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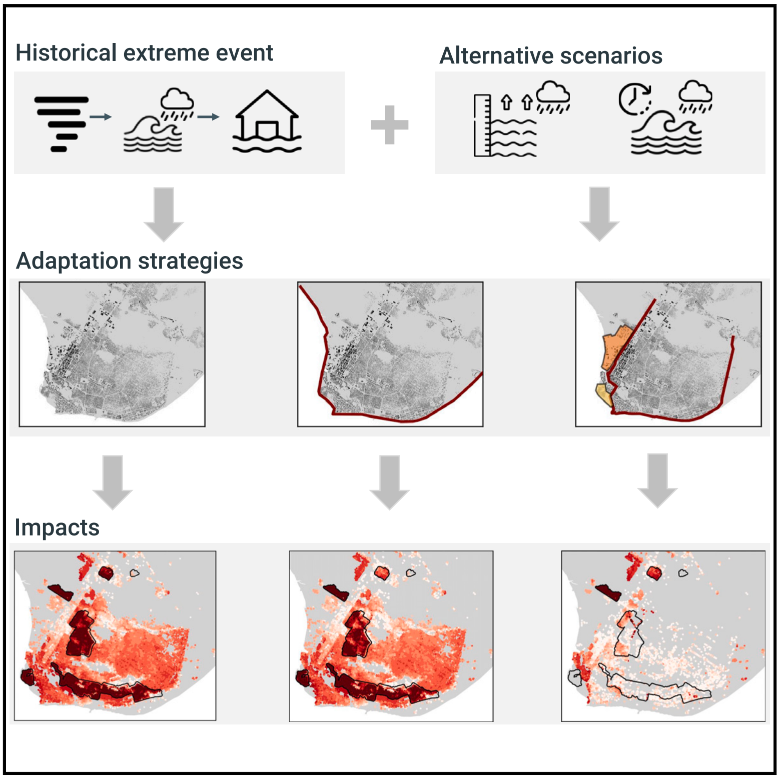
Exploring coastal climate adaptation through storylines: Insights from cyclone Idai in Beira, Mozambique

Graphical abstract



Highlights

- An approach that combines storylines with local adaptation strategies
- Climate change and spring tides amplify impacts of Idai up to 37 times
- Certain climate adaptation strategies reduce future impacts by 83%
- Storylines support decision-making by exploring adaptation under extreme scenarios

Authors

Henrique M.D. Goulart,
Panagiotis Athanasiou, Kees van Ginkel,
Karin van der Wiel, Gundula Winter,
Izidine Pinto, Bart van den Hurk

Correspondence

henrique.goulart@deltares.nl

In brief

Goulart et al. explore the effectiveness of storylines in evaluating adaptation strategies for extreme climate events. They highlight how these narrative-based approaches can complement traditional climate risk assessments by showcasing the consequences of each adaptation strategy selected, quantifying residual impacts and testing robustness across different scenarios. This research offers insights for policymakers and communities, emphasizing the importance of integrating narrative approaches in climate adaptation planning to make informed decisions that better protect communities.

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

Henrique M.D. Goulart,[1,2,4,*] Panagiotis Athanasiou,[1] Kees van Ginkel,[1,2] Karin van der Wiel,[3] Gundula Winter,[1] Izidine Pinto,[3] and Bart van den Hurk[1,2]

[1]Deltares, Delft, the Netherlands

[2]Institute for Environmental Studies, VU University Amsterdam, Amsterdam, the Netherlands

[3]Royal Netherlands Meteorological Institute (KNMI), De Bilt, the Netherlands

[4]Lead contact

*Correspondence: henrique.goulart@deltares.nl

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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 cyclone Idai in Beira, Mozambique, as a case study of a powerful cyclone that has caused extensive damage to 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. We find that climate change and higher tides greatly increase Idai's impacts. The effectiveness of the adaptation strategies considered varies considerably, with some significantly reducing impacts. This approach empowers communities to visualize and understand the impacts of future extreme weather events and make informed decisions on how to best adapt against these events.

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 localized, 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.

