of the proposed framework (Figure 19 and Figure 20) to the case study region (Objective 2) are given in the following sub-sections, including relevant background on the case study (Section 4.3.1), details of the socio-economic development scenarios used in order to consider the impact of deep uncertainty (Section 4.3.2), details of the land use model (Section 4.3.3), details of the flood model (Section 4.3.4), details of the impact assessment (Section 4.3.5) and details of the computational experiments conducted in order to address objectives 2 a) and 2 b) using the operational version of the proposed framework (Section 4.3.6).

4.3.1 Background

For this case study, the Gawler River region, depicted in Figure 21, is considered, which is located on the northern outskirts of Adelaide, South Australia. The region covers an area 683.22km^2 and spans seven different Local Government Areas. It is considered a rural region, mainly occupied by horticulture and agriculture. However, it also includes several townships and urban developments distributed sparsely throughout the region. As such, the catchment is a mix of rural land use classes with a number of urbanised clusters.

The Gawler River has two river influxes on the eastern border: the North Para River, and the South Para River. Even with flood protection measures in place (most prominently the Bruce Eastick dam, constructed in 2007 to restrict the flow from the North Para River to reduce the impact of recurring floods), the region is still susceptible to larger flood events. The most recent event in 2016 caused approximately AU$50 million in damage, concentrated within the horticultural developments (Tonkin Consulting, 2018, Fisher et al., 2017).

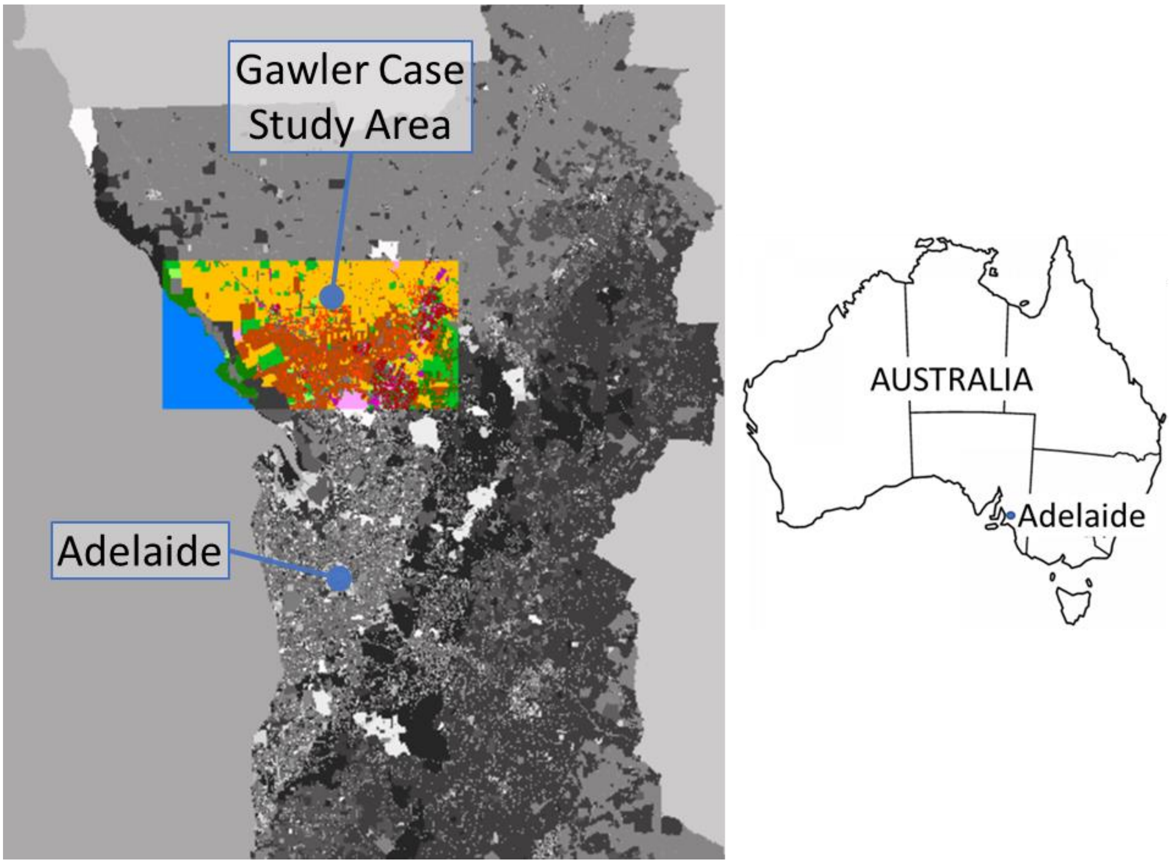

Figure 21 The Gawler case study area in the North of Adelaide, South Australia

4.3.2 Socio-Economic Development Scenarios

Four socio-economic development scenarios spanning from 2018 to 2100 are used to characterise the deep uncertainty associated with future land use change. The land use model determines the land use change over this time period based on the set of model inputs associated with each scenario, where the main differentiating aspect between the scenarios is how land use demands vary in the future (e.g. high growth scenarios will have a greater demand for the allocation of residential land use classes). One scenario is used as a baseline and adopts business-as-usual (BAU) socio-economic projections, while the other three are examples of plausible futures that result in challenges to community resilience (Ignorance of the Lambs scenario), challenges to government action (Cynical Villagers scenario) or challenges to both community resilience and government action (Internet of Risk scenario) (Riddell et al., 2019, Riddell et al., 2017). The scenarios were developed involving stakeholders from state and local government to investigate possible pathways for the future development of Greater Adelaide. To fit the purpose of this study, the land use demand curves used as input were adjusted by adopting the growth rates taken from van Delden et al. (2022) for each exploratory scenario to include the narrative aspect of the scenarios into the model environment. The initial occupied area in 2018 for significant land use classes can be seen in Table 3 to compare with the individual increases for each scenario.

As mentioned above, the **Business as Usual (BAU)** scenario is considered a baseline case. The growth in population and economic development in this scenario is based on the projections of the Australian Bureau of Statistics and extended to the simulation end date of 2100 (Riddell et al., 2017).

Compared to the BAU scenario, the **Cynical Villagers** scenario is a slower growth scenario. The communities consist of an aging population with a growing connection to nature. Climate and nature protection play a dominant role in the interest of these communities, relying on high quality agricultural products and turning away from heavy industry. The demographics is based on a slowing population growth and increase in rural living is especially significant for rural residential development (Riddell et al., 2017). The impact on future land use demand can be seen in Table 3.

The **Ignorance of the Lambs** scenario narrative is based around an increase in overseas immigration, especially from crisis regions across the globe, and migration due to climate change. The increase in population growth is disconnected from economic development, resulting in dense residential developments but a decrease in industrial and commercial areas (Riddell et al., 2017). The impact on future land use demand can be seen in Table 3.

In the **Internet of Risk** scenario, the community relies heavily on the internet and modern technologies for work and socialising. The location of residence does not play a large role in personal wealth and employability. On the other hand, people choose their residential locations by other factors, such as density and aesthetics. This leads to an increase in rural residential development, with a highly qualified workforce. This correlation allows for an increase in commercial development. Overall, this scenario has a lower population growth than the Business as Usual scenario (Riddell et al., 2017). The impact on future land use demand can be seen in Table 3.

A full description of the exploratory scenarios for deep uncertainty can be found in Riddell et al. (2017).

Table 3 Distribution of land use classes for the initial condition in 2018 and across the four different scenarios for deep uncertainty in 2100 for the Gawler River case study

Scenario	**Year**	**Residential (ha)**	**Commercial (ha)**	**Industry (ha)**	**Rural Residential (ha)**	**Agri-culture (ha)**	**Horti-culture (ha)**
Initial Conditions	2018	2,721	359	733	4,355	26,445	12,237
BAU	2100	3,859	406	830	6,675	23,020	12,697
Cynical Villagers	2100	2,802	393	655	6,431	26,019	11,476
Ignorance of the Lambs	2100	5,123	276	652	4,963	27,589	12,423
Internet of Risk	2100	3,147	459	715	6,656	26,443	12,535

4.3.3 Land Use Model

The Metronamica land use model (Van Delden et al., 2005) was used to determine future land use change up to 2100 based on demand from the four scenarios, as Metronamica was developed specifically to simulate land use scenarios of future change. As part of this study, an existing Metronamica model that was calibrated and validated for the Greater Adelaide region (Riddell et al., 2017) was adapted for the scope of this case study. This involved translating the socio-economic development scenarios into demands for different land use classes, as shown in Table 3.

The land use classes for which there are future demands belong to the “function” category, which means that they can change during the simulation based on these demands. Land use classes that do not belong to this category can either belong to the “feature” or “vacant” category. Land use classes set as features can neither be moved nor removed from the cell they are occupying, whereas vacant land use classes consist of empty space that can be filled in order to satisfy the demand associated with active land use classes. It should be noted that cells belonging to the “function” category can also become “vacant” as part of the simulation process (van Delden and Vanhout, 2018).

Different attraction rules determine the likelihood of “function” land use classes neighbouring with already allocated land use classes in a predefined radius (van Delden and Vanhout, 2018). These rules, combined with suitability and demand, determine the location of future land use. In this case study, the Metronamica model uses a spatial resolution of 100 by 100 m and differentiates between 16 different land use classes. Example 2100 land use maps for the four socio-economic development scenarios considered are shown in Figure 22. Compared with the BAU scenario (Figure 22 a)), the Cynical Villagers scenario (Figure

22 b)) exhibits slower development, with visible increases happening mostly in rural land use classes, such as agriculture and rural residential. The scenarios with higher socio-

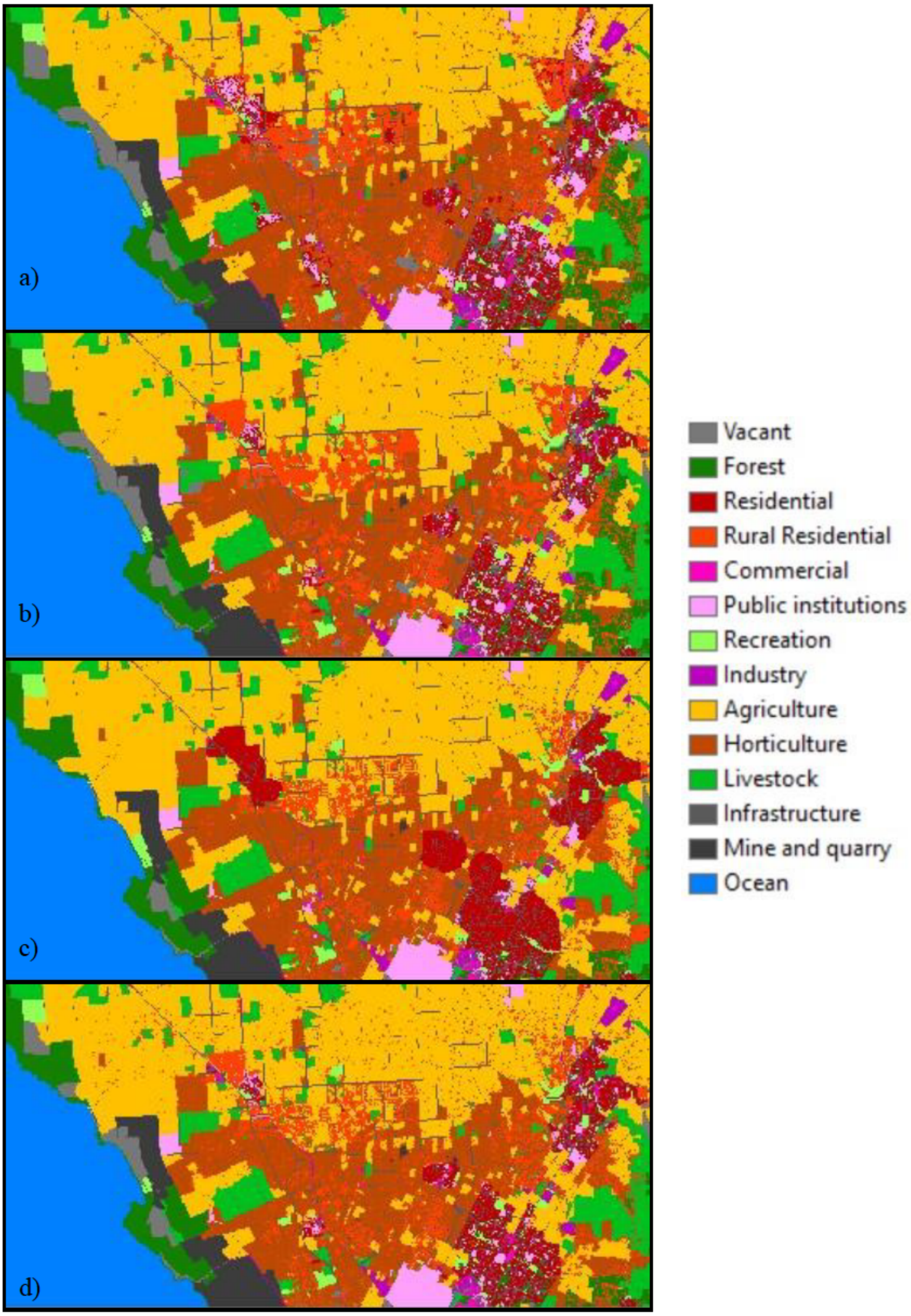

Figure 22 Land Use development for 2100 for the different explorative scenarios for deep uncertainty a) Business as Usual b) Cynical Villagers c) Ignorance of the Lambs d) Internet of Risk. The individual maps can be found in Appendix C.2.

economic growth, such as the Ignorance of the Lambs (Figure 22 c)) and Internet of Risk (Figure 22 d)) scenarios show visual differences in the allocation in residential and rural residential cells in contrast to the Business as Usual scenario. The Internet of Risk scenario exhibits a significant increase in rural residential land use cells, visibly higher than in the other three scenarios. In contrast, the high demand in residential cells for the Ignorance of the Lambs scenario causes large clusters of residential land use cells.

In Metronamica, the local uncertainty associated with the land use allocation process is represented via a random coefficient and an in-built MCS feature can be used to calculate the probability of allocation of a series of maps (RIKS BV, 2012). Examples of a set of the resulting probability maps for the BAU scenario are given in Figure 23. As can be seen, future locations of residential, industry, horticulture and agriculture land use classes are very

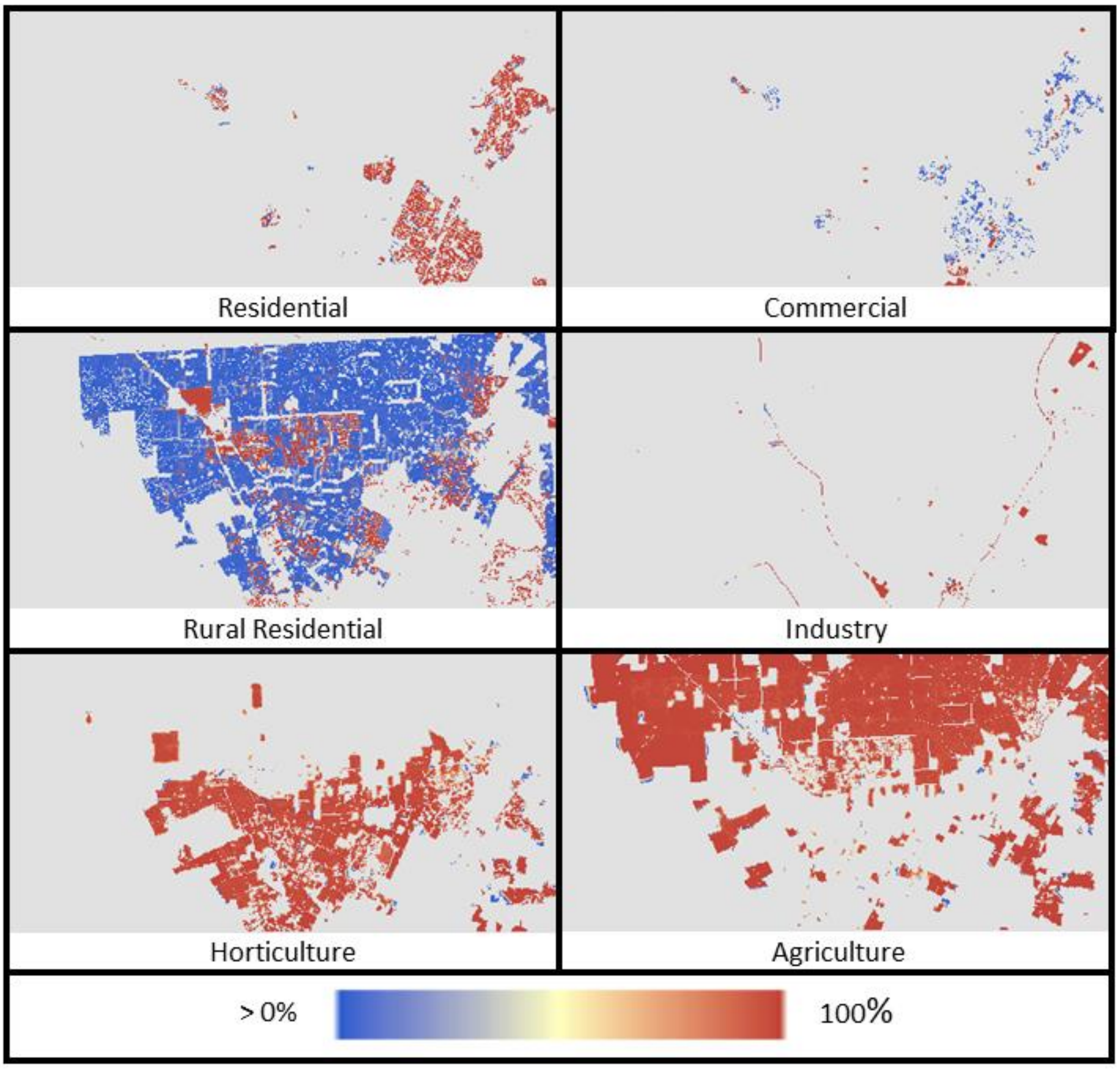

Figure 23 Probability maps for BAU scenario for residential, commercial, and industrial land use classes of urban character and rural residential, horticultural, and agricultural land use classes of rural character

well defined, with most regions having a probability of 100% and only a few regions with low probabilities. In contrast, the opposite is the case for rural residential and commercial land use classes, where the majority of future locations are highly uncertain, with low probabilities.

4.3.4 Flood Model

Flood extent and depths were modelled using Mike Flood (DHI, 2017), which is a coupled 1D/2D hydrodynamic flood model. Flow in the main watercourses in the catchment was modelled using a 1-D Mike-Hydro river model. This model was used to route flood event hydrographs from two upstream entry points, corresponding to inflows from the Para North and Para South river tributaries, through the catchment, as was done in a previous study (Tonkin Consulting, 2018). The inflow from the North Para river includes a reduction in peak flow caused by a dam located upstream outside of the modelling area. Overland flow was modelled in 2-D using Mike 21 FM. Digital elevation was represented in the Mike 21 FM model via a flexible mesh with a maximum area of 225m^2 and a maximum angle of 25°. The interaction between the 1D representations of channels and the 2D representation of the floodplain was modelled using Mike Flood. The model was calibrated and validated by comparing modelled results with those of a model used in a study conducted by Tonkin Consulting (2018) for a 1 in 100 year event. As this study has used the 1 in 100 year event and the data was readily available, the same flood event was also chosen for this proof of-concept.

