Exploring coastal climate adaptation through storylines: Insights from Cyclone Idai in Beira, Mozambique

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1 Preprint statement

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2 Science for Society

Rising seas and stronger storms due to climate change pose significant threats to coastal communities. To effectively plan for adaptation against these events, local climate information is essential. Our study uses storylines — detailed narratives of potential high-impact events — to evaluate adaptation strategies based on local data. We use as case study a powerful tropical cyclone that has caused extensive damage on a coastal city and imagine how these impacts would change under multiple scenarios. Then we calculate the reductions in impacts due to different adaptation strategies. This approach empowers communities to visualise and understand the impacts of future extreme weather events and make informed decisions on how to best adapt against these events.

3 Summary

Coastal settlements, facing increasing flood risk from Tropical Cyclones (TCs) under climate change, need local and detailed climate information for effective adaptation. Analysis of historical events and their impacts provides such information. This study uses storylines to evaluate adaptation strategies, focusing on Cyclone Idai's impact on Beira, Mozambique, under different climate conditions and tidal cycles. A storyline of Idai under 3°C warming increases flood impacts by 1.8 times, while aligning Idai with spring tides amplifies these by 21 times. Combining both conditions increases impacts beyond 37 times. An adaptation strategy combining flood protection and accommodation measures reduces impacts by maximum 83%, while a seawall strategy reduces these by 10%. By offering localised, detailed information, storylines can be used to measure the effectiveness of adaptation strategies against extreme events, evaluating their robustness across different scenarios, and quantifying residual impacts, complementing traditional climate risk assessments for informed decision making.

Keywords: storylines, coastal adaptation, decision making, coastal flooding, compound events, tropical cyclones, climate change

4 Introduction

Human settlements in coastal areas around the world face significant threats from tropical cyclones (TCs) (Dullaart et al., 2021; Ranasinghe et al., 2021). TCs cause extensive floods in coastal regions through heavy precipitation and storm surges (Bevacqua et al., 2019; Gori et al., 2020; Lai et al., 2021), which lead to casualties, property damage, and on longer time scales exacerbate poverty and hinder development in affected areas (Hallegatte et al., 2016a). Climate change is expected to increase the flood hazard from TCs globally (Knutson et al., 2021; Gori et al., 2022), mainly through sea level rise (Woodruff et al., 2013; Knutson et al., 2020) and more extreme precipitation (Patricola and Wehner, 2018; Knutson et al., 2010). This increased risk is particularly severe for low-income and vulnerable regions (Winsemius et al., 2016; Jongman, 2018; Rentschler et al., 2022), where local adaptation capacities are often limited (Fankhauser and McDermott, 2014; Hallegatte et al., 2016b). Consequently, the provision of localised and actionable climate information becomes imperative to support effective coastal adaptation (Nordgren et al., 2016).

There is a gap between traditional climate sciences and decision making (Hazeleger et al., 2015; Sutton, 2019; Rodrigues and Shepherd, 2022). Traditional approaches use probabilities to estimate future climate projections. These projections carry considerable uncertainty, and may impose limitations on exploring the full range of outcomes including the less likely ones (Hazeleger et al., 2015; Shepherd, 2019; Sutton, 2019). This is further exacerbated at the local scale, where uncertainties in the climate system, but also in human and environmental aspects increase (Shepherd and Lloyd, 2021; Sobel, 2021; Lehner and Deser, 2023). Yet, at this scale extreme events, e.g., TCs, generate impacts to society, requiring adaptation strategies to be implemented at a corresponding scale (Sobel, 2021; van den Hurk et al., 2023a). Therefore, probabilistic approaches relying on future climate projections might not fully satisfy the needs for effective adaptation and decision-making at the local scale (Dessai and Hulme, 2004; Shepherd and Sobel, 2020).

An alternative approach to these probabilistic approaches is the use of event storylines (Shepherd et al., 2018). Storylines, in this context, are physically plausible narratives of an event, considering their meteorological and climatic context and societal implications, without assessing prior probabilities of the events or their drivers (Shepherd et al., 2018). The potential to analyse detailed sequential hazard-to-impact chains allows storylines to serve as a bridge between global climate projections and local scale impacts (Shepherd and Lloyd, 2021; Rodrigues and Shepherd, 2022; van den Hurk et al., 2023a). Their contribution to providing decision-oriented information is achieved by expanding a reference event with alternative realisations under explicit assumptions on all – also non-climatic – drivers of the impact, offering a clear and meaningful way to assess and communicate potential impacts under different conditions to decision makers (Shepherd and Sobel, 2020; Sillmann et al., 2020). Previous studies have adopted storylines to explore the effects of climate change for multiple impact sectors (e.g. Wiel et al., 2020; Goulart et al., 2021; Ciullo et al., 2021).

In flood modelling, risk-based approaches are commonly employed to identify flood risk and obtain cost-effective adaptation measures (de Moel and Aerts, 2011; Ward et al., 2017). However, they suffer from uncertainty in flood event probabilities (de Moel et al., 2015) and underestimate the significance of low-probability high-impact events (Merz et al., 2009). Incorporating climate change projections adds further uncertainty (McInerney et al., 2012; Haasnoot et al., 2013). Scenario-based approaches, which include storylines, offer an alternative to address the need for robust solutions amidst these uncertainties (Hall et al., 2012; Haasnoot et al., 2013; van der Pol et al., 2017). For coastal flooding, storylines were applied to efficiently stress-test flood scenarios (Qiu et al., 2022), to assess impacts from alternative flood events (Goulart et al., 2024), and to explore generic adaptation options across different regions Koks et al. (2023). However, using storylines to inform localised decision making through the integration of local adaptation strategies against specific high impact events is not yet common practice.

This study uses storylines to evaluate the effectiveness of different local adaptation strategies against a high impact event. Specifically, we investigate flood levels and societal impacts from TC Idai (2019) on the city of Beira, Mozambique. Our storylines are built using four different hydrometeorological scenarios (Figure 1), including climate change effects on precipitation and sea level rise, and changes in the timing of the storm relative to tidal cycles. We consider three local coastal adaptation strategies reflecting different approaches to flood protection. Our modelling framework spans the event's meteorological conditions, compound flooding using a hydrodynamic model, and the flood impacts on Beira, specifically population exposure and building damage via an object-based impact model (details for all steps in experimental procedures).

