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A novel approach to developing local flood vulnerability scenarios based on the Shared Socioeconomic Pathways framework: Sectoral risks and policy implications

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A R T I C L E I N F O

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A B S T R A C T

Developing locally tailored vulnerability scenarios is crucial for effective flood risk management, yet existing approaches often lack integration with long-term socioeconomic trajectories. To address this gap, the study introduces an innovative methodology that downscales global Shared Socioeconomic Pathways (SSPs) and integrates them with current vulnerability data to create future vulnerability scenarios for key sectors. This approach is applied to Hue City, Central Vietnam as a case study, focusing on health, agriculture, transport, and water, to illustrate its practical application. The findings indicate that under SSP1, characterized by sustainable growth, socio-economic policies focused on sustainability lead to substantial vulnerability reductions across all sectors. Health systems become more resilient, sustainable agricultural practices minimize economic losses, and improved infrastructure reduces transport disruptions and water contamination risks. SSP2 reflects a continuation of current socio-economic trends, resulting in moderate improvements; however, incremental policy changes and resource constraints leave persistent vulnerabilities. In contrast, SSP3, marked by fragmented and poorly managed growth, exacerbates flood risks, where weak healthcare systems, fragile agricultural practices, inadequate transport infrastructure, and minimal water contamination controls intensify flood-related impacts. This study demonstrates the importance of mainstreaming socioeconomic dynamics into flood risk management and offers a transferable framework for scenario-based planning in diverse regional contexts. Future research should aim to quantify vulnerability trajectories, thereby enhancing resilience planning and supporting data-driven decision-making in flood-prone areas.

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1. Introduction

Flooding is a pressing global concern (WMO, 2023; Rentschler et al., 2022). It is exacerbated by the persistent impacts of climate change and human activities, with both the severity and likelihood expected to increase over time (IPCC, 2022a). Specifically, rising global temperatures contribute to more intense precipitation events, rising sea levels, and changing hydrological patterns, all heightening flood risks in urban and rural areas (Hirabayashi et al., 2013). Moreover, rapid urbanization, land-use changes, and inadequate infrastructure further amplify flood hazards, particularly in developing regions where governance and financial constraints hinder effective adaptation (Vu et al., 2025; Tabari et al., 2021; Winsemius et al., 2016).

Given these growing threats, effective flood risk management is crucial to enhancing resilience and minimizing socio-economic losses (Van Wesenbeeck et al., 2017). However, traditional flood risk management approaches often fail to address the complex and interrelated factors that significantly shape vulnerability and resilience (Peck et al., 2022; Awah et al., 2024; Nguyen et al., 2021). These approaches often emphasize engineering solutions, such as levees and drainage systems, while neglecting the broader socio-economic drivers of flood vulnerability, such as social dynamics, governance structures, and demographic shifts (Liao et al., 2019; IPCC, 2022b).

To develop more effective adaptation strategies, it is essential to incorporate future flood vulnerability scenarios that account for socio-economic trends (Garschagen and Kraas, 2010; Birkmann et al., 2015; Birkmann et al., 2021; Puntub et al., 2023). These scenarios are crucial for guiding long-term adaptation planning as they explore how different socio-economic trajectories may influence future flood vulnerabilities (Garschagen et al., 2021). In this context, the Shared Socioeconomic Pathways (SSPs) describe possible future societal states based on projected changes in key drivers such as demographics, economic development, governance, technology, and societal values (O'Neill et al., 2014), thereby providing a structured basis for examining how these socio-economic conditions could exacerbate or mitigate future flood risks (Petzold et al., 2024).

The SSPs framework was initially developed for global-scale projections, with five SSP scenarios ranging from sustainable and equitable growth (SSP1) to fragmented and unequal development (SSP3 and SSP4), and resource-intensive pathways (SSP5) (Riahi et al., 2017; O'Neill et al., 2014; O'Neill et al., 2017). However, to better align with local needs, the growing recognition of the importance of region-specific climate adaptation strategies has led to a stronger focus on extending the SSPs framework from its original global-scale narratives to sub-national, local, and regional contexts. In this approach, often referred to as "extended SSPs" the global socio-economic storylines are adapted and enriched with locally relevant details, data, and drivers to ensure that the scenarios meaningfully reflect local realities (Absar and Preston, 2015). For example, research in Flensburg, Germany, adapted the global SSPs for local adaptation planning by modeling the potential impacts of different socio-economic pathways on local risks like coastal flooding (Reimann et al., 2021). A study on Tokyo adapted the global SSPs framework to create three future pathways, addressing local challenges like an aging population and urban regeneration, focusing on sustainability priorities such as energy efficiency, local culture, and social capital (Kamei et al., 2016). In Mumbai, India, a participatory scenario approach was applied to downscale the global SSPs, creating localized narratives for future urban development (Petzold et al., 2024). A significant study by Kok et al. (2019) extended the global SSPs to create region-specific scenarios for Europe, reflecting the expected socio-economic and environmental changes in the region. Additionally, a participatory co-design process in the UK extended SSPs by incorporating relevant socio-economic drivers, adding geographic, sectoral, and temporal details to improve their applicability for local climate resilience planning (Harmáčková et al., 2022).

Beyond SSP scenarios, scenario-based approaches more broadly are valuable tools for assessing global environmental change, as they allow researchers and decision-makers to explore a range of plausible futures under varying socio-economic, environmental, and governance conditions (Cradock-Henry and Frame, 2021). Such approaches help identify potential risks, trade-offs, and opportunities, particularly under conditions of deep uncertainty, thereby supporting more robust and adaptive policy planning. Among them, vulnerability scenarios are especially important for assessing the specific risks and impacts that these pathways may entail, particularly in relation to local contexts. Given their role in understanding future risks (O'Neill et al., 2022), vulnerability scenarios complement socio-economic scenarios by explicitly linking socio-economic and environmental changes to the exposure, sensitivity, and adaptive capacity of specific systems or communities (Birkmann et al., 2015). This makes them highly relevant for translating global-scale narratives into actionable local adaptation strategies. However, only a limited number of studies have developed such scenarios to inform local risk management and adaptation strategies. For example, Birkmann et al. (2020) created heat stress vulnerability scenarios in Ludwigsburg, Germany, using both participatory and quantitative methods, emphasizing the influence of socio-economic factors such as population growth and urbanization. Similarly, Garschagen and Birkmann (2014) employed participatory methods to identify key drivers of vulnerability scenarios in Jakarta, Indonesia, while a recent study by Puntub et al. (2023) focused on local heat vulnerability scenarios in Bonn, Germany. Despite these advances, existing approaches often face challenges in capturing long-term trends and systemic changes, which are essential for credible and relevant scenario planning. In this study, we argue that, although extended SSPs offer socio-economic change scenarios, they have not yet been effectively applied in developing sector-specific vulnerability scenarios. Bridging this gap requires new methodologies that integrate downscaled SSPs with detailed vulnerability assessments for specific sectors.

This study introduces a novel methodology to develop vulnerability scenarios for key sectors within the SSPs framework. Using Hue City, a highly flood-prone mid-sized city in Central Vietnam, as a case study, the study aims to achieve two main objectives: (1) Developing local SSPs narratives from global SSPs frameworks, incorporating key socio-economic, environmental, governance, and technological drivers; (2) Creating future flood vulnerability scenarios to understand how different SSP pathways might affect key vulnerable sectors, including health impacts, rice livelihood disruptions, transport disruptions, and water contamination.

2. Description of the case study: Hue City, Central Vietnam

Hue City (Fig. 1a) is located in Central Vietnam, between latitudes 16° and 16.8° North and longitudes 107° and 108.2° East. Spanning approximately 5033 km^2, it is home to around 1.3 million residents, with population growth projected in the coming decades (TTH, 2023). Formerly known as Thua Thien Hue Province, Hue City was officially established as a centrally governed city following Resolution No. 175/2024/QH15 issued by the National Assembly of Vietnam. Hue City features a diverse geography, including coastal lagoons and plains dominated by rice fields and mixed woodlands, hilly midlands primarily covered by acacia plantations, and mountainous uplands with natural forests interspersed with some plantations (Vu et al., 2023).