INTRODUCTION

Human settlements in coastal areas around the world face significant threats from tropical cyclones (TCs).[1,2] TCs cause extensive floods in coastal regions through heavy precipitation and storm surges,[3–5] which lead to casualties, property damage, and on longer timescales exacerbate poverty and hinder development in affected areas.[6] Climate change is expected to increase the flood hazard from TCs globally,[7,8] mainly through sea-level rise (SLR)[9,10] and more extreme precipitation.[11,12] This increased risk is particularly severe for low-income and vulnerable regions,[13–15] where local adaptation capacities are often limited.[16,17] Consequently, the provision of localized and actionable climate information becomes imperative to support effective coastal adaptation.[18]

There is a gap between traditional climate sciences and decision-making.[19–21] 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.[19,20,22] This is further exacerbated at the local scale, where uncertainties in the climate system, but also in human and

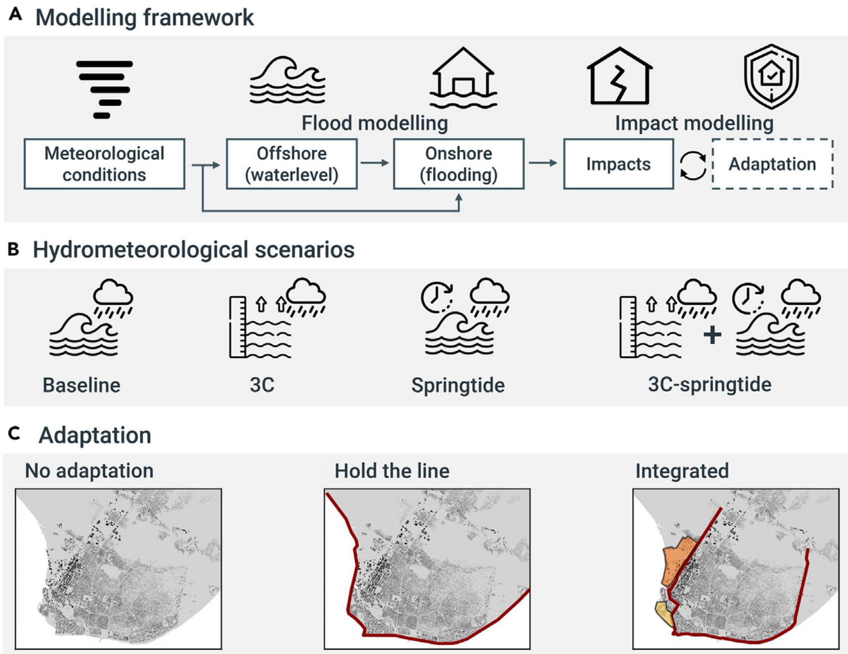

Figure 1. General framework of the study

(A) The modeling 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 supplemental methods for details).

environmental aspects increase.[23–25] Yet, at this scale extreme events, e.g., TCs, generate impacts to society, requiring adaptation strategies to be implemented at a corresponding scale.[24,26] Therefore, probabilistic approaches relying on future climate projections might not fully satisfy the needs for effective adaptation and decision-making at the local scale.[27,28]

An alternative approach to these probabilistic approaches is the use of event storylines.[29] 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.[29] The potential to analyze detailed sequential hazard-to-impact chains allows storylines to serve as a bridge between global climate projections and local scale impacts.[21,23,26] Their contribution to providing decision-oriented information is achieved by expanding a reference event with alternative realizations 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.[28,30] Previous studies have adopted storylines to explore the effects of climate change for multiple impact sectors e.g., van der Wiel et al.,[31] Goulart et al.,[32] and Ciullo et al.[33]

In flood modeling, risk-based approaches are commonly employed to identify flood risk and obtain cost-effective adaptation measures.[34,35] However, they suffer from uncertainty in flood event probabilities[36] and underestimate the significance of low-probability high-impact events.[37] Incorporating climate change projections adds further uncertainty.[38,39] Scenario-based approaches, which include storylines, offer an alternative to address the need for robust solutions amidst these uncertainties.[39–41] For coastal flooding, storylines were applied to efficiently stress-test flood scenarios,[42] to assess impacts from alternative flood events,[43] and to explore generic adaptation options across different regions.[44] However, using storylines to inform localized 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 SLR, 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 modeling 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 methods).