5 Results

5.1 Flood impacts from Idai in Beira substantially increase with climate change and spring tides

We evaluate the hazards and impacts of TC Idai in Beira for four hydrometeorological scenarios. Idai, one of the strongest storms ever recorded in Southern Africa, caused extensive damage in Beira, Mozambique in 2019 (see Experimental Procedures for more details). In the hydrometeorological Baseline scenario, which reflects the historic event, widespread compound coastal flooding occurs in Beira and specifically along its west coast (Figure 2a). Idai originally made landfall during neap tides, and having the storm coincide with spring tides – the Springtide scenario – leads to a substantially larger inundation extent and depth (Figure 2b). A 3°C climate change by 2100 (3C scenario) leads to an increase in flood extent and depth through precipitation increase and sea level rise (Figure 2c). The 3C scenario shows smaller flood increases compared to the Springtide scenario. This is because sea level rise in 3C scenario leads to lower increase in water levels (0.59 m) than the tidal effect in the Springtide scenario (1.24 m difference between neap and spring tides). Ultimately, the combination of these two scenarios (3C-springtide) leads to the largest flood extent and depth, with most of the study area experiencing flooding (Figure 2d).

We quantify the flood impacts of Idai in Beira in terms of population exposure and building damage. Our results show that approximately 5,000 people are exposed to water depths >15 cm in the Baseline scenario (Figure 3). The Springtide scenario indicates approximately 103,000 people are exposed (20x the Baseline), which is substantially more than the 9,400 exposed

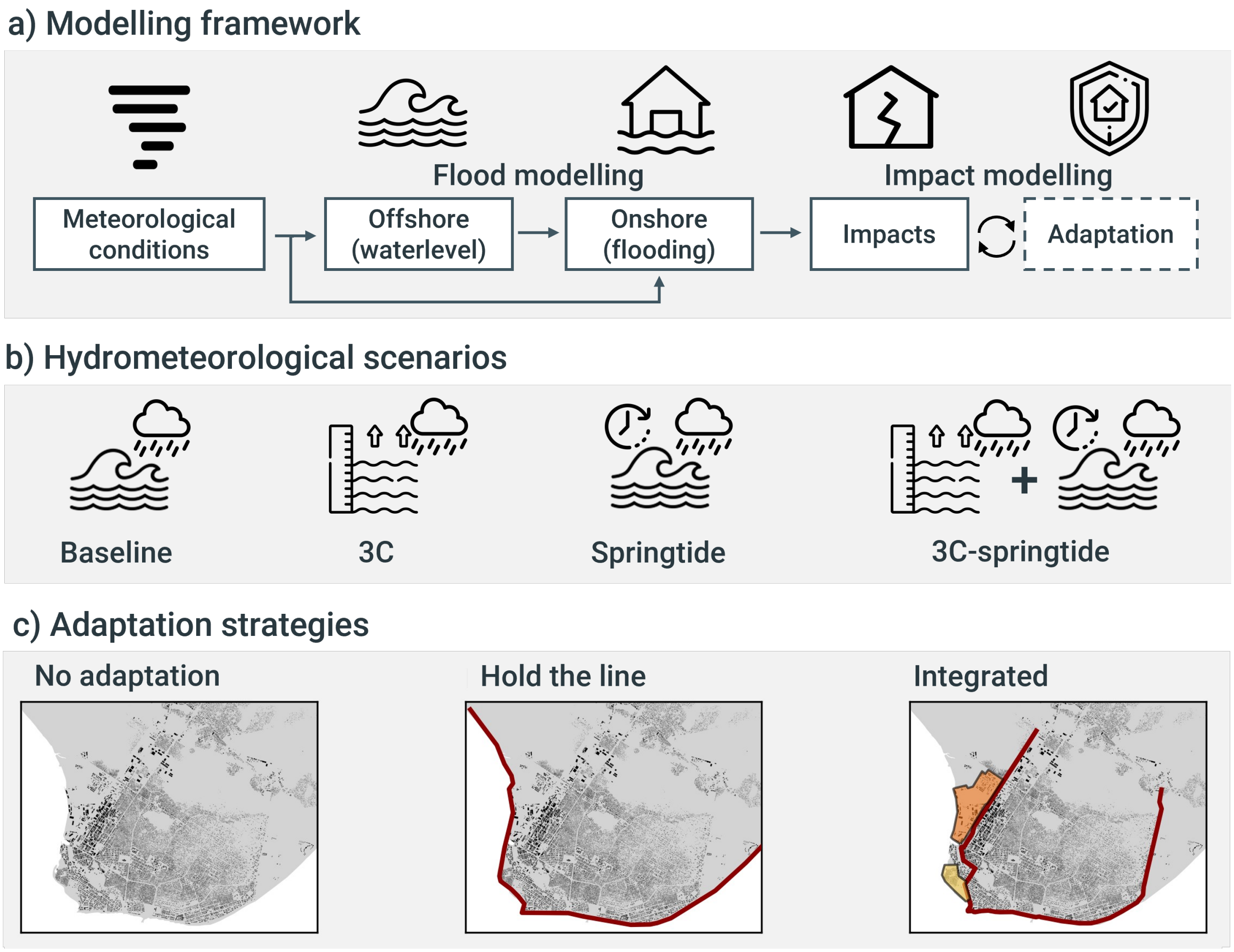

Figure 1. General framework of the study. a) The modelling framework connecting meteorological conditions, such as wind speed and precipitation, to compound flood and impact. b) The four hydrometeorological scenarios considered: Baseline, 3C, Springtide, and 3C-springtide. c) The three adaptation strategies for the city of Beira: no adaptation, Hold the Line, and Integrated strategies. The red lines indicate walls and dikes; the orange polygon indicates the port region to be elevated, and the yellow polygon indicate the coastal area to retreat from (see Experimental procedures for details).

people in the 3C scenario (1.8x the Baseline). The 3C-springtide scenario leads to the highest number of people exposed, around 194,000 (37x the Baseline). In addition to changes in flood extent, a noticeable shift towards higher flood levels for more extreme events is shown (colours in Figure 3). Fraction of people exposed to high flood levels, representing depths above 150 cm, go from 1.6% of the exposed population in the Baseline scenario to 14.5% on the 3C-springtide scenario. Concluding,