Hue City is an important economic region in Central Vietnam, with a growing emphasis on tourism and service provision. The city, with its historic architecture and status as a UNESCO World Heritage site, is a major tourist destination, contributing significantly to the local economy (TTH, 2023). However, it is also marked by socio-economic disparities, particularly between urban and rural areas, and between the mountainous regions and the coastal plains (Le et al., 2021). Urbanization in Hue City is ongoing, with significant infrastructure projects to improve connectivity and support economic growth (TTH, 2023). Notably, as of January 2025, Hue City has officially transitioned into a

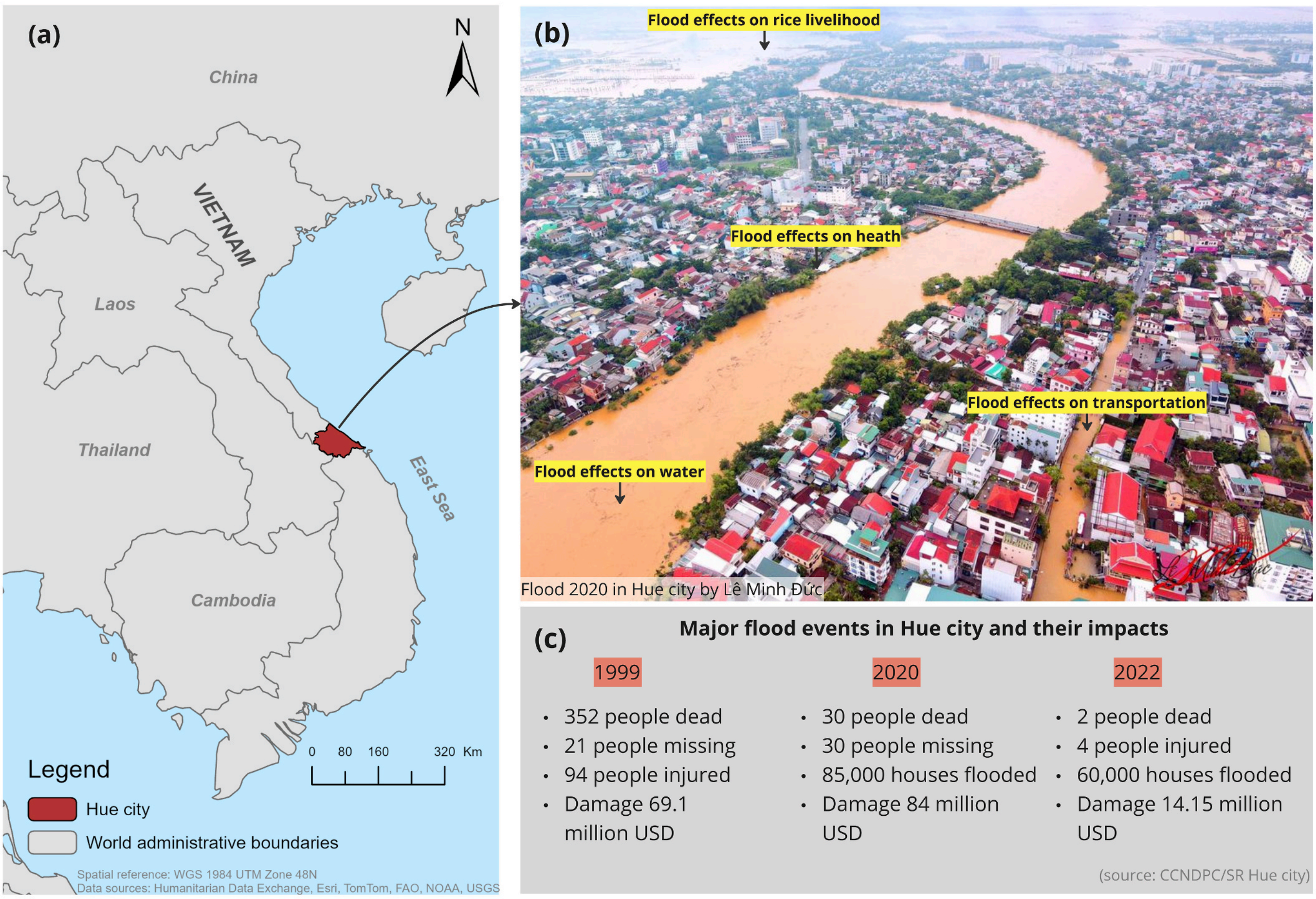

Fig. 1. (a) Case study of Hue City, Central Vietnam; (b) Flood event 2020 in Hue City; (c) Flood impact statistics in Hue City.

centrally governed city, providing a dynamic context for examining shifting socio-economic trends. This transition will bring notable changes in governance, economic policies, and urban development, further influencing the city's resilience to climate-related challenges.

Hue City frequently faces severe flooding, particularly during the rainy season from October to December (TTH, 2020). The low-lying coastal areas and river systems are especially prone to overflowing during heavy rains and typhoons. These floods often significantly damage to public health, rice-based agriculture, transportation, and water resources, causing widespread disruptions to daily life and economic activities (Sett et al., 2024). This is evident in the major flood events in Hue City, such as those in 1999, 2020, and 2022, which caused significant loss of life, widespread property damage, and economic challenges (Fig. 1b–c). In response, the city government has initiated planning efforts and is prioritizing climate resilience in future development planning (TTH, 2020, 2023; Vu et al., 2025).

3. Methodology

Qualitative and quantitative approaches exist for developing future vulnerability scenarios (de Ruiter and Van Loon, 2022; Fuchs et al., 2012). Qualitative scenarios often rely on expert judgment, stakeholder engagement, and narrative development to explore potential futures (de Ruiter and Van Loon, 2022; Garschagen & Birkmann, 2014). Quantitative scenarios, on the other hand, use models such as Agent-Based Modelling and statistical techniques to project future conditions based on current trends (Riddell et al., 2019; Preston, 2013; Acosta-Michlik and Rounsevell, 2012). However, quantifying scenarios presents challenges due to the lack of future socio-economic data (Ford et al., 2018; Birkmann et al., 2020). Qualitative methods offer a robust alternative for creating plausible and context-specific vulnerability scenarios, providing a more nuanced understanding of vulnerability (Garschagen and Birkmann, 2014; de Ruiter and Van Loon, 2022). Additionally, the qualitative approach compensates for the uncertainty in quantitative projections by capturing socio-political uncertainties that numerical models often overlook (Pye et al., 2018). This study, therefore, adopts a qualitative approach to develop flood vulnerability scenarios, employing a structured methodology that encompasses three primary stages (see Fig. 2).

3.1. Local SSP scenarios development

The initial stage focuses on developing SSP narratives specifically tailored for Hue City, projecting to the year 2050 (Fig. 2a). The selection of this timeframe aligns with the provincial development strategy of Hue City and Vietnam's national policies on climate change adaptation and disaster risk reduction, which have long-term visions extending to 2050, ensuring coherence with broader policy objectives. To achieve this, a combined process is used that integrates desk-based research, expert consultations, and scenario workshops with stakeholders. This iterative approach ensures that the SSP narratives for Hue City are grounded in both global and local contexts. The detailed methodology for developing local SSPs includes three steps as follows:

Step 1: Downscaling global SSPs to local context

Global SSP scenarios are downscaled to the local context by tailoring them to the specific conditions of Hue City. These narratives are aligned with local policies and address the unique vulnerabilities and adaptive capacities of Hue City. The local SSPs account for key factors that have