4.3.5 Impact Assessment

The vulnerability (depth-damage) curves used were adapted from the Gawler River UNHaRMED Mitigation Project (van Delden et al., 2022) and are based on Wehner et al. (2017) and Huizinga et al. (2017) (Figure 24). These curves were used to determine the impact of flooding on a cell-by-cell basis by translating water depth into a damage factor based on the vulnerability of a land use class, as mentioned previously. This was done in ArcGIS Python through overlaying the land use and flood maps, with details given in Appendix D.2. The provided vulnerability curves include residential, commercial, industrial, and agricultural land use. Because a significant area in this case study is occupied by rural residential and horticultural land use, both the residential curve for rural residential and the agricultural curve to horticultural cells are applied. It is assumed that in both cases the building type is closely related to the curves taken from van Delden et al. (2022).

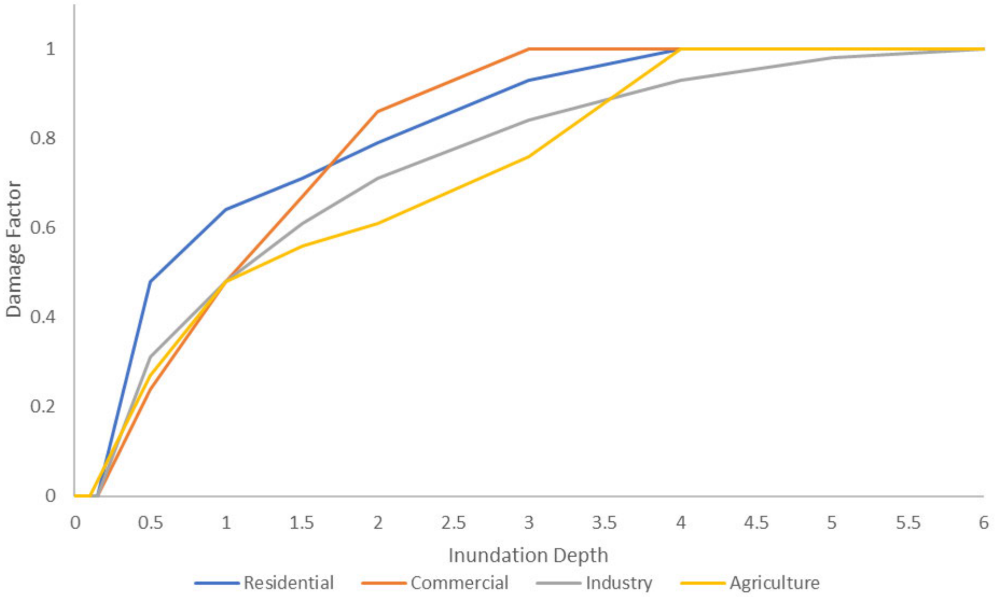

Figure 24 Vulnerability curves adapted from the Gawler River Unharmed Mitigation Project (van Delden et al., 2022)

4.3.6 Computational experiments

The computational experiments can be separated into two parts, addressing both Objectives 2 a) and b). The experiments outlined in Section 4.3.6.1 are designed to test the influence of local and deep uncertainty in land use change on flood impact (Objective 2 a)). The computational experiments in Section 4.3.6.2 are designed to test the impact of different methods of quantifying local uncertainty on estimates of future flood impact in terms of direct economic losses.

4.3.6.1 Influence of local and deep uncertainty in land use change on flood impact

As part of these computational experiments, the land use maps acquired by using the four socio-economic development scenarios for deep uncertainty (i.e. BAU, Ignorance of the Lambs, Cynical Villagers, Internet of Risk) are used as inputs into the flood model. Based on the difference in allocation of rural and urban land use classes, the cellular roughness coefficients and infiltration rates are changed for each scenario. Two hydrographs for channel flow at the two different entry locations (i.e. North and South Para Rivers), representing a 1 in 100 year return period, are used to simulate the resulting fluvial flood for each of the four scenarios with individual flood maps for each scenario. The resulting flood maps are used in an impact assessment, as shown in Figure 19, to determine the difference in impact.

Additionally, to determine the impact of local uncertainty on flood loss, the BAU scenario is simulated with different random factor seeds to introduce a controlled randomness in the land use change from run to run. A random factor regulates the stochasticity within the land use model simulation, which leads to slightly different sequences of land use maps for each different seed. A total of five different seeds were considered, and the resulting land use maps used in the impact assessment with the same flood map to identify differences in flood loss between the different runs. Any variation in the impact across these runs arises from the local uncertainty.

4.3.6.2 Impact of different methods of quantifying local uncertainty on estimates of future flood impact

To test the methods introduced in Section 4.2.3, different experiments were adopted varying in the method used to deal with uncertainty. To begin with, the different exploratory scenarios are used to determine probability maps for each land use class using the Monte Carlo simulation tool in Metronamica, as well as running each scenario 100 times to get a wide spread of different maps. This allowed for a wide range of results while still being computationally efficient. The methods introduced in Figure 20 are then used with the resulting probability maps to produce a value map to be used in the impact assessment. For this assessment, the flood map for the BAU scenario is taken from the experiment in 4.3.4.1. With the experiments in Section 4.3.4.1 the use of a static flood map across all scenarios is investigated, instead of running a flood model in every experiment. This depends on the sensitivity of the flood model on land use change, and the correlation with the increase in flood loss.

4.4 Results and Discussion

The results shown in Sections 4.4.1 and 4.4.2 address Objective 2 in Section 4.1. Sub-section 4.4.1 focuses on the influence of local and deep uncertainty in land use change on flood impact (Objective 2 a)). Section 4.4.2 then presents results on the testing of the different methods to deal with local uncertainty of land use change in impact assessment (Objective 2 b)).

4.4.1 Influence of local and deep uncertainty in land use change on flood impact

This section examines the influence of deep uncertainty on inundation depth and flood impact to determine the importance of land use change as a driver for future impact assessment (Section 4.4.1.1). In addition, Section 4.4.1.2 presents the influence of local uncertainty in land use change modelling on future flood impact.

4.4.1.1 Influence of deep uncertainty in land use change on flood impact

In order to understand the influence of deep uncertainty in land use change modelling on the behaviour of a flood model and the resulting flood map, this subsection compares the impact of the four exploratory scenarios for deep uncertainty on inundation depth and flood loss. As discussed in Section 4.3.4.1, to assess the impact of deep uncertainty in land use change, the four scenarios were used as the basis of the land-use simulation. The resulting land use maps representing one possible future for each scenario were used as inputs to the Mike Flood model. The flood model was used to simulate the extent and inundation depth of a flood event with a 100-year return period.

As shown earlier, a comparison at a cell-by-cell scale of the land use distribution for 2100 for the four different scenarios for deep uncertainty verifies significant changes between the four scenarios in terms of land use allocation. As seen in Figure 25 b), the difference in inundation depth between 2018 and 2100 for these scenarios is below 1%, while Figure 25 a) shows the change in overall loss for each individual scenario with an increase ranging from 5% for the Cynical Villagers scenario up to 82% for the Ignorance of the Lambs scenario. Even though there are apparent reductions for both the BAU and Cynical Villages scenarios, and increases for the other two scenarios, the changes are small enough to be considered insignificant with respect to flood mapping modelling accuracy, which is further supported by Figure 26 a). While the change in inundation, in Figure 27, is limited to small areas and relatively small depths, the change in loss is significantly impacted by the different exploratory scenarios (Figure 25 a) and Figure 26 b)). Depending on the scenario, not only the magnitude of the impact changes, but also its location (Figure 27).

The above results lead to the conclusion that changes in land use, as considered in this study, have little impact on inundation depth. This lack of impact results from the relatively small and localised changes in roughness and infiltration, and the large size of catchment considered. On the other hand, the potential loss caused by the flood is significantly impacted by the change in land use. The differences in loss across the scenarios can be seen in Figure 26, which can be quite significant. For example, while the smallest increase in loss is obtained for the Cynical Villagers scenario, with under 10%, the largest change is observed for the Ignorance of the Lamb scenario, with over 80%. For the other two scenarios, Business as Usual and Internet of Risk, increases in loss are about 50%.

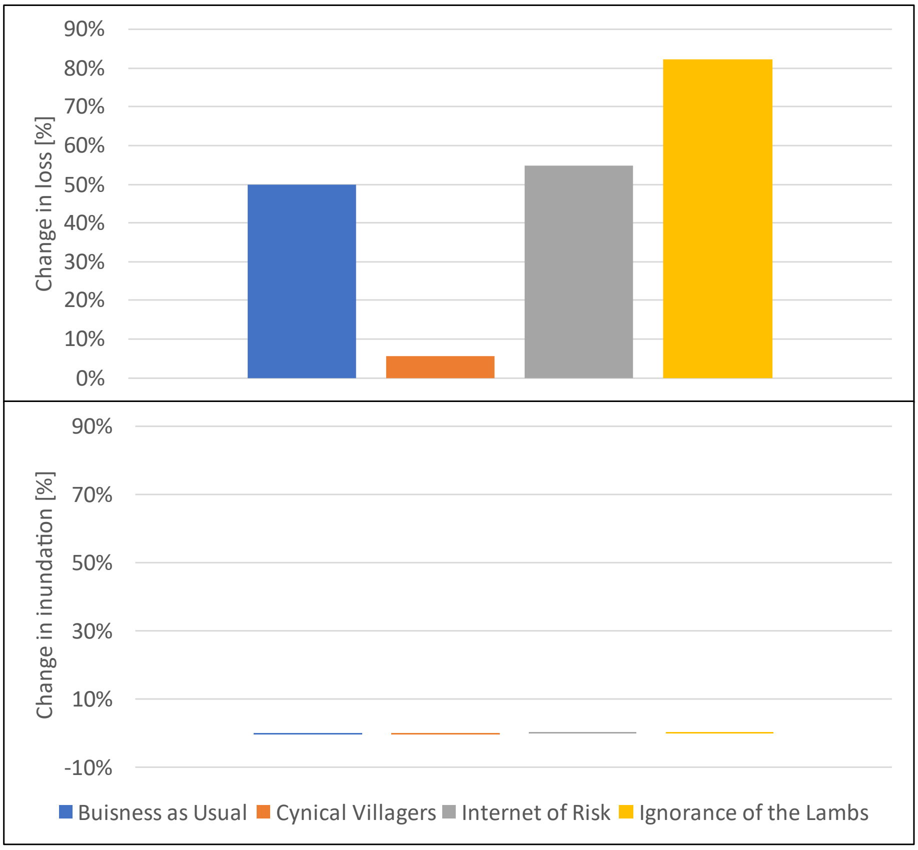

Figure 25 Change in loss and inundation depth over the four scenarios for deep uncertainty

While the flood characteristics are similar for all four scenarios, the resulting changes in damage are significantly different, which is caused by significant differences in the increase in value across the floodplain. This can be seen clearly by looking at Figure 25 in relation to Figure 22, where a connection between large increases in flood loss and a higher rate of urban development, such as residential land use in the Ignorance of the Lambs scenario, can be drawn. Similarly, the Cynical Villagers scenario, with little growth from 2018 to 2100, also has the lowest increase in flood loss. However, changes in inundation depth fluctuate between -0.30% and 0.10%, highlighting the influence of cellular value as a critical driver in impact assessment.

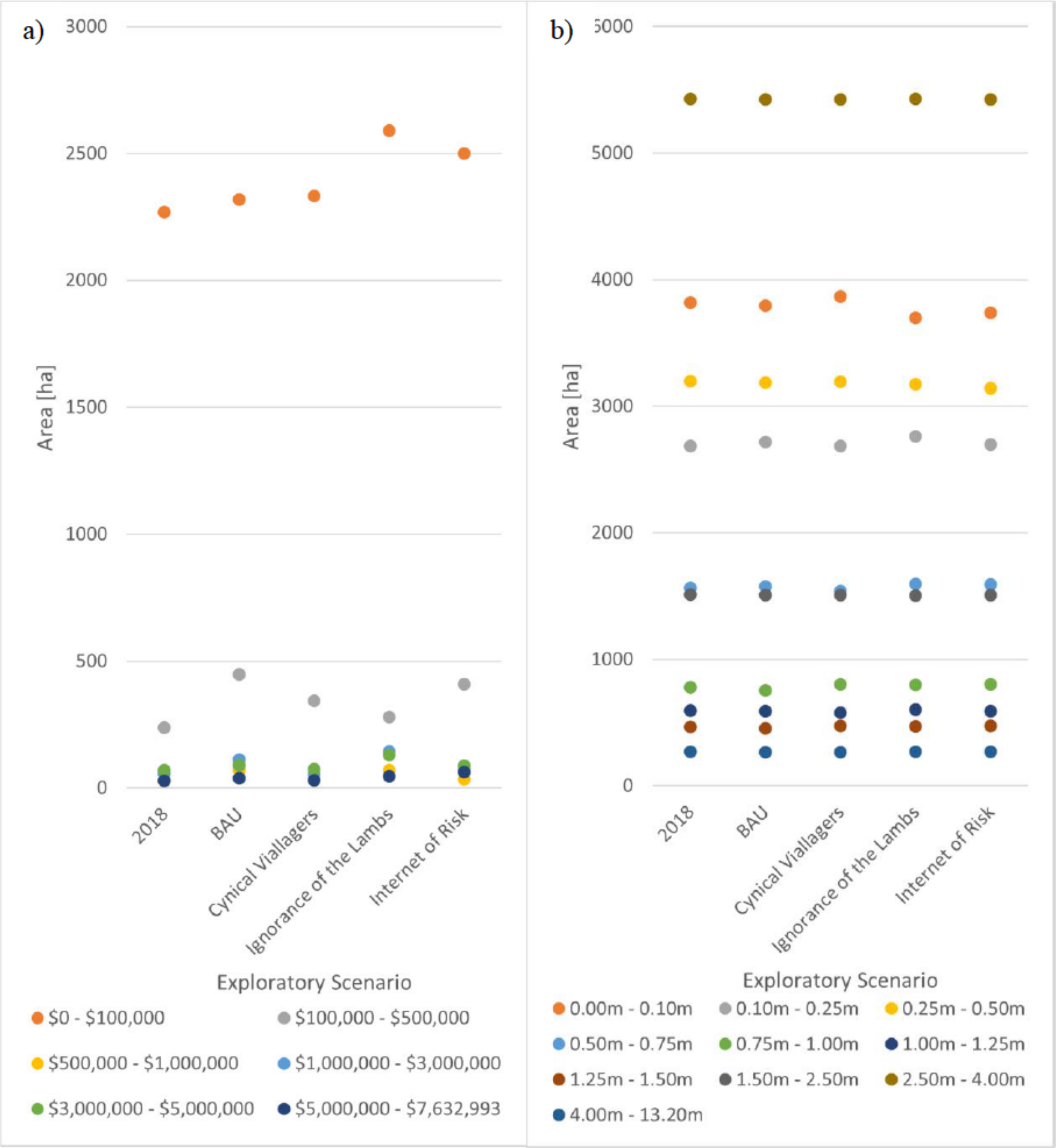

Figure 26 Area impacted by a) inundation and b) loss across the different exploratory scenarios to deal with deep uncertainty and the original state in 2018

Looking at the spread of area affected by flooding, Figure 28 confirms the varied impacts of scenarios for deep uncertainty. This underlines the importance of considering deep uncertainty in a spatially explicit form when looking at future flood risk. It also highlights the rural characteristics of the case study area. In this environment, the different scenarios perform differently in each land use class due to the high level of variation in their individual characteristics.

The results presented in this section show the insensitivity of the flood model towards the deep uncertainties of land use change and allows for the assumption to use one flood map for different future scenarios. The results also provide insight on the difference in the flood impact of the exploratory scenarios and highlight the effectiveness of using such scenarios in order to obtain a better understanding of plausible future flood risk and impact.