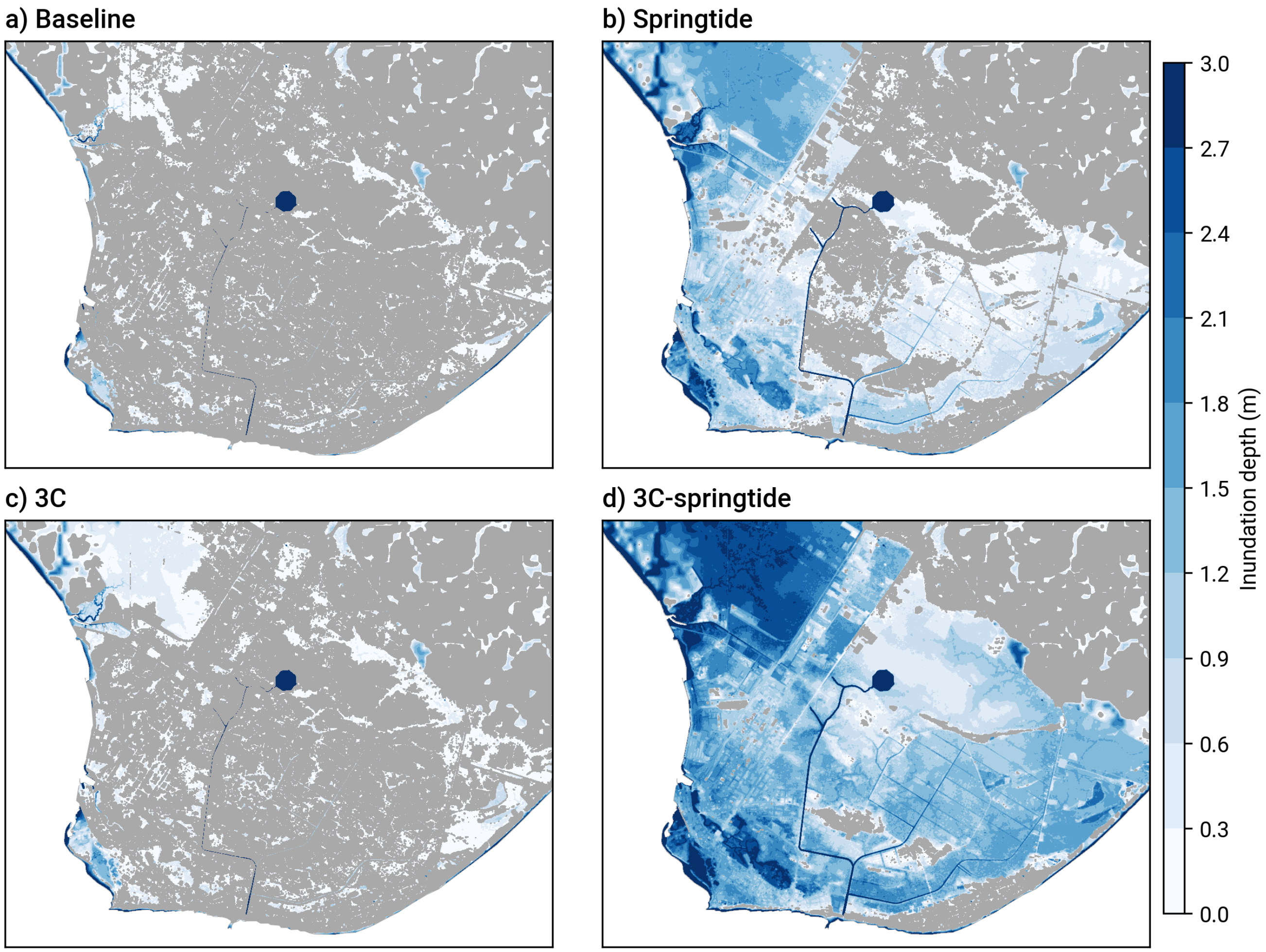

Figure 2. Flood maps of Idai in Beira. Flood hazard maps of TC Idai under different hydrometeorological scenarios. Different shades of blue indicate flood depth. Note the blue circle in the centre is a small lake within the city bounds.

the more extreme the hydrometeorological scenario of Idai, the more people are directly exposed, and their exposure is to increasingly severe hazards.

Economic damage shows similar patterns to population exposure (Figure 3b). The Baseline scenario indicates damages of USD 2.73 million in Beira. The Springtide scenario presents damages of USD 61 million, an increase of 22x the Baseline, and more than the damages in the 3C scenario, USD 4.6 million (1.7x the Baseline). As a consequence of both spring tides and 3C climate scenario, the 3C-springtide peaks at USD 152 million, which is 56x the Baseline, showing non-linear compounding effects. Damage maps at the building level show spatial details on the impacts in Beira (Figure 4) and reveal that informal settlements suffer significantly, with numerous cases of total losses in more extreme scenarios.

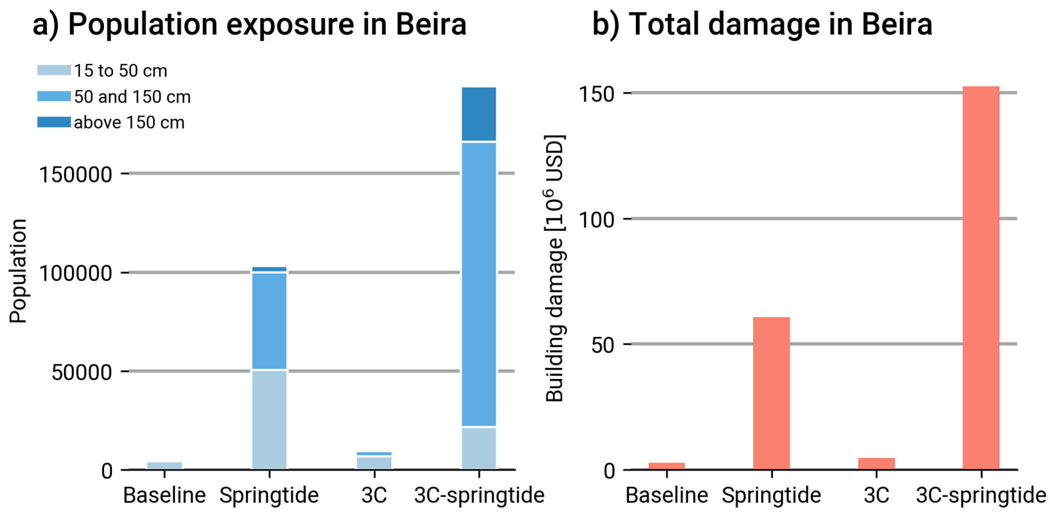

Figure 3. Impacts of Idai in Beira. a) Total population exposure and b) total building damage in the city of Beira from Idai floodings under different hydrometeorological scenarios. Light blue indicates water level between 15 and 50cm, medium blue 50 and 150cm, and dark blue above 150cm.