RESULTS

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 methods 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 SLR (Figure 2C). The 3C scenario shows smaller flood increases compared with the springtide scenario. This is because SLR 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

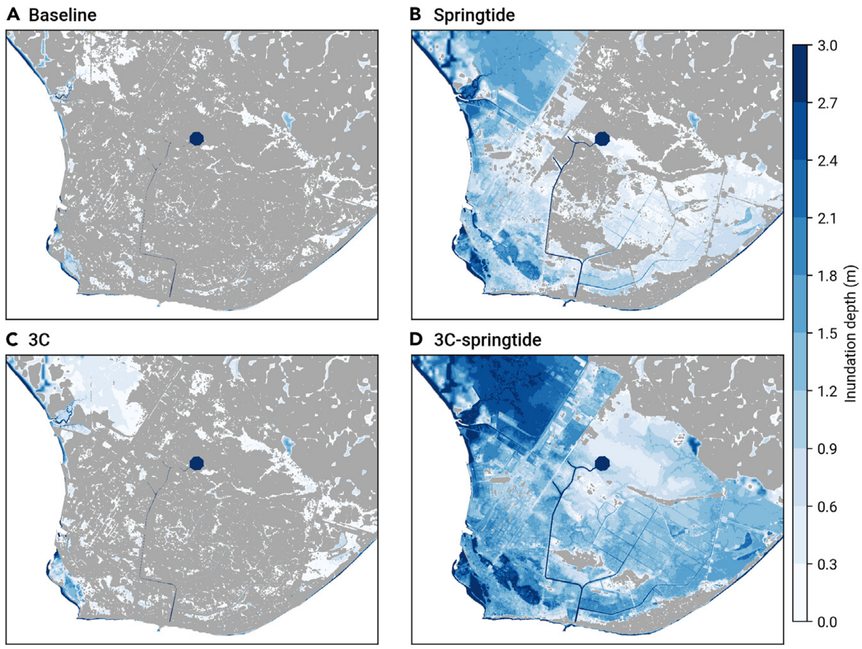

Figure 2. Flood maps of Idai in Beira

Flood hazard maps of TC Idai under different hydrometeorological scenarios: (A) baseline, (B) springtide, (C) 3C, and (D) 3C-springtide scenarios. Different shades of blue indicate flood depth. Note the blue circle in the center is a small lake within the city bounds.

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; Table 1). The springtide scenario indicates approximately 103,000 people are exposed (20× the baseline), which is substantially more than the 9,400 exposed people in the 3C scenario (1.8× the baseline). The 3C-springtide scenario leads to the highest number of people exposed, around 194,000 (37× the baseline). In addition to changes in flood extent, a noticeable shift toward higher flood levels for more extreme events is shown (colors 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, 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 22 times the baseline, and more than the damages in the 3C scenario, USD 4.6 million (1.7× the baseline). As a consequence of both spring tides and 3C climate scenario, the 3C-springtide peaks at USD 152 million, which is 56× the baseline, showing non-linear compounding effects.

Our local scale study enables us to examine impacts at the building level and assess how specific groups, such as informal settlements, are affected (Figure 4). These maps reveal that despite informal settlements not showing high absolute damages (Figure S4), they are relatively more impacted than the rest of the city, with numerous cases of total losses in more extreme scenarios. For more details on impacts in informal settlements, see section supplemental information Section 1.2.

The integrated strategy reduces flood impacts more than the hold the line strategy

We assess how effectively each adaptation strategy (described in detail in methods) 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 center, 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 with the hold the line strategy (Figure S1). 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). The difference in damage reduction is also observable spatially in Figure S2. All results are summarized in Table 2. In informal settlements, the hold the line has decreasing capacity in reducing impacts as scenarios become more extreme (Figure S5). On the other hand, the integrated strategy reduces substantially impacts in informal settlements, with 60% fewer exposed people and 80% less building damage. This reduction is also higher compared with the rest of the city (Figure S2). More information on the effectiveness of adaptation strategies in informal settlements is available on supplemental information Section 1.3.