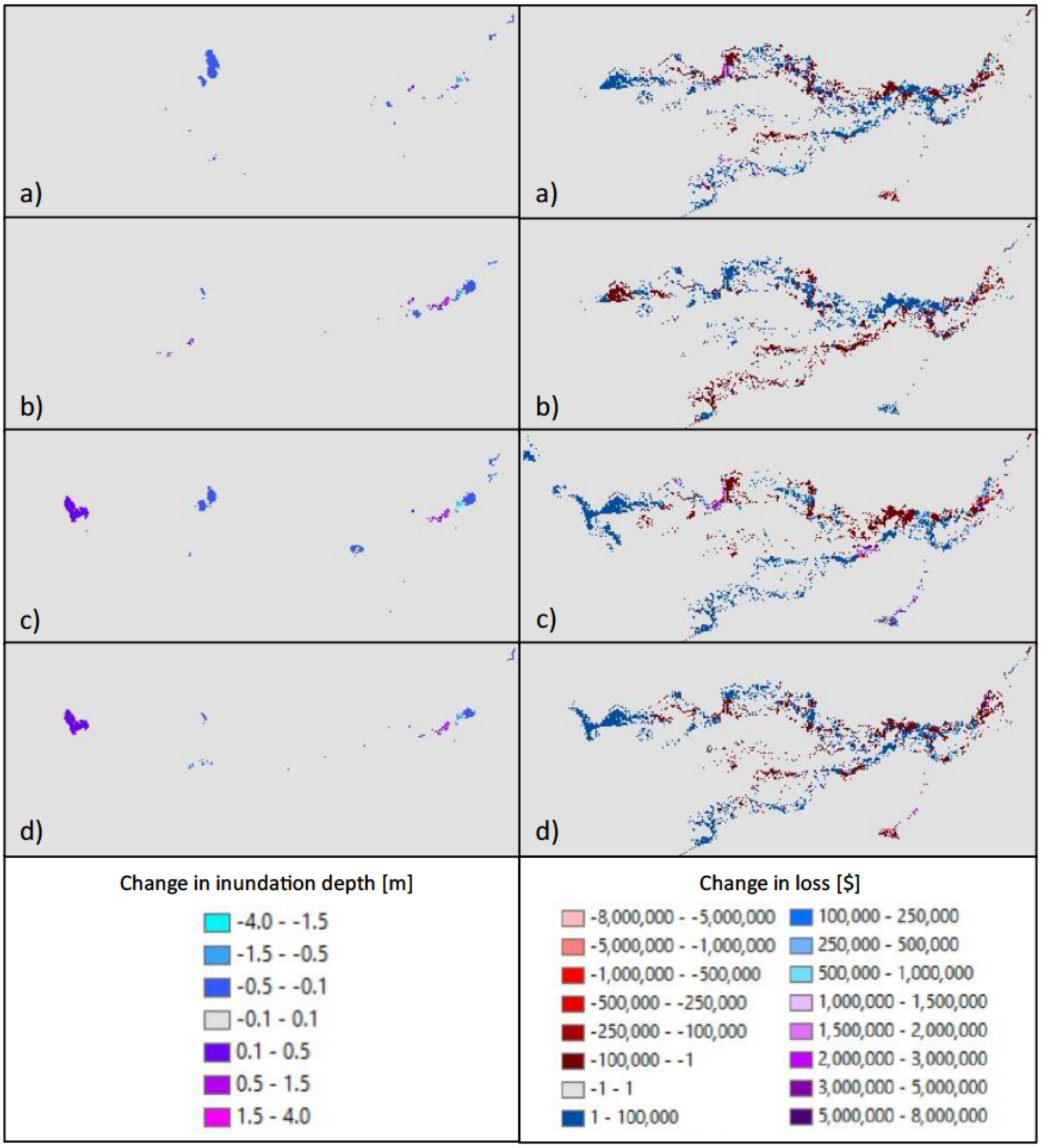

Figure 27 Comparison of inundation depth and loss change from 2018 to 2100 between the different socio-economic development scenarios, a) Business as Usual, b) Cynical Villagers, c) Ignorance of the Lambs, d) Internet of Risk

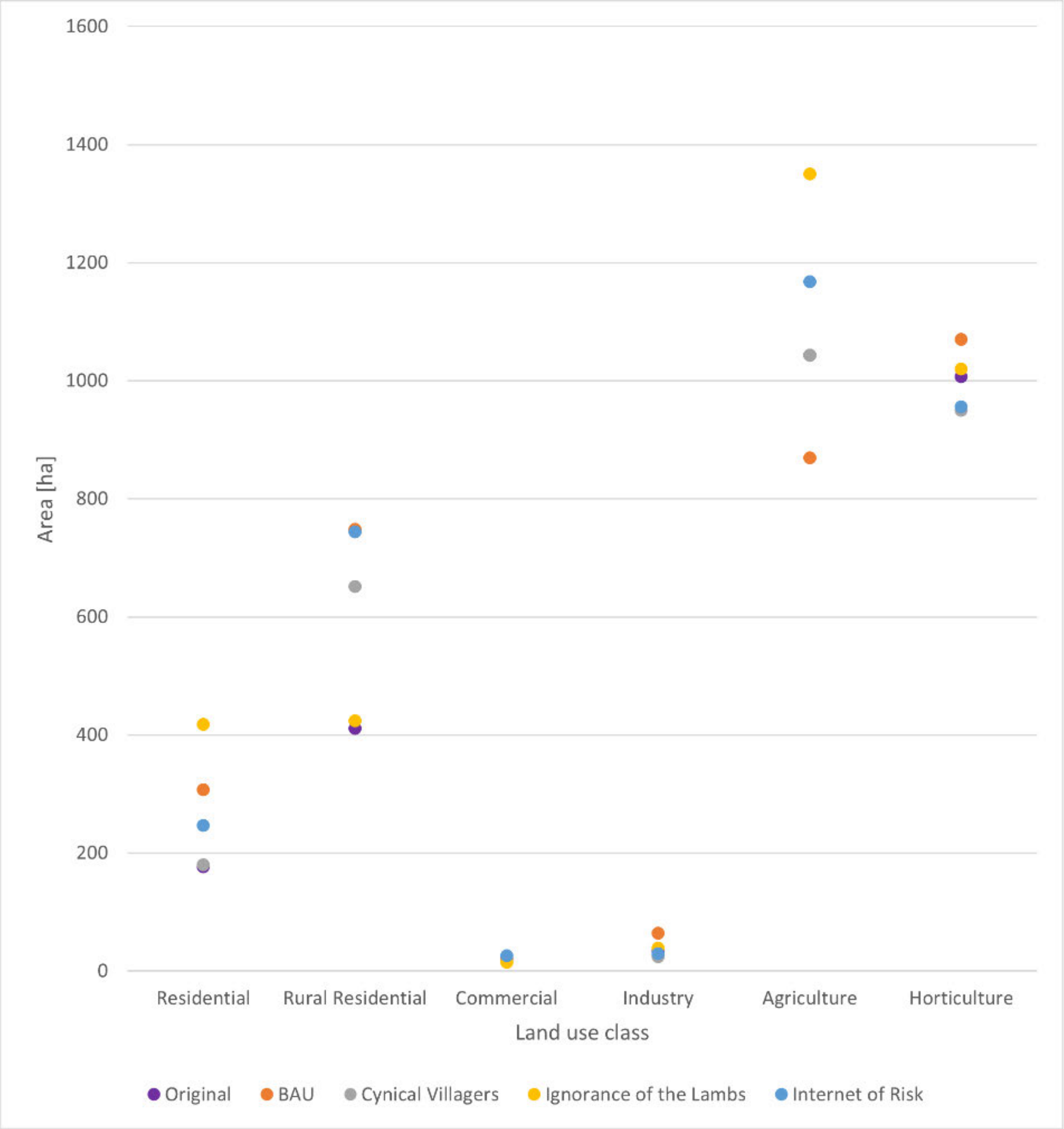

Figure 28 Area affected by flood loss for the exploratory scenarios across different land use classes

4.4.1.2Influence of local uncertainty in land use change on flood impact

The variation in change in loss caused by the local uncertainty in land use change modelling is illustrated in Figure 29, which was obtained by running the land use model five times with varying random seeds. As can be seen, differences range from 25% to 50%, with a median of 35%, which, as the same flood map is used for all five impact assessments, signals a significant shift in land use allocation. While A and D, with a 1% difference, as well as B and C, with a 2% difference, produce similar results, the difference between the two groups and the fifth scenario, E, is quite significant. The high level of observed variation in losses highlights the importance of considering the influence of local uncertainty in land use change for future flood impact assessment.

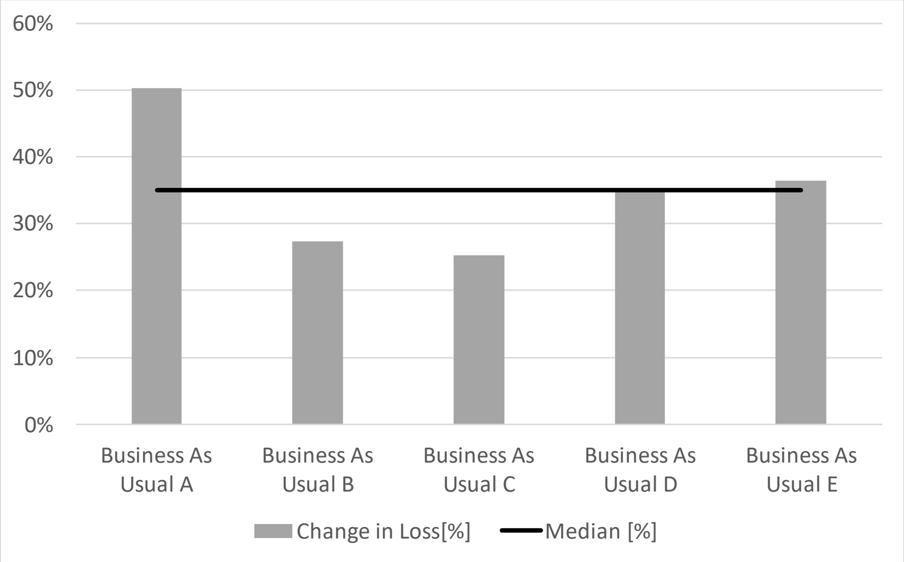

Figure 29 The spread in change in flood loss caused by local uncertainty for the Business as Usual scenario varying in the seeds of randomness

In Figure 30, the impact of local uncertainty on future flood loss is shown across the different land use classes considered in the impact assessment. The results for the Residential land use class show substantial differences between the different runs in Metronamica, while there is almost no variation in change in loss for Agriculture and Horticulture and only minimal changes for Rural Residential, Commercial and Industry. This further emphasises the importance of considering local uncertainty in land use models on future flood loss.

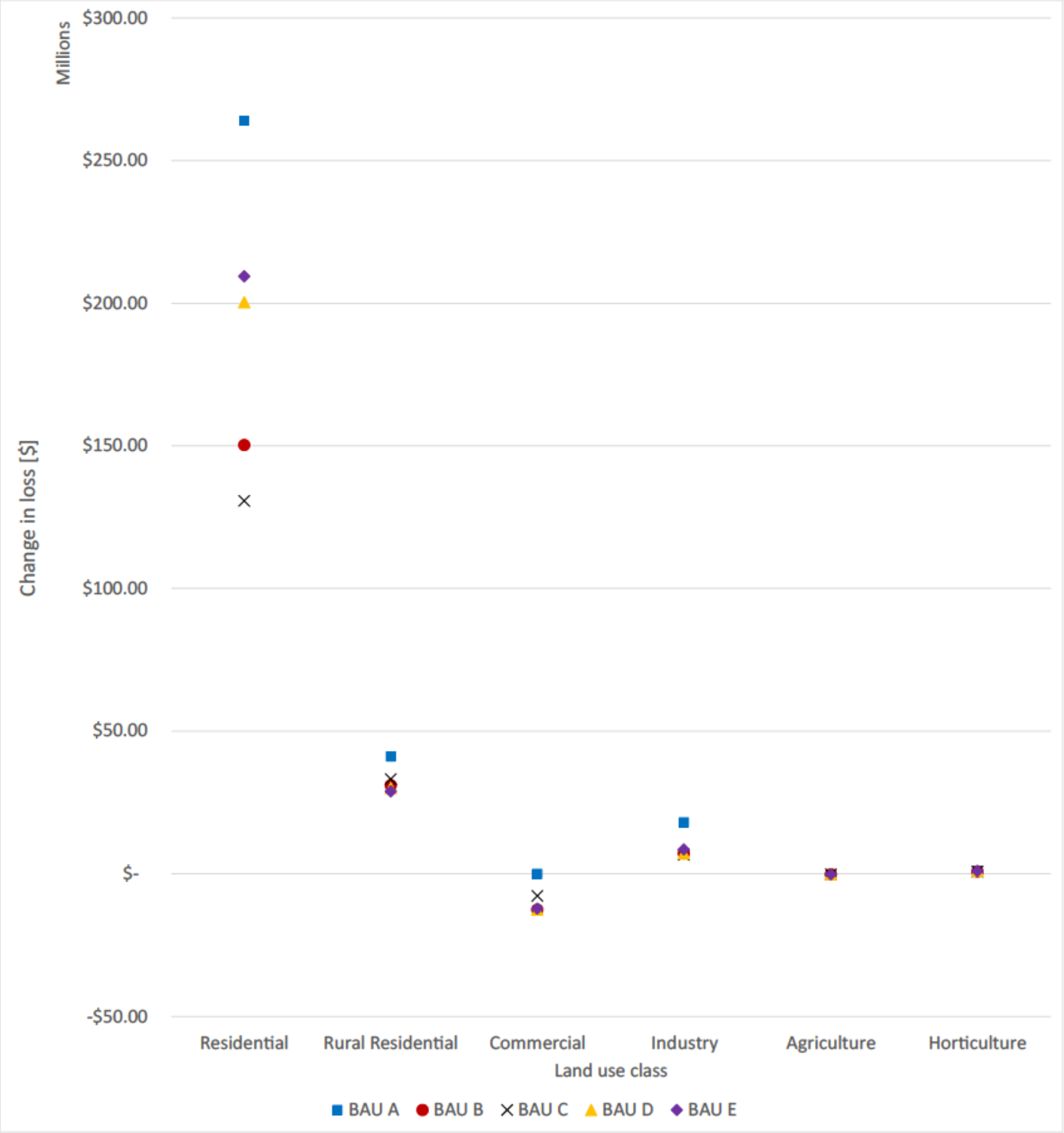

Figure 30 Change in loss for different land use classes while considering local uncertainty

4.4.2 Impact of different methods of quantifying local uncertainty

This section shows the impact of local uncertainty by comparing the change in loss across the different methods for dealing with local uncertainty in land use models outlined in Figure 20 and the scenarios for deep uncertainty from Section 4.3.2. A more in-depth analysis of the performance of the different methods is provided by comparing the spatial spread of loss across the region and different exploratory scenarios.

Figure 31 shows the change in loss across the different scenarios for each of the four methods considered. While the overall shape of the performance distribution across the four methods is similar for the BAU, Cynical Villagers and Ignorance of the Lamb scenarios, this is not the case for the Internet of Risk scenario. The results also indicate that Method 3 results in the biggest increase in loss across all four scenarios by far. In contrast, Method 1 results in the smallest increase in loss for the Business as Usual, Cynical Villagers, and Ignorance of the Lamb scenarios. Only for Internet of Risk scenario is Method 4 the approach with the least increase in loss. Overall, the relative distribution between the four methods in each scenario, disregarding the difference already mentioned, look very similar.

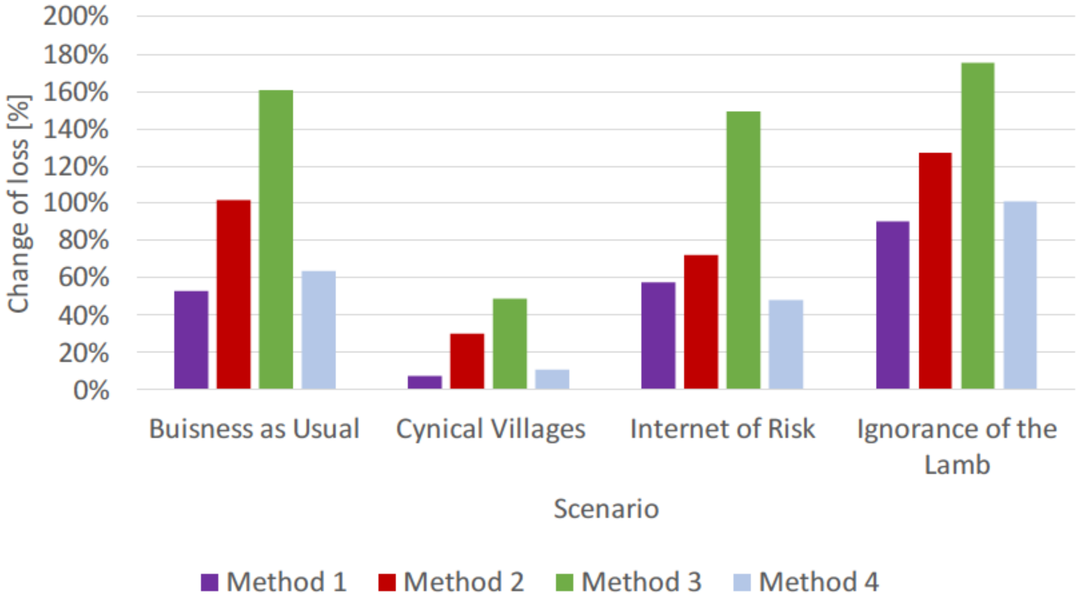

Figure 31 Change in loss for all four methods for dealing with local uncertainty in land use modelling across the different socio-economic development scenarios for deep uncertainty

When ranked, Method 3 produces the highest increase in loss across all four scenarios. This is to be expected, as it will add the most value to the floodplain, by using only the most valuable possible land use class in each cell. The lowest change can be seen in Method 1 for three of the four scenarios. Only in the Internet of Risk scenario does Method 4 produce a smaller increase than Method 1. This is likely to be related to the probabilities used for each land use class, as they have a direct impact on the weighted value. When taking probability maps into account, the land use classes with higher values (Commercial, Residential, and Industrial) do not always occupy the same cells, because they have different rules of attraction. For example, a cell with 40% probability of Residential allocation might have a distribution of the remaining 60% between land use classes of far lesser value, such as Agriculture with, for example, 21%, and Vacant with, for example, 39%. For Methods 2 and 3, the cell would be occupied by residential land use, but when using Method 4, this can lead to an overall decrease in value for this cell compared to that obtained using the other two methods. At least for this case study and the chosen scenarios for deep uncertainty, this seems to be the case. Details of the values for all considered land use classes can be found in Appendix D.2.

Ignorance of the Lambs, as shown in Figure 31, is the scenario with the highest increase in loss across all four methods considered. Figure 32 provides further insight into this by looking at the distribution of the loss itself, separated into segments, and the area impacted by loss for just this scenario. As can be seen, between the different segments of loss, each method performs differently. While the methods resulting in smaller losses in Figure 31 (i.e. Methods 1 and 4) are especially strongly represented in the lower segments of loss, Method 3, with the highest change in loss, has the largest area impacted in the higher ranges of loss. This is to be expected, as Method 3 uses only the highest values in each cell, which leads to an accumulation of damage. The variation in in each segment can only be caused by the different allocation method chosen, as both the flood map and the probability map of land use classes are the same for Methods 2, 3, and 4. It is also interesting to note that the results for Method 1, as the only method not considering local uncertainty and using a single land use map, are still in close proximity to those obtained using the other methods. Even so, the losses on the lower side of the spectrum obtained using this method confirm the results in Figure 31.