5.2 The Integrated strategy reduces flood impacts more than the Hold the Line strategy

We assess how effectively each adaptation strategy (described in detail in Experimental procedures) performs across the hydrometeorological scenarios (Figure 5). In the Baseline scenario, the Hold the Line strategy, consisting of an extensive seawall along the coast of Beira, reduces population exposure and building damage by approximately 11% and 7.6%, respectively. The Integrated strategy, including dikes around the city centre, port elevation and managed retreat of wetlands, reduces population exposure and damage by 2% and 9.5%, respectively. However, for the counterfactual scenarios, the Integrated strategy consistently outperforms the Hold the Line strategy in reducing population exposure: for the Springtide, 3C, and 3C-springtide scenarios, exposure reductions are 83%, 8%, and 75%, respectively, versus reductions of 9%, 0.3%, and 3.4% with the Hold the Line strategy (Figure 5a). Consequently, we observe a greater decrease in exposure to high water levels with the Integrated strategy compared to the Hold the Line strategy (Figure SI A1). Economic damage follows a similar trend, with the Integrated strategy reducing damages by 84%, 30%, and 81% for the Springtide, 3C and 3C-springtide scenarios, respectively. The Hold the Line strategy shows lower reductions of 10%, 0.7%, and 7.4% (Figure 5b). While none of the included adaptation strategies completely protects Beira from the impacts from Idai across our tested scenarios, the Integrated strategy proves more effective than the Hold the Line in reducing building damage and population exposed, especially for the more extreme hydrometeorological scenarios. These results offer insights on the effectiveness of each adaptation strategy across different scenarios and on the corresponding residual impacts in Beira (Figure 5c,d).

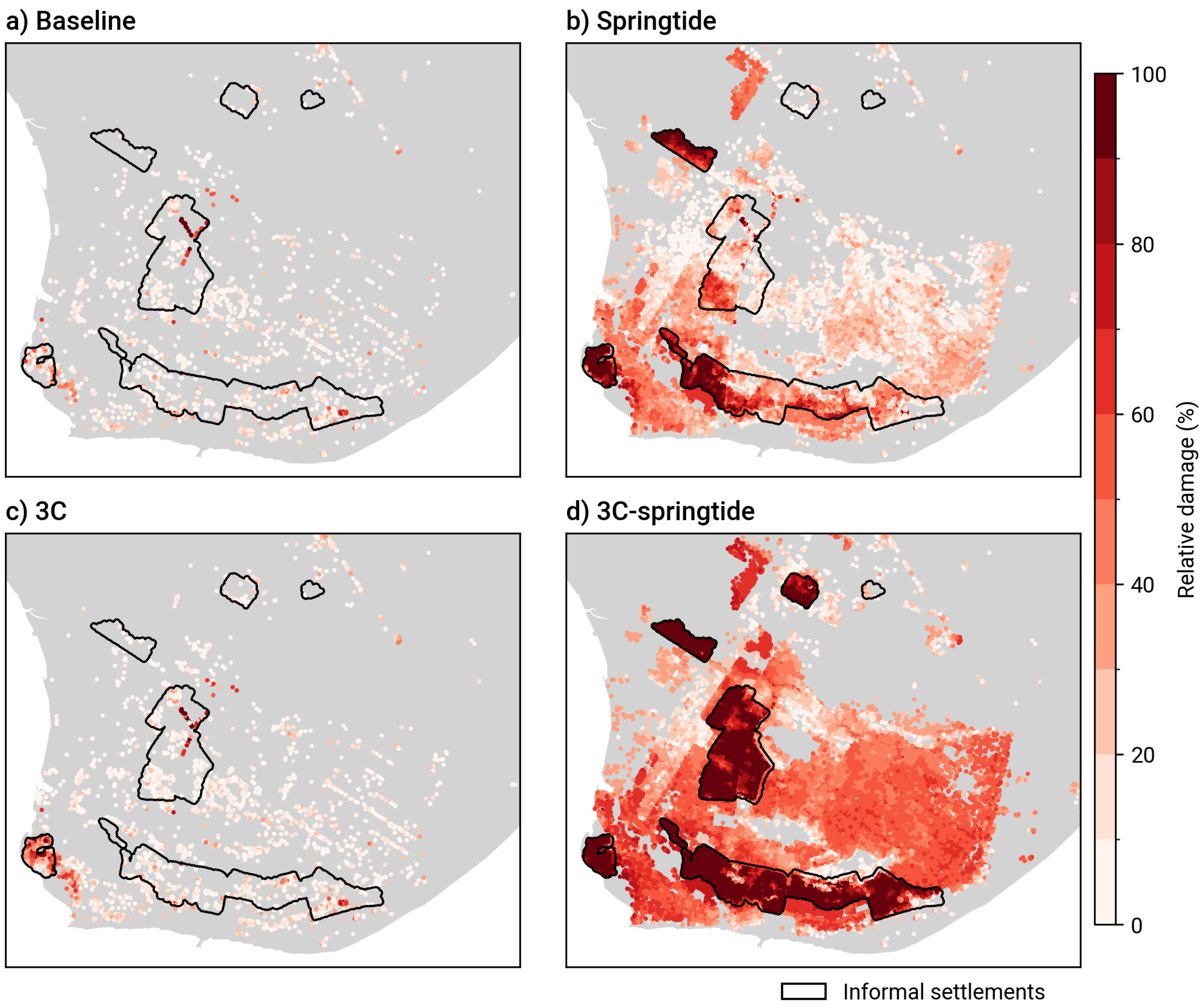

Figure 4. Damage maps of Beira. Maps of Beira showing relative economic damage relative to the total value of each building in Beira for each hydrometeorological scenarios. Black contours indicate informal settlements.

6 Discussion

Our study develops storylines of Idai to assess the effectiveness of different local coastal adaptation strategies under diverse hydrometeorological scenarios. These include the effects of climate change, sea level rise, and changes in the tidal cycle. We use a comprehensive modelling framework that includes the event's meteorological conditions, compound flood simulation, and the modelling of population exposure and building damage.