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. The results for this case study demonstrate how storylines can be used for climate adaptation. They offer insights

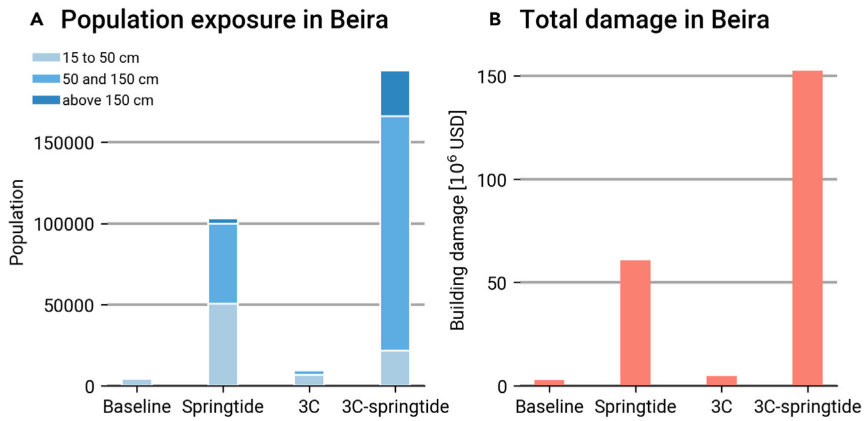

Figure 3. Impacts of Idai in Beira

(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 50 cm, medium blue 50 and 150 cm, and dark blue above 150 cm.

on the effectiveness of adaptation strategies against high-impact events, assessing their robustness across different scenarios, and estimating residual impacts.

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, SLR, and changes in the tidal cycle. We use a comprehensive modeling framework that includes the event's meteorological conditions, compound flood simulation, and the modeling of population exposure and building damage.

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 SLR. These findings align with existing research showing the threat of rising sea levels to coastal settlements.[45,46] 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.[25,47,48] Our results highlight the importance of incorporating internal variability next to the role of climate change in adaptation planning.[49–51]

The scope of our study diverges from existing risk-based studies for Beira, such as Eilander et al.[52] and van Berchum et al.[53] 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[36,37] and climate change uncertainties.[38,39] While Eilander et al.[52] identified managed retreat in highly exposed areas of Beira as the most efficient to reduce expected annual impacts, van Berchum et al.[53] suggest that coastal defenses are the most effective long-term measure. Our approach shifts the 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 visualize 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[40,41] and quantifying residual impacts,[54,55] which can inform the planning of complementary measures such as evacuation plans or financial aid programs.[56]

Table 1. Summary of impacts in Beira under different climate scenarios

Scenario	Total exposed people	Relative change	Total building damage (million USD)	Relative change
Baseline	5,265	1.00	2.73	1.00
Springtide	103,114	19.59	60.71	22.24
3C	9,479	1.80	4.60	1.69
3C-springtide	194,128	36.87	152.66	55.92

Metrics correspond to total exposed people, the relative change in exposed people with respect to the baseline scenario, total building damage (in million USD), and relative change based on the baseline scenario.

Validation of simulations

We faced some challenges in validating our flood results for the specific event and study area. There are no available data from coastal water level or rain gauges in Beira during the occurrence of Idai that could be used to directly compare our results.[52] The main source for flood validation we found was the satellite imagery from the Emergency Management Service (EMS).[57] Our baseline simulations show more extensive inundation than the satellite imagery, but differences lie mostly on small and shallow flood areas along narrow streets or between buildings that are caused by precipitation (Figure S3). Our model setup does not include drainage systems, which could overestimate rain-driven flooding. However, satellite imagery has limitations in densely populated urban areas.[58,59,60] found this to be the case for