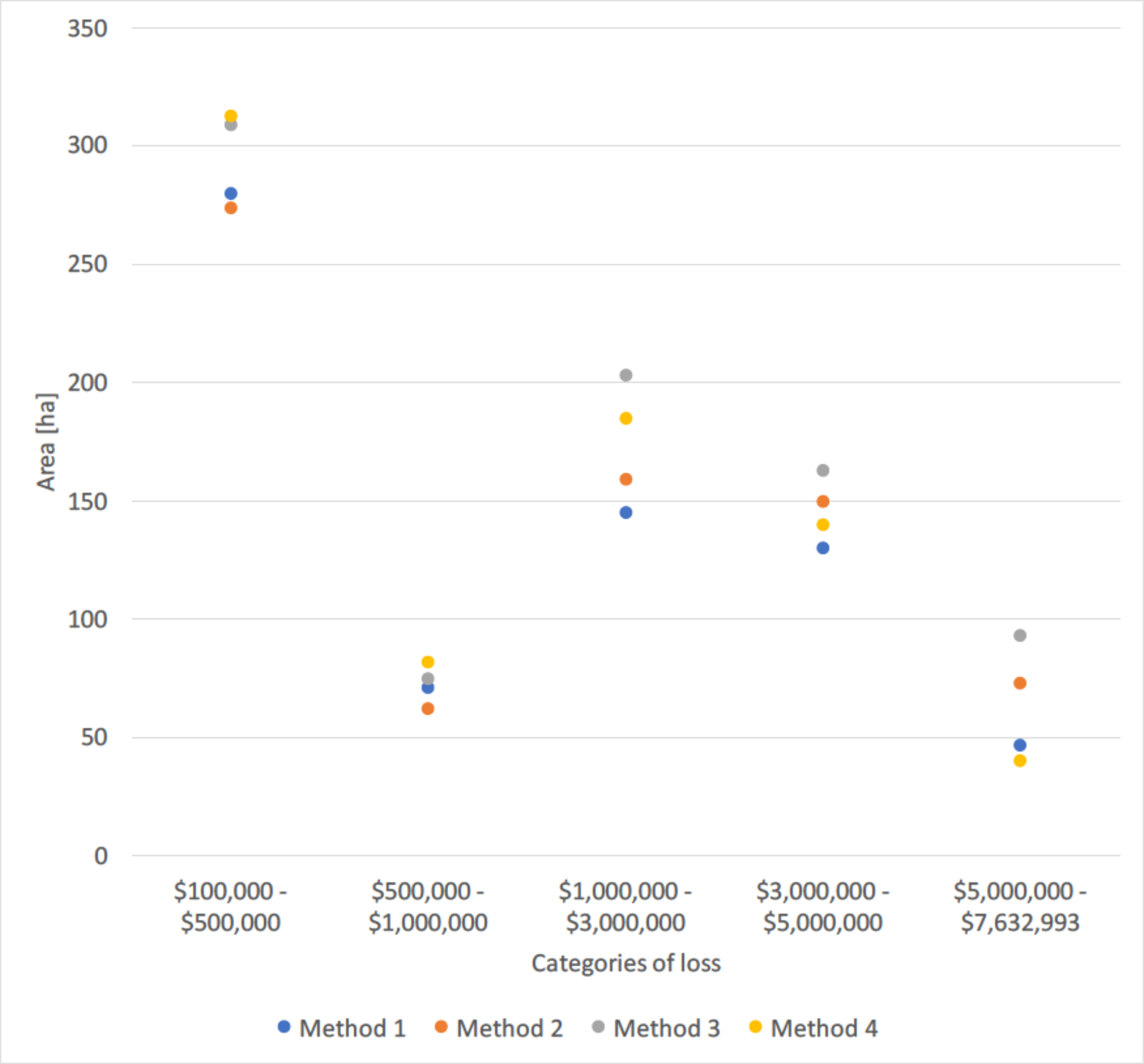

Figure 32 Performance of methods across loss based on the area affected for the Ignorance of the Lambs scenario

The damage maps for the Cynical Villagers and the Ignorance of the Lambs scenarios in Figure 33 (damage maps for the other scenarios can be found in Appendix C3) also show differences in the spatial distribution of losses across the different scenarios for deep uncertainty for Methods 1 and 3, which are the methods resulting in the most significant differences in loss. The Cynical Villagers scenario has the smallest area of loss across the case study area, with only one area of high flood loss, whereas the Ignorance of the Lambs scenario has the highest area of loss for both Methods. The maps also demonstrate the distribution of hotspots of loss. While the location of hotspots varies between the different scenarios for deep uncertainty, especially between the Cynical Villagers and Ignorance of the Lambs scenarios, the method chosen has an impact on the intensity in each hotspot. For example, while in the Ignorance of the Lambs scenario the spatial distribution between the two Methods varies only slightly in extent, the variation in intensity is visibly greater for Method 3 (see Figure 33 b.2)). This further highlights the importance of considering deep uncertainty under spatially explicit conditions.

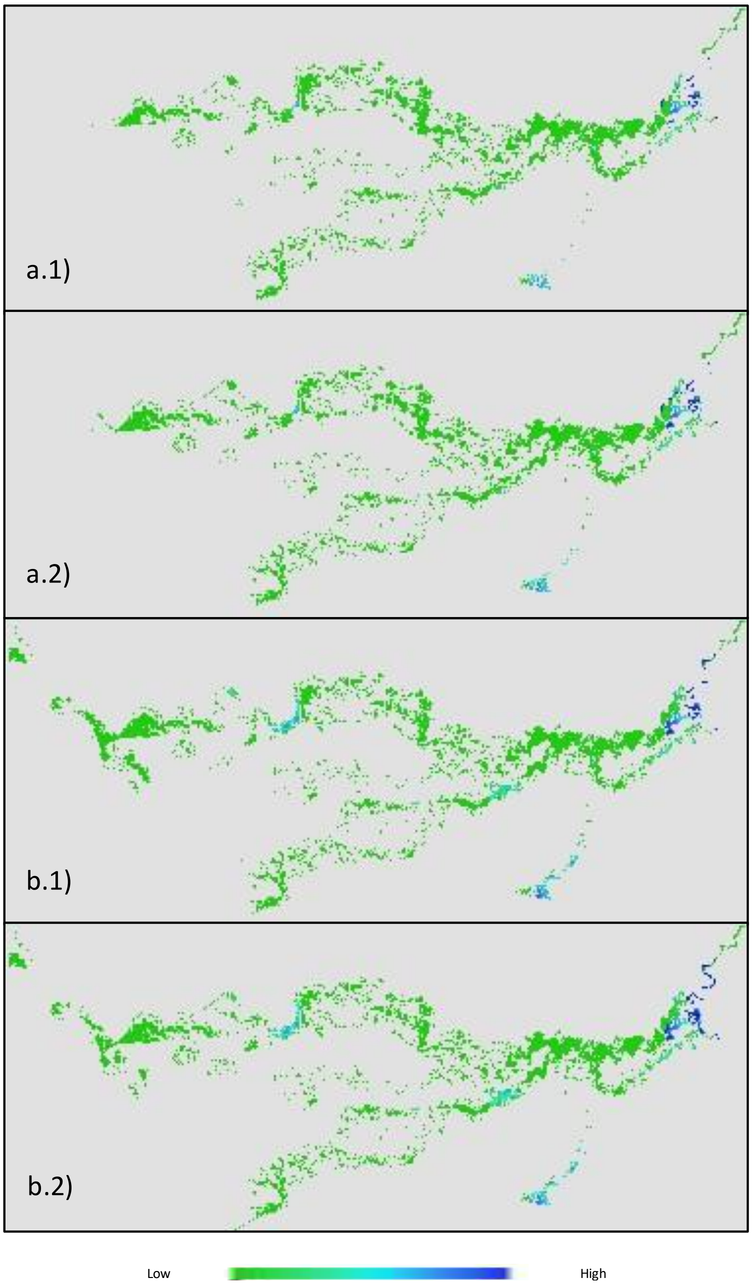

Figure 33 Damage maps for the different scenarios for deep uncertainty a) Cynical Villagers and b) Ignorance of the Lambs, and 1) Method 1 and 2) Method 3 to deal with local uncertainty

Overall, the different methods for considering local uncertainty in land use models performed as expected and resulted in significant differences in loss, which highlights that local uncertainty in land use models is important to consider (i) as the method that does not consider local uncertainty (Method 1) resulted in losses at the lower end of the spectrum of values obtained and (ii) as the method chosen had a big influence on the resulting loss and therefore needs to be selected carefully.

4.5 Summary and Conclusions

This paper introduces a framework for considering uncertainty in exposure in future flood risk assessment via the inclusion of local and deep uncertainty in land use modelling. The approach is applied to the Gawler River region in South Australia to quantify the impact of deep and local uncertainty, as well as different approaches to dealing with local uncertainty, on future flood loss. Deep uncertainty is represented via four socio-economic development scenarios driving land use change and local uncertainty is represented via stochasticity in the land use allocation process in the land use model, resulting in probabilistic future land use maps. Four different approaches to using the information in the probabilistic maps to quantify flood loss are considered.

Results indicate that while deep uncertainty had little impact on inundation levels due to the minimal impact the relatively small and localised changes in roughness and infiltration resulting from the different socio-economic development scenarios had on runoff, it had a significant impact on flood loss, due to the vastly different amounts and distributions of values in the landscape resulting from the scenarios. In addition, local uncertainty due to the stochasticity in the allocation of different land use classes also had a significant impact on future flood loss, as it resulted in significantly different probabilistic spatial distributions of values at stake. The different ways in which the information in the probabilistic land use maps was converted to loss also made a substantial difference to estimates of future flood loss.

Overall, the results from this study highlight the importance of considering both deep- and local- uncertainty in land use modelling in the estimation of future flood loss, as both can have a significant impact on loss estimates. For example, when considering deep uncertainty in isolation, there was an up to 30% difference in estimates of future flood loss over the 82-year period from 2018 to 2100 when different socio-economic development scenarios were considered. When considering local uncertainty in conjunction with the business-as-usual future scenario, the variation in estimates of future flood loss was in excess of 25%, even when only five different stochastic variants of the land use model were considered. The combined effect of local and deep uncertainty was even more pronounced, with variations in future losses resulting from the consideration of the four different methods of dealing with local uncertainty ranging from around 45% to 105% for low- and high- socio-economic development scenarios, respectively.

The absolute and relative impact of deep and local uncertainty in future land use on flood loss is likely to depend on factors such as the distribution of values and flooding throughout the landscape, the different socio-economic development scenarios considered and the time period over which the assessment is done. Consequently, there is a need to apply the framework introduced in this paper to a larger number of case studies under a wider range of conditions in order to better understand the likely range of impacts of deep and local uncertainty in land use on future flood loss, as well as the factors and conditions that have the biggest influence. In addition, there is also a need to consider other sources of uncertainty affecting future flood loss, such as the effects of climate change on the hazard side of the risk triangle. However, the results of this paper clearly demonstrate the value of and need to consider uncertainties in future land use as part of flood risk assessments.

Acknowledgments

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Chapter 5: Conclusion, limitations, and future work

Flooding has been identified as one of the most dangerous natural hazards today. Flood risk is a function of hazard, exposure and vulnerability. Exposure and vulnerability are based on the land use occupying the flood plain while hazard expresses the flood as an event with inundation depth, flow speeds, and extent. Further, exposure describes the existence of vulnerable objects within the flood prone area and vulnerability, on the other hand, is related to the building structure and its weakness to flood damage. A high percentage of today's flood risk is caused by urban development, leading to an increase in high value at risk within the floodplains worldwide.

Quantifying changes in the nexus between flooding and land use is critical to our ability to better understand, quantify and mitigate this future risk. One reason for the urbanisation of floodplains is the global socio and economic growth resulting in the expansion of urban development within floodplains. Past studies have shown that the increase in urban land use throughout a catchment can have significant impact on the occurring floods and the added "values-at-stake" exposed to flooding, increasing flood-related losses. By raising the degree of sealed surfaces, vital surface characteristics such as infiltration and roughness are reduced, causing faster and larger flood events. At the same time, changes in flood extent and depth can change land use via policy measures aimed at reducing losses due to flooding, such as buy-backs and zoning policies. While more traditional mitigation strategies, such as structural options, have limitations with adapting to future change, land use based options, such as land use planning and nature-based solutions, offer flexibility in an uncertain future.

The developed modelling framework that considers the flood-land use nexus in an integrated fashion by including the impacts of both climate and socio-economic drivers of change, as well as the impacts of policy interventions based on zoning, provides an insight on the progression in future flood risk. Chapter 2 was able to show the effect of the flood-land-use-nexus on future flood risk by applying the framework to a case study in Adelaide, South Australia, in order to better understand (i) the relative influence of climate change and socio-economic development on future flood inundation levels and damage, (ii) the relative effectiveness of zoning policies in reducing future flood risk, and (iii) the importance of considering the two-way interaction between changes in land use due to socio-economic development on future flood risk and resulting changes in land use as part of policy interventions based on zoning.

Adding to the framework by developing a formal approach it is able to (i) identify suitable locations of portfolios of NBSs at regional scales, enabling trade-offs between portfolio size and the corresponding reduction in flood impact to be determined and (ii) model the flood reduction impact of portfolios of NBSs at regional scales at a resolution that enables the requisite analyses to be integrated with land use planning practises and to be conducted in a computationally efficient manner, as shown in Figure 1. Chapter 3 was able to illustrate the utility of the proposed approach and assess the degree to which portfolios of nature-based solutions can mitigate pluvial flooding at the catchment scale for the case study in Adelaide, South Australia.

Modelling is a viable option to demonstrate the impact of future change. But even though it can help to better understand potential developments in the future it cannot predict a certain future. During the development of the flood-land-use-nexus framework local uncertainty as part of the modelling of land use change was identified to have a significant impact on future flood risk. Based on that observation a generic framework to include local uncertainty into risk assessment based on land use allocation probability was developed in Chapter 4. The approach is applied to the Gawler River region in South Australia to quantify the impact of deep and local uncertainty, as well as different approaches to dealing with local uncertainty, on future flood loss. Deep uncertainty is represented via four socio-economic development scenarios driving land use change and local uncertainty is represented via stochasticity in the land use allocation process in the land use model, resulting in probabilistic future land use maps. Four different approaches to using the information in the probabilistic maps to quantify flood loss are considered.

5.1 Research contributions

The main contribution of this research has been the improvement of future flood risk management at a regional scale through the development of a flood-land-use-nexus modelling framework. To add to the modelling of land use based mitigation options and further enhance the proposed modelling framework a formal approach was developed, which is capable of identifying suitable locations for NBS portfolios at a regional scale and model the flood reduction impact of portfolios of NBSs at regional scales at a resolution that enables the requisite analyses to be integrated with land use planning practises and to be conducted in a computationally efficient manner. To deal with occurrence and impact of local uncertainty in land use modelling on future flood risk, a generic approach was developed using approaches of (i) most valuable (ii) most likely, and (iii) weighted average to better assess the effect on future flood risk within the flood-land-use-nexus.

In Chapter 2 (Paper 1), a modelling framework was introduced that enables changes in the flood-land use nexus to be modelled dynamically by linking the inputs and outputs of spatially and temporally explicit flood and land use models. The framework was applied to the Gawler River region in South Australia to assess (i) the relative importance of climate and socio-economic drivers of change, (ii) the relative effectiveness of zoning policies and (iii) the impact of considering the two-way nexus between impacts of land use on flooding and the impacts of flooding on land use. Results indicate that socio-economic drivers had a significantly greater impact on flood damage than climate drivers, highlighting the importance of considering the impacts of socio-economic drivers of change on future flood risk. Additionally, zoning policies and buy-backs resulted in significant reductions in flood damage as they were able to remove “values-at-stake” from, and curtail future development in, flood-prone areas. Finally, consideration of the two-way interaction between flooding and land use made a noticeable difference when considering both climate and socio-economic drivers, as this enabled zoning policies to be adapted in response to increased flood extents and depths caused by climate change.

Chapter 3 (Paper 2) introduced and illustrated an approach that enables the utility of NBSs to be assessed at regional scales, including the ability to model the flood reduction benefits of NBSs at spatial resolutions that are commensurate with those commonly used in spatial planning studies (e.g. 50m x 50m to 500m x 500m) and the ability to identify the most suitable locations for placing portfolios of NBSs at regional scales. The proposed approach was applied to the Gawler River region in South Australia, which is prone to flooding and has the potential to cause significant damage. The most suitable locations for the placement of portfolios of NBSs to reduce flood risk were identified and the potential benefit of using portfolios of NBSs was assessed. Results indicate that the strategic placement of portfolios of NBSs has the potential to reduce regional flood risk significantly. For the case study considered, by placing portfolios of NBSs on 0.2% of the area under consideration, the resulting damage to building stock can be reduced by 20% for a 1:10 year event, 16% for a 1:20 year event and 14% for a 1:50 year event. These reductions in building stock damage increase to around 32% for the 1:10 year event, 30% for a 1:20 year event and 27% for a 1:50 year event if the area covered is 1%.

Chapter 4 (Paper 3) established a framework for considering local uncertainty in the land use modelling component of the proposed flood-land use nexus framework (Chapter 2), thereby enabling the impact of this uncertainty on future flood losses to be assessed. As part of the proposed framework, different probability approaches, such as Monte Carlo, are used in the land use allocation process in order to deal with the local uncertainty in land use modelling. The framework was applied to the Gawler River case study in conjunction with a number of narrative storylines to consider both local and deep uncertainty. The results indicate that while deep uncertainty had little impact on inundation levels due the minimal impact the relatively small and localised changes in roughness and infiltration resulting from the different socio-economic development scenarios had on runoff, it had a significant impact on flood loss, due to the vastly different amounts and distributions of values in the landscape resulting from the scenarios. In addition, local uncertainty due to the stochasticity in the allocation of different land use classes also had a significant impact on future flood loss, as it resulted in significantly different probabilistic spatial distributions of values at stake. The different ways in which the information in the probabilistic land use maps was converted to loss also made a substantial difference to estimates of future flood loss. Overall, the results from this study highlight the importance of considering both deep- and local-uncertainty in land use modelling in the estimation of future flood loss, as both can have a significant impact on loss estimates.

5.2 Limitations and future research

The following section discusses limitations of the research presented above and future work to further improve the application to regional flood risk management.

5.2.1 The flood-land use nexus

While the proposed framework of a flood-land use nexus is generally applicable, the findings from the analysis are specific to the case study and scenarios considered, including the relative importance of climate and socio-economic drivers, the effectiveness of zoning and the impact of the consideration of the two-way interaction between flooding on the quantification of future risk.

Consequently, there is a need to apply the proposed framework to a wider range of case studies with different characteristics. For one, the region considered in this case study is influenced by a large proportion of rural development. Considering a more urban setting might cause variation in result as the impact of land use change on flooding could increase significantly as shown in previous studies (Öztürk et al., 2013, Yan et al., 2013, Sanyal et al., 2014). The same would most likely apply when choosing a location with higher flood intensity to begin with, as this would even further increase the impact of climate change.

In addition, further research on the implementation of different mitigation strategies with the impact on land use change, such as NBSs and structural mitigation, would provide insight into the progression of flood risk under different risk perceptions. Especially the implementation of structural mitigation has a significant impact on risk perception and therefore has a passive effect on land use change. This would demand the creation of a suitability factor based on flood risk within the land use model to account for the positive effect of the structural flood defence or the negative effects flood experiences provide.

5.2.2 Nature-based solution portfolios in regional flood risk management

The potential of using portfolios of NBSs to reduce flood risk at regional scales was demonstrated by the case study but an application of the proposed approach to a wider range of case studies is needed to better understand the conditions under which such an approach might provide potentially viable alternatives to more commonly used structural mitigation strategies. In addition, it should be noted that risk reduction is only one of the criteria determining the viability of such an approach. For example, there is a need to consider a range of economic, social and environmental criteria as part of a multi-criterion assessment to ascertain which approach to regional flood risk reduction is most appropriate in a given decision context. This includes consideration of the feasibility and acceptance of placing portfolios of NBSs over larger urban areas, which will most likely require significant stakeholder engagement.

For the development of the NBS portfolios, modelling resolution was also a limiting factor in the case study considered. A flood model with higher resolution would allow for the modelling of NBSs with more detail and lead to uniform infiltration rates of better quality. This would improve the accuracy of the NBS portfolios in representing different NBS options and allow for a better differentiation between different solutions within a scheme. Improving the NBS portfolios would further help with the assessment of suitable locations and allow planners to test specific sets of different schemes. Also combining the NBS portfolios with conventional mitigation strategies such as structural mitigation would provide increased flexibility in regional flood risk management.

In addition, it is likely that use of a micro-scale flood model with high resolution only covering a small section within the region of interest to determine the uniform infiltration rates, and use of a second model with lower resolution to perform the large-scale modelling, would reduce the accuracy of the results.