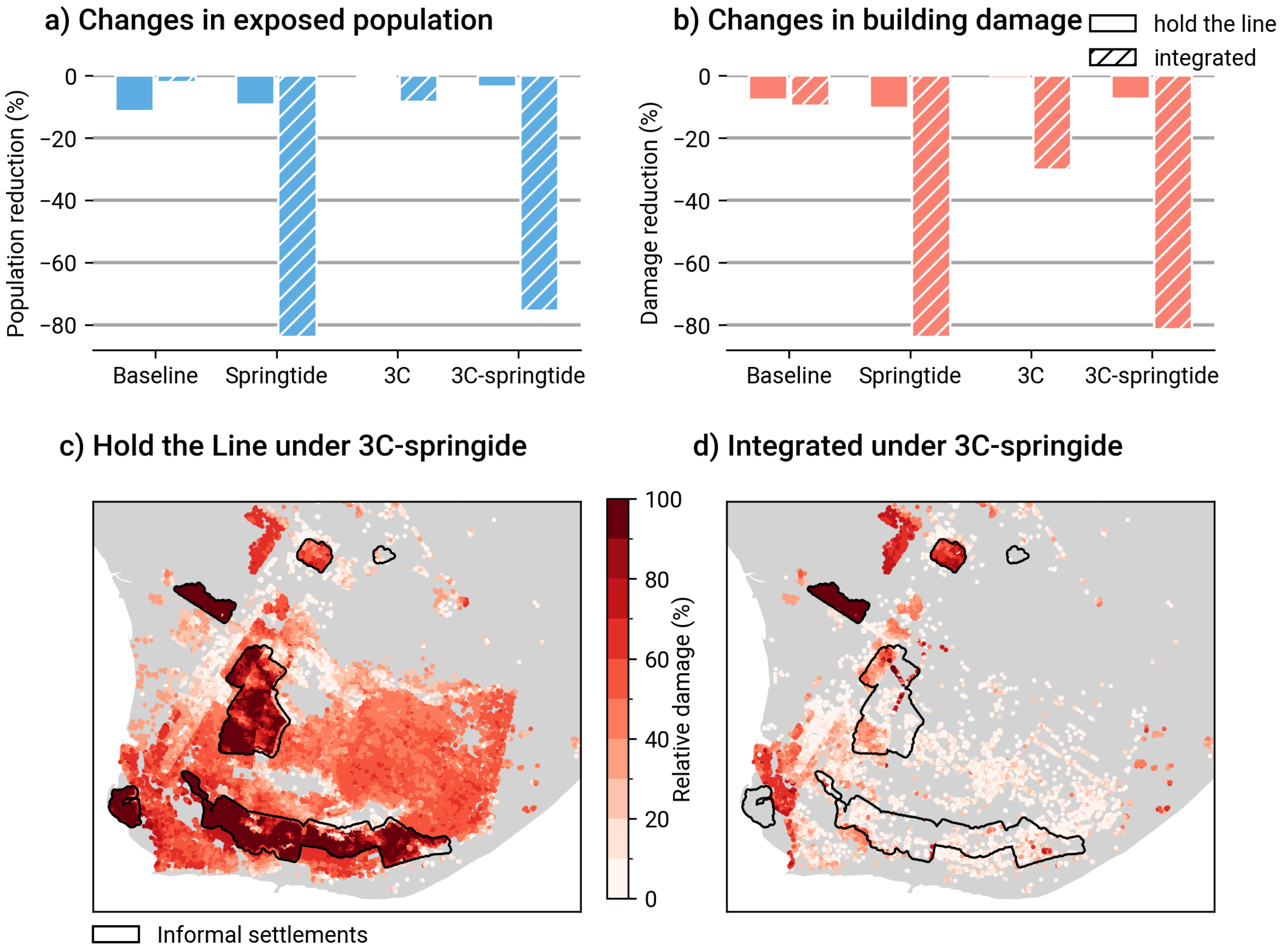

Figure 5. Effectiveness of adaptation strategies. Reductions in a) population exposure and b) building damage for each adaptation strategy and hydrometeorological scenario. Plain bars represent Hold the Line strategy and hatched bars represent integrated strategy. Maps of relative building damage for c) the Hold the Line and d) Integrated strategies under the 3C-springtide scenario. Black contours show informal settlements.

6.1 Insights of using storylines for coastal adaptation in Beira

Our results show that flood impacts in Beira will likely worsen due to climate change, primarily driven by sea level rise. These findings align with existing research showing the threat of rising sea levels to coastal settlements (Hallegatte et al., 2013; Hinkel et al., 2018). We find that a shift in TC Idai's timing to coincide with spring tides could lead to even more severe flooding. This is because the difference in surge height between neap tide and spring tide is more than double the projected SLR by 2100 in a 3°C warming scenario. Our most impactful storyline of Idai is the combination of both climate change and spring tides, showing again the strong negative effects of climate change for Beira and its inhabitants. In addition, it shows that climate change is one of multiple contributing factors to impacts, as explored here by altering the compound timing of storm landfall and the tidal cycle. This change in timing demonstrates the large range of impacts of local extreme events due to internal variability (Done et al., 2014; Goulart et al., 2023; Lehner and Deser, 2023). Our results highlight the importance of incorporating internal variability next to the role of climate change in adaptation planning (Hinkel et al., 2014; Haasnoot et al., 2020; Herman et al., 2020).

The scope of our study diverges from existing risk-based studies for Beira, such as Eilander et al. (2023b) and van Berchum et al. (2020). Risk-based studies are able to quantify expected annual flood impacts based on probabilities and to determine cost-effective solutions. However, they may not fully account for the complexities of extreme weather events (de Moel et al., 2015; Merz et al., 2009) and climate change uncertainties (McInerney et al., 2012; Haasnoot et al., 2013). While Eilander et al. (2023b) identified managed retreat in highly exposed areas of Beira as the most efficient to reduce expected annual impacts, van Berchum et al. (2020) suggest coastal defences are the most effective long-term measure. Our approach shift focus from estimating the most optimal or cost-effective measures to assessing the performance of specified local adaptation strategies under different scenarios. We find that no strategy fully prevents flooding in Beira from Cyclone Idai, but that the Integrated strategy substantially outperforms the Hold the Line approach in more extreme scenarios. The wide range of impacts across scenarios and strategies in our results enable policymakers and stakeholders to visualise the benefits and limitations of different adaptation strategies when faced with extreme events similar to Cyclone Idai under different scenarios. This includes assessing the robustness of each adaptation strategy against the selected events (Hall et al., 2012; van der Pol et al., 2017) and quantifying residual impacts (Lim et al., 2018; Tanoue et al., 2021), which can inform the planning of complementary measures like evacuation plans or financial aid programs (van den Hurk et al., 2023b).

