

Flood Risk Management in the Face of Climate Change: Strategic Spatial Planning for Integrating River Basin Management and Residual Risk

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Abstract

In response to the impacts of climate change, the increasing risk of flooding has traditionally been addressed by identifying flood-prone areas using floodplain maps to regulate land development. However, the interconnected dynamics of runoff in the river basin and levee effect have highlighted the potential threats posed by residual flood risk. Consequently, this paper integrates residual risks and flood source areas into flood risk management within the river basin. Utilising the SOBEK model, this study simulates three flood scenarios—without levees, with existing levees, and with failed levees—to conduct flood hazard analysis and flood source-to-impact analysis. Based on these findings, this paper proposes land use management strategies aimed at enhancing water resilience through strategic spatial planning in the face of climate change.

Keywords: flood risk management, spatial planning, residual risk, flood source area, SOBEK model

1. Introduction

As climate change escalates, the frequency and severity of extreme rainfall events are increasing significantly. Taiwan's extensive and mountainous terrain, characterised by steep slopes and fast-flowing rivers, presents significant challenges for water retention, often resulting in frequent flooding. Traditionally, flood threats like these have been mitigated through structural flood control measures designed to protect urban areas. However, research into the "levee effect" indicates that reliance on structural flood control in flood-prone areas can foster a false sense of security among governmental bodies and local communities. This misplaced confidence may cultivate an illusion of enduring immunity from flooding, thereby accelerating development within floodplains and consequently amplifying long-term flood risks (Di Baldassarre et al., 2018; Ding et al., 2023). Moreover, as climate change intensifies, not only do the frequency and intensity of extreme rainfall events increase, but the existing standards of flood protection facilities also reach their limits, failing to entirely eliminate flood risk (Associated Programme on Flood Management, 2017). Incidents surpassing these thresholds may result in levee overtopping or breaches, representing significant residual flood risks (Serra-Llobet et al., 2022). In light of this, there has been an increased focus on the importance of non-structural measures in flood risk management. The Intergovernmental Panel on Climate Change (IPCC) in its Sixth Assessment Report advocates a holistic approach that integrates both structural and non-structural measures in managing flood-prone zones. Serra-Llobet et al. (2022) emphasise the effectiveness of regulatory flood maps in reducing exposure and vulnerability by either prohibiting or limiting development in high-risk areas.

In the context of disaster management, it is emphasised that disaster mitigation can be achieved through spatial planning, thus minimising flood risk (Hartmann, Slavíková, and Wilkinson, 2022). In the integration of spatial planning and flood risk management, flood hazard analysis often utilises flood maps as a basis for risk assessment in land management policies for flood-prone areas. However, these maps are only the final output of hydrological modelling, which

leads to the formation of flood-prone areas not only due to natural topographic factors, but also as a result of human development, which is a significant driver of flooding. Changes in land use due to development reduce the infiltration capacity of the soil, thereby increasing surface runoff and peak flood volumes (O'Donnell and Thorne, 2020). Furthermore, when considering the spatial scale of entire river basins, there are flood risk externalities within the system: land development changes in upstream areas are likely to increase flood threats downstream, demonstrating the spatial interconnectivity between flood source areas and flood impact areas (Seher and Löschner, 2018; Chang, H.-S., & Hsueh, P.-R., 2023).

In conclusion, traditional spatial planning has predominantly focused on identifying flood-prone areas using flood maps. However, this approach frequently overlooks the residual flood risk associated with levee failures and the equitable distribution of runoff within comprehensive river basin management. Consequently, this paper aims to address the limitations of considering only flood-prone areas in flood risk assessment. It examines the variances in flood hazard levels both with and without levees and explores the residual risks should these defences fail. Additionally, this study integrates river basin management to reassess the spatial correlations between flood source areas and flood impact areas, aiming to develop strategic spatial planning to meet the challenges posed by climate change.

Initially, this study will establish three flood simulation scenarios: without levees, with existing levees, and with failed levees. Subsequently, through flood hazard analysis, it will generate flood hazard maps for each scenario, considering changes in flood spatial distribution and land use. This process will also entail the creation of a Composite flood risk zone map that categorises areas into high, medium, and low flood risk zones. Moreover, a flood source-to-impact analysis will chart the spatial distributions of flood sources areas and flood impact areas within the river basin for each scenario. Based on these variations in spatial distribution under each scenario, a comprehensive flood source area map will be developed.

Following this, the study will develop land use management strategies predicated on varying flood risk levels and outline responsibilities for flood management in primary flood source areas. These measures are crucial for flood risk management strategies in response to the challenges posed by climate change. Ultimately, this paper will simulate four flood risk management scenarios: no change, a land use management policy based on flood risk zones, flood responsibility in primary flood source areas, and a combination of land use management policy and flood responsibilities. The study will evaluate changes in flood risks across these scenarios and devise strategic spatial planning based on flood risk assessment.

