



Impact attribution of compound flooding from Tropical Cyclone Idai: Assessing the influence of land cover change and underlying socio-economic drivers using a mixed-methods approach.

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Abstract. In this study, we investigate the influence of socio-economic drivers on the impacts of compound flooding induced by tropical cyclone (TC) Idai. Making landfall close to the city of Beira in Mozambique in 2019, TC Idai was one of the most devastating TC's to have hit the Southern Hemisphere. Attribution studies generally quantify the contribution of climate change to extreme events and their societal impacts; however, few studies assess how socio-economic drivers amplify or attenuate those impacts. We develop a mixed-methods approach, combining qualitative data from Key Informant Interviews (KIIs) and Causal Loop Diagrams (CLDs) with quantitative data from a physics-based modelling chain to assess how land use and land cover (LULC) changes over 20 years prior to TC Idai plausibly influenced the compound flooding impacts from TC Idai. Results from the quantitative approach show that land use changes (irrespective of climate change) potentially worsened the flood hazard from TC Idai. Results from the qualitative approach explain the underlying drivers of these land use changes such as deforestation driven by charcoal production and informal urban expansion. By integrating two methodologies, we find that the impacts of TC Idai were not only the result of intense climatic hazards but were amplified by complex, deeply rooted socio-economic processes that create reinforcing cycles of vulnerability and exposure. This research demonstrates the value of an interdisciplinary, mixed-methods approach, using localised contextual information to advance impact attribution in data-scarce settings.

1 Introduction

Climate change is increasing the likelihood and magnitude of extreme weather events (Pörtner et al., 2022; Seneviratne et al., 2021). This includes compound flooding associated with tropical cyclones (TC's), which occurs as the combination of fluvial (river discharge), pluvial (extreme rainfall) and coastal flooding (surge and waves). Such a multi-driver flood event can be more severe than an isolated occurrence of a single flood driver (Eilander et al., 2023; Green et al., 2025; Zscheischler et al.,



2018). However, the severity of flood impacts is not only a result of the complex interactions between the different flood drivers but also between the different socio-economic drivers that operate across multiple spatial and temporal scales (Douglas, 2017; Echendu, 2023; Metin et al., 2018). Socio-economic drivers, such as population growth and economic development, alter underlying exposure (presence of people in harm's way) and vulnerability (ability to cope) of an impacted region, potentially worsening or alleviating compound flooding impacts (Collins et al., 2019; Nhundu et al., 2021; Rogers et al., 2025). One mechanism through which socio-economic drivers, both direct and indirect, alter the severity of flood impacts is through land use and land cover (LULC) changes; altering both the distribution of people and hydrological flood risk (Enu et al., 2024; Hounkpè et al., 2019; Polong et al., 2023; Yira et al., 2016).

40 Impact attribution, an evolving concept within attribution science, aims to quantify the extent to which observed social or economic impacts from an extreme event are attributable to climate change (Hope et al., 2022). Tropical cyclones, due to their low-probability, fine scale compared to climate model resolution, and limited physical understanding, are challenging extreme events to attribute (Camargo et al., 2023; Coumou et al., 2024; Knutson et al., 2020; Philip et al., 2020; Philp et al., 2022; Wehner et al., 2019). However, an increasing number of attribution studies have shown that climate change can worsen these extremes (Knutson et al., 2020; Otto et al., 2022; Pflieger et al., 2022; Reed et al., 2022; Sparks & Toumi, 2025), including the flood hazard (Grimley et al., 2024; Lin et al., 2016), and associated societal impacts (Frame et al., 2020; Smiley et al., 2022; Strauss et al., 2021). Yet to date, most attribution studies focus on how climate-driven hazards affect impacts, overlooking key socio-economic drivers that influence exposure and vulnerability, and therefore can also affect overall impacts (Jézéquel et al., 2024; Perkins-Kirkpatrick et al., 2024; Singh et al., 2025). Few impact-attribution studies quantitatively include vulnerability and exposure components; Sebastian et al. (2021) studied the effect of urbanisation on runoff characteristics and volume in the United States, whilst for Europe, Paprotny et al. (2025) showed the importance of socio-economic drivers in reducing flood damages, despite the increase in hazard due to climate change. Often, the absence of observational data makes fully quantitative impact assessments difficult, particularly when trying to integrate socio-economic processes (Goulart et al., 2025; Hansen et al., 2016; Mester et al., 2023; van Oldenborgh et al., 2021). This is especially the case in low-income countries, which are unrepresented in attribution studies (Callaghan et al., 2021). Moreover, impact attribution studies, but also flood risk studies, often overlook the mechanisms that drive changes in exposure and vulnerability and their complex interactions between flooding and humans (e.g. Barendrecht et al., 2017; Schlumberger et al., 2025).

60 One flood driver that couples flooding and human systems is LULC changes. LULC changes are driven by direct changes such as deforestation and urbanisation, but are also a result of underlying driving forces; factors with indirect impacts such as socio-economic developments and population pressures (Ibrahim & Boru, 2025; Mabutana et al., 2025). Embedded in broader socio-economic and environmental processes, LULC changes can influence flood hazards through a multitude of interconnected positive and negative feedback processes (Douglas, 2017; Rogger et al., 2017). For example, increased use of asphalt and concrete surfaces, a product of urbanization, reduces infiltration and increases run-off, leading to an increase in flood risk



65 (Douglas, 2017; Enu et al., 2024; Xu et al., 2022; Zhang et al., 2018). LULC change has been used for quantitative impact
attribution assessments and flood risk studies to infer changes in exposure (de Moel & Aerts, 2011; Metin et al., 2018),
However, to fully understand the complexity of how socio-economic drivers contributed to the impact of an extreme
event requires the integration of qualitative exposure and vulnerability factors (Singh et al., 2025). This can be achieved by
using a mixed-method approach that combines qualitative and qualitative methods; however, to date, and to the best of the
70 authors' knowledge, no attribution studies have explored such approaches.