Additionally, the development of a database of NBS portfolios would improve the decision making and modelling of possible solutions.

5.2.3 Local and deep uncertainty in land use change and their impact on flood risk

The absolute and relative impact of deep and local uncertainty in future land use on flood loss, introduced in Chapter 4, is likely to depend on factors such as the distribution of values and flooding throughout the landscape, the different socio-economic development scenarios considered and the time period over which the assessment is done.

Consequently, there is a need to apply the framework introduced in this paper to a larger number of case studies under a wider range of conditions in order to better understand the likely range of impacts of deep and local uncertainty in land use on future flood loss, as well as the factors and conditions that have the biggest influence.

In addition, there is also a need to consider other sources of uncertainty affecting future flood loss, such as the effects of climate change on the hazard side of the risk triangle. This demands the development of further methods to identify robust solutions given the multiple sources of uncertainty.

As the aim is to limit uncertainty, the development of improved models to forecast land use and other changes in the future is necessary. However, the results of this paper clearly demonstrate the value of and need to consider uncertainties in future land use as part of flood risk assessments.

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Appendix

Appendix A: Additional material Chapter 2

A.1 Result Maps Experiment 1

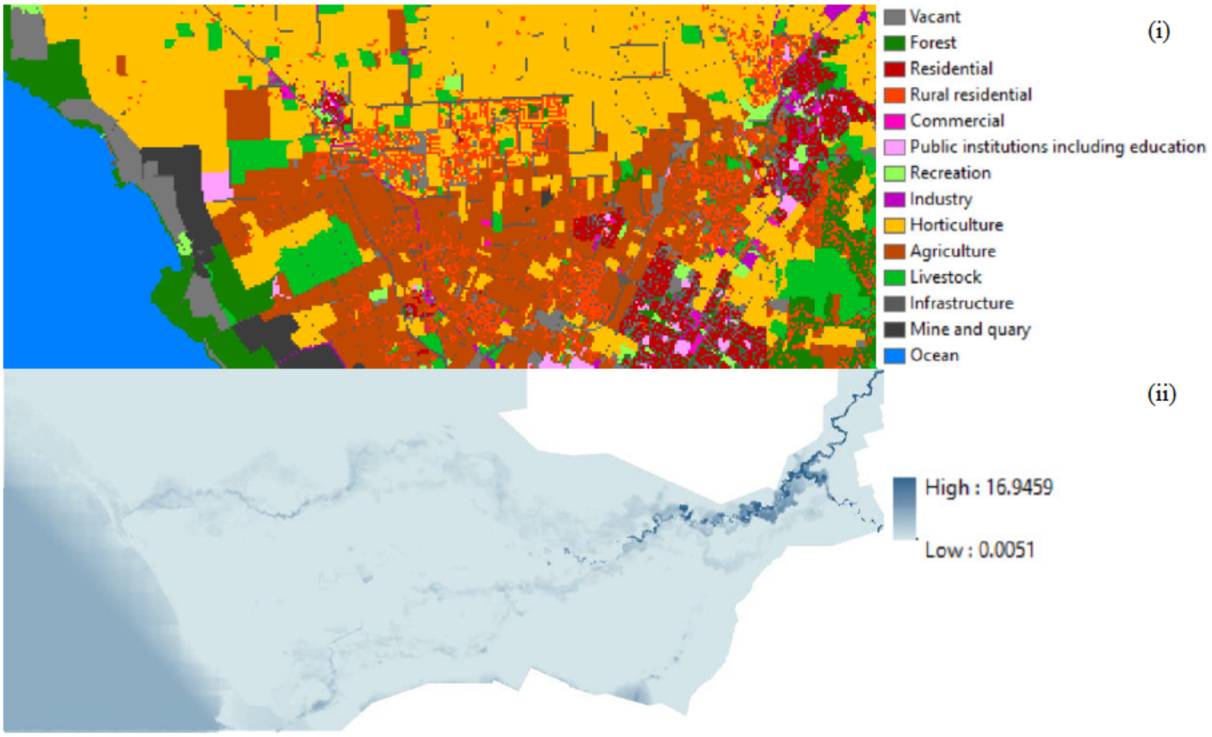

Figure A-1 Result maps Experiment 1 from top to bottom: (i) land use map 2020 (ii) flood map 2020

(iv
)

A.2 Result and comparison maps Experiment 2

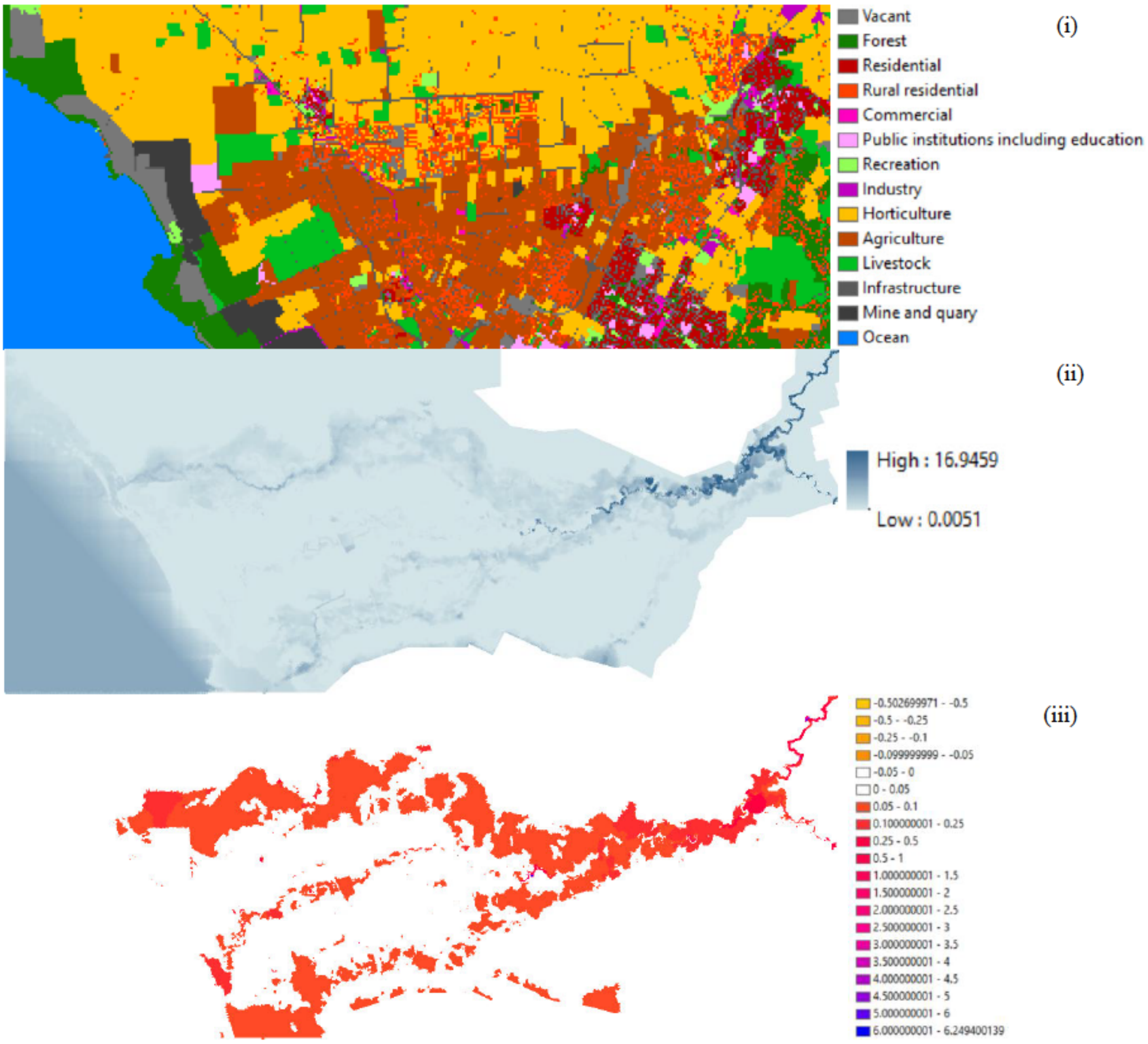

Figure A-2 Result maps Experiment 2 from top to bottom: (i) land use map 2020 (ii) flood map 2080 (iii) difference in inundation depth 2080 to 2020

A .3 Result and comparison maps Experiment 2

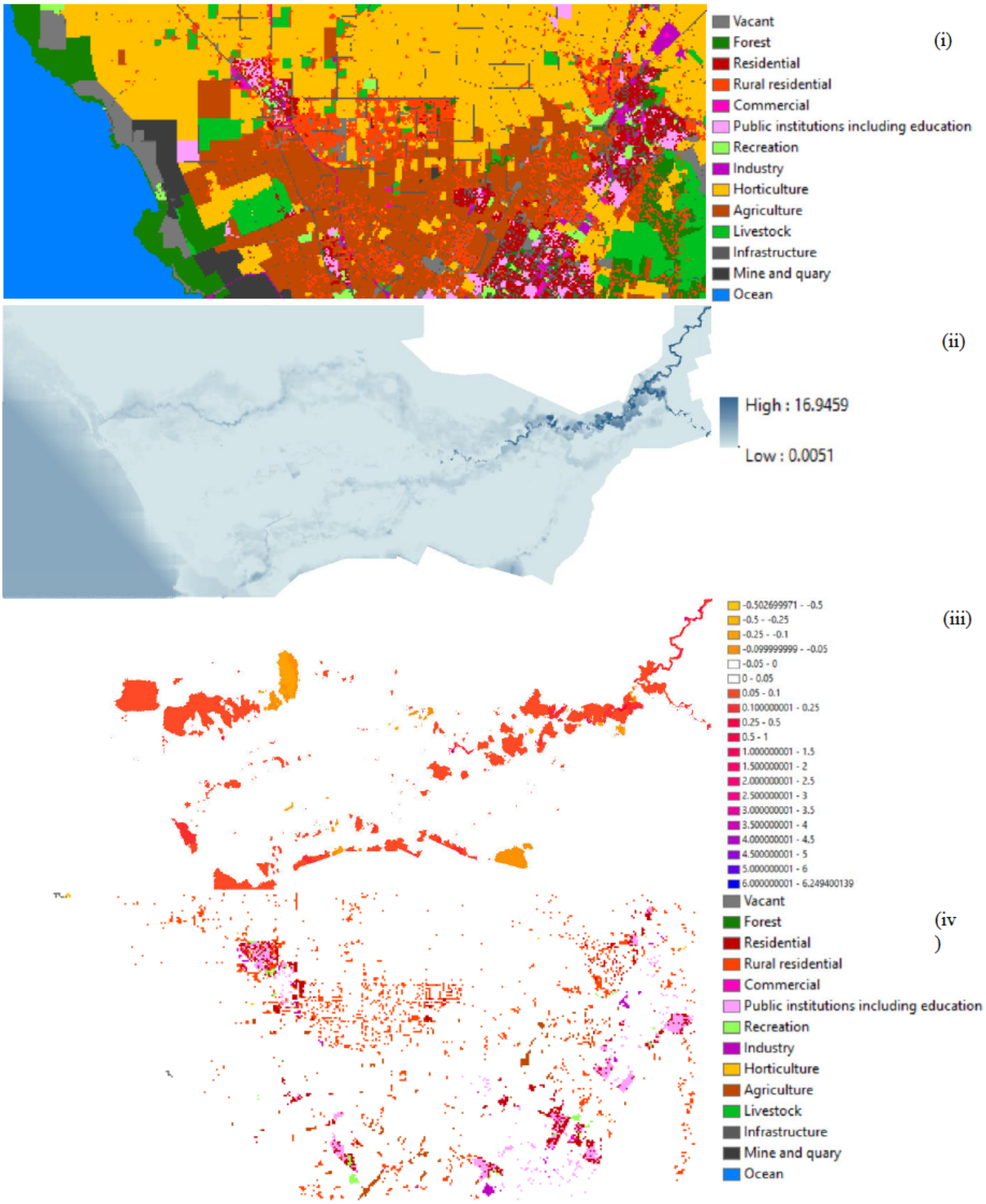

Figure A-3 Result maps Experiment 3 from top to bottom: (i) land use map 2020 (ii) flood map 2080 (iii) difference in inundation depth 2080 to 2020 (iv) difference in land use 2080 to 2020

A.4 Result and comparison maps Experiment 4

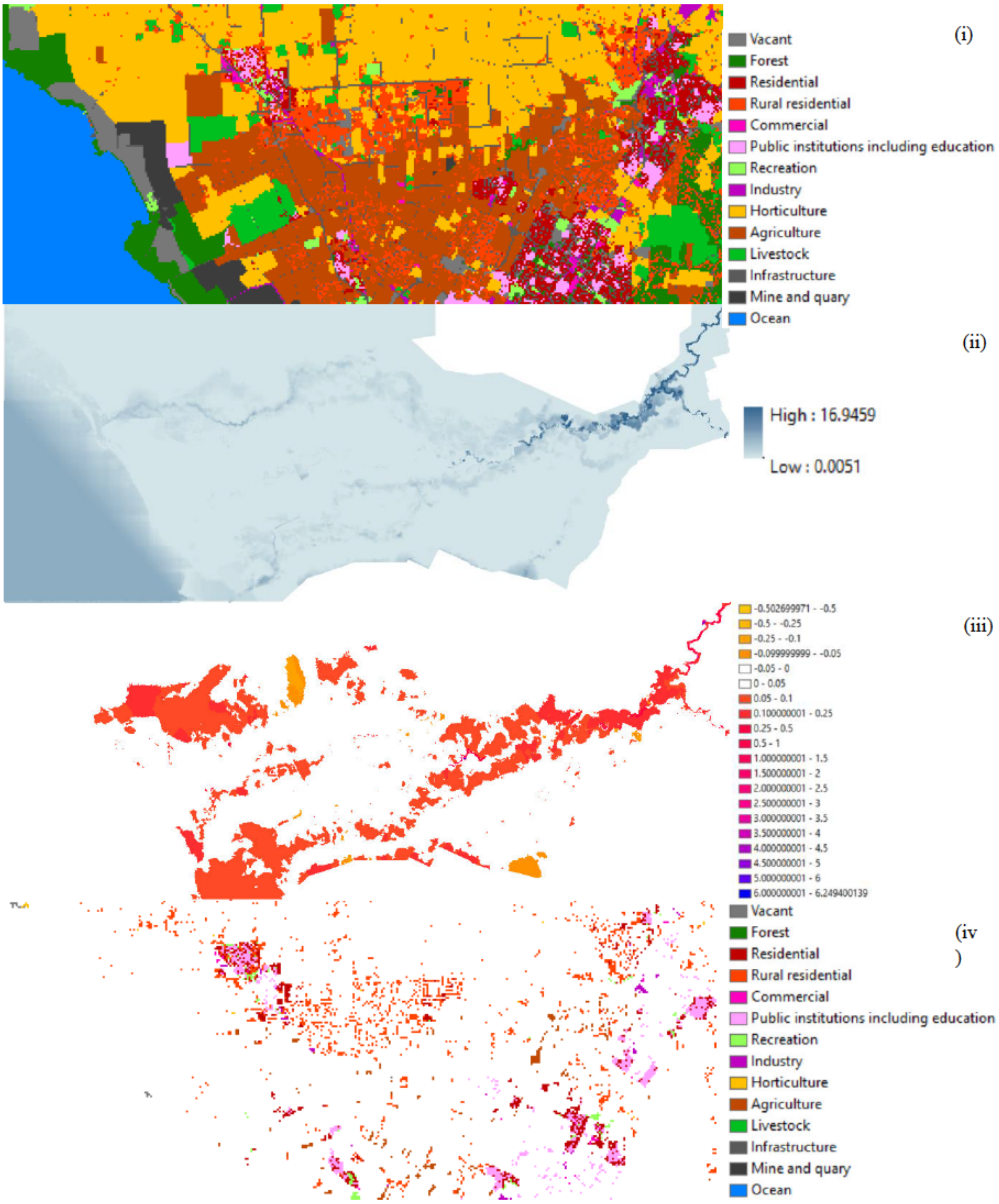

Figure A- 4 Result maps Experiment 4 from top to bottom: (i) land use map 2020 (ii) flood map 2080 (iii) difference in inundation depth 2080 to 2020 (iv) difference in land use 2080 to 2020

A.5 Result and comparison maps Experiment 5

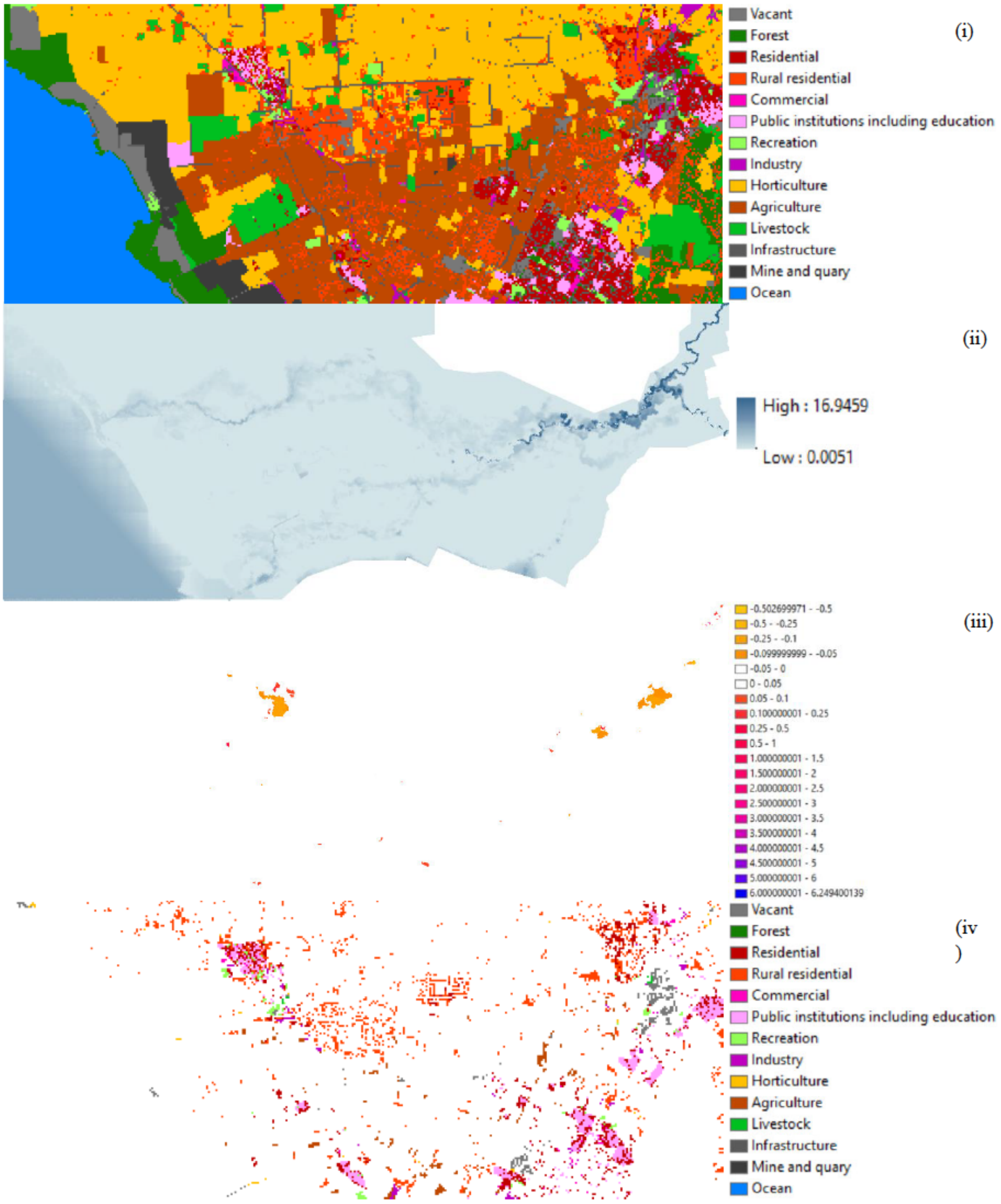

Figure A-5 Result maps Experiment 5 from top to bottom: (i) land use map 2020 (ii) flood map 2080 (iii) difference in inundation depth 2080 to 2020 (iv) difference in land use 2080 to 2020