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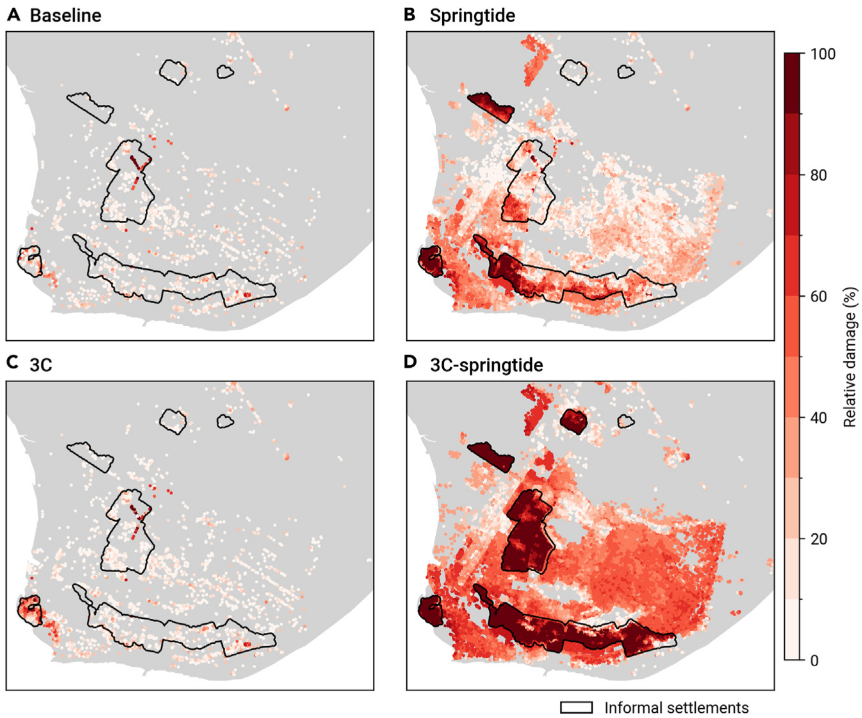

Figure 4. Damage maps of Beira

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.

cyclone Idai's impact on Beira, as satellite imagery demonstrated substantially less flooded areas than what has been documented in reports and media.[61] Another study showed that a combined 10-year rainfall and 10-year coastal surge event is expected to cause more extensive flooding in Beira than observed in the satellite imagery.[53] TC Idai is considered to have a lower probability than once per 10 years,[62] which could further support that the satellite imagery may have underestimated the potential flood extent.

Additionally, we compared our results with that of Mester et al.[60] and found that our baseline simulation showed less inundation than theirs and resembled more closely the satellite imagery (Figure S3). The super-fast inundation of coasts (SFINCS) model has been used and validated in previous works exploring multiple events and larger areas in Mozambique and East Africa.[52,63,64] Last, we calibrated the meteorological inputs to match the historical meteorological conditions (see methods). These factors support the physical plausibility of our baseline results and suggest that our setup is suitable for exploring differences in flood hazards and impacts under alternative storylines.

Limitations and contextualization

While storylines offer an alternative approach to managing uncertainty in future climate,[29] they are still affected by