6.2 Validation of simulations, limitations, and recommendations

Our Baseline simulations show more extensive inundation than satellite imagery from the Emergency Management Service (EMS) has shown for Idai landfall in Beira (Copernicus Emergency Management Service, 2019). Satellite imagery has limitations in densely populated areas (Fang Zhang and Liu, 2014). Mester et al. (2023) found this to be the case for Cyclone Idai's impact on Beira, as satellite imagery showed substantially less flooded areas than what has been documented in reports and media (Segerlin et al., 2020). Another study showed that a combined 10-year rainfall and 10-year coastal surge event causes more extensive flooding in Beira than the satellite images (van Berchum et al., 2020), and TC Idai is considered to have a lower probability than once per 10 years (Emerton et al., 2020). Given the uncertainty around the actual flooding extent induced by Idai and our focus on exploring differences between the storylines, we consider the simulated data suitable for this study's purpose.

This study focuses on the physical aspects of climate change, without incorporating socio-economic or land use changes, which greatly influence vulnerability and exposure, and therefore impacts (Koks et al., 2023). Exploring these and other relevant drivers of local change could lead to a more comprehensive impact analysis of future scenarios and adaptation strategies. In this study, we have used "robustness" to refer to how well an adaptation strategy performs across a variety of scenarios (Hall et al., 2012; Haasnoot et al., 2013; van der Pol et al., 2017). Our focus on Cyclone Idai, despite varying scenarios, implies only one type of event is being examined. Future studies applying storylines for robust adaptation could consider multiple extreme events with different characteristics, e.g. a precipitation-dominated flood event.

We adopt three adaptation strategies in our study, but future work could evaluate a broader range of potential adaptation options for the study area, such as drainage systems, nature-based solutions, and evacuation plans. Our adaptation strategy designs are based on recommendations for the city of Beira from local sources (Van Logchem and Queface, 2012). Some adaptation measures, like the managed retreat included in the Integrated strategy, carry considerable social implications (Bongarts Lebbe et al., 2021; Hino et al., 2017; Gussmann and Hinkel, 2021). The findings in this study are mostly exploratory, and actual adaptation could emerge from collaborative efforts directly involving the communities and stakeholders impacted(Bongarts Lebbe et al., 2021). Our analysis focuses solely on building damage and population exposure. Future work could broaden this scope to include indirect effects, such as interrupted services and economic disruption due to supply shortages (Pant et al., 2018; Tanoue et al., 2020)

6.3 Storylines for decision making on adaptation

To effectively support local adaption and decision making, climate information needs to be usable, relevant and local (Sutton, 2019; Sobel, 2021; Rodrigues and Shepherd, 2022). Our study extends the storyline approach to include adaptation strategies specifically designed for local scale decision making. In this way, they enable stakeholders to visualise the consequences of specific local adaptation measures against high-impact events across relevant possible futures (“what if” scenarios). Consequently, they provide a practical method for quantifying the effectiveness of adaptation strategies under different scenarios, facilitating the identification of robust adaptation strategies. Finally, they can also be used to quantify residual impacts, which supports the planning of complementary adaptation measures, including early warning systems and evacuation plans (van den Hurk et al., 2023b), and post-disaster recovery mechanisms such as insurance schemes (Kousky, 2019). We find that, by including specific adaptation strategies to local contexts, storylines offer a complementary perspective to traditional probabilistic approaches for informing climate adaptation strategies against high impact events.

7 Experimental procedures

7.1 Resource availability

7.1.1 Lead contact

Further information and requests for resources and reagents should be directed to and will be fulfilled by the lead contact, Henrique M. D. Goulart (henrique.goulart@deltares.nl).

7.1.2 Materials availability

This study did not generate new unique materials.

7.1.3 Data and code availability

The code and data generated for this experiment is available at: https://github.com/dumontgoulart/storylines_for_adaptation. SFINCS is available at https://sfincs.readthedocs.io and HydroMT is available at https://deltares.github.io/hydromt/. Delft-FIAT is available at https://github.com/Deltares/Delft-FIAT.

7.2 Overview

Our storylines explore two components of the event and its impacts: the meteorological hazard and adaptation strategies in the city of Beira (Figure 1). We have developed a modelling framework that captures meteorology, coastal flooding and societal impacts (economic damage to buildings and exposed population) (Figure 1). Based on four distinct meteorological/hydrometeorological scenarios and three local adaptation strategies, we develop twelve unique storylines. They enable an exploration of the potential impacts of TC Idai on the city of Beira, and the effectiveness of different adaptation strategies in reducing these impacts.

7.3 Case study

We explore the impacts of TC Idai on the city of Beira, Mozambique. TC Idai was one of the most impactful TCs to occur in Southern Africa, affecting mainly Mozambique, Zimbabwe, and Malawi. In Mozambique, 598 casualties were reported, and a further 1600 people were reported injured. Furthermore, it caused damage or complete destruction to nearly 198,000 homes, decimated crop fields, triggered a cholera epidemic, and left an estimated 1.85 million people affected (UN Office for the Coordination of Humanitarian Affairs, 2019).

TC Idai originated off the East coast of Mozambique on March 4, 2019, and it briefly reached Category 4 with peak wind speeds of 59 m/s (Dube et al., 2021). Idai made landfall twice, with the second one being March 14 near Beira city, the fourth largest city in Mozambique (Figure 6). The region experienced severe impacts mainly from extreme wind speeds and compound coastal flooding, driven by intense precipitation and the storm surge. Though storm surge levels in Beira reached approximately 4 m, the event coincided with a neap tide period which had a limiting effect on water levels (van Berchum et al., 2020; Eilander et al., 2023b).

7.4 Hydrometeorological scenarios

The Idai storylines are built based on hydrometeorological scenarios designed to explore both the influence of internal variability and climate change around the event. We consider four scenarios:

- the **Baseline** scenario reflects the event as it occurred in 2019. Note that also in this scenario there is some climate change component: global temperatures lie at 1.2 °C above pre-industrial levels, and there is a sea level rise (SLR) of 5 cm relative to the 1995-2014 average.