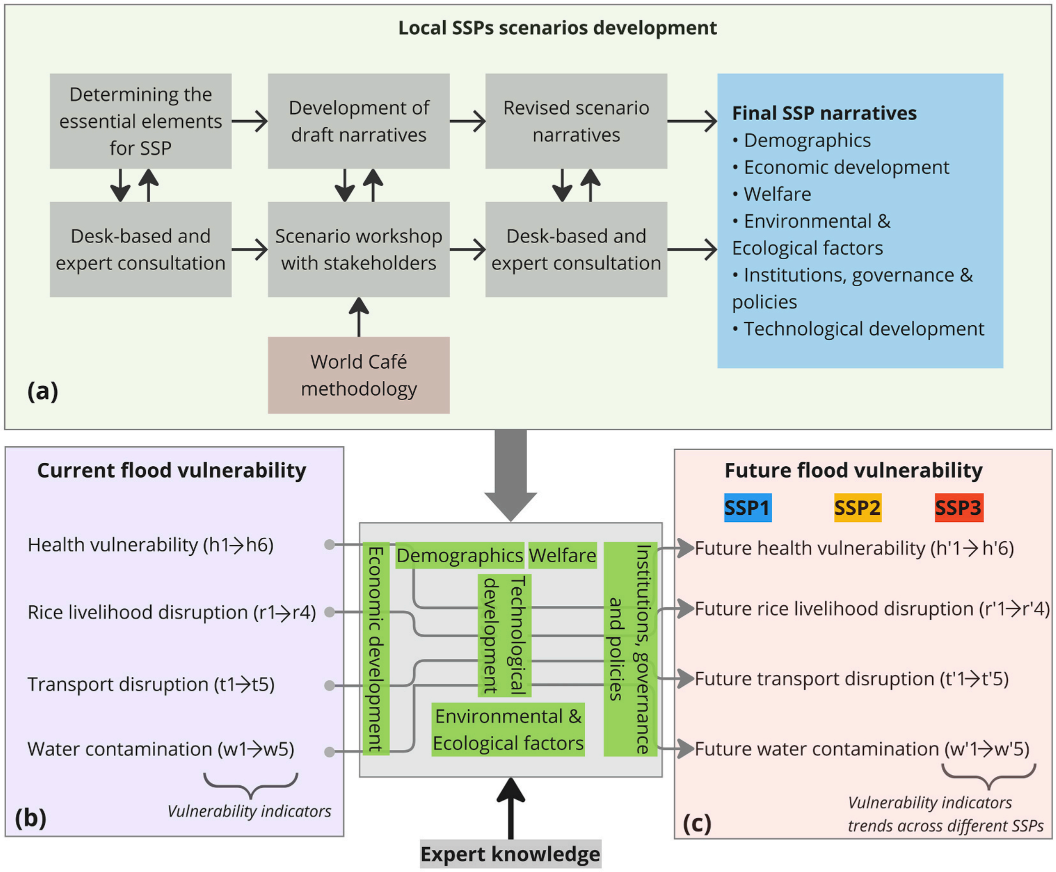

Fig. 2. Process for developing flood vulnerability scenarios narrative. Panel a) shows the process of developing SSPs-based scenarios. Panel b) presents current flood vulnerability across sectors. Panel c) shows future flood vulnerability under SSP1, SSP2, and SSP3 for each sector.

been classified in line with the nine standard SSP socio-economic categories (O'Neill et al., 2014), including demographics, economic development, welfare, environmental and ecological factors, institutions/governance/policies, technological development, and other locally relevant drivers. In this study, some categories have been merged or adapted to better capture the most pertinent local drivers for Hue City, while maintaining conceptual consistency with the SSP framework. Fig. 3 illustrates the configuration of local SSP scenarios.

Moreover, the initial phase of scenario development included a selection process to identify the most suitable SSP narratives for downscaling. In this study, SSP1, SSP2, and SSP3 were chosen as the most relevant for addressing the spectrum of adaptation challenges and potential socio-economic futures in Hue City. Importantly, this selection was also informed by stakeholder consultations, where local experts and decision-makers consistently emphasized SSP1-3 as the most plausible and relevant pathways for Hue. SSP4 and SSP5 were excluded from this study as they were considered of less relevance for the Vietnamese context by assuming context conditions with either low challenges on climate change mitigation (SSP4) or low challenges to climate change adaptation (SSP5). They were also considered to be too far away from current policy direction to be debatable as serious scenarios. That is, SSP4 assumes a rather weak national government, much in contrast to the given political goal (National Assembly of Vietnam, 2021), and SSP5 assumes development that is mainly driven by fossil fuels, contradicting current zero-emission goals (Vietnam, 2022). As discussed in Section 5.1, excluding of SSP4 and SSP5 is recognized as a methodological limitation that may have narrowed the range of plausible futures explored. Following this selection, a comprehensive desk-based literature review was undertaken to inform the development of the initial scenarios (see Section A in Supplementary material S1). The review covered national and city policy documents, socio-economic development plans, climate change and disaster risk strategies, and sectoral development frameworks, which together provided the contextual foundation for tailoring the global SSPs to Hue City's conditions.

Step 2: Scenario workshop

In July 2022, we organized the first SSPs workshop, bringing together key local stakeholders (n = 18) to explore the initial scenario narratives developed in the first step. Building on the insights gained, a second SSPs workshop was conducted in 2023 (n = 15) to facilitate in-depth discussions and refine the developed scenarios. The second workshop involved the same group of experts as the first workshop.

The March 2023 workshop employed the World Café methodology (Löhr et al., 2020; Silva and Guenther, 2018). Participants from various sectors, including government, NGOs, community members from affected communes, scientific institutions, and practitioners, were identified and invited to participate in the workshop. This diverse representation was crucial to ensuring that the developed scenarios were comprehensive and inclusive of different perspectives. Participants were divided into three groups, each focusing on one of the tailored scenarios: Strong and sustainable growth (SSP1), Current trends continue (SSP2), and Partially controlled growth and fragmentation (SSP3). Each group was assigned a table, where discussions were guided by a Vietnamese-speaking facilitator to ensure that all participants could engage fully in their native language. This setup was particularly important for fostering open and inclusive dialogue, which was essential for capturing the nuanced views and insights of local stakeholders.

The discussion process was structured so that each group spent 40 minutes on their assigned scenario before rotating to the next table. This ensured that all participants had the opportunity to contribute to each scenario. During these discussions, participants were encouraged to