This study addresses this important research gap by assessing the influence of LULC changes, in combination with the effects
of climate change, on the compound flood hazard from TC Idai. TC Idai, was one of the most devastating cyclones to have
ever hit the Southern Hemisphere (Warren, 2019). Making landfall close to Beira City, Sofala Province, in central
75 Mozambique in March 2019, the magnitude of TC Idai's impact was not solely due to the cyclone (extreme winds, storm
surge, fluvial and pluvial flooding) but heightened due to the region's very high vulnerability and exposure to flood hazards,
factors that turned the hazards into a humanitarian crisis (IFRC, 2019; Schofield & Deprez, 2019; UNDP, 2019). Recent
attribution analyses indicate that climate change worsened the impacts of TC Idai (Mester et al., 2023; Vertegaal et al., 2026),
but the role of socio-economic drivers on the impacts of this hazard has not yet been explored; despite significant LULC
80 changes (e.g. deforestation) in the region over the past two decades prior to TC Idai (De Vleeschauwer, 2019.; Lisboa et al.,
2024). In addition, Beira has experienced rapid urban expansion, and to combat recurrent flooding, the Beira Masterplan 2035
was initiated in 2013 to improve resilience (Macamo, 2021). However, the plan's mixed success during Idai reflects the
complex socio-economic and land-use processes shaping exposure and vulnerability in the city (Beunder, 2019; Shannon et
al., 2021).

85 We use a mixed-method approach and combine a storyline attribution framework based on a state-of-the-art modelling chain
for assessing plausible climate change effects on TC compound flooding developed by (Vertegaal et al., 2026) with qualitative
causal mapping using findings from eight Key Informant Interviews (KII). The modelling framework is extended to
quantitatively assess how LULC changes affects the flood hazard (Vertegaal et al., 2026), in addition to plausible effects of
90 climate change. The KII's, with consultants, disaster risk reduction practitioners, researchers and humanitarian aid workers
with experience in Beira, pre- and/or post-TC Idai, formed the development of a qualitative Causal Loop Diagram (CLD), a
subset of causal mapping. Causal mapping can bridge quantitative and qualitative analyses, helping to make sense of large
amounts of qualitative data, such as KII's, into clear insightful diagrams comprised of causal claims (Powell et al., 2023; Singh
et al., 2025). We use a CLD to help visualize feedback loops and interconnections between direct and underlying socio-
95 economic drivers of land use changes, and their influence on the flooding impacts of TC Idai. By integrating qualitative and
quantitative information, using an interdisciplinary, mixed-methods approach, we are able to provide a more comprehensive
understanding of the drivers of impacts from TC Idai.



2 Methods

The conceptual framework used for this paper is summarized in Figure 1. This methodology consists of combining a qualitative approach, consisting of KII's and causal mapping (Section 2.1) with a quantitative approach, consisting of a compound flood modelling chain (Section 2.2). This modelling chain is based on Vertegaal et al. (2026) and simulates compound flooding under two different land covers, representing a factual and counterfactual scenario, and a factual and plausible climate scenario from Vertegaal et al. (2026) (Section 2.3). The entire workflow is built on open-source models and accessible on GitHub (Vertegaal et al., 2025). We use the term 'counterfactual' to represent alternative land cover and climate conditions, (described in more detail in Table 2).

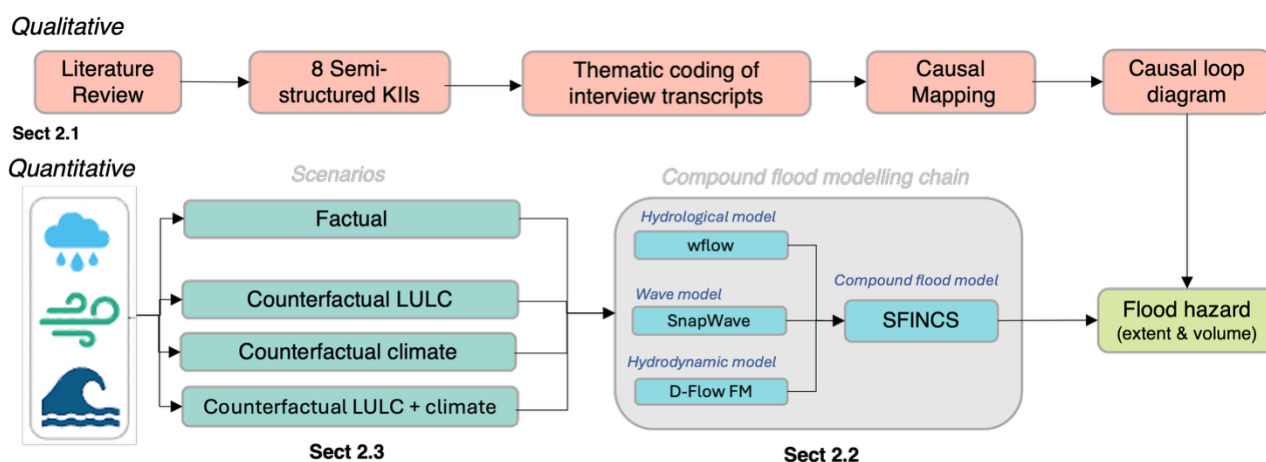


Figure 1: A method diagram summarizing the methods used in this study, depicting the qualitative, KIIs and casual mapping approach (in red) and the quantitative, compound flood modelling chain (in blue). The four scenarios used, representing factual and counterfactual climate and LULC are described in more detail in Sect 2.3. These were used in a compound modelled chain (Sect 2.2) to see how changes in LULC and climate influenced the simulated flood hazard of TC Idai.

2.1 Key Informant Interviews and Causal Mapping

The qualitative method aims to identify and disentangle the drivers of land use change and its flood impact in the region. The approach consists of three main steps.

First, we performed an in-depth literature review to get a better understanding of the context of Beira and the main impacts of TC Idai in order to construct an interview guide for the KIIs (Figure S1 in the Supplement). Using the interview guide, eight semi-structured KII's were conducted with researchers, humanitarian workers, and consultants who had professional experience in Beira before or after TC Idai. We use a semi-structured interview approach; a qualitative method commonly used across other African contexts to assess localised contextual drivers of flooding (Arinabo, 2022; Baddianaah, 2023; Echendu, 2023; Enu et al., 2024) and to inform casual mapping (Galletta & Cross, 2013).