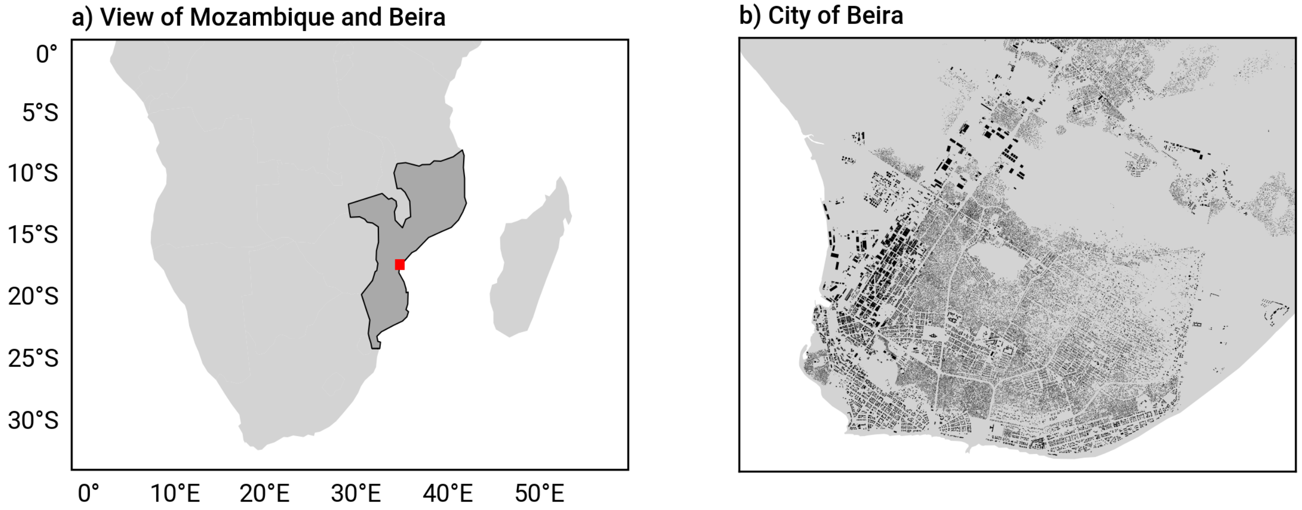

Figure 6. Location of Mozambique and Beira. a) The location of Mozambique (dark gray) and the city of Beira (red square). b) Expanded view of Beira with buildings footprints (black polygons).

- the **Springtide** scenario, a counterfactual scenario that simulates TC Idai occurring in conjunction with spring tides. This introduces an element of internal variability, reflecting natural fluctuations in environmental conditions that can significantly influence local flooding. It involves adjusting the timing of Idai by four days to coincide with the spring tides, while maintaining climatological conditions identical to the baseline.
- the **3C** scenario, a future counterfactual scenario assuming a global temperature rise of 3°C above pre-industrial levels by 2100. This scenario includes a SLR of 0.59 m and a precipitation increase of 13 % compared to the baseline. This scenario aligns with the global warming projections of 3.2°C by 2100 based on current Nationally Determined Contributions (NDCs) (IPCC, 2023).
- the **3C-springtide** scenario, a compound scenario that combines the springtide event with the future 3°C global warming condition.

SLR data was derived from the sixth assessment report (AR6) from the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2021). We calculate the change in precipitation in a warmer climate using the Clausius-Clapeyron (CC) relation, which establishes a 7 % increase in saturation vapour pressure for each degree of warming. This is in line with findings from recent studies on the increase of precipitation rates of TCs due to climate change in the southern Indian Ocean (Liu et al., 2019; Knutson et al., 2020).

7.5 Adaptation strategies

This study assesses the effectiveness of three local coastal adaptation strategies in Beira city. They are based on previous local reports (Van Logchem and Queface, 2012) and designed to provide a clear comparison between distinct approaches to reduce the societal impacts of the Idai event:

- **No adaptation** strategy, where no further protective measures are adopted.
- **Hold the Line** strategy (Figure 1), focused on protecting the entire land area through the construction of hard infrastructure along the coastline Bongarts Lebbe et al. (2021). Here, it consists of a 2 m wall along the Beira coastline.
- **Integrated** strategy (Figure 1), which combines infrastructure with management and accommodation measures (Bongarts Lebbe et al., 2021; IPCC, 2022). In this study, it consists of a 2 m wall along part of the coast and around the centre of the city, a managed retreat of settlements from the vulnerable coastal wetlands in the city's southwest, and raising the port's elevation by 2 m.

The 2 m height adopted for seawalls and port elevation is based on the 100-year return period surge projections for the region, as identified in Eilander et al. (2023b). All measures, including the managed retreats, are based on recommendations from a local report by the Maputo National Institute for Disaster Management (INGC) (Van Logchem and Queface, 2012). Managed retreats carry societal implications, which requires careful planning and stakeholder involvement Bongarts Lebbe et al. (2021).

7.6 Modelling framework

7.6.1 Meteorological data and evaluation

Idai meteorological data for mean sea level pressure (MSLP), wind speed and precipitation is obtained from the high resolution Integrated Forecast System (IFS) model of the European Centre for Medium-Range Weather Forecasts (ECMWF). It is based on a coupled atmosphere–wave–ocean model (Mogensen et al., 2017), has hourly temporal resolution, and offers the highest spatial resolution among global forecasts, 0.1°, which improves TC simulation (Knutson et al., 2020; Magnusson et al., 2019; Zhang et al., 2023). Previous studies have assessed the capabilities, advancements, and limitations of IFS in simulating TCs (Mogensen et al., 2017; Magnusson et al., 2019; Heming et al., 2019; Becker et al., 2021; Christophersen et al., 2022).

There is limited observation data for TC Idai and its impacts in Beira (van Berchum et al., 2020; Mester et al., 2023). We adopt the International Best Track Archive for Climate Stewardship (IBTrACS) (Knapp et al., 2010) to evaluate the IFS-simulated minimum MSLP and maximum wind speeds, and the Integrated Multi-satellitE Retrievals for GPM (IMERG-GPM) (Huffman et al., 2015) for precipitation. Subsequently, we align the values from IFS with observed values, so that floods and impacts in Beira are more accurately simulated. This involves adjusting the model's mean values around the storm's centre during its landfall between March 14th and 15th to match the evaluation data.