A.6 Result and comparison maps Experiment 6

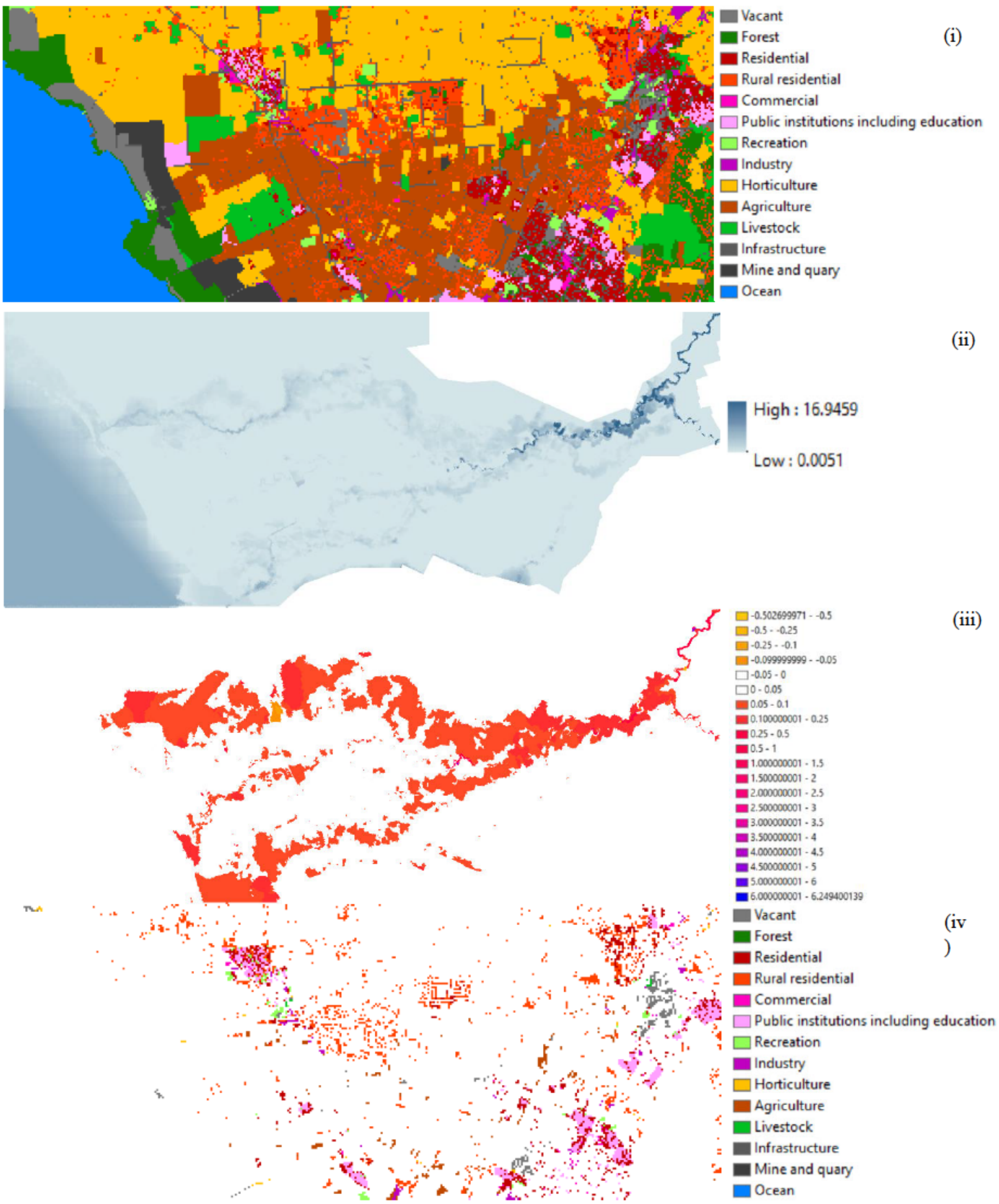

Figure A-6 Result maps Experiment 6 from top to bottom: (i) land use map 2020 (ii) flood map 2080 (iii) difference in inundation depth 2080 to 2020 (iv) difference in land use 2080 to 2020

A.7 Result and comparison maps Experiment 7

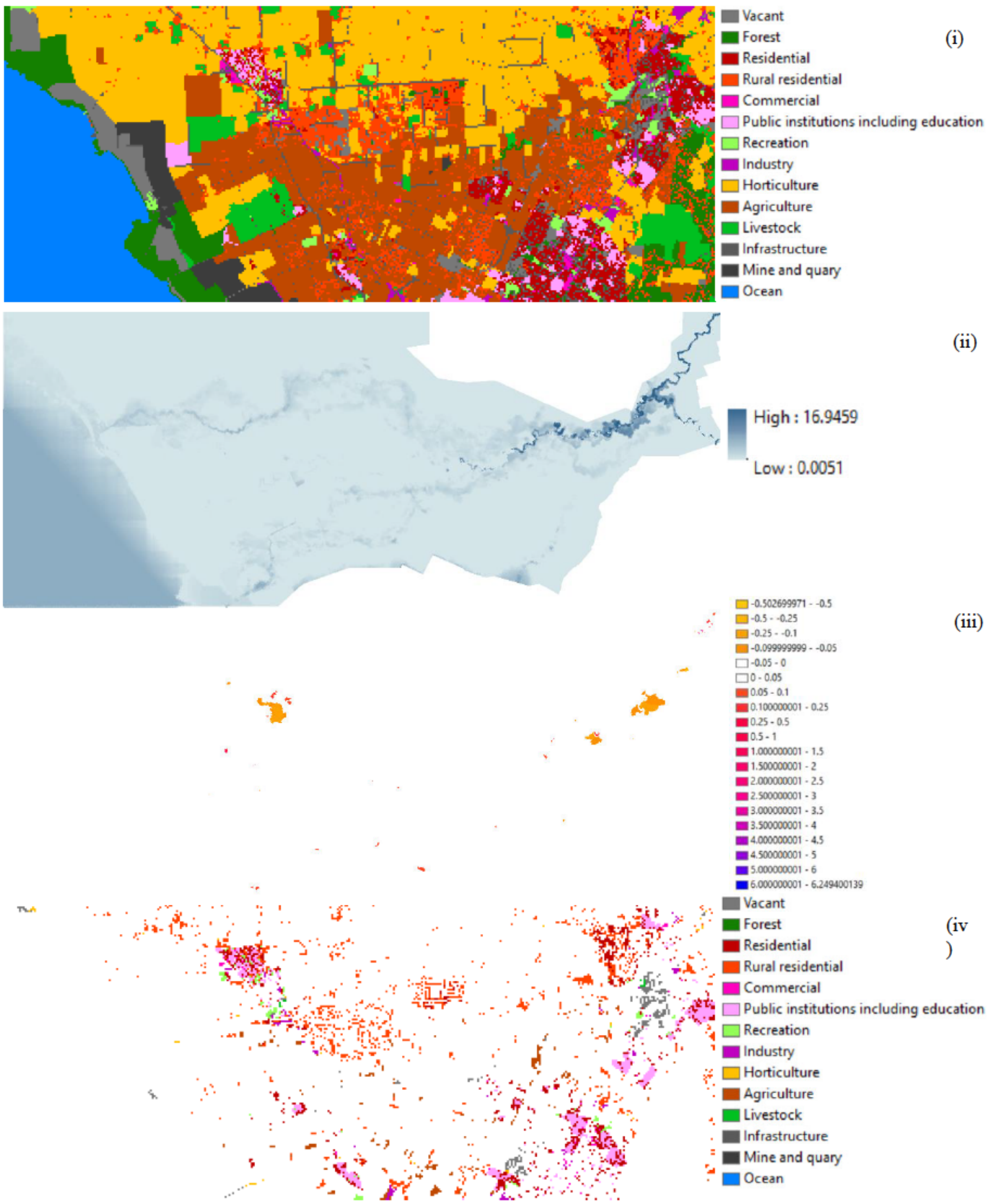

Figure A-7 Result maps Experiment 7 from top to bottom: (i) land use map 2020 (ii) flood map 2080 (iii) difference in inundation depth 2080 to 2020 (iv) difference in land use 2080 to 2020

A.8 Result and comparison maps Experiment 8

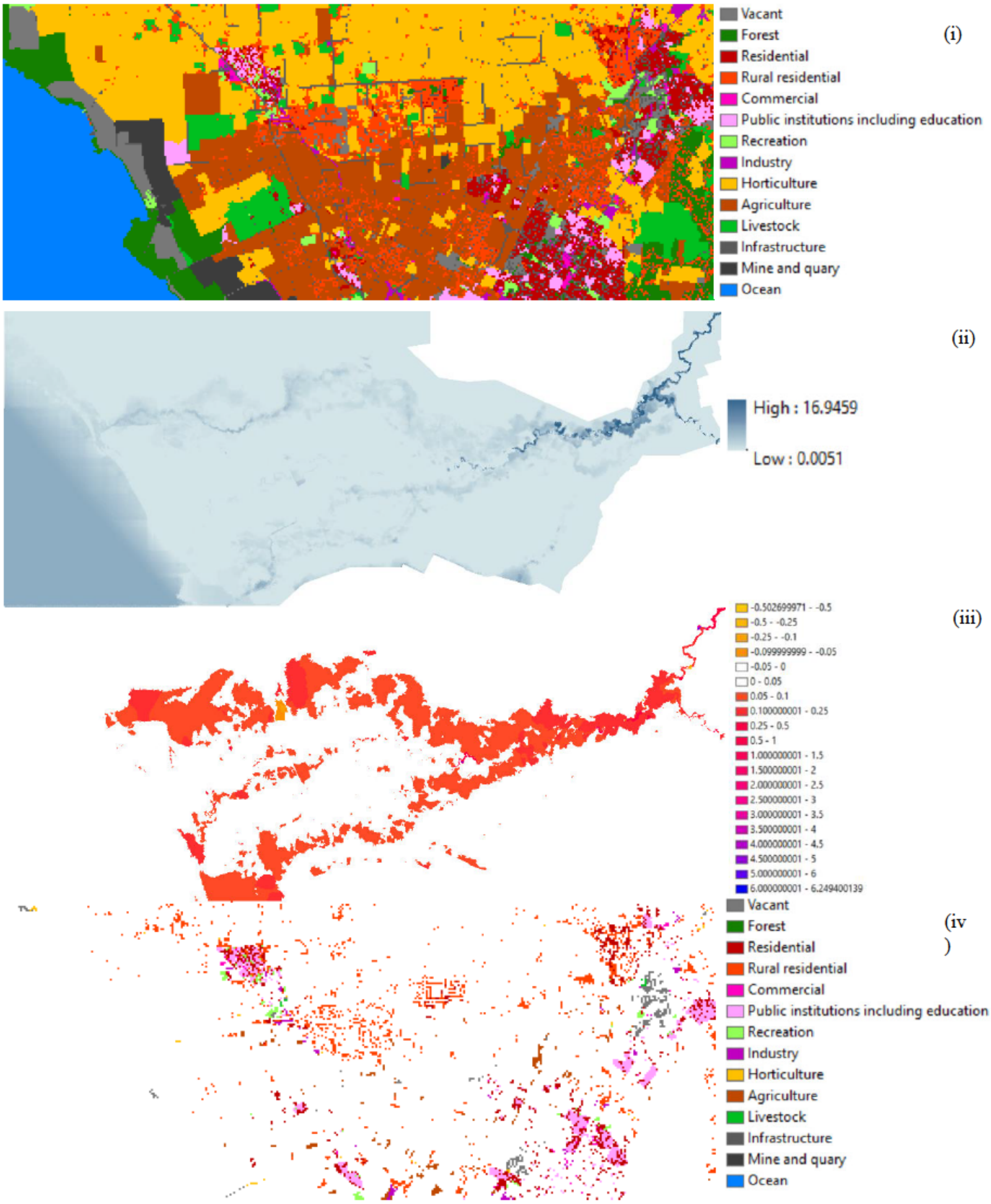

Figure A-8 Result maps Experiment 8 from top to bottom: (i) land use map 2020 (ii) flood map 2080 (iii) difference in inundation depth 2080 to 2020 (iv) difference in land use 2080 to 2020

A.9 Zoning maps used in Metronamica

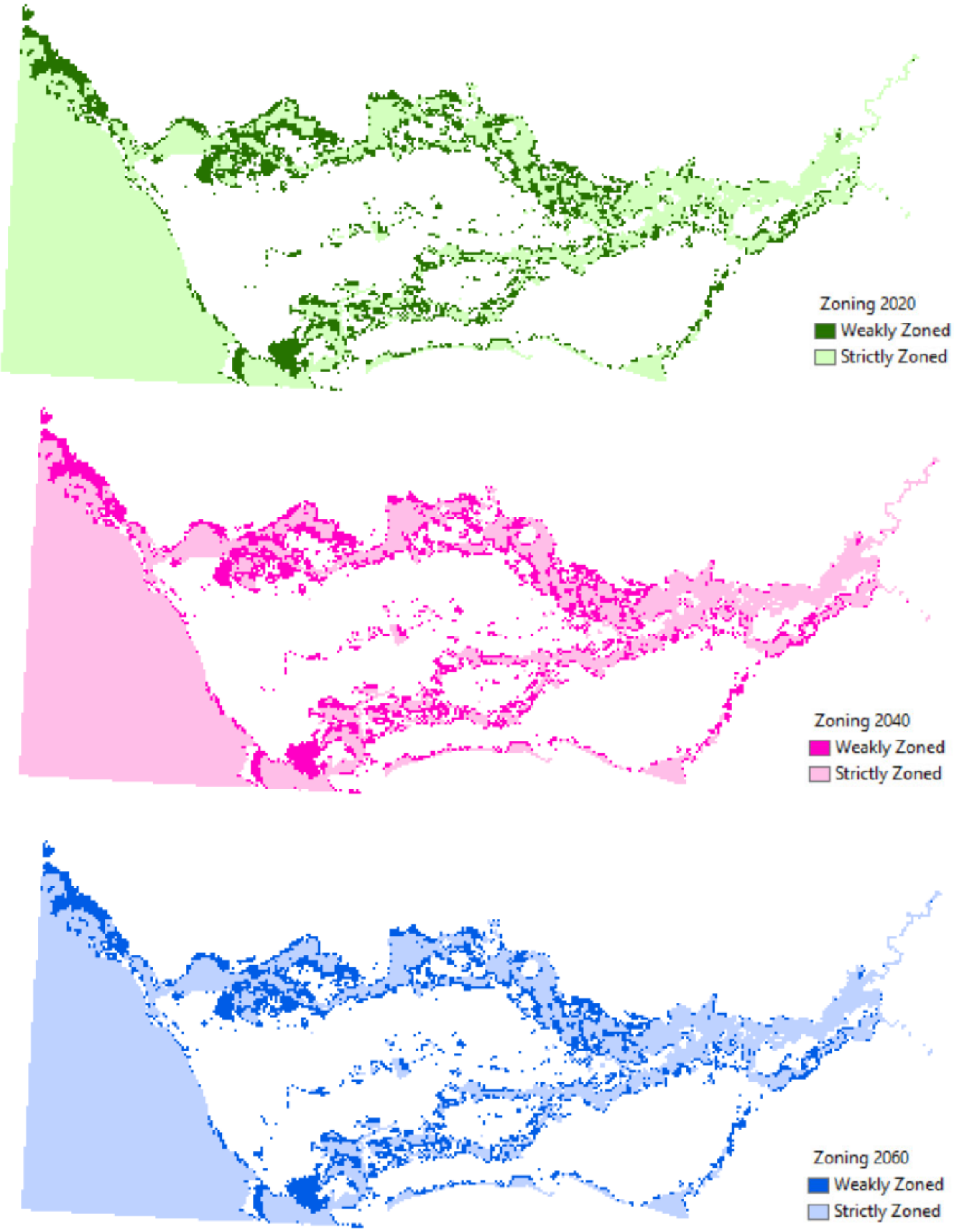

Figure A-9 Different zoning maps used in 2020 (Experiments 5 to 8), 2040, and 2060 (Experiments 7 and 8)