2. Methodology

To explore the residual flood risk associated with levee failure and the spatial relationship between flood source areas and impact areas within the river basin management, this study will employ the SOBEK model as the flood simulation software. The SOBEK model, jointly developed by Taiwan's Water Resources Agency and the Dutch company WL|Delft Hydraulic, is also the model used for creating the current flood inundation maps in Taiwan. As shown in Figure 1, the research will establish three flood simulation scenarios: without levees, with existing levees, and with failed levees (Figure 1a). It will then conduct a flood hazard analysis and produce a composite flood source and impact analysis a flood source-to-impact analysis (Figure 1c). The study will formulate land use management strategies based on different flood risk zone levels identified in the Composite flood risk zone map, and assign flood responsibility in the primary flood source areas depicted in the composite flood source area map, as part of the main flood risk management strategies in response to climate change challenges (Figure 1d).

Finally, the study will simulate and compare the outcomes under four flood risk management strategies scenarios: no change, a land use management policy based on flood risk zones, flood responsibility in primary flood source areas, and a combination of land use management policy and flood responsibilities (Figure 1e). It will assess the more effective flood risk management strategies.

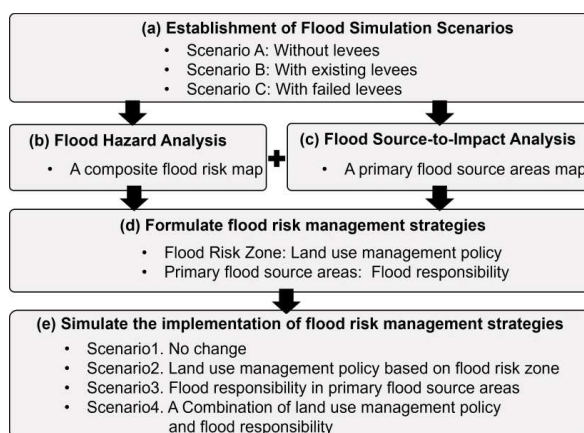


Figure 1. Research framework

2.1 Establishment of Flood Simulation Scenarios

This study will establish three flood simulation scenarios as shown in Figure 2, to explore the variations in flood hazard levels and the spatial distribution of flood source areas and flood impact areas with and without flood defence infrastructure, as well as under conditions of defence failure. Scenario A "Without levees" assesses the flooding situation under a 200-year return period rainfall scenario without any flood control infrastructure, representing the "inherent flood risk" of the area. Scenario B "With existing levees" evaluates the flooding situation under the current flood defence standards for a 200-year return period, representing the "existing flood risk" of the area. Scenario C "With failed levees" assesses the flooding situation when levees are overtopped, exceeding the 200-year return period flood defence standards, with climate change or extreme rainfall events used as the simulation rainfall scenarios, representing the "residual flood risk" of the area.

The outcomes of scenario A "Without levees" and B "With existing levees" will reflect the changes in the spatial distribution of flood risks with and without flood defence infrastructure, identifying areas where flood hazard levels are inherently high despite reduced flooding due to the construction of defences. The outcomes of scenario B "With existing levees" and C "With failed levees" will reflect the flood threats posed by levee failure under future climate change rainfall scenarios or extreme rainfall events, highlighting areas where residual flood risks are overlooked due to the protection afforded by flood defences.



Figure 2. Flood Simulation Scene Setup

2.2 Flood Hazard Analysis

As shown in Figure 3, this study utilises the SOBEK model to simulate three flood scenario settings and conducts flood hazard analysis to explore the variations in flooding under conditions with and without levees, as well as in cases of levee failure. Initially, three flood hazard maps will be generated: one for without levees, one for existing levees, and one for failed levees (Figure 3a). Scenario A "Without levees" reflects the inherent flood risk based on topography without any flood control measures, showcasing areas with high flood hazard due to natural geographical factors. Scenario B "With existing levees" illustrates the existing flood risks under the current 200-year return period flood protection standards, where flooding still occurs. Scenario C "With failed levees" displays the residual risks in the event of levee overtopping during future climate change-driven rainfall or extreme rainfall events, highlighting areas with potential flood threats.

Subsequently, an overlay analysis of the flood hazard maps from the three scenarios will be conducted (Figure 3b). This analysis will particularly focus on comparing scenario A "Without levees" and B "With existing levees" to identify areas where flood situations have decreased due to the construction of levees but still possess inherent high flood hazard. It will also compare scenario B "With existing levees" and C "With failed levees" to pinpoint areas at risk of flooding beyond the protection standards during climate change-induced or extreme rainfall events. Lastly, by overlaying information on land use map, current land use status, and future development plans, a Composite flood risk zone map will be drawn (Figure 3c). This map will categorise areas into high, medium, and low flood risk zones, serving as a foundation for formulating spatial flood risk management strategies.