Participants were selected using purposive sampling – targeting individuals with relevant knowledge, and snowball sampling – targeting individuals that were suggested by earlier interviewees (Moser & Korstjens, 2017). The interviews, each lasting 30–45 minutes, were conducted online between March–June 2025, recorded with consent. Secondly, the interviews were transcribed for analysis to extract key themes and causal relationship between drivers (Kim & Andersen, 2012). The method of thematically coding this data is outlined in Table S1 in the Supplement.

In the third step, we used a causal mapping approach to synthesise the coded interview data into visual representations of cause–effect relationships among variables influencing flood impacts (Buzogany et al., 2024; Powell et al., 2023). CLDs, a subset of causal mapping, were developed as a systems dynamics tool to describe complexity and graphically visualise identified variables, connected by causal links (arrows), that represent causality (Littlejohns et al., 2021; Coletta et al., 2024; Sterman, 2002). CLD’s have been used to combine technical and non-technical variables, capturing social drivers often missed by standard flood models and helping to prioritize key variables for inclusion in quantitative analysis and understanding the underlying dynamics (Arinabo, 2022; Coletta et al., 2024; Hanf et al., 2025). The overall causal mapping method to construct the CLDs is explained in Table S2 in the Supplement. This method was derived from previous research using qualitative interviews to inform causal mapping and CLDs (Crabolu et al., 2023; Kenzie et al., 2024; Kim & Andersen, 2012; Newberry & Carhart, 2023). The job description and relevance of each key informant (KI) are described in Table 1 below.

Table 1. The 8 KIs and their job description, and relevance to the region, pre and post TC Idai.

KI Number	Job description and relevance
KI1	Water and environmental governance researcher with experience in Beira.
KI2	Senior humanitarian shelter specialist with operational experience in Mozambique post-Tropical Cyclone Idai
KI3	Postdoctoral researcher specialising in household food insecurity and post-TC Idai vulnerability in Beira.
KI4	Urban climate adaptation researcher with a focus on coastal cities in Mozambique and experience research in Beira.
KI5	Humanitarian emergency response lead specialising in shelter and displacement in the region after TC Idai.
KI6	Postdoctoral researcher conducting ethnographic research on climate change impacts on livelihoods in Mozambique.
KI7	Urban resilience and recovery planning expert involved in post-TC reconstruction in Beira.
KI8	Academic researcher specialising in charcoal production, energy livelihoods, and environmental change in Mozambique



2.2 Compound flood modelling and attribution

2.2.1 Modelling framework

145 The quantitative method is based on simulating TC-induced compound flooding due to fluvial, pluvial, and
coastal forcing. For this, we apply the modelling chain developed by (Vertegaal et al., 2026). Compound flooding is modelled
with the Super-Fast INundation of CoastS (SFINCS) model (van Ormondt et al., 2025), a reduced complexity model. The
coastal boundary conditions consist of tide and storm surge levels, modelled using the hydrodynamic model D-Flow FM from
the Delft3D Flexible Mesh Suite (D-Flow FM; Kernkamp et al., 2011), nearshore wave setup, modelled using the coupled
150 wave model SnapWave (Roelvink et al., 2025), that is integrated into SFINCS (Leijnse, 2025). The upstream discharge
boundary conditions are modelled using the hydrological model wflow (van Verseveld et al., 2024). To simulate the flooding
induced by tropical cyclones Idai, we use meteorological forcing derived from the ERA5 reanalysis dataset (Hersbach et al.,
2020) and IBTrACS best track data (Gahtan et al., 2024; Knapp et al., 2010). For further details on the modelling chain
and its validation, we refer to (Vertegaal et al., 2026).

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We apply the modelling chain to different factual and counterfactual scenarios, following the attribution framework developed
by Vertegaal et al. (2026), as shown in Fig. 1. The simulations are based on a storyline approach, which means we assess how
the flooding of Idai would change under different plausible conditions. We assess the combined and individual effect of
historical climate change and LULC change to disentangle the effect of different flood drivers. The four scenarios are described
160 in Table 2.

2.2.2 Land cover change scenarios

To simulate flooding under a factual and counterfactual scenario of land cover change, we use two LULC maps from Lisboa
et al. (2024). These regional LULC maps cover the majority of the model region and are derived from Landsat imagery for the
years 2000 and 2020 images into eight classes: forest, mangroves, forestry plantation, cropland, grassland, wetland, settlement,
165 and other land (Lisboa et al., 2024). With a 30_m resolution, these LULC maps have a higher resolution than global
datasets. We use the LULC map of 2020 to represent the factual conditions during TC Idai, which occurred in 2019. The LULC
map of 2000 is used as counterfactual scenario and represents the situation before the socio-economic development of the
region in the last two decades.

170 We performed data pre-processing to ensure the LULC map extents cover the entire model domain, which required minor
merging with the global LULC dataset for 2019 from (Buchhorn et al., 2020). LULC classes of the Lisboa et al., (2024)
dataset were reclassified into the same corresponding land cover classes as the Buchhorn et al. (2020) dataset using expert
judgement. Details of this can be found in Table S3 in Section S2 of the Supplement.



175 Each LULC class has an assigned land Manning roughness value, derived from the Buchhorn et al. (2020) dataset, as shown
 in Table S3 in the Supplementary Material. This roughness parameter is input to the wflow and SFINCS model and represents
 the surface roughness and vegetation cover as an empirical parameter, descriptive of how water interacts with the land surface,
 and a crucial component to flood modelling (Kalyanapu et al., 2009; Soliman et al., 2022). For example, a lower roughness
 coefficient implies that the land surface is smoother and offers less resistance to the flow of water, resulting in less infiltration
 180 (Masoodi & Kraft, 2026). In addition, LULC class also control several other hydrological parameters in wflow, including
 vegetation root depth, leaf storage, etc. (for full detail see parameter lookup tables in the HydroMT-Wflow repository in
 Eilander et al., (2026).