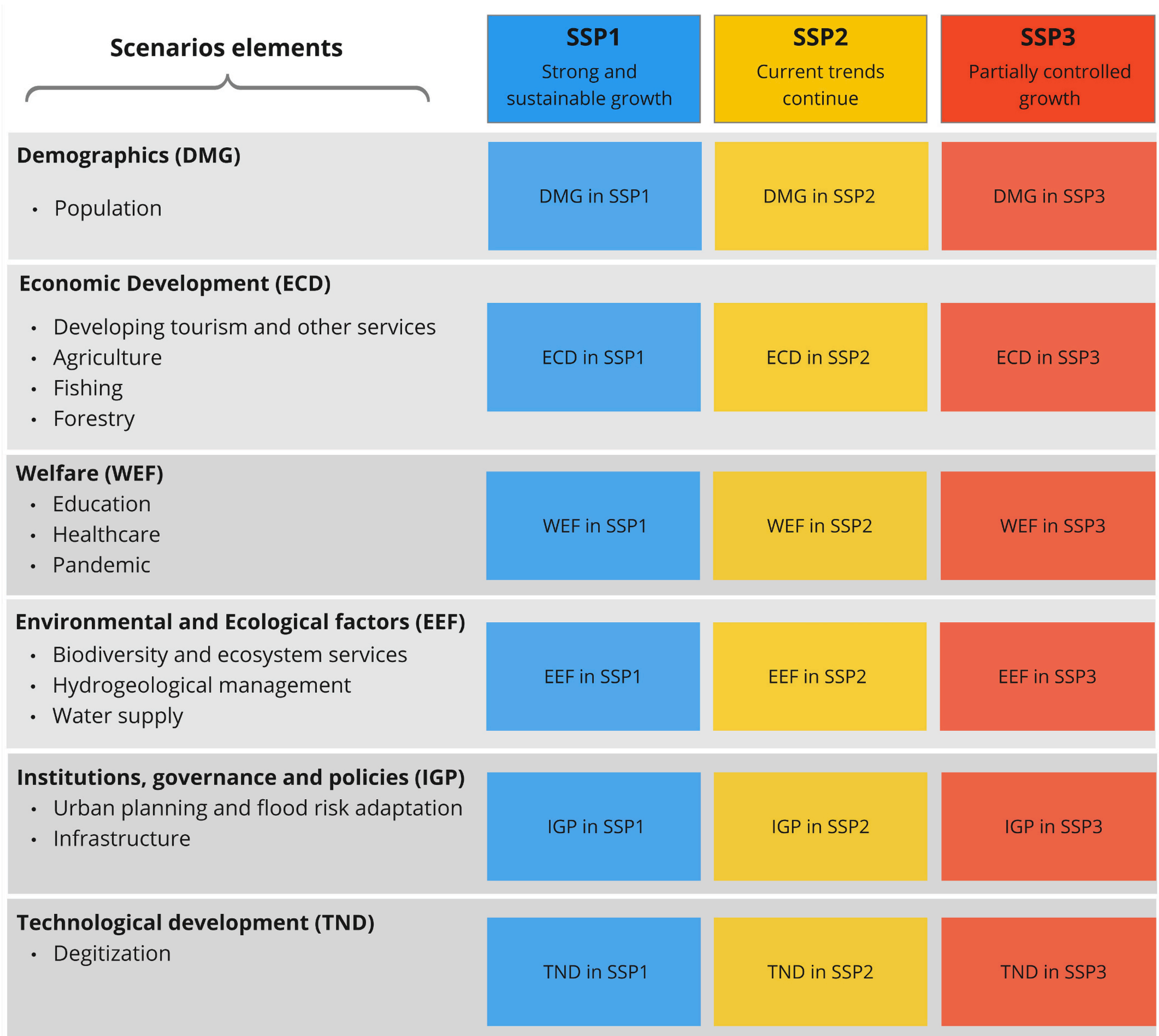

Fig. 3. Configuration of local SSP scenarios, with the left column outlining key elements of extended SSPs, and the three right columns depicting the trends of these elements under each scenario.

explore several key areas: the relevance of additional drivers or sectors to the scenario, the identification of cross-paths or interactions between different scenarios, and potential amendments based on their local expertise. The facilitators documented the key points of each discussion on flip charts, ensuring that all insights were captured for further analysis.

Step 3: Post-workshop analysis and scenario refinement

The final step in the scenario development process involved a detailed analysis of the workshop outputs. The documentation from the discussions was thoroughly reviewed to further refine the scenarios. In addition to these discussions, we also incorporated newly issued legal documents published after the second SSPs workshop (see Section B in Supplementary material S1). Finally, we shared the final versions of the SSPs with experts who participated in the second workshops for their review and validation to ensure the scenarios were relevant, plausible, and feasible.

3.2. *Current vulnerability indicators*

The integration of current flood vulnerability data, as reported by Sett et al. (2024) and Sett et al. (2025), is a crucial step in this study. Sett et al. (2024) and Sett et al. (2025) have identified specific indicators of vulnerability across four key sectors: health impacts, rice livelihood disruptions, transport disruption, and water contamination (Fig. 2b). These indicators provide a detailed framework for understanding the socio-economic and environmental vulnerabilities relevant to the context of Hue City. The current flood vulnerability data serves as a reference scenario for developing future vulnerability scenarios. The current vulnerabilities of the four sectors are detailed in Supplementary material S4. Table 1 summaries and explains of the key vulnerability indicators for each sector used in this study.

3.3. *Flood vulnerability scenarios development*

The final stage involves developing detailed flood vulnerability

Table 1
Summary of flood vulnerability indicators across key sectors.

Vulnerability indicators	Explanation
1. Health vulnerability	
Age susceptibility *(h1)*	Older populations and children are more vulnerable to flood-related health impacts.
Health conditions *(h2)*	Pre-existing health conditions can exacerbate the effects of flooding.
Access to health services *(h3)*	Limited or disrupted access to healthcare can delay or worsen health outcomes.
Response behavior *(h4)*	Community preparedness and behavior during floods affect health outcomes.
WASH (Water, Sanitation, and Hygiene) practices *(h5)*	Poor hygiene and sanitation increase risks of waterborne diseases after floods.
Building conditions *(h6)*	Poor housing conditions can increase exposure to flood-related health risks, such as injury or illness.
2. Rice livelihood disruption	
Dependence on agriculture *(r1)*	Households heavily reliant on rice farming are more vulnerable to livelihood disruptions from floods.
Crop insurance adoption *(r2)*	Lack of insurance leaves farmers more vulnerable to financial losses due to crop failure.
Ecosystem health *(r3)*	The health of local ecosystems, including soil and water quality, affects rice productivity.
Agricultural practices *(r4)*	Traditional or unsustainable farming methods may exacerbate the impact of floods on rice production.
3. Transport disruption	
Response behavior *(t1)*	Risky actions like driving through flooded areas stem from low risk awareness and poor early warning systems, increasing vulnerability.
Transport dependency *(t2)*	Heavy reliance on transport heightens vulnerability, as many depend on it for daily needs and livelihoods.
Individual transportation options *(t3)*	Limited personal transport restricts evacuation and access to services, raising vulnerability during floods.
Public transportation alternatives *(t4)*	Lack of reliable public transport increases risks during floods.
Road conditions *(t5)*	Poorly maintained roads are more prone to flood damage, disrupting mobility.
4. Water contamination vulnerability	
Waste treatment capacity *(w1)*	Limited capacity to treat waste increases the risk of water contamination during floods.
Fertilizers and pesticides *(w2)*	Runoff from excessive use of chemicals in agriculture can contaminate floodwaters.
Disposal of livestock *(w3)*	Unsafe disposal of livestock waste can lead to water contamination.
Harmful materials *(w4)*	Industrial and household waste, including chemicals, can enter water systems during floods.
Ecosystem health *(w5)*	Poor ecosystem health weakens the natural ability to filter and reduce water contamination during floods.

scenarios (Fig. 2c) based on the SSPs narratives (Section 3.1) and the four key areas of current vulnerability (Section 3.2). These scenarios project future vulnerabilities by analyzing how different SSP pathways might influence vulnerability indicators across the four sectors. This includes examining future trends in vulnerability indicators and understanding the underlying drivers of these changes.

Flood vulnerability scenarios are developed with input from 11 experts across four key sectors: public health (n = 2), agriculture (n = 3), transportation and urban planning (n = 3), and environmental science (n = 3). The development follows a two-round expert consultation process, structured as follows:

- Round 1: Expert opinions were gathered through semi-structured interviews regarding the trends in vulnerability indicators across the four key sectors. Experts discussed the primary drivers of these trends, which helped build an initial framework for how these indicators might evolve under different SSP scenarios.
- Round 2: Experts were provided with the trends and drivers identified in Round 1. They assessed the relevance and accuracy of these factors and suggested modifications or additional elements that might influence future vulnerabilities. This round facilitated the refinement of both trends and drivers, aiming to reach a consensus on the most important trends and factors affecting future flood vulnerabilities.

4. Results

4.1. Local SSP scenario narratives and their crucial role in enhancing flood risk management

In this section, the SSP scenarios for Hue City in 2050 are presented, each representing different development trajectories and their impact on flood risk management. Fig. 4 summarizes the local SSPs, highlighting key socio-economic, environmental, governance, and technological trends. Detailed information on these trends is provided in Supplementary material S2, with the full narratives available in Supplementary material S3.

SSP1: Strong and sustainable growth: "*Hue City follows a path of robust, sustainable growth driven by green development and innovation. Economic prosperity flourishes through eco-friendly tourism and agriculture, while investments in education and healthcare enhance social equity and climate resilience. Advanced technologies, nature-based solutions, and integrated urban planning strengthen flood management and sustainability. With balanced economic, social, and environmental priorities, SSP1 envisions Hue City as a model of resilient, inclusive, and sustainable development*".