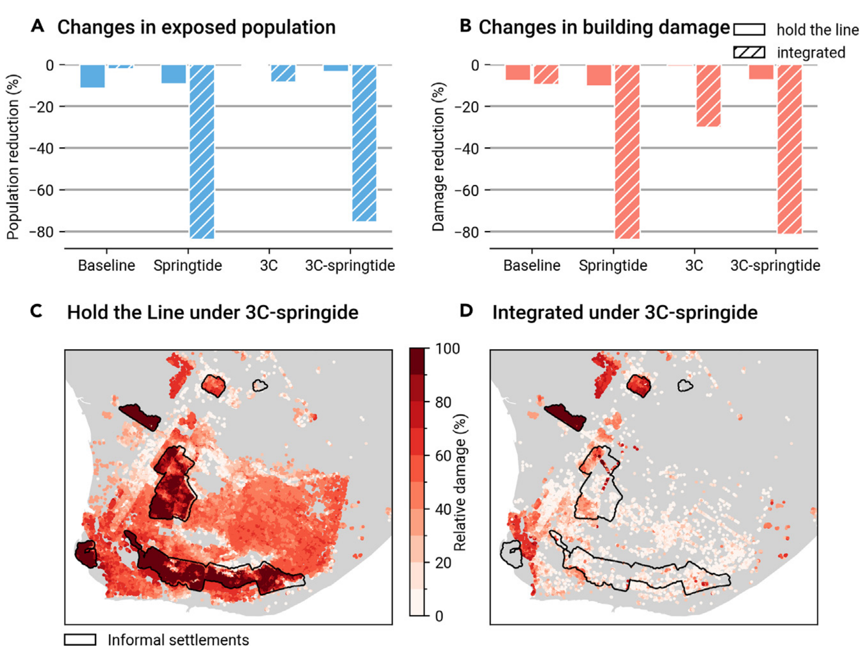

Figure 5. Effectiveness of adaptation strategies

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.

Table 2. Summary of impacts in Beira due to Idai under different scenarios and adaptation strategies

Scenario	Impact metric	No adaptation	Hold the line	Integrated
Baseline	total damage (M USD)	2.73	2.52	2.47
	exposed population	5,264.78	4,670.31	5,157.77
	damage change (%)	0.00%	−7.62%	−9.55%
	population change (%)	0.00%	−11.29%	−2.03%
Springtide 3C	total damage (M USD)	60.71	54.48	9.82
	exposed population	103,114.29	93,523.77	16,636.26
	damage change (%)	0.00%	−10.26%	−83.83%
	population change (%)	0.00%	−9.30%	−83.87%
	total damage (M USD)	4.60	4.57	3.21
	exposed population	9,478.56	9,445.53	8,689.22
	damage change (%)	0.00%	−0.74%	−30.15%
	population change (%)	0.00%	−0.35%	−8.33%
3C-springtide	total damage (M USD)	152.66	141.38	28.47
	exposed population	194,127.91	187,445.08	47,706.85
	damage change (%)	0.00%	−7.39%	−81.35%
	population change (%)	0.00%	−3.44%	−75.43%

Impact metrics to total exposed people, total building damage (in million USD), and the percentual change (%) in exposed people and damage with respect to the no adaptation strategy.

uncertainties in climate projections. In our hydrometeorological scenarios (see methods), the 3C scenario is based on the expected global warming levels by 2100, which have a considerable confidence interval. The corresponding SLR values also carry uncertainties due to the ice-melting processes considered,[65] and the scenarios could be widely different depending on which processes are included. As a result, the outcomes of our storylines could change based on those uncertainties. We document all assumptions to ensure the storylines are clear and transparent.

We compare our study with similar storyline studies on coastal areas and climate adaptation. Qiu et al.[42] developed a storyline framework to stress-test events and scenarios in an efficient way. They provide recommendations for adaptation and highlight the importance of high resolution simulations for climate adaptation, but they do not include adaptation in their framework. Mester et al.[60] also developed storylines of Idai in Mozambique, but their focus was on human displacements and the potential attribution of climate change to the historical event, not explicitly considering adaptation in their setup. Tian et al.[66] combined storylines with regret theory to create a non-probabilistic flood risk framework. By identifying worst-case scenarios, this framework finds tipping points to determine the timing of interventions. Their focus on protection standards differs from our study. We model flood hazards and impacts at the building level, allowing us to estimate impacts on different groups and quantify residual flood impacts. Koks et al.[44] accounts for adaptation options in their storylines, but the study is based on generic and uniform adaptation options that might not be suited for decision-making at the local scale. In our study, there is special attention to the local scale, as it has an important role in promoting climate adaptation.[21]

Our analysis focuses exclusively on direct impacts, such as building damage and population exposure. Indirect impacts of extreme events are also relevant for society but are generally less studied. Testing adaptation strategies for indirect impacts produces different insights, as shown by Mühlhofer et al.[67] They used a framework to test different adaptation strategies against the historical Idai event, focusing on their effectiveness in protecting against different indirect impacts and identifying potential synergies and trade-offs. Future work could combine physical climate storylines with indirect impacts to explore different indirect impacts, such as interrupted services, health impacts and economic disruption due to supply shortages,[68,69] under a relevant set of future climate scenarios.