2.2.3 Climate change scenario

To simulate the flooding from TC Idai under a factual scenario, we use ERA5 reanalysis meteorological forcing data, as
 185 described by Vertegaal et al., (2026). To simulate the counterfactual scenario of climate change, we remove the long-term
 climate trend from multiple physical flood drivers, which includes the TC precipitation, maximum wind speed and sea level
 rise. These three TC flood drivers are known to be affected climate change and have high to medium scientific confidence
 (Knutson et al., 2020). Following (Vertegaal et al., 2026), we consider a plausible reduction of 8 % in rainfall, 5 % in
 maximum wind speed and 10 cm in SLR for the counterfactual climate scenario. For more information on how these
 190 counterfactual climate scenarios are constructed, we refer to (Vertegaal et al., 2026).

Table 2. A brief description of the factual, and three counterfactual scenarios as shown in Fig. 1.

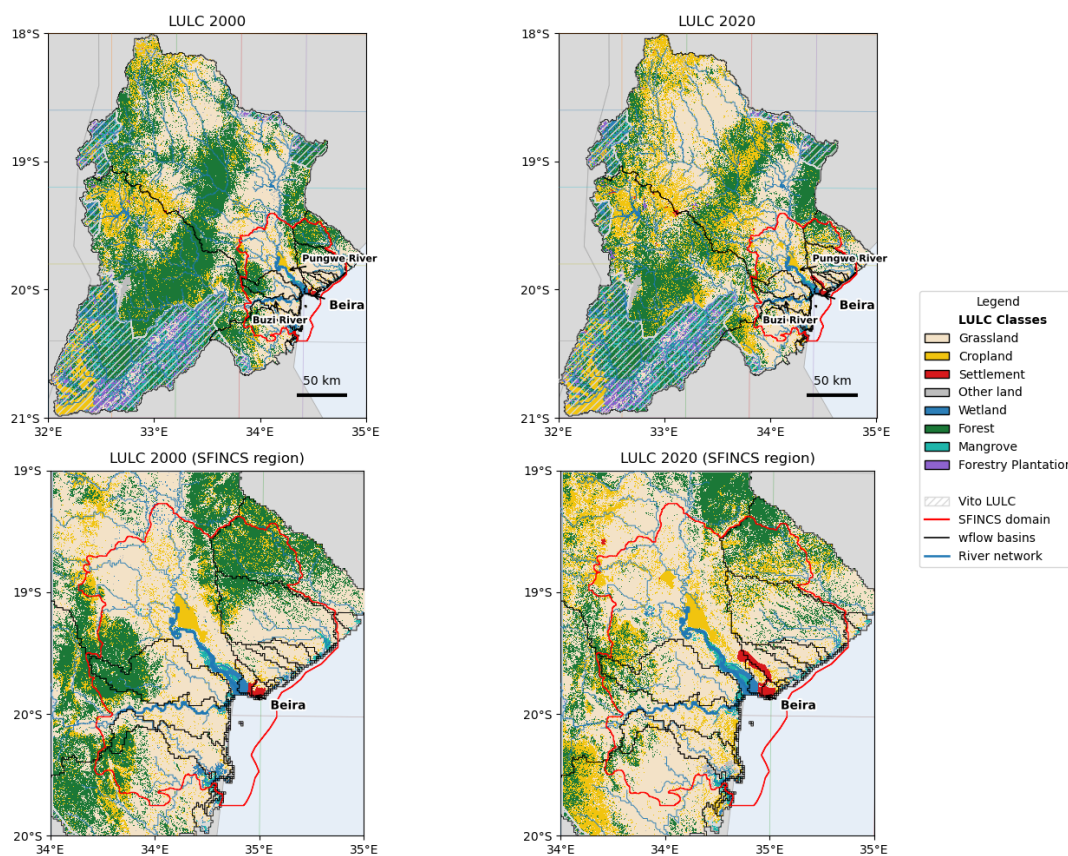
Scenario	Description
Factual	Representative of the LULC and climate conditions during TC Idai.
Counterfactual LULC	LULC conditions from 2000, to isolate the effect of LULC change.
Counterfactual climate	Climate conditions with the long-term climate change trend removed, to isolate the effect of climate change.
Counterfactual LULC and climate	LULC conditions from 2000, and climate conditions with the long-term climate change trend is removed, to isolate the combined effect of LULC change and climate change.



195 **3 Results**

3.1 Observed land cover change

Observed LULC change across the study region illustrates significant deforestation between 2000 and 2020, primarily through the conversion of natural forested to non-forested land (Lisboa et al., 2024). The largest change in LULC area was the conversion from forest to cropland, accounting for 72.9% of the net change (Lisboa et al., 2024). As shown in Figure 2, these changes are spatially concentrated in the central part of the study area, while urban expansion is localised around Beira. Although the absolute increase in settlement area is relatively small compared to cropland expansion, it occurs in predominantly low-lying flood prone areas, suggesting a greater effect on flood exposure. For a clear visualisation of the LULC changes that occurred in the study region, see Figure 7 from Lisboa et al. (2024).