SSP1 provides a compelling example of how a strong commitment to sustainable growth, environmental stewardship, and social equity can substantially reduce vulnerability to floods. The scenario shows that when socio-economic policies prioritize long-term sustainability and environmental health, the resulting investments in flood management infrastructure and innovative technologies are both effective and wide-reaching (Dawson et al., 2011). The proactive approach described in SSP1, where there is significant emphasis on education, healthcare, and environmentally friendly practices, not only strengthens the city's infrastructure but also enhances the adaptive capacity of the population. This aligns with the findings of Shah et al. (2018), who highlight the importance of integrating sustainability and social equity into disaster risk reduction efforts. In this context, SSP1 demonstrates that sustained and well-coordinated efforts across economic and social sectors, while considering the environment, are essential for reducing flood vulnerability. This scenario highlights that sustainable growth is not merely an environmental issue but a comprehensive development strategy that integrates economic progress with social welfare and disaster resilience (Grobicki et al., 2015).

SSP2: Current trends continue: *"Hue City maintains moderate growth but faces limitations in fully realizing green development. While tourism, agriculture, and fishing sectors progress, sustainability challenges persist. Social welfare improves, but disparities remain, particularly for vulnerable populations. Infrastructure and environmental initiatives advance but lack full effectiveness due to funding and engagement gaps. Urbanization increases pressure on flood mitigation efforts, resulting in suboptimal adaptation strategies. SSP2 portrays a scenario of steady but constrained development, where balancing growth with sustainability remains a challenge".*

SSP2 reflects the difficulties that arise when economic growth is prioritized without fully integrating sustainability into development strategies. Although there are improvements in infrastructure and social services, the progress is uneven and insufficient to fully mitigate flood risks. This scenario demonstrates the limitations of a business-as-usual approach, where improvements are made but not at the scale or speed required to significantly reduce vulnerabilities. The moderate

Fig. 4. Overview of SSP1, SSP2, and SSP3 scenarios for Hue City in 2050 (Credits for background photos: SSP1-2 by B.T.V; SSP3 by Hue-S).

advancements seen in SSP2 emphasize the need for more comprehensive and equitable policies that can address the disparities in resilience across different sectors and populations (Meerow et al., 2019; Gan et al., 2021). This scenario suggests that without a strong commitment to equity and inclusivity, economic development can inadvertently exacerbate vulnerabilities, particularly for marginalized communities (Eriksen et al., 2021). The findings from SSP2 underline the importance of integrating climate adaptation measures into all aspects of development planning, rather than treating it as a separate issue (Lebel et al., 2012).

SSP3: Partially controlled growth and fragmentation: "*Hue City faces economic stagnation and growing disparities due to fragmented development. Migration intensifies, increasing urban density while investments in rural areas decline. Tourism and agriculture struggle, constrained by environmental degradation and market limitations. Social services, including healthcare and education, deteriorate, exacerbating inequality. Infrastructure and digitalization lag, while environmental sustainability efforts remain weak. Unplanned urban expansion and inadequate flood protection heighten vulnerabilities, making SSP3 a scenario of increasing socio-economic and environmental risks*".

SSP3 paints a stark picture of what could happen if socio-economic development is poorly managed and fragmented. While the global SSP3 narrative (O'Neill et al., 2017) describes overall low and poorly managed urbanization, the Hue-specific storyline anticipates rapid but poorly planned urban growth (Bachofer et al., 2025). This divergence reflects differences between global averages and local realities: in Hue, rural economic decline and environmental degradation are likely to intensify rural-to-urban migration (Nguyen et al., 2015), increasing urban density despite limited capacity for effective urban management.

The scenario highlights how inadequate investments in infrastructure, combined with socio-economic fragmentation, can severely exacerbate flood vulnerabilities. In SSP3, the lack of cohesive planning, insufficient resources for flood management, and uncontrolled urban expansion could lead to high levels of susceptibility to flood impacts. This scenario is particularly concerning in the context of rapid urbanization and demographic shifts, which are likely to increase the pressure on already strained resources. The findings indicate that, without coordinated policy interventions and targeted investments, the risks of flood damage, exacerbated by fragmented socio-economic development and urban expansion, will likely lead to increased vulnerability and greater social inequality (Djalante et al., 2013; Thapa et al., 2022). Therefore, it calls on policymakers to strengthen governance, improve coordination across government levels, and ensure urban planning includes comprehensive flood risk assessments (Van Herk et al., 2011).

4.2. Sectoral analysis of flood vulnerability scenarios

4.2.1. Future flood vulnerability scenarios for health impacts

Table 2 compares health vulnerability across SSPs scenarios, highlighting the underlying factors and key expert insights regarding future health vulnerability under each SSP. Experts highlight that under SSP1, strong healthcare investments and infrastructure improvements reduce health risks, supported by universal healthcare access and well-funded public health programs. Under SSP2, uneven healthcare funding and moderate public awareness lead to inconsistent access and response behaviors, with slow progress in infrastructure and building resilience. Under SSP3, low healthcare investment and weak disaster preparedness exacerbate health crises, particularly in marginalized communities, with poor infrastructure and urban planning further increasing vulnerability.

The stark contrast between future health vulnerability scenarios under SSP1 and under SSP3 highlights the critical role of robust healthcare systems and public health initiatives in flood risk management. Under SSP1, significant investments in healthcare infrastructure, coupled with widespread public education, lead to a reduction in health vulnerabilities. This scenario illustrates the effectiveness of proactive public health measures in enhancing community resilience to floods, aligning with the findings of Shah et al. (2020), who emphasize the importance of effective health systems in disaster risk reduction. On the other hand, under SSP3, the health sector exposes the severe consequences of neglecting healthcare investments. Poor health conditions and inconsistent access to healthcare exacerbate the population's vulnerability to flood-related health issues, a finding consistent with the work of Van Minh et al. (2014) and Gan et al. (2021). This comparison highlights that without substantial and sustained investment in health infrastructure, populations will remain highly vulnerable to the health

Table 2
Future health vulnerability across SSPs.

Vulnerability indicators	Underlying factors	Key expert insights into future health vulnerability		
		SSP1	SSP2	SSP3
Age susceptibility	Social support system; Demographic structure	Significant investments in healthcare and proactive population planning improve support for vulnerable groups.	Healthcare improvements are inconsistent, and vulnerable populations receive limited support during floods.	Health care access depends on individual capacity, with disparities leaving vulnerable groups at higher risk during floods.
Health conditions	Healthcare investment; Public health programs	Well-funded hospitals and healthcare systems improve overall health, enhancing resilience to flood impacts.	Healthcare infrastructure improves, but many areas remain unprepared for flood-related health emergencies.	Inconsistent healthcare access increases health vulnerabilities during floods, with limited resources for emergencies.
Access to health services	Rural-urban disparities; government spending; healthcare infrastructure	Universal healthcare and well-equipped facilities ensure all residents, including flood-prone areas, have access to essential health services.	Healthcare services are inadequate in many areas, lacking the capacity to manage flood-related health impacts.	Access to healthcare is inconsistent, worsening health risks during floods due to resource and funding shortages.
Response behavior	Risk perception; Community engagement; Disaster preparedness programs	Increased disaster prevention education leads to better public awareness and improved response behavior during floods.	Disaster preparedness improves slightly, but response behavior remains poor due to limited focus on education.	Poor public awareness and limited education result in inadequate disaster preparedness and response behaviors.
WASH practices	Sanitation policies; Public hygiene awareness; water supply infrastructure	Investments in water supply and sanitation reduce the risk of waterborne diseases during floods.	Water supply and sanitation improve, but issues persist in some areas, and unsafe WASH practices continue.	Water quality issues persist, with illegal waste dumps and pollution exacerbating health risks during floods.
Building conditions	Urban planning; construction regulations; Investment in flood-resilient housing	Adoption of environmentally friendly building practices reduces damage and injuries during floods.	Infrastructure improvements are slow, and many buildings remain vulnerable to flood damage.	Poor building conditions persist, leading to increased risks and injuries due to inadequate infrastructure development.

impacts of floods. It also suggests that health policies should prioritize disaster preparedness and resilience, integrating these elements into broader public health strategies to protect vulnerable populations.