In this study, we use "robustness" to refer to how well an adaptation strategy performs across a variety of scenarios.[39–41] Our focus on a single high-impact event, despite the multiple scenarios built around it, implies certain limitations regarding evaluating adaptation strategies. Adaptation strategies designed for a specific event may not provide adequate protection against other events, potentially leading to maladaptation cases.[70] Thus, future studies on storylines for adaptation could include multiple (and physically different) events. Adapting to very-high-impact events often requires substantial resources, which may be financially unfeasible.[71] Less severe yet more frequent events also lead to relevant socio-economic impacts and adapting against these events is typically more cost effective, which is one of the purposes of risk-based approaches. This highlights the potential for combining risk-based and storyline approaches, as previously suggested by Shepherd[72]: risk-based approaches can identify cost-effective adaptation strategies that offer some protection across a wide set of moderate events, while storylines can stress-test these strategies against extreme events, quantify residual impacts and help design complementary adaptation measures.

This study analyses the physical aspects of climate change, without incorporating socio-economic or land use changes, which greatly influence vulnerability and exposure, and therefore impacts.[44] Exploring these and other relevant drivers of local change could lead to a more comprehensive impact analysis of future scenarios and adaptation strategies. We adopt three adaptation strategies in our study, but future work could

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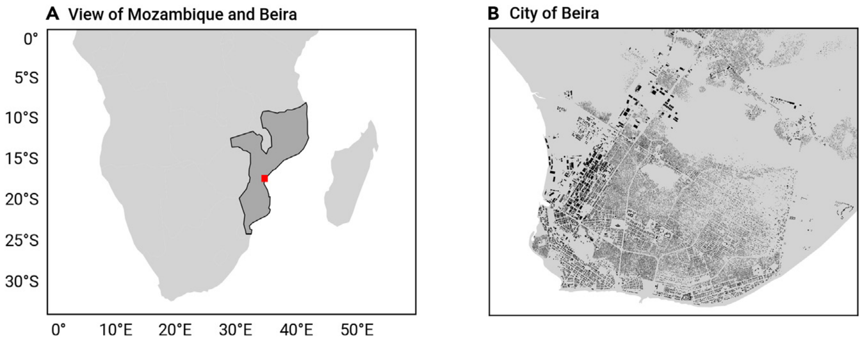

Figure 6. Location of Mozambique and Beira
(A) The location of Mozambique (dark gray) and the city of Beira (red square).
(B) Expanded view of Beira with buildings footprints (black polygons). Source: OpenStreetMap.[80]

evaluate a broader range of potential adaptation options for the study area, including drainage systems, nature-based solutions, and evacuation plans. Our adaptation strategy designs are based on recommendations for the city of Beira from local sources.[73] Some adaptation measures, such as the managed retreat included in the integrated strategy, carry considerable social implications.[74–76] The findings in this study are mostly exploratory, and actual adaptation could emerge from collaborative efforts directly involving the communities and stakeholders impacted.[74]

Storylines for decision making on adaptation

To effectively support local adaptation and decision-making, climate information needs to be usable, relevant, and local.[20,21,24] Our study extends the storyline approach to include adaptation strategies specifically designed for local scale decision-making. The purpose of such method differs from risk-based approaches, which use probabilities to quantify annual flood damages and to find cost-effective adaptation solutions across a wide range of events. Instead, the storylines with adaptation strategies explore the potential impacts of high-impact events across relevant possible futures ("what if" scenarios) and the effectiveness of specific local adaptation measures. This allows for the identification of strategies that are robust across the scenarios tested. Additionally, they can also estimate residual impacts, which support the planning of complementary adaptation measures, including early warning systems and evacuation plans,[56] and post-disaster recovery mechanisms such as insurance schemes.[77] By visualizing these potential impacts and consequences to different adaptation strategies, stakeholders can make more informed decisions.