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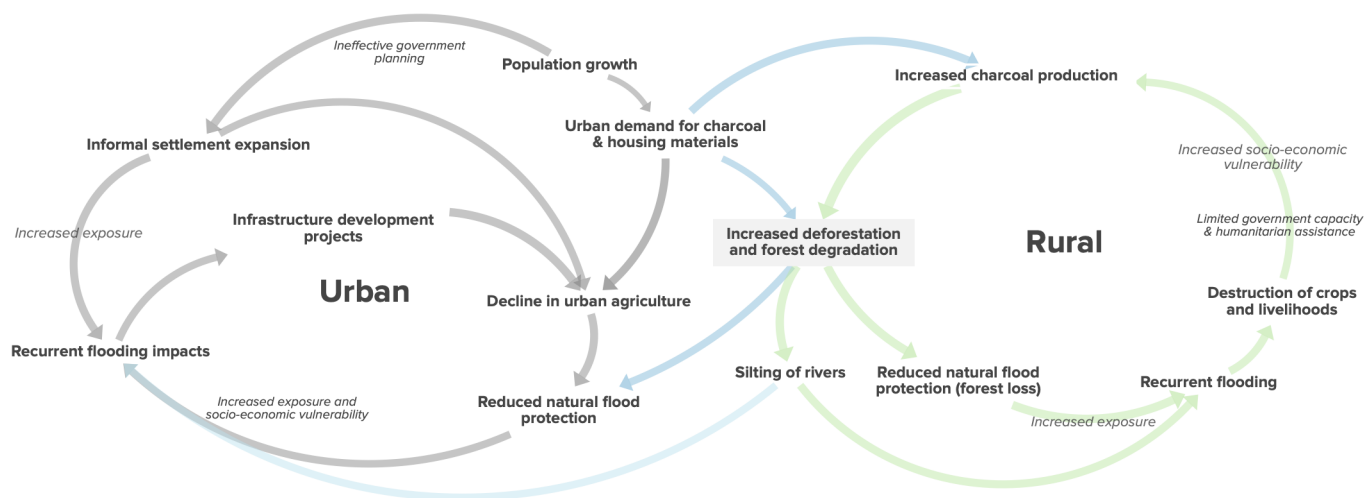
Figure 2. Maps of LULC change from 2000 and 2020 for our case study region, the Beira corridor, based on data from Lisboa et al. (2024). For areas with missing data, we use data from Buchhorn et al., (2020), shown by white dashed lines. The maps show the full case study model domain of the compound flood modelling chain (top panels; Sect. 2.2) and zoomed into the SFINCS model (red outline; bottom panels).



210 **3.2 Socio-economic drivers of LULC change**

The underlying socio-economic drivers of the LULC changes were further investigated using qualitative methods. Figure 3 shows the CLD that synthesises the dominant causal mechanisms and feedback loops that were revealed from the KIIs. The KI's reiterated the differentiated impacts experienced from Idai between rural and urban areas. Rural communities, whose livelihoods are dependent on agriculture and charcoal production, experienced total devastation and destruction from TC Idai, with traditional building materials “completely washed away by floodwaters” (KI3). In addition, the inaccessibility of rural areas limited humanitarian assistance in the direct aftermath ‘because of access issues’, and therefore worsened and prolonged the impacts (KI5). In urban areas however, KIs agreed that in Beira, there were fewer fatalities, and impacts were less extensive being with only ‘partial damage to buildings’ (KI5) and damages concentrated to informal settlements built at the periphery of the city. Better building qualities, greater access to humanitarian assistance, and more livelihood diversification in urban areas ensured the impacts of TC Idai were felt unequally between rural and urban settings. However, the drivers of LULC changes and feedback mechanisms remain highly interconnected, reinforcing cycles of vulnerability and exposure. For example, upstream deforestation and agricultural expansion influence the downstream flooding hazards in Beira, while increasing urban demand for charcoal and housing materials exacerbates rural land use change, heightening flood risk across the region. Key drivers and their interactions, depicted in the CLD in Figure 3, are discussed in more detail below.

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230 **Figure 3. A Causal Loop Diagram (CLD) showing the direct drivers of Land Use and Land Cover (LULC) change (e.g. deforestation and urbanisation), underlying socio-economic drivers (e.g. population growth and high socio-economic vulnerability), their outcomes (flooding impacts), for urban (grey arrows) and rural (green arrows) settings, and their interactions (blue arrows). This map was made using the KUMU relationship mapping software (Kumu, n.d.).**



235 **3.2.1 Direct drivers of LULC change (and flooding impacts)**

Across all interviewees, the two dominant direct drivers of LULC change influencing flood impacts were deforestation and urban expansion. While interviewees explained that the flooding impacts experienced from TC Idai were very different between rural and urban areas, their drivers remain interlinked as represented in the CLD (Figure 3). Among many interviewees, the role of deforestation on the flooding impacts experienced from TC Idai was important and yet
240 ‘underdiscussed’ (KI6). Respondents attributed deforestation in the region primarily driven by charcoal production, housing needs, and ‘slash and burn’ agriculture. In particular, charcoal production is a reliable alternative livelihood that rural communities can fall back when crops have been destroyed by flooding; contributing to high deforestation in the region. Upstream, deforestation degrades and silts the rivers, whilst the removal of mangroves at the coast removes natural flood protection, which both “makes the city (Beira) more exposed to the severe impacts from cyclone” (KI6).

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Interviewees also commented that in Beira, the main LULC was urban expansion, and the accompanied decline in urban agriculture in the city, despite its importance for food security and flood protection. Two key pressures emerged from the KIIs as driving this decline; the expansion of informal settlements built at the periphery of the city, and secondly infrastructure developments that prioritise a technocratic flood control approach over local realities of ‘living with water’. KI7 highlighted
250 how agriculture has historically occurred in flood prone areas that are “later converted to housing due to population pressures”. In addition, KI1 explained how developers see urban agriculture as “backward” and a “waste of space” or merely “land waiting to be developed.” Replacing permeable agricultural land with impervious surfaces (informal housing or private sector developments), not only increases the exposure to flooding, but also increases household food insecurities, compounding the impacts from flooding.

255 **3.2.2 Indirect socio-economic drivers of LULC**

High vulnerability and socio-economic deprivation are one of the multiple underlying socio-economic drivers and pressures that influenced the observed direct LULC changes and impacts of flooding in the region, as described by the interviewees. Many interviewees stressed the context of the region where TC Idai hit as extremely poor, and therefore highly vulnerable to the impacts of a major flooding event. Interviewees described rural areas as ‘marginalised in all aspects - lack of education,
260 basic health care, basic sanitation’, and urban expansion zones where levels of “socioeconomic deprivation ... was quite staggering” (KI3, KI5, KI6). Widespread poverty and limited employment opportunities were cited as a key driver of high deforestation, particular in periods, after a disaster such as TC Idai, when charcoal production is one of the only alternatives to make a living. Respondents also commented on the importance of small-scale urban agricultural practices in urban areas, as a means of food source and income diversification; “that people resort to agriculture as a safety net” (KI6), yet they also
265 mentioned how these traditional practices are under threat from informal urban expansion and larger developments.