Appendix B: Additional material Chapter 3

B.1 Land Use Map Gawler River region

Figure B-1 Land use map case study region

B.2 Flood Maps

Figure B-2 1 in 10 rainfall event flood map

B.3 NBS portfolio placement throughout Gawler River region

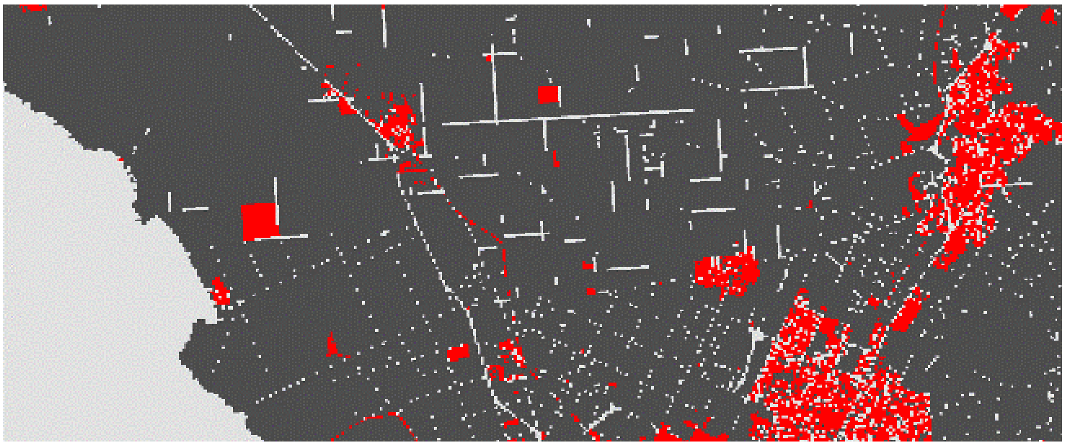

Figure B-3 NBS potential locations

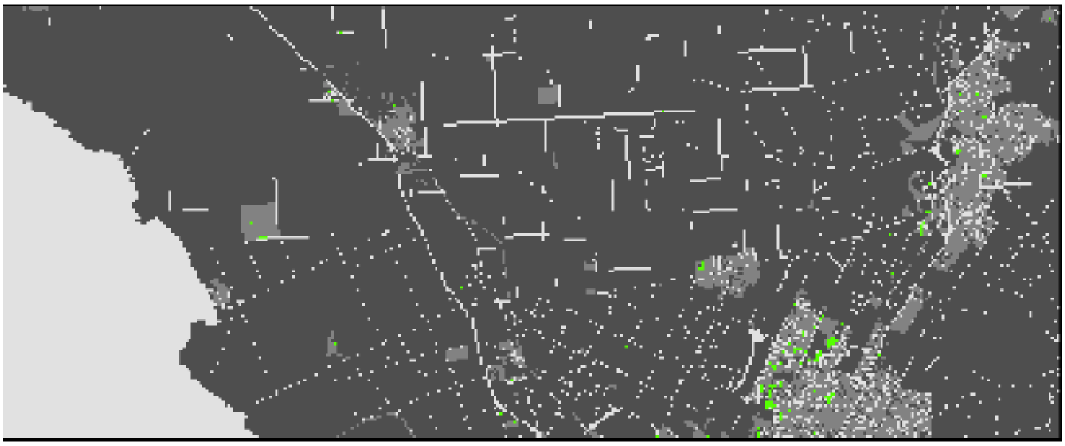

Figure B-4 NBS feasible locations

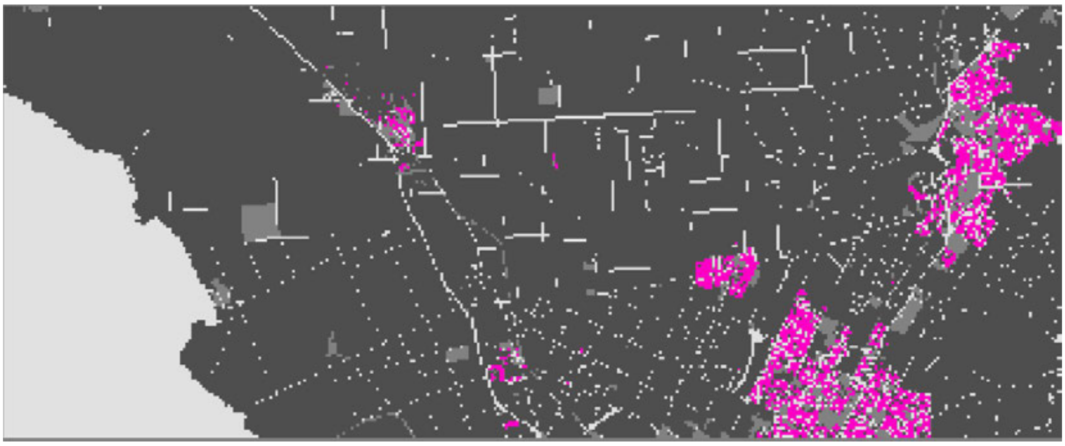

Figure B-5 NBS portfolio placement based on all residential cells

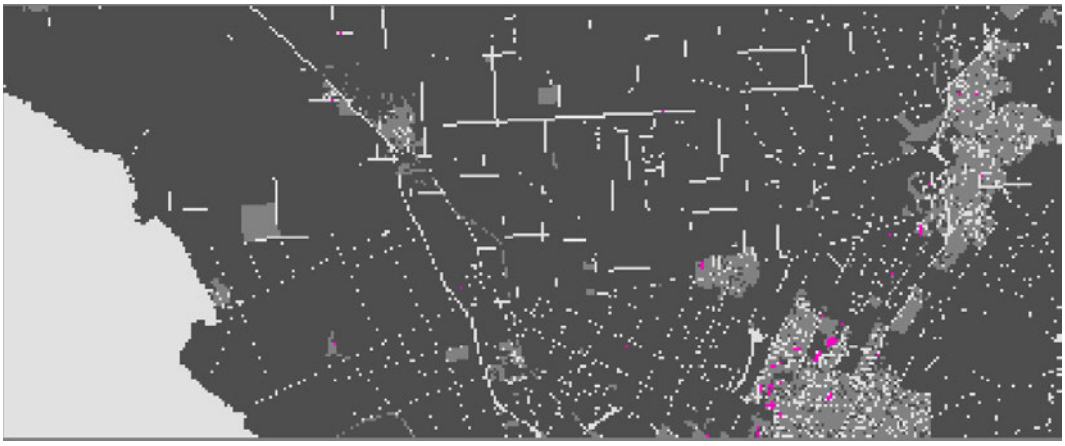

Figure B-6 NBS portfolio placement based on 30cm threshold

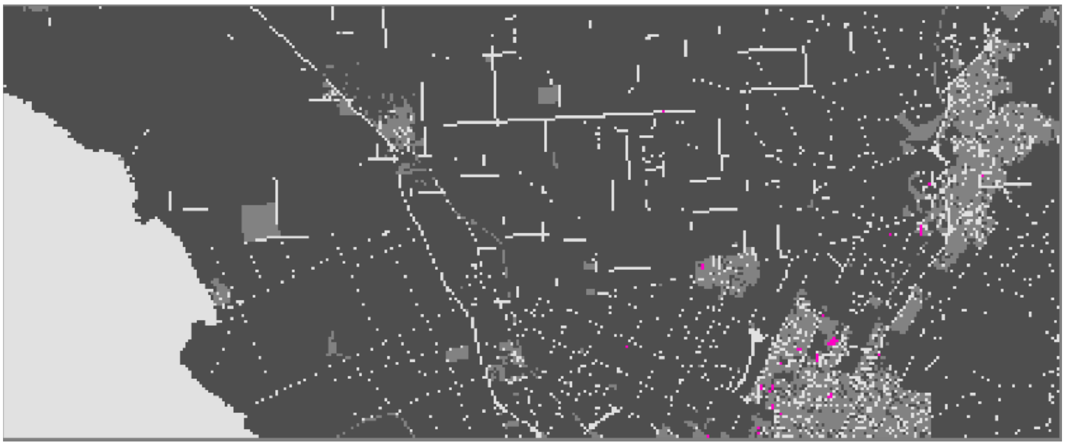

Figure B-7 NBS portfolio placement based on 50cm threshold

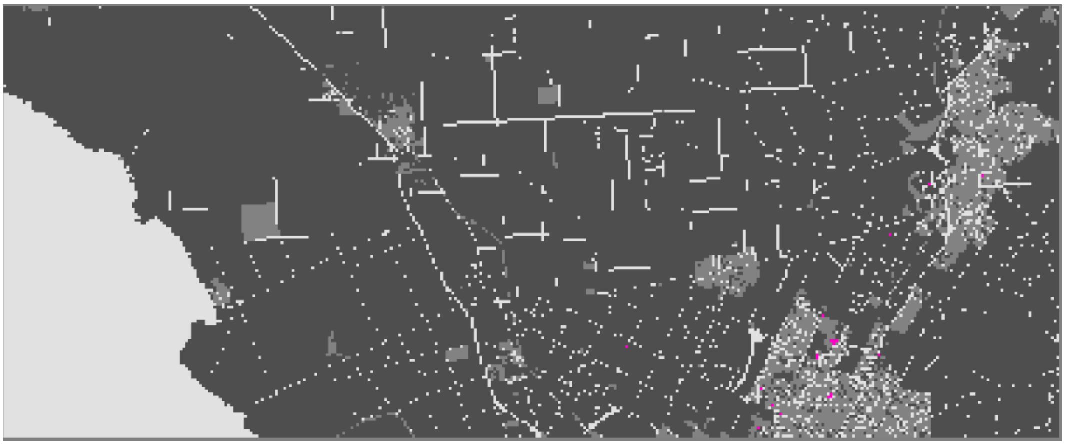

Figure B-8 NBS portfolio placement based on 70cm threshold

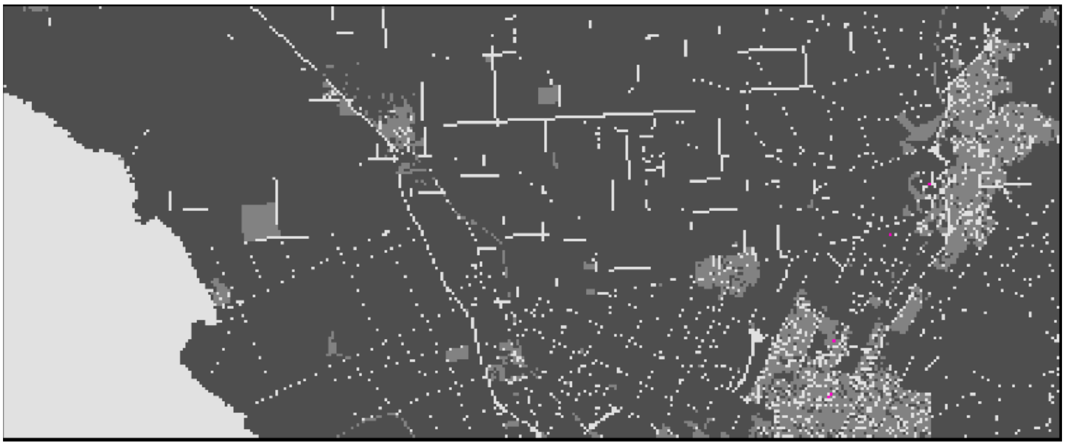

Figure B-9 NBS portfolio placement based on 90cm threshold

B.4 Performance of uniform infiltration rate against the two different schemes across the 100mx200m area