Nevertheless, this approach also has limitations for decision-making. Relying on a few high-impact events may not guarantee solutions that are effective across a wider range of events, and the solutions could prove costly due to the extreme nature of the events. A potential way to address these limitations is to combine this approach with the risk-based approach.[72] The risk-based approach can determine a set of cost-effective solutions, while the storylines can be used to stress-test them under different scenarios. Consequently, 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.

METHODS

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 modeling framework that captures meteorology, coastal flooding, and societal impacts (economic damage to buildings and exposed population) (Figure 1). Based on four distinct 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.

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 1,600 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.[78]

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.[79] 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.[52,53]

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 SLR of 5 cm relative to the 1995–2014 average.
- 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 4 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 with the baseline. This scenario aligns with the global warming projections of 3.2°C by 2100 based on current Nationally Determined Contributions (NDCs)[81].
- the 3C-springtide scenario, a compound scenario that combines the springtide event with the future 3°C global warming condition.

SLR data were derived from the sixth assessment report (AR6) from the Intergovernmental Panel on Climate Change (IPCC).[82] We calculate the change in precipitation in a warmer climate using the Clausius-Clapeyron (CC) relation, which establishes a 7% increase in saturation vapor 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.[10,83]

Adaptation strategies

This study assesses the effectiveness of three local coastal adaptation strategies in Beira city. They are based on previous local reports[73] 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[74]. Here, it consists of a 2 m wall along the Beira coastline.
- Integrated strategy (Figure 1), which combines infrastructure with management and accommodation measures.[74,84] In this study, it consists of a 2-m wall along part of the coast and around the center 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.[52] All measures, including the managed retreats, are based on recommendations from a local report by the Maputo National Institute for Disaster Management (INGC).[73] Managed retreats carry societal implications, which requires careful planning and stakeholder involvement.[74]

Modeling framework

Meteorological data and evaluation

Idai meteorological data for mean sea-level pressure (MSLP), wind speed, and precipitation are 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,[85] has hourly temporal resolution, and offers the highest spatial resolution among global forecasts, 0.1°, which improves TC simulation.[10,86,87] Previous studies have assessed the capabilities, advancements, and limitations of IFS in simulating TCs.[85,86,88–90]

There are limited observation data for TC Idai and its impacts in Beira.[53,60] We adopt the International Best Track Archive for Climate Stewardship (IBTrACS)[91] to evaluate the IFS-simulated minimum MSLP and maximum wind speeds, and the integrated multi-satellite retrievals for GPM (IMERG-GPM)[92] 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 center during its landfall between March 14th and 15th to match the evaluation data.

Compound coastal flooding modeling

We use the SFINCS model[93] 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.[43,52,63,93,94] A full description of the model is available at Leijnse et al.[93] 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.[63] The roughness coefficients are sourced from the Copernicus Global Land Service[95] and infiltration rates derived from the GCN250 dataset.[96] For the management and processing of input data, we use the Python package HydroMT.[97] More information on the parameters used in our models is available on supplemental information section 1.1.

Impact modeling

We use the Delft-FIAT impact model[52,98] 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 modeling at the individual building level. For building exposure, including location and footprint, we use data from OpenStreetMap.[80] Population data from WorldPop 2020 UN adjusted database at 100-m resolution[99] are 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.[100]

RESOURCE AVAILABILITY

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).

Materials availability

This study did not generate new unique materials.

Data and code availability

The code and data generated for this experiment is available at https://github.com/dumontgoulart/storylines_for_adaptation or at https://doi.org/10.5281/zenodo.14001572. 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.

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AUTHOR CONTRIBUTIONS

H.M.D.G., K.v.d.W., and B.v.d.H. contributed to the concept of the study. H.M.D.G conducted the research and edited the manuscript. H.M.D.G., I.P., and K.v.d.W. obtained and evaluated the meteorological data. K.v.G., H.M.D.G., and I.P. designed and implemented adaptation strategies. H.M.D.G., P.A., and G.W. set up the hydrodynamic and impact models. All authors discussed the analysis and results and revised the manuscript. B.v.d.H. and K.v.d.W. supervised the work.

DECLARATION OF INTERESTS

The authors declare no competing interests.

SUPPLEMENTAL INFORMATION

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