Underlying, indirect drivers of deforestation in rural areas were also attributed to the limited government capacity whereby “the majority of people affected, have to recover by themselves” (KI5). Interviewees explained that due to the recurrent nature of flooding in the region, often communities are hit by a subsequent disaster before they have recovered, heightening their vulnerability and limited socio-economic situation, and the advantage of deforestation by charcoal production as a means to recover (KI2).

In urban areas, interviewees cited failures in urban planning and ineffectual new developments have exacerbated land use changes and increased exposure to flooding. Despite significant investments through the Beira Masterplan (2013-2035), new infrastructure developments and housing ‘are so expensive that poor people cannot afford it’ (KI3). Whilst new developments and their construction methods have inadvertently made “poorer_neighbourhoods next to big industrial developments ... extra susceptible to flooding, because of the ‘backfilling’ (KI2)”; displacing water to lower-lying, often informal settlements, worsening flood exposure. In addition, continued population growth has continued to drive urban expansion zones of informal housing, built on low-elevation, flood susceptible areas.

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3.2.3 Feedback mechanisms

As demonstrated through the CLD (Figure 3), the interactions between direct and indirect drivers, form reinforcing feedback mechanisms that amplify both LULC change and flood impacts over time, across both rural and urban settings.

In rural areas, key reinforcing feedback depicted in Figure 3, is how upstream deforestation, driven largely by charcoal production and agricultural expansion, reduced natural flood protection (e.g. forest cover and mangroves), thereby increasing downstream flood risk. As KI8, explained this “feedback effect” that ‘flooding is worsened by deforestation’, because when there is a flood, crops are destroyed and therefore people “harvest more charcoal to make up for the lost income”. Extreme flood events (like Idai) therefore create ‘cycles of impoverishment’ whereby rural communities ‘resort to producing charcoal’, creating a negative feedback mechanism of heightened vulnerability and exposure (KI6). With the absence of viable coping alternatives, charcoal production and associated deforestation is “interwoven with, the economic vulnerability of the communities” and therefore difficult to address (KI6).

This rural feedback is further intensified by urban demand (the blue lines in Figure 3). Growing urban populations, such as cities such as Beira, sustains the demand for charcoal that drives continued deforestation upstream. Compounding this demand is a strong preference for cooking with charcoal; “traditional ways of cooking are hard to change” (KI8).

In urban areas, Figure 3 highlights a second reinforcing feedback loop between complex land-use competitions, that act to alleviate, or worsen vulnerability and exposure to flooding impacts. In Beira, population growth and limited affordable housing



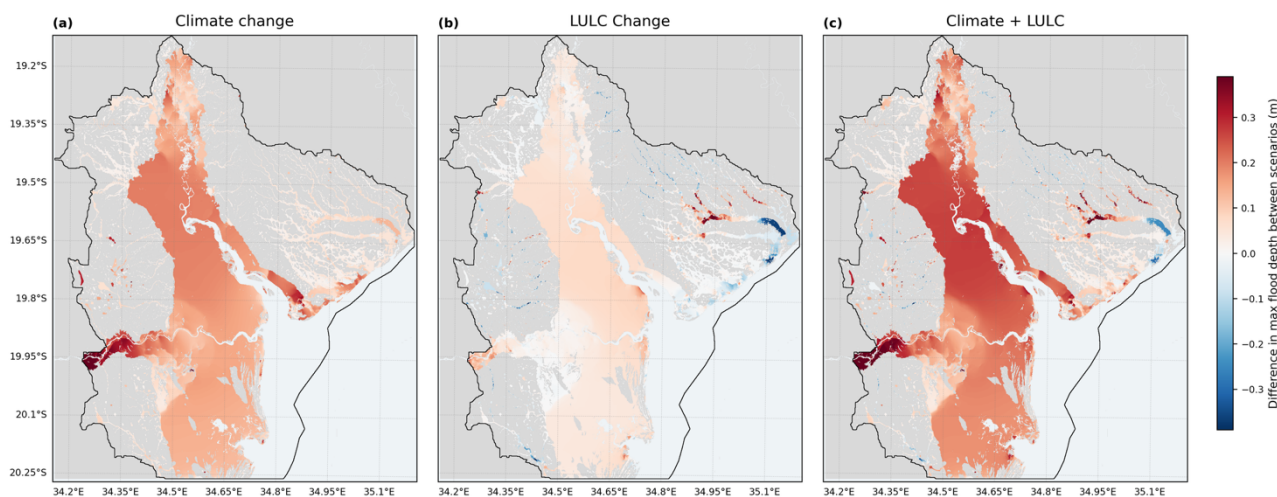
300 drives the expansion of informal housing to low-elevation, flood prone areas, often at the expense of urban agriculture land. At the same time, formal infrastructure developments, often shaped by technocratic approaches to flood control can unintentionally increase localised flood risk through backfilling processes, increasing flood exposure among already vulnerable populations. Following major flood events such as TC Idai, recovery efforts aiming to ‘build back better’ can reinforce this loop. Interviews highlighted the tension between ‘attempts to recover from a more individual perspective’ (KI6) and larger
305 infrastructure development projects. For example, devastating images in the media of impacts of TC Idai in the coastal neighbourhood of Praia Nova in Beira were paradoxically used to legitimize projects that are ultimately not to their advantage, reinforcing the disconnect between those impacted and who development plans designed for, ultimately worsening exposure to the next extreme event (KI1). The displacement of urban agricultural practices, also reduces food security, and livelihood diversification, thereby increasing socio-economic vulnerabilities, and heighten future flooding impacts.

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Together, the interconnected feedback loops identified in Figure 3 highlights that LULC change and flooding impacts are shaped by complex reinforcing socio-economic and environmental processes that operate and interact between both rural and urban settings.