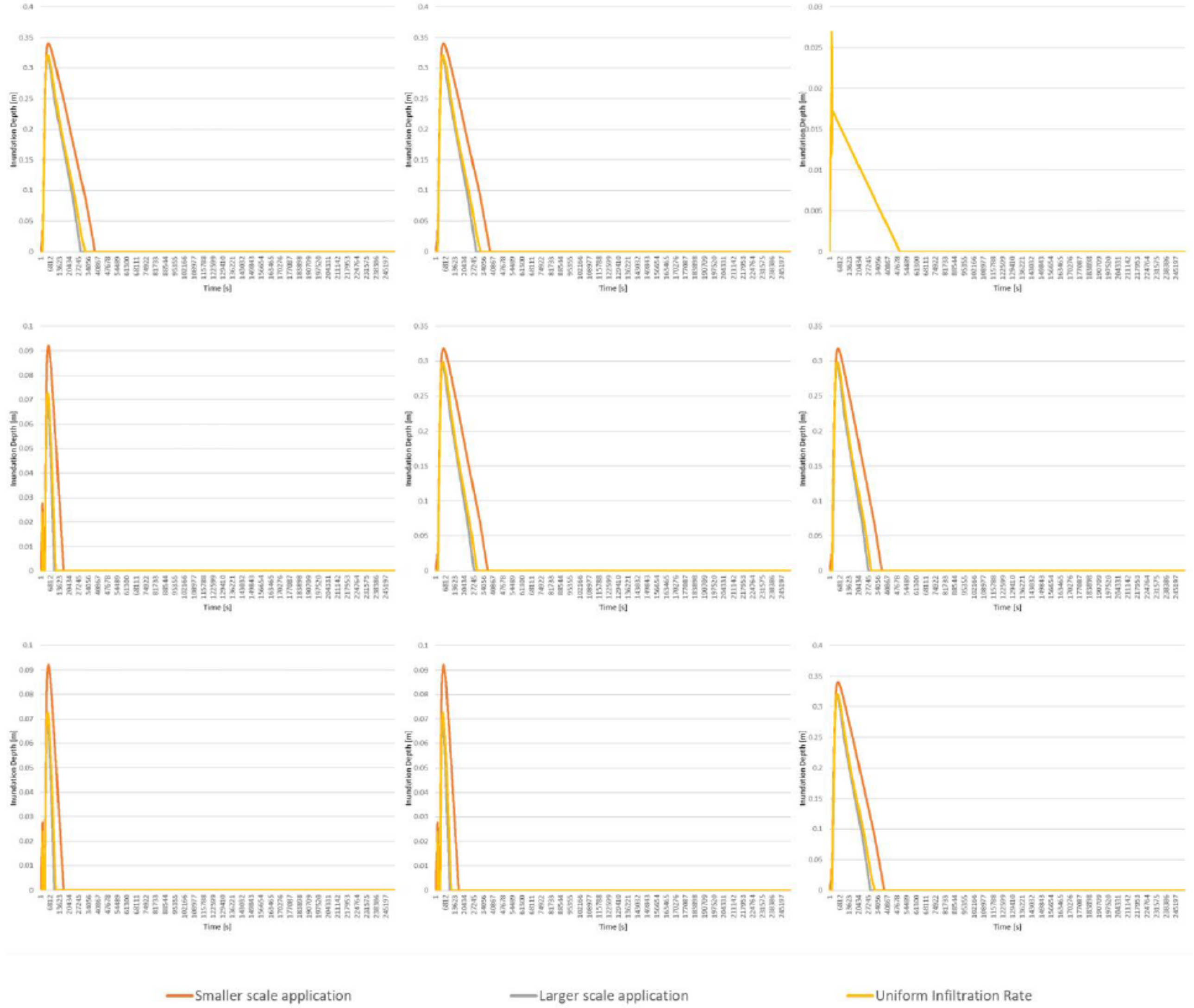

Figure B-10 Location graphs to determine uniform infiltration rate

Appendix C: Additional material Chapter 4

C.1 Resulting land use map under varying fixed seed

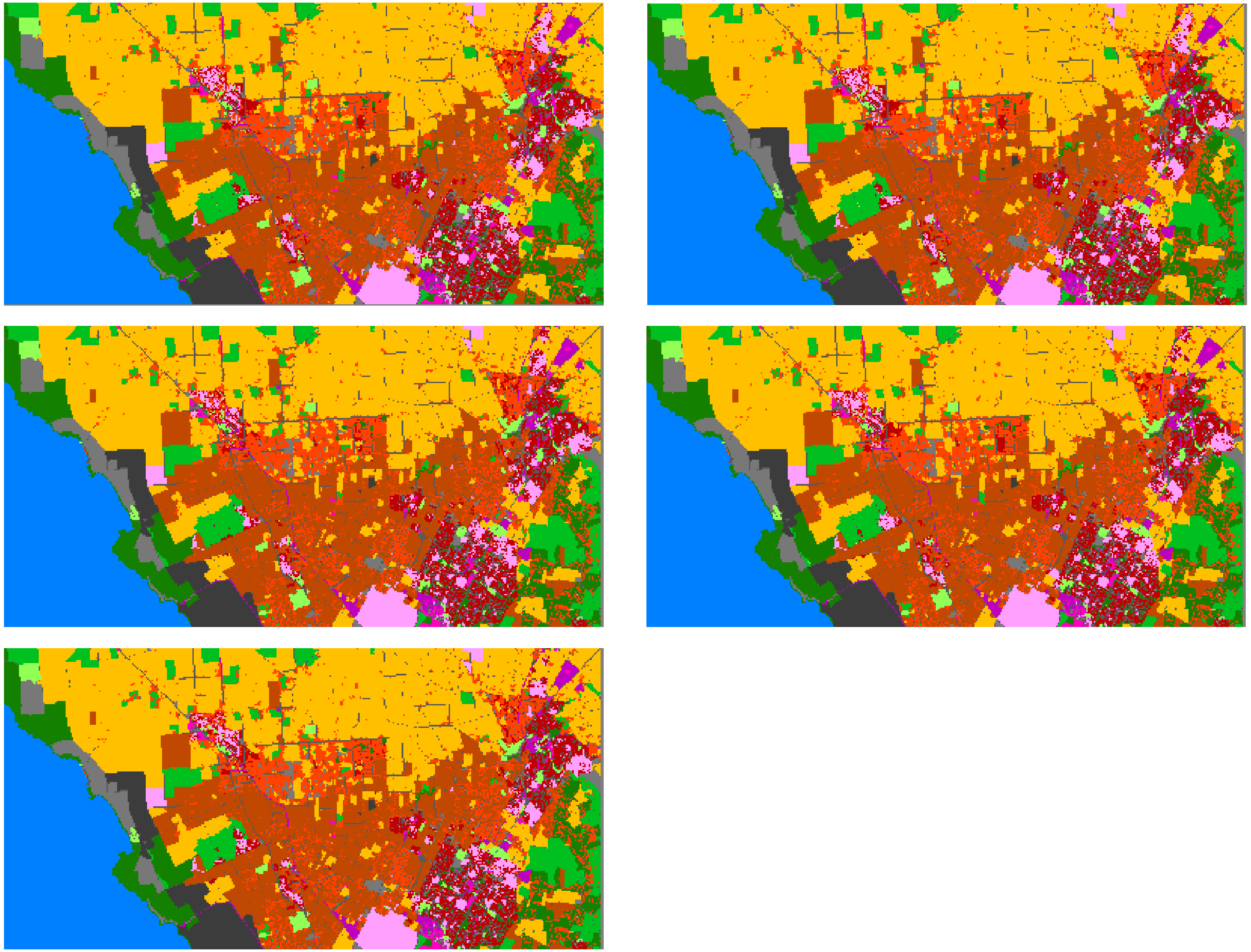

Figure C-1 Resulting land use maps for varying fixed seed random coefficients

C.2 Resulting land use maps for the deep uncertainty scenarios

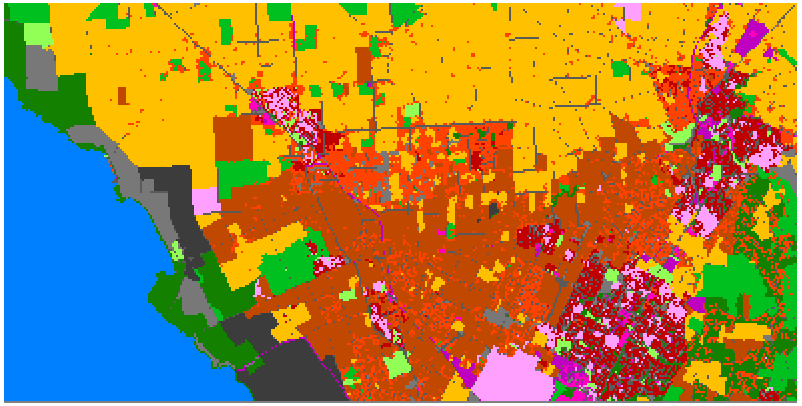

Figure C-3 2100 land use map Business as Usual

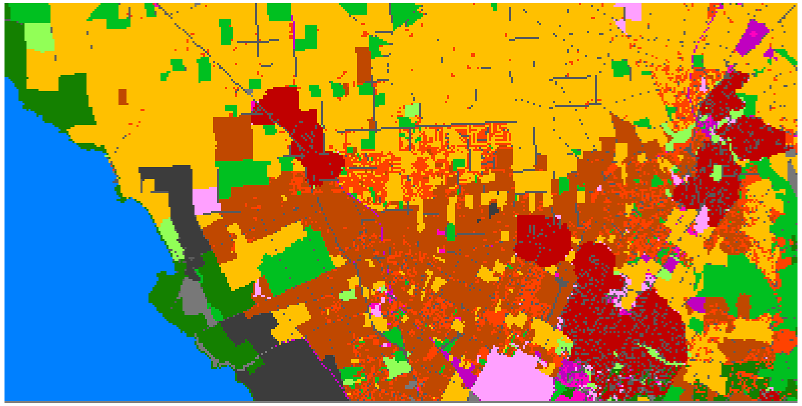

Figure C-2 2100 land use map Ignorance of the Lamb

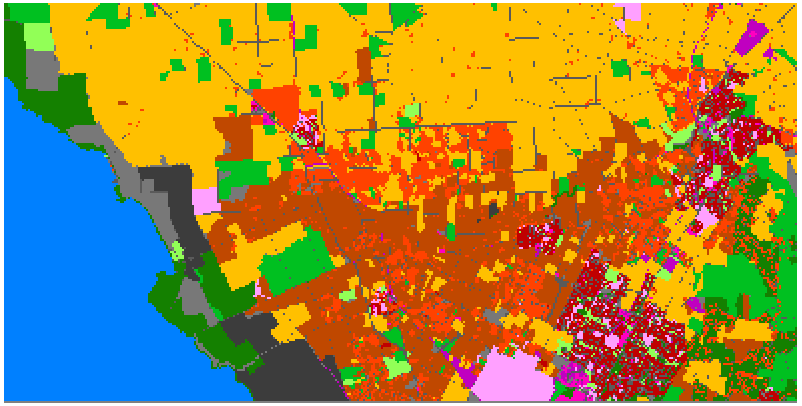

Figure C-4 2100 land use map Cynical Villages

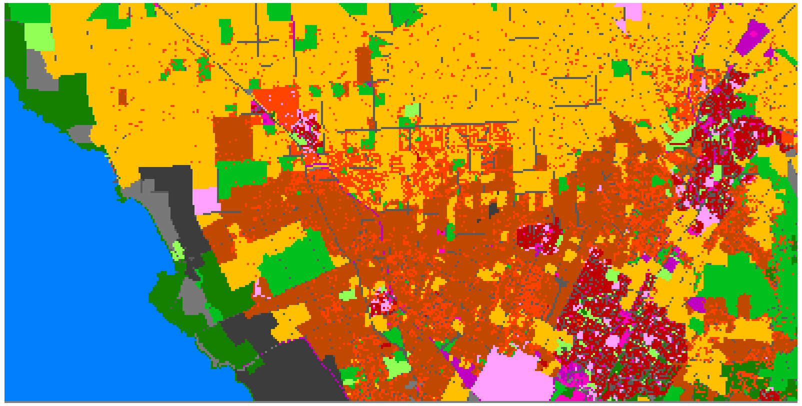

Figure C-5 2100 land use map Internet of Risk

C.3 Probability maps for residential, commercial, industry, rural residential, agriculture, and horticulture for the Business as Usual scenario

Figure C-6 Business as Usual probability maps for different land use classes from left to right

First row: Residential, Commercial, Industry

Second row: Rural Residential, Horticulture, Agriculture

C.4 Damage maps for uncertainty methods 1 and 3

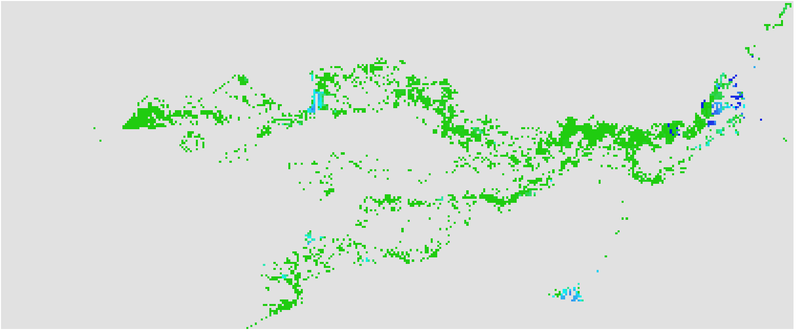

Figure C-7 Damage map Method 1 Business as Usual

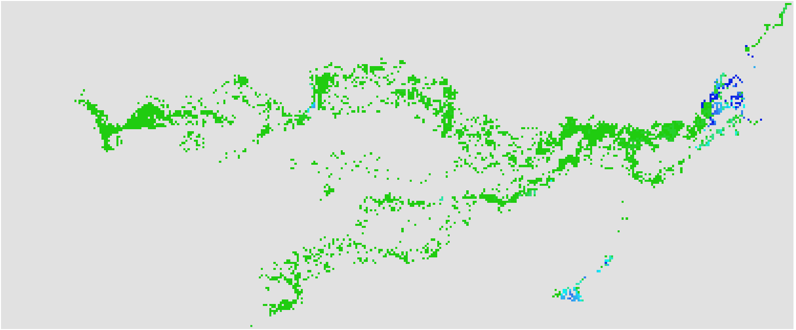

Figure C-8 Damage map Method 1 Internet of Risk

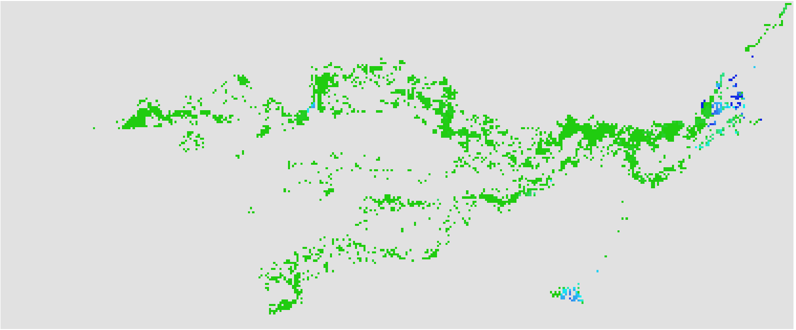

Figure C-9 Damage map Method 1 Cynical Villages

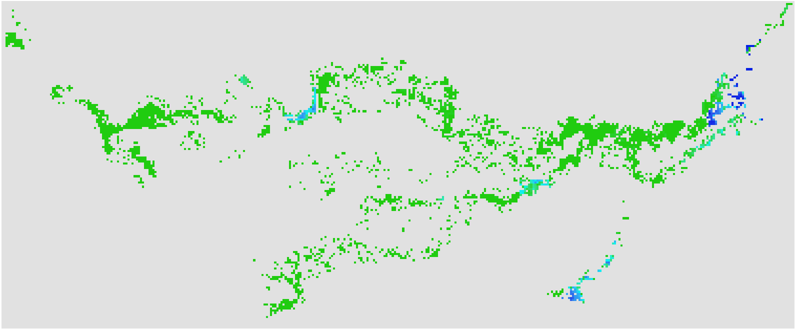

Figure C-10 Damage map Method 1 Ignorance of the Lambs

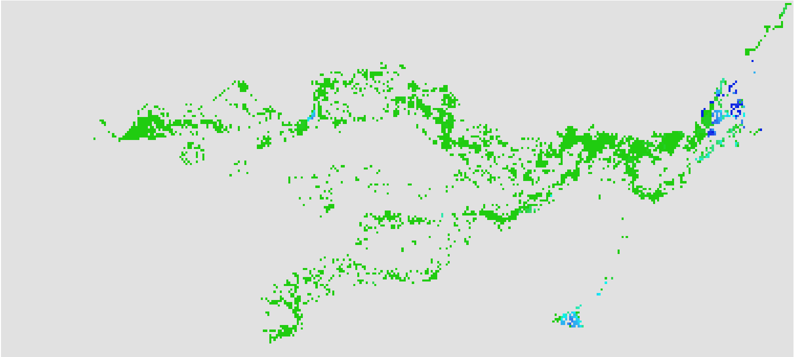

Figure C-11 Damage map Method 3 Cynical Villages

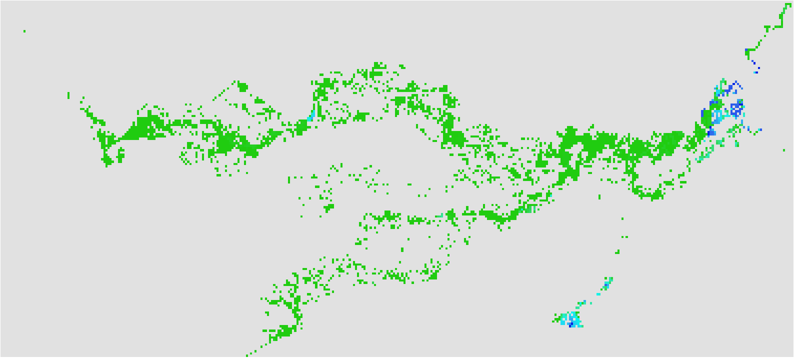

Figure C-12 Damage map Method 3 Internet of Risk

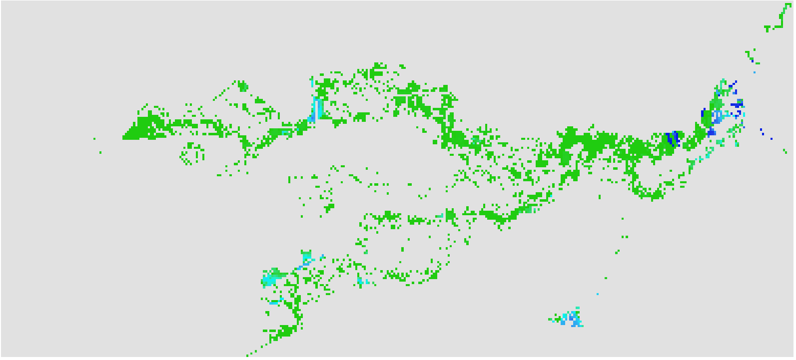

Figure C-13 Damage map Method 3 Business as Usual

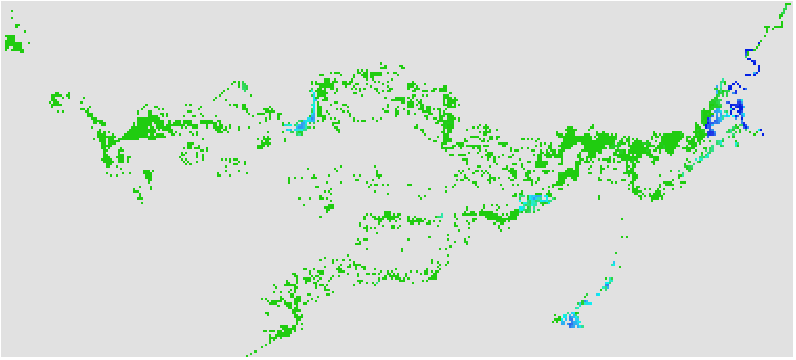

Figure C-14 Damage map Method 3 Ignorance of the Lambs

Appendix D: General additional material

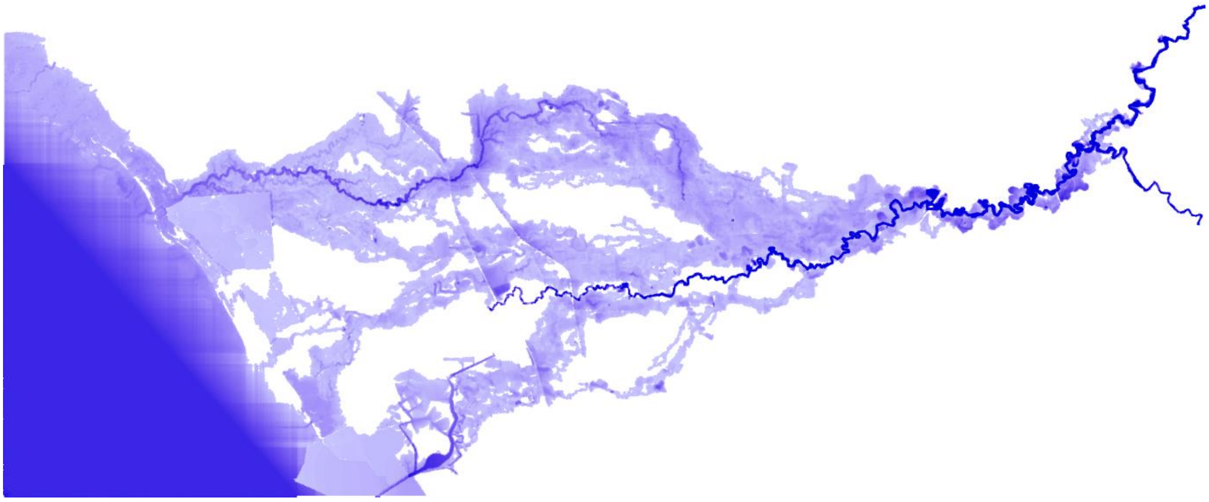

Figure D-1 Flood map result simulated by model provided by WaterTech

D.1 Flood model validation

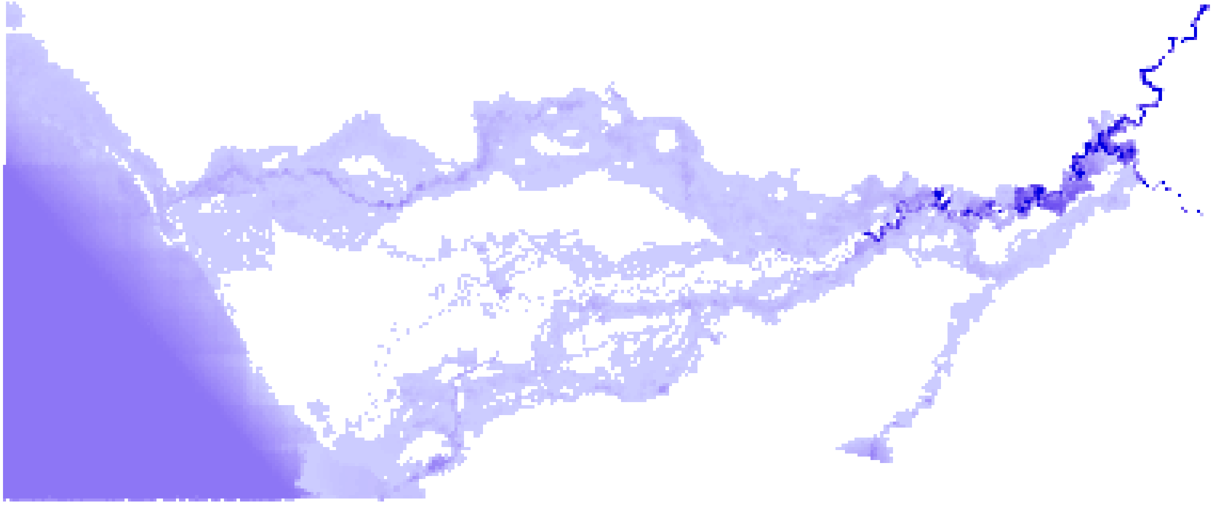

Figure D-2 Flood map result simulated by new Mike Flood model

D.2 Impact assessment

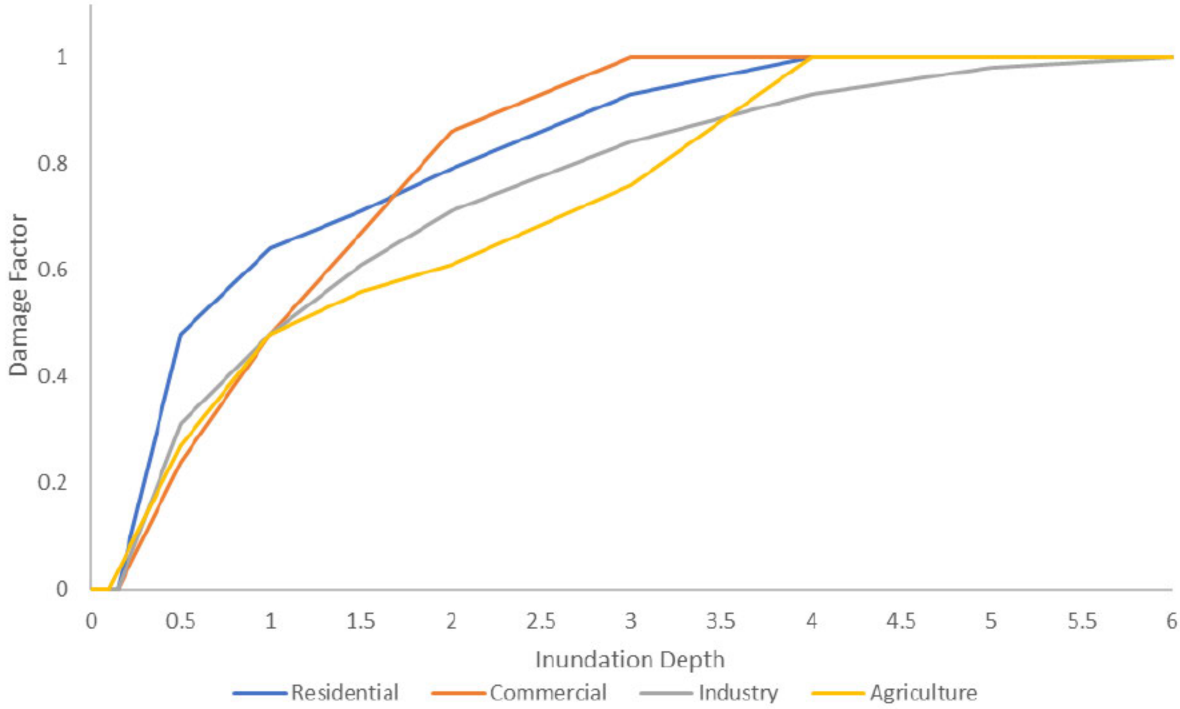

Figure D-3 Vulnerability curves used in impact assessment

Table D-1 Damage factor based on inundation depth for different land use classes

	Damage factor			
Inundation depth	Residential	Commercial	Industry	Agriculture
0	0	0	0	0
0.15	0	0	0	0
0.5	0.48	0.24	0.31	0.27
1	0.64	0.48	0.48	0.48
1.5	0.71	0.67	0.61	0.56
2	0.79	0.86	0.71	0.61
3	0.93	1	0.84	0.76
4	1	1	0.93	1
5	1	1	0.98	1
6	1	1	1	1

Table D-2 Value per land use class considered in impact assessment

	Residential	**Rural Residential**	**Commercial**	**Industry**	**Agriculture**	**Horticulture**
Value	$5,769,663	$338,349	$7,632,993	$732,208	$3,053	$24,845