7.6.2 Compound coastal flooding modelling

We use the Super-Fast INundation of CoastS (SFINCS) model (Leijnse et al., 2021) for both offshore and onshore hydrodynamic simulation. SFINCS is a reduced-physics solver that accurately simulates compound coastal flooding by solving simplified two-dimensional overland flow equations. Its suitability for simulating compound flooding resulting from TCs has been demonstrated in previous studies (Leijnse et al., 2021; Sebastian et al., 2021; Eilander et al., 2023b; Goulart et al., 2024; Nederhoff et al., 2024). A full description of the model is available at Leijnse et al. (2021). The offshore simulation is forced with MSLP and wind speed data from IFS, generating water levels along the coastline of Beira. The onshore simulation is then forced with the generated water levels and precipitation to produce inland flooding levels in Beira. The surface elevation is obtained from a merged dataset that combines several local and global datasets, achieving a 5 m resolution in Beira (Nederhoff et al., 2024). The roughness coefficients are sourced from the Copernicus Global Land Service (Buchhorn et al., 2020) and infiltration rates derived from the GCN250 dataset (Jaafar et al., 2019). For the management and processing of input data, we use the Python package HydroMT (Eilander et al., 2023a).

7.6.3 Impact modelling

We use the Delft-FIAT impact model (Slager et al., 2016; Eilander et al., 2023b) to quantify building damages and the population exposed to floods under the different storylines. Delft-FIAT combines flood extent and depths with exposure and vulnerability data, enabling impact modelling at the individual building level. For building exposure, including location and footprint, we use data from OpenStreetMap (Haklay and Weber, 2008). Population data from WorldPop 2020 UN adjusted database at 100 m resolution (Bondarenko et al., 2020) is downscaled to the building level by using the buildings footprints size as weights. Vulnerability curves to estimate the economic damages due to flooding for different types of building are obtained from Huizinga et al. (2017).

Appendix A: Supplemental information

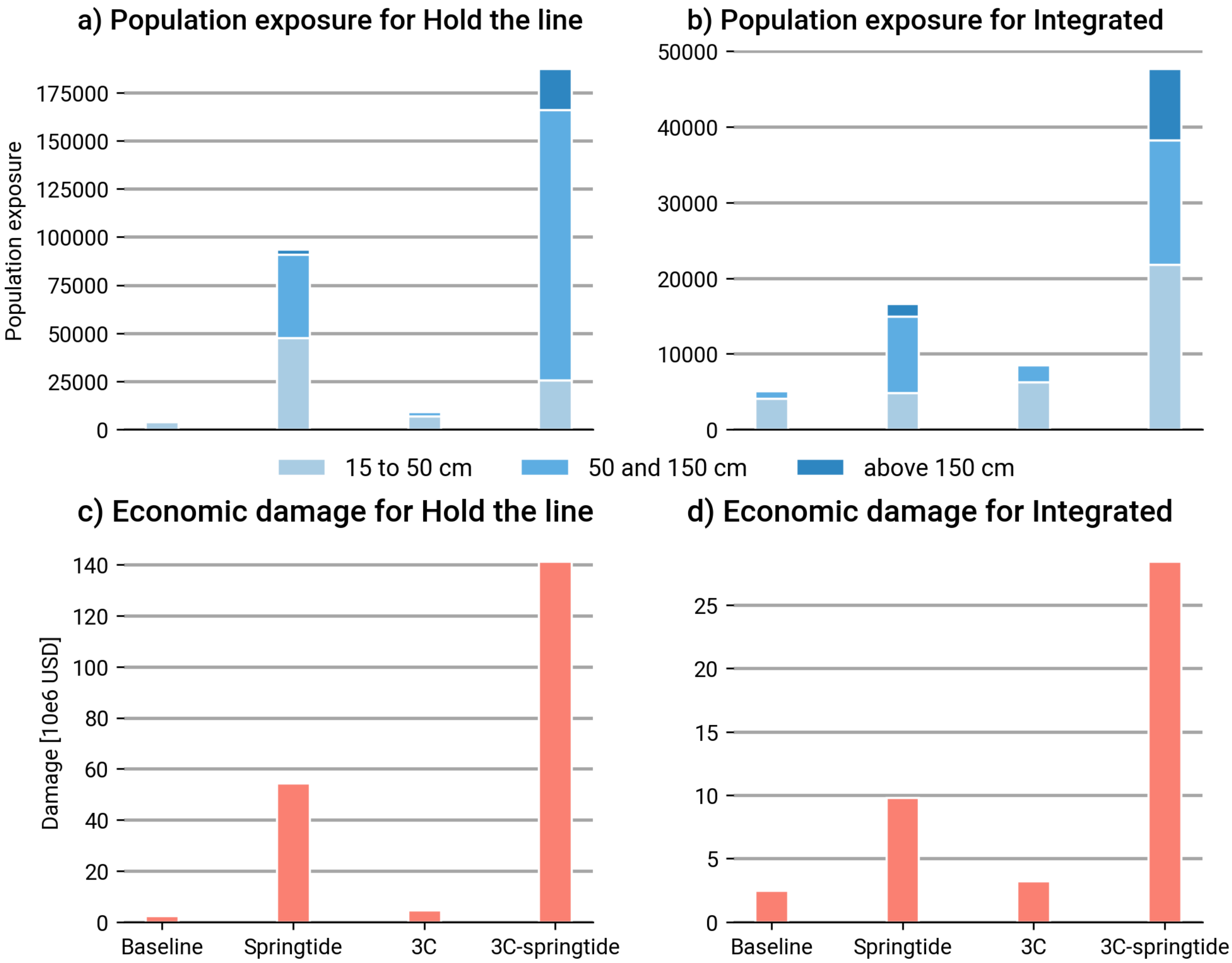

Figure A1. Impacts in Beira with different adaptation strategies. Similar to Figure 3 but showing residual impact for each adaptation strategy.

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Author contributions. HG, KvdW and BvdH contributed to the concept of the study. HG conducted the research and edited the manuscript. HG, IP and KvdW obtained and evaluated the meteorological data. KvG, HG and IP designed and implemented adaptation strategies. HG, PA, GW set up the hydrodynamic and impact models. All authors discussed the analysis and results, and revised the manuscript. BvdH and KvdW supervised the work.

Competing interests. The authors declare that they have no competing interests.

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