4.2.2. Future flood vulnerability scenarios for rice livelihood disruption

Table 3 examines the vulnerability of rice livelihood disruption across SSP scenarios, emphasizing the underlying factors and expert insights on the potential future impacts under each SSP. Experts highlight that under SSP1, economic diversification through eco-tourism and services reduces agricultural dependence and flood risks. High crop insurance adoption, supported by strong policies, provides financial protection. Enhanced ecosystem health and modern farming techniques mitigate flood damage and improve sustainability. Under SSP2, limited diversification leads to moderate agriculture dependency, with partial insurance coverage and mixed ecosystem health. Ecosystem degradation risks from urbanization and inconsistent crop adoption increase flood vulnerability. Under SSP3, heavy reliance on agriculture, low insurance adoption, and poor ecosystem health heighten flood-related disruption risks, with low technological adoption and weak support systems.

The analysis of rice livelihood disruptions underscores the importance of sustainable agricultural practices and the adoption of risk mitigation strategies, such as crop insurance, in reducing vulnerabilities. Under SSP1, the agricultural sector demonstrates that resilient agricultural practices, including the adoption of flood-tolerant crop varieties and widespread crop insurance, significantly reduce the sector's vulnerability to floods (Akter et al., 2022; Aina et al., 2024). These findings suggest that agricultural policies should prioritize sustainability and resilience to safeguard food security in flood-prone regions. In contrast, under SSP3, farmers reliance on sensitive high-yield crops and the absence of crop insurance highlight the increased risk of livelihood disruptions. This scenario points to the dangers of short-term agricultural practices that prioritize immediate yield over long-term resilience, a trend that could exacerbate vulnerabilities in the face of climate change (Kuchimanchi et al., 2021). The results suggest that policymakers need to incentivize the adoption of resilient agricultural practices and develop comprehensive insurance schemes that protect farmers from the economic impacts of floods (Falco et al., 2014; Swain, 2014).

Table 3
Future rice livelihood disruption vulnerability across SSPs.

Vulnerability indicators	Underlying factors	Key expert insights into future rice livelihood vulnerability		
		SSP1	SSP2	SSP3
Dependence on agriculture	Economic diversification; Alternative income.	Strong agricultural policies and diversified economies reduce dependency on agriculture, ensuring food security and resilience.	Moderate diversification in agriculture leads to reduced but persistent dependency, especially in rural communities.	High reliance on agriculture continues, with limited diversification, increasing vulnerability to climate shocks.
Crop insurance adoption	Accessibility of insurance; Financial policies; Farmer awareness	Wide access to crop insurance ensures protection against climate risks, supporting farmers' resilience.	Access to crop insurance remains limited, with uneven coverage leading to varied protection for farmers.	Minimal access to crop insurance and lack of risk management strategies increase farmers' vulnerability to climate extremes.
Ecosystem health	Industrial impact; Land-use management; Environmental policies	Investment in ecosystem restoration and conservation enhances resilience and supports agricultural productivity.	Ecosystem health declines slightly, with moderate conservation efforts, affecting agricultural outputs and biodiversity.	Severe degradation of ecosystems leads to loss of biodiversity and increased agricultural vulnerability.
Agricultural practices	Technological adoption; Access to resilient crop varieties; Agricultural extension programs	Climate-resilient crop varieties and sustainable farming practices reduce sensitivity to climate extremes.	Crops become more sensitive to climate changes due to moderate adaptation efforts, affecting yields.	High crop sensitivity to climate change with minimal adaptation efforts, leading to significant yield losses.

4.2.3. Future flood vulnerability scenarios for transport disruption

Table 4 analyzes transport disruption vulnerability across SSP scenarios, focusing on the underlying factors and expert insights on future transport disruption vulnerability under each SSP. Experts highlight that under SSP1, strong disaster preparedness and public awareness ensure effective response behaviors, minimizing disruptions. Low transport dependency, achieved through economic diversification and alternative transport modes, enhances resilience. Well-maintained roads and flood-resilient infrastructure reduce disruption risks. Under SSP2, moderate disaster preparedness and mixed transport dependency increase exposure to disruptions. Inconsistent infrastructure investment and uneven public transport coverage leave key routes vulnerable. Under SSP3, weak disaster preparedness, high transport dependency, and poor infrastructure investment exacerbate transport disruptions, with poor road conditions further increasing flood risks.

The findings related to transport disruption reveal the critical importance of integrating flood resilience into transportation planning and infrastructure development. In SSP1, substantial investments in sustainable transport options and infrastructure lead to a more resilient transportation system, which is better equipped to handle the disruptions caused by floods. This scenario illustrates the value of forward-thinking infrastructure planning that incorporates climate adaptation measures, ensuring that transportation networks remain functional during and after flood events. Conversely, under SSP3, poor road conditions and lack of public transportation alternatives highlight the vulnerabilities that arise from inadequate infrastructure planning and investment. These results stress that without adequate investment in resilient infrastructure, transportation systems will remain vulnerable to disruption, which can have cascading effects on economic activity, emergency response, and overall community resilience (Kurth et al., 2020). Policy-makers should therefore prioritize the development of flood-resilient transportation systems, integrating these considerations into all stages of infrastructure planning and development (Merk, 2024).

4.2.4. Future flood vulnerability scenarios for water contamination

Table 5 presents water contamination vulnerability across SSPs scenarios, focusing on the underlying factors and expert insights on future water contamination vulnerability under each SSP. Experts highlight that under SSP1, strong investments in wastewater infrastructure, sustainable farming practices, and effective waste management minimize contamination risks. Strict regulation of hazardous materials, coupled with a healthy ecosystem, further reduces risks. Under SSP2, moderate wastewater treatment capacity, inconsistent fertilizer and pesticide use, and weak waste management lead to moderate contamination risks. Ecosystem health is stable but threatened by urbanization and industrial expansion. Under SSP3, poor wastewater treatment, unregulated chemicals, and inadequate waste management exacerbate contamination, while a degraded ecosystem worsens water quality and flood mitigation.

The sectoral analysis of water contamination risks highlights the critical role of environmental management and pollution control in reducing flood-related health risks. In SSP1, the water sector focuses on enhancing waste treatment capacity and reducing harmful agricultural practices. This leads to a significant reduction in water contamination risks, aligning with the findings of Ingrao et al. (2023) and Juncal et al. (2023). This scenario demonstrates that investments in environmental infrastructure and the promotion of sustainable practices can significantly mitigate the public health impacts of water contamination during floods. In contrast, under SSP3, low investments in waste treatment and continued use of harmful materials result in high contamination risks, exacerbating the vulnerability of communities to waterborne diseases during flood events. This scenario underscores the dangers of neglecting environmental management and the need for robust policies that address pollution control and sustainable waste management. Effective environmental policies should prioritize the protection of water resources and the reduction of contamination risks, particularly in regions vulnerable to flooding (Sinisi and Aertgeerts, 2011; Zuniga-Teran et al., 2021).

5. Discussion

5.1. Reflections on methodology: strengths, limitations, and future directions

A key methodological contribution of this study is its explicit linkage between participatory scenario development and sector-specific vulnerability assessments, implemented through a structured expert consultation process. Similar to the iterative Delphi method described in Flood et al. (2023), this approach involved repeated expert engagement, allowing for the iterative validation and refinement of socio-economic narratives. Through continuous involvement of experts across multiple rounds of feedback, this method ensured that the scenarios were contextually grounded and analytically connected to vulnerability indicators. In contrast to prior studies that often rely on one-time stakeholder input or generic scenario narratives, this approach emphasizes co-production through repeated expert engagement. We therefore consider the outputs to have high validity, as the iterative process allowed for triangulation across diverse knowledge sources. As a result,

Table 4
Future transport disruption vulnerability across SSPs.