3.3 Impacts of changes in climate and LULC on flood hazard

315 Comparing the maximum flood depth differences between the factual and counterfactual scenarios reveals the historical LULC changes act as a local modifier of flood depth (panel b in Figure 4), whereas climate change is a more large-scale driver of increased flood depths from TC Idai (panel a in Figure 4). The maximum change in flood depth due to climate change reaches up to > 0.3 m, affecting most strongly the coastal areas around Beira and the riverbanks of the Buzi River. Changes in flood volume and flood extent due to climate change are 9 % (454 Mm^3) and 2% (67 km^2), respectively. The maximum altered flood
320 depth due to LULC change reached up to 1 m, affecting mostly the floodplains and river banks, but also led to reduction in flood depth up to 1.2 m in the coastal areas north of Beira. The overall flood volume due to LULC change is increased by 2% (120 Mm^3), while changes in flood extent are negligible. Climate change has larger effect on the overall flood hazard while LULC change effects vary locally. In addition, LULC change influences the river discharge experienced during the TC Idai flood event more strongly for smaller rivers, than the major Buzi and Pungwe rivers (Figure S2 in Section S3 in the
325 Supplement) which highlights the role of upstream area and more localised LULC responses of smaller catchments. Northwest of Beira a local decrease in flood depth can be linked to local reforestation, which causes a reduce in land cover roughness, thus decreased water velocity, and therefore leads to less seaward drainage. The effect of LULC change and climate change combined leads to the largest change in flood hazard with a change of 12 % (568 Mm^3) and 2 % (68 km^2) in flood volume and flood extent, respectively, with a more widespread max depth increase of > 0.3 m.



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Figure 4. Maps showing the difference in maximum flood depth between the factual and counterfactual scenarios for the study region (the counterfactual is subtracted from the factual scenario). The left panel (a) isolates the climate change signal by keeping the LULC unchanged. The middle panel (b), isolates the LULC change signal by keeping the climate conditions unchanged. The right panel (c), shows the combined effect of both climate change and LULC change.

4 Discussion

4.1 Integrating qualitative and quantitative methods

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In our study, we attribute impacts of TC Idai in Mozambique to climate change and LULC change by developing counterfactuals that are supported with a qualitative analysis. This mixed-method approach allows us to show that both climate change and LULC change generally increased the flood depth of compound flooding from TC Idai, and that the resulting impacts were amplified by reinforcing socio-economic feedbacks that increase vulnerability and exposure. The quantitative modelling alone was not able to explain experienced impacts that have been influenced by underlying socio-economic processes and feedbacks such as deforestation driven by charcoal production, and urban land-use changes. Hence, this study provides additional insights into the attribution of the flood impacts of TC Idai with respect to previous studies that focussed on climate change (Mester et al., 2023; Vertegaal et al., 2026).

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The integration of local contextual insights with quantitative modelling, enabled us to interpret the quantitative results and identify socio-economic drivers and their interactions that contributed to the experienced cascade of impacts associated with TC Idai. We identified direct and indirect drivers of LULC change in rural and urban areas that give insights on how and why TC Idai was so devastating. In rural areas, deforestation and forest degradation driven by charcoal production as an alternative livelihood emerged as an influential direct driver of LULC change. This finding corresponds to previous research also identifying charcoal production and agricultural expansion as the main drivers of deforestation in the region (De Vleeschauer, 2019.; Lisboa et al., 2024; Mabutana et al., 2025). In urban areas, we identified feedbacks driving LULC between informal settlement expansion, declining urban agriculture and infrastructure developments. Across both settings, the qualitative



insights revealed important indirect drivers such as widespread poverty and limited government capacity that reinforce and compound with these direct drivers. Interconnected feedbacks between urban and rural settings such as population growth increasing the demand for charcoal, and consequential downstream flooding impacts, further amplify and compound LULC change and their flooding impacts.

Insights from the KII's and causal mapping also help explain the local heterogeneity observed in the quantitative modelling results, when comparing the LULC change scenarios. For example, one interviewee described that "because the land changes happen in different places, the impacts are different across areas" (KI8), aligning with the resulting localised flooding response from LULC change from the quantitative analysis. In addition, interviewees recognised that deforestation alone does not explain the severity of the impacts experienced by TC Idai. As KI5 explained 'deforestation is one of the bigger reasons, but there are a lot of other issues as well', citing climate change making 'these events more frequent and intense'. This perspective aligns with the model results, which shows the relatively small hazard changes from LULC change, compared to the climate change signal. The importance of silting of the major rivers which 'widens the breadth of the watercourse, making it most susceptible to flooding' (KI6) cannot be captured by the model parameters, potentially underestimating the flood hazard and highlighting the importance of underlying local hydrological conditions.

4.2 Implications for flood impact attribution

This study advances impact attribution of compound flooding from tropical cyclones in data-scarce regions by 1) quantifying the effects of a non-climate driver, i.e. LULC change, in addition to quantifying the effect of climate change and 2) including indirect qualitative socio-economic drivers by using a mixed-method approach. We combine a quantitative attribution framework with KIIs visualised in a CLD to assess cascading drivers, impacts, their interactions and consequently reinforcing socio-economic feedback cycles in rural and urban areas. We propose a mixed-methods approach to truly understand real-world impacts, and identify drivers of vulnerability and exposure for compound flooding after TC Idai. By doing so, we consider all risk components (Simpson et al., 2021), particularly integrating exposure and vulnerability as they drive the experienced impacts (Lahsen & Ribot, 2022; Perkins-Kirkpatrick et al., 2024; Raju et al., 2022). The consideration of non-climate drivers in impact attribution is a relatively new field and can play a role to better explain real-world impacts (Jézéquel et al., 2024). Integrating the complexity of socio-economic drivers in attribution can diagnose the underlying drivers of impacts, and produce more policy-relevant insights (Jack., 2025; Grant et al., 2015). Although it is difficult to quantify these impacts, it is important to integrate qualitative methods, in particular local knowledge, for a holistic systems-based approach (Nkwasa et al., 2025; Singh et al., 2025; Singh et al., 2026). Within the rapidly evolving field of impact attribution (Perkins-Kirkpatrick et al.,



2024), this research shows how integrating qualitative causal mapping with quantitative modelling provides a practical
390 pathway for advancing impact attribution where observational data are limited.