Vulnerability indicators	Underlying factors	Key expert insights into transport disruption vulnerability		
		SSP1	SSP2	SSP3
Response behavior	Disaster preparedness programs; Public awareness; Emergency management	High levels of public awareness and community engagement lead to proactive disaster response behaviors.	Moderate awareness programs result in inconsistent response behaviors, especially in vulnerable areas.	Limited awareness and poor preparedness contribute to ineffective disaster response behaviors.
Transport dependency	Economic diversification; Access to alternative transport modes	Efficient and diversified transport systems reduce dependency, promoting resilience and accessibility.	Moderate transport systems reduce dependency, but many areas still rely on traditional transport networks.	High dependency on traditional transport systems increases vulnerability to disruptions, especially in rural areas.
Individual transportation options	Technological accessibility; Infrastructure investment; Affordability	Widespread access to private vehicles ensures mobility, enhancing resilience to disruptions.	Limited access to private vehicles leads to reliance on public transport, which is less flexible.	Low access to private vehicles and poor public transport systems increase vulnerability to transport disruptions.
Public transportation alternatives	Government policies; Urban planning; Transport network expansion	Strong investment in public transport alternatives ensures equitable mobility and reduces transport dependency.	Moderate availability of alternatives reduces dependency, but access is limited in less urbanized areas.	Minimal investment in public transport alternatives leaves many regions with limited mobility options.
Road conditions	Road maintenance funding; Flood-resilient infrastructure; Hydrometeorological systems	Well-maintained roads and infrastructure ensure smooth mobility and reduce disruptions during emergencies.	Road conditions are moderate, with some areas prone to disruptions due to limited infrastructure maintenance.	Poor road conditions and lack of infrastructure investment significantly disrupt mobility and exacerbate vulnerabilities.

Table 5
Future water contamination vulnerability across SSPs.

Vulnerability indicators	Underlying factors	Key expert insights into water contamination vulnerability		
		SSP1	SSP2	SSP3
Waste treatment capacity	Drainage infrastructure; Investment in wastewater treatment	Strong investments in waste treatment infrastructure ensure effective waste management and reduced environmental impact.	Moderate investments in waste treatment improve capacity but challenges in maintenance persist.	Low investment in waste treatment leads to poor management and increased pollution risks.
Fertilizers and pesticides	Fertilizer regulations; Sustainable farming practices; Agricultural policies	Sustainable fertilizer use, guided by policy and regulation, ensures agricultural productivity without compromising the environment.	Moderate fertilizer use continues with some regulation, leading to mixed environmental impacts.	Excessive fertilizer use without regulation leads to environmental degradation and health risks.
Disposal of livestock	Livestock waste management policies; Enforcement of disposal regulations	Effective livestock waste management systems ensure minimal environmental impact and support sustainable farming.	Moderate waste management practices reduce risks but do not fully address livestock waste disposal.	Inadequate waste disposal systems lead to contamination of water and soil, increasing health risks.
Harmful materials	Public awareness; Industrial waste control; Hazardous waste regulations	Strict regulation and management of harmful materials reduce exposure and environmental risks.	Moderate regulations help manage harmful materials, but improper disposal and gaps in enforcement persist.	Weak regulation and improper disposal lead to widespread contamination and public health risks.
Ecosystem health	Conservation efforts; Urbanization impacts; Land-use planning	Investment in ecosystem restoration and conservation supports biodiversity and reduces environmental degradation.	Ecosystem health is moderately preserved, but degradation continues due to limited conservation efforts.	Severe degradation of ecosystems leads to loss of biodiversity and increased vulnerability to climate impacts.

sectoral risks are identified with greater precision, and the scenarios produced are more robust, credible, and directly usable for informing policy and adaptive planning (Bauer et al., 2017; Popp et al., 2017).

In addition, the downscaling of global SSPs to the local context using the World Café method created a structured space for dialogue, enabling stakeholders to iteratively refine scenario narratives and enhance their credibility and policy relevance (Löhr et al., 2020). Relevance was strengthened by aligning scenario content with locally identified vulnerability factors and sectoral policy priorities, ensuring that the narratives addressed issues of immediate concern to decision-makers. This participatory approach aligns with previous research emphasizing co-created adaptation planning as a means to enhance the legitimacy and applicability of climate risk assessments (Döll and Romero-Lankao, 2017). Legitimacy was supported by the inclusive engagement of diverse stakeholders including local government, technical experts, and community representatives, although we acknowledge that the voices of certain marginalized groups may have been underrepresented – potentially influencing which futures were prioritized. This potential bias is explicitly recognized as a caveat when interpreting the scenarios.

The methodology also benefits from a mixed-methods approach, combining SSPs narratives with current vulnerability information. The SSPs approach allows for a context-specific understanding of vulnerability evolution (Birkmann et al., 2020), while current vulnerability indicators provide empirical grounding for the constructed scenarios (Jones and Mearns, 2005). Another major strength of this study is its ability to identify the underlying factors driving vulnerability across key sectors through a structured analytical approach. The identification of these drivers is particularly valuable for policymakers, as it allows for targeted interventions that address the root causes of vulnerability rather than just their immediate consequences (Sett et al., 2024).

Despite these strengths, one key methodological limitation must be acknowledged. It relates to the selection of SSP1, SSP2, and SSP3 and the exclusion of SSP4 and SSP5 in this study. The initial rationale for this choice was to align with Vietnam's current adaptation priorities and policy directions. We acknowledge that this decision inevitably omits certain plausible futures. Global and supra-national dynamics, such as persistent inequality patterns or continued global reliance on fossil fuels, could still have substantial effects on Hue City's vulnerability, regardless of national ambitions. This choice partly reflects the reasoning in Frame et al. (2018), who excluded SSP2, the middle-of-the-road pathway, from their assessment of New Zealand in order "to test sensitivity to alternative socio-economic futures" that diverge more from current trends. The omission of SSP2 in their work helped to avoid a convergence towards median outcomes and encouraged the exploration of a broader range of extremes. In our case, the inclusion of SSP2 provides a baseline for comparison, but the exclusion of SSP4 and SSP5 may have narrowed the diversity of challenges examined and made the scenario set more aligned with policy objectives or optimistic futures. This limitation is further compounded by the fact that, while SSP3 introduces adverse conditions such as regional fragmentation and weaker institutional capacity, these may not fully reflect the severity of challenges described in SSP4 or SSP5. Moreover, SSP3 may still be closer to a constrained version of current trends than to a truly confronting or disruptive future, and therefore might be less effective in prompting critical reflection beyond business-as-usual assumptions. Carlsen et al. (2024) emphasize that maintaining diversity in scenario conditions, including those that are less desirable or more extreme, is essential for ensuring internal consistency and robustness in scenario-based climate risk assessments. Although our approach is consistent with previous downscaling efforts that have used fewer than five SSPs for contextual relevance (for example Kamei et al., 2016; Kok et al., 2019; Petzold et al., 2024), we recognize the value of including SSP4 and SSP5 in future studies. Doing so would enable the testing of adaptation strategies under more adverse and divergent conditions, expanding the scenario set to capture high inequality and high emission trajectories and providing a fuller range of challenges for local adaptation planning.

Finally, while this study deliberately focused on developing qualitative scenarios, we see future research opportunities in integrating quantitative modeling approaches. Such approaches, such as Agent-Based Modeling and Bayesian Network modeling, could allow for the estimation of probabilistic flood risks, quantification of uncertainty ranges, and improved causal analysis of socio-economic drivers and flood impacts (Anshuka et al., 2022; Zwirglmaier and Garschagen, 2024).

5.2. *Mainstreaming SSPs-based vulnerability scenarios in flood risk governance*

The integration of SSPs-based vulnerability scenarios into flood risk management policies presents an opportunity to enhance long-term resilience planning by systematically considering socio-economic trajectories alongside climate adaptation strategies (Rojas et al., 2013). To ensure effective mainstreaming of SSPs-based vulnerability scenarios, a structured integration approach within flood risk management frameworks is necessary (Kok et al., 2019). This requires embedding socio-economic scenario analysis into local and national planning systems to systematically assess how different development pathways influence flood vulnerability. For example, aligning socio-economic pathways with climate adaptation policies through strategic planning can help decision-makers proactively mitigate emerging risks rather than reacting to them retrospectively (Prall et al., 2023). Additionally, scenario-based risk assessments should be incorporated into national disaster risk management strategies, allowing policymakers to evaluate the implications of varying development trajectories on flood risks (Vu et al., 2025; Nguyen et al., 2021; Garschagen et al., 2021).