4.3 Key limitations and future research directions

There are several limitations that underly this work. With regard to the qualitative approach, this study uses a limited number
of KII's. Whilst all KII's had relevant experience in the study region, the strong weight of KI's towards academic researchers
395 and humanitarian responders has potential for a biased perspective, failing to represent the viewpoint of marginal groups in
the CLD (Singh et al., 2025). Moreover, the perspectives of local communities or government officials are not included. Future
research should promote co-production with local stakeholders through participatory methods and reiteration, so that learning
from stakeholders inform model improvements and help to ask relevant societal questions (Nkwasa et al., 2025; Singh et al.,
2025).

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With regards to the quantitative approach, the modelling approach is limited by LULC resolution in combination with the
simplified assumptions representing the hydrological response to LULC change. We represent LULC change primarily by
changing the Manning roughness coefficient value, altering the overland flow. The Manning coefficient itself simplifies and
homogenizes hydrodynamic characteristics (Ong et al., 2017). In our approach, these values are only dependent on the
405 classification of the LULC datasets itself, which involves uncertainty (Lisboa et al., 2024), and are also limited by the spatial
resolution of the data that neglects differences within classes (Shadmehri Toosi et al., 2025). In addition, the interception and
evapotranspiration parameters in the hydrological model are updated based on the LULC class, altering the streamflow.
However, land cover change is a complex process and changes in vegetation can have profound impact on the infiltration
capacity of soil and the rainfall-runoff response of a catchment. (e.g Liao et al., 2023)(Bond et al., 2020; Masoodi & Kraft,
410 2026). Because of the lack of observational data (coastal water levels, rain gauges, and river discharge data) available in the
study area, it is not possible to verify the ability of our modelling approach in representing these changes accurately. A larger
number of local observations would also enable a more thorough validation and calibration of the hydrological and
hydrodynamic model, however, a comparison against remotely-sensed data shows a reasonable performance for flood extent
(Vertegaal et al., 2026). Therefore, our flood modelling results have considerable uncertainty and should be should be
415 interpreted with caution.

Future research directions include improving LULC datasets, the representation of modelled hydrological LULC response,
and extending the attribution framework to identify potential adaptation options. To improve the accuracy and resolution of
LULC data, ground-based trained data to classify land cover rather than Google Earth imagery would help reduce uncertainties
420 in the LULC classifications (Mellor et al., 2015). Higher-resolution LULC data could also help monitor forest degradation
driven by charcoal production and its influence on forest cover loss – a currently under-researched driver of deforestation, and
it's influence on flooding from TC Idai (Abascal et al., 2024; Georganos et al., 2021; Sedano et al., 2016; Xia et al., 2026). A



higher temporal resolution of LULC data can enable studying the effect of change at multiple time scales. In future research, it would be relevant to include additional LULC counterfactual scenarios to identify potential adaptation options and management options for local implementation to reduce future impacts (Boran & Heath, 2016; Grant et al., 2015; Goulart et al., 2025). For example, counterfactual scenarios could access the potential of different land use management strategies, such as reforestation, and income generating measures to ensure communities are less dependent on charcoal production. Further research into the role of LULC changes in amplifying or reducing flood risk will enable a more robust understanding of management options for local implementation (Grant et al., 2015; Lahsen & Ribot, 2022). Research considering the roles of both climate and LULC changes is also needed to understand how these risks change for implementation of cost-effective solutions (Kaluarachchi & Alila, 2026).

5 Conclusion

This research demonstrates the benefits and feasibility of a truly interdisciplinary, mixed-methods approach to the impact attribution of compound flooding, specifically for TC Idai in Mozambique. Quantitative hydrodynamic modelling showed that land use changes can amplify flooding, while the qualitative methods revealed the main socio-economic drivers of impact and contextualized the modelling results. This research exposed under-discussed but crucial drivers of the impacts of TC Idai such as that of charcoal driven deforestation and informal urban land conversions. By employing a mixed-method approach, our study highlights that TC Idai's impacts were not only the result of the intense climatic hazards but also amplified by socio-economic drivers that cannot be understood fully by quantitative models alone.

Our study highlights the need for future research to strengthen the use of mixed-methods approaches for impact attribution and recognizing the role of direct and indirect socio-economic impact drivers. Qualitatively, including participatory approaches of those actually impacted by Idai would gain even greater in-depth localized insights. Quantitatively, refining model parameterisation to better represent the hydrodynamic effects of LULC change, alongside higher-resolution LULC datasets, would improve the attribution accuracy and usefulness for policy insights. In the context of rapid population growth, environmental degradation, increasing climate risks and shrinking international aid, Mozambique faces compounding developmental pressures. Building long-term resilience will require interdisciplinary approaches such as the approach used in this research, to bridge the technical modelling, with more grounded localised understandings.



455 **Code availability**

The scripts used to set up the experiments and resulting output is available at <https://doi.org/10.5281/zenodo.19328562> (Webb et al., 2026).

Supplement link

460 The link to the supplement will be included by Copernicus, if applicable.

Author contributions

PW, DV and SM conceived the idea for this study, jointly designed the experiments, and interpreted initial results. For the quantitative analysis, PW pre-processed the LULC maps and together with DV executed the modelling experiments. For the qualitative analysis, PW contacted the interviewees, developed the interview guides with input from CJ and MV and PW
465 conducted the interviews. For both the qualitative and quantitative analysis, PW conducted the analysis of results. PW wrote the manuscript with input from DV, SM, MV and CJ.

Competing interests

The authors declare that they have no conflict of interest.

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Review statement

485 The review statement will be added by Copernicus Publications listing the handling editor as well as all contributing referees according to their status anonymous or identified.

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