Additionally, mainstreaming SSPs-based vulnerability scenarios into global disaster risk governance is essential for achieving cohesive and sustainable resilience strategies. Two major global frameworks, the Sendai Framework for Disaster Risk Reduction (SFDRR) 2015 to 2030 and the Sustainable Development Goals (SDGs), provide critical opportunities for embedding socio-economic scenario-based flood risk management into global resilience policies. Integrating SSPs-based flood risk assessments within SFDRR's priority areas, particularly Priority 2 (Strengthening disaster risk governance) and Priority 3 (Investing in disaster risk reduction for resilience), can enhance global risk governance by systematically incorporating socio-economic development pathways into disaster preparedness planning (UNDRR, 2015). Similarly, SSPs-based vulnerability assessments can significantly contribute to the advancement of the SDGs, particularly Sustainable Cities and Communities (SDG 11) and Climate Action (SDG 13). Integrating flood vulnerability scenarios into urban planning and climate resilience policies supports the goal of making cities more resilient and adaptive to climate-related hazards while also enhancing adaptive capacity to climate-induced extreme events (Sun et al., 2022). Additionally, the cross-cutting nature of SSPs enables their integration into broader development objectives such as No Poverty (SDG 1) and Reduced Inequalities (SDG 10) by illustrating how socio-economic disparities shape flood vulnerabilities, thereby guiding more inclusive and equitable adaptation measures.

A key requirement for mainstreaming SSPs into policy frameworks is enhancing cross-sectoral coordination between socio-economic planning, infrastructure development, and environmental governance. Policy fragmentation, where flood risk management is treated as a standalone issue, often leads to inefficiencies and maladaptive outcomes (Schipper, 2020). Collaboration across multiple governance levels, including national agencies, provincial authorities, and local stakeholders, fosters better alignment between flood adaptation strategies and broader socio-economic goals (Wamsler et al., 2014). Another crucial aspect of mainstreaming local SSPs into policy is institutional capacity-building and the development of adaptive governance mechanisms. Given that socio-economic conditions are dynamic and continuously evolving, policy frameworks must remain flexible and capable of adjusting to new information (Vu et al., 2025). This requires institutional learning processes (Ison et al., 2014), where scenario-based insights inform iterative policy adjustments rather than being treated as static assessments. Embedding participatory scenario planning approaches within governance structures can also improve decision-making by ensuring that policies reflect the needs and perspectives of diverse stakeholders, including vulnerable communities, private sector actors, and local governments (Collins and Ison, 2009). Integrating SSPs-based vulnerability scenarios into funding mechanisms is key to long-term implementation. Policymakers should use SSPs insights to guide risk-sensitive investments in infrastructure, land-use planning, and economic development. Financial incentives, such as tax benefits or resilience bonds, can also encourage private sector alignment with sustainable development (Vu et al., 2025). Finally, enhancing data integration and knowledge-sharing is crucial for implementation (Mohammed Zain et al., 2023). Open-access databases consolidating socio-economic scenarios, climate projections, and vulnerability assessments can support evidence-based policymaking and improve coordination among stakeholders, ensuring SSPs-based flood risk analyses remain updated and accessible.

5.3. Transferability and lessons learned to other regions

The findings provide valuable insights that can inform research and planning for vulnerability scenarios in other regions. The approach, which integrates SSP pathways with sectoral vulnerability analysis, can be adapted to various contexts for more effective flood risk assessment and management. A key takeaway is the demonstrated value of incorporating socio-economic dimensions into flood management strategies, particularly when adapting these strategies to different regional contexts, as supported by previous studies (Surminski et al., 2020; ADB, 2022). As Brouwer et al. (2007) highlight, flood vulnerability is closely linked to local economic conditions, social equity, and the community's capacity to adapt. This emphasizes the need for flood management efforts to go beyond technical solutions and include a thorough understanding of socio-economic dynamics (Auerswald et al., 2019; Klijn et al., 2021). Such a holistic approach is not only crucial for the region studied but also applicable to other areas facing similar challenges, ensuring that interventions are both technically effective and socially inclusive.

Additionally, the success of the SSP1 scenario highlights the centrality of sustainability in reducing flood vulnerability. Embedding sustainable practices into policy frameworks, including promoting resilient agricultural methods, strengthening healthcare infrastructure, enhancing transport systems, and implementing nature-based approaches such as wetland restoration, mangrove rehabilitation, and green infrastructure, can lead to substantial reductions in vulnerability (Sunkur et al., 2023; Junqueira et al., 2022). This emphasis on long-term sustainability rather than short-term economic gains can serve as a guiding principle for other regions. However, despite the potential benefits of sustainable development pathways like those in SSP1, several challenges may impede their full implementation, including limited financial resources, political constraints, and the institutional capacity of local authorities. These obstacles are not exclusive to Central Vietnam and must be carefully assessed when adapting similar strategies to other regions, particularly those with distinct governance frameworks or economic conditions (Vu et al., 2025). The findings also illustrates the critical need for cross-sectoral coordination. The interdependencies between sectors (Sett et al., 2024) such as health, agriculture, transportation, and water management observed in the analysis indicate that isolated interventions may not be as effective as integrated, cross-sectoral approaches. Addressing vulnerabilities in one sector can have positive ripple effects on others, creating a more resilient overall system. Applying these insights enables other regions to develop more resilient flood management strategies that are tailored to their socio-economic contexts while also benefiting from integrated planning and sustainability-driven development.

6. Conclusion

This study has introduced an innovative approach to developing future flood vulnerability scenarios within the SSPs framework. The results indicate that socioeconomic factors are critical in determining future flood vulnerabilities. Scenarios that emphasize sustainable development (SSP1) demonstrate significant reductions in vulnerability through investments in infrastructure, healthcare, agriculture, and water management. Meanwhile, scenarios reflecting moderate growth and continuity of current trends (SSP2) show incremental improvements across sectors but underscore lingering vulnerabilities due to limited policy changes and resource constraints. In contrast, scenarios characterized by fragmented growth (SSP3) reveal higher vulnerabilities across sectors, highlighting the dangers of inadequate planning and investment. Furthermore, this study highlights the importance of mainstreaming SSPs-based vulnerability scenarios into flood risk governance and broader policy frameworks.

One of the most significant outcomes of this study is its methodological advancement in flood risk research. By downscaling global SSPs narratives to fit regional contexts, the study ensures that vulnerability scenarios capture localized economic trends, governance structures, and environmental challenges, making them more relevant for decision-making. The integration of sectoral breakdowns enhances the practical applicability of findings, allowing policymakers to identify targeted interventions that align with sector-specific risks.

Beyond its direct findings, the methodological approach employed in this study offers transferable insights for other regions facing similar flood risks. The structured integration of vulnerability indicators with scenario-building techniques provides a replicable framework that can be adapted to different geographic and socio-economic contexts. The study also highlights the importance of identifying underlying factors driving vulnerability to improve adaptation strategies beyond conventional flood risk assessments. However, while the approach provides a strong foundation, future research should incorporate quantitative modeling techniques to complement qualitative scenario-building.

Declaration of Generative AI and AI-assisted technologies in the writing process

After drafting the text, the authors used QuillBot to improve the language and readability of the text. Subsequently, the authors reviewed and edited the content manually to assure that language edits made by QuillBot had not introduced changes the meaning or content of text. The authors take full responsibility for the content of the published article.

CRediT authorship contribution statement

Bien Thanh Vu: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Olabisi S. Obaitor:** Writing – review & editing, Validation, Methodology, Investigation. **Antje Katzschner:** Writing – review & editing, Validation, Methodology, Investigation. **Lena C. Grobusch:** Writing – review & editing. **Dominic Sett:** Writing – review & editing. **Andrea Ortiz-Vargas:** Writing – review & editing. **Michael Hagenlocher:** Writing – review & editing. **Ulrike Schinkel:** Writing – review & editing. **Felix Bachofer:** Writing – review & editing, Funding acquisition. **Linh Khanh Hoang Nguyen:** Writing – review & editing. **Matthias Garschagen:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gloenvcha.2025.103079.

Data availability

Summary data is in the supplementary information. Raw data is confidential under our ethics agreement, but anonymized data may be available upon request for result verification.

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