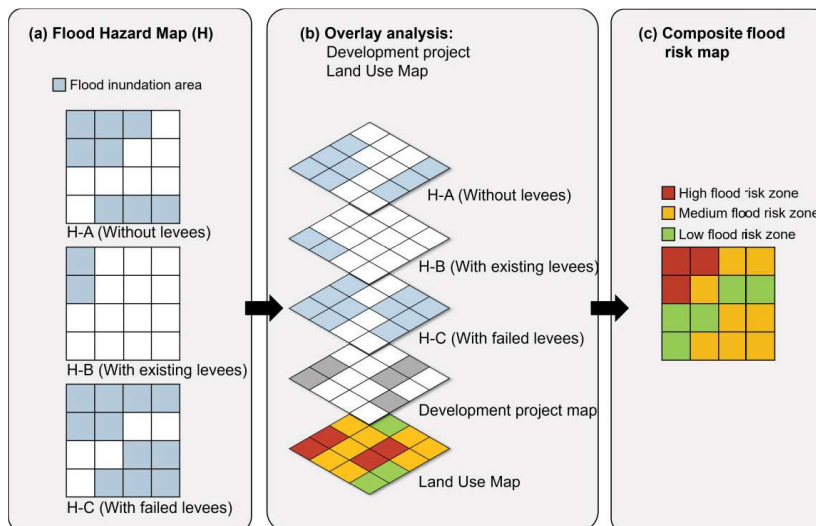


Figure 3. Flood hazard analysis research design

2.3 Flood Source-to-Impact Analysis

Considering the interconnected impact of surface runoff within river basin, it is challenging to distinctly delineate flood source areas from impact areas due to the mutual influences of runoff across upstream, midstream, and downstream regions. This study will employ the Flood Source-to-Impact Analysis (Vercruyssen et al., 2019; Chang, H.-S., & Hsueh, P.-R., 2023) as illustrated in Figure 4, to re-examine the flood volumes generated by flood source areas and the spatial distribution of impact areas within the river basin.

- (i) Divide Calculation Grid: Grids are delineated based on regional topography and land use;
- (ii) Baseline Rainfall Scenario (BS): Simulates surface runoff under a baseline rainfall scenario with uniform rainfall across all grids, resulting in a flood depth (Fd_{BS}^R);
- (iii) Grid i Rainfall Scenario (i): Sets zero rainfall for a specific grid ' i ' (meaning no rainfall in grid ' i ') while maintaining uniform rainfall across the remaining grids to simulate surface runoff, resulting in a flood depth (Fd_i^R). This step is repeated sequentially for each grid treated as grid ' i ';
- (iv) Flood Source Identification: Compares the Baseline Rainfall Scenario with the Grid i Rainfall Scenario. The difference in surface runoff distribution between the two scenarios ($F_i = Fd_{BS}^R - Fd_i^R$), identifies the contribution of grid ' i ' to flood generation in other grid units.

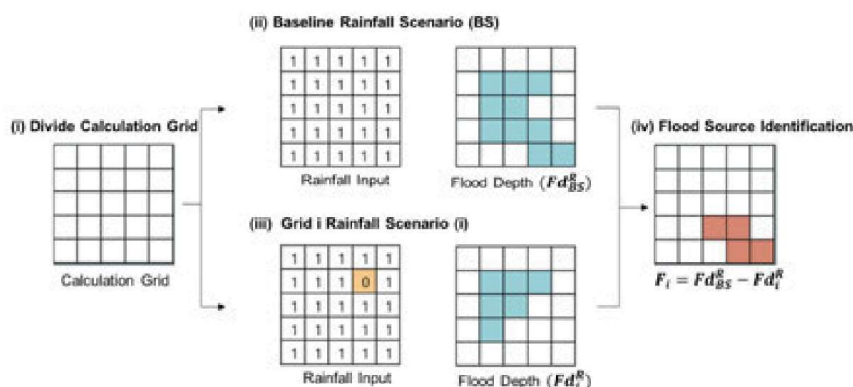


Figure 4. Illustration of Flood Source-to-Impact Analysis
Source: Verduyck et al., (2019); Chang, H.-S., & Hsueh, P.-R., (2023)

As illustrated in Figure 5, this research has established three flood simulation scenarios for conducting flood source-to-impact analysis, resulting in the production of three maps of flood source and impact areas under conditions of without levees, with existing levees, and with failed levees (Figure 5a). Subsequently, an overlay analysis of these three maps will be performed to compare the flood source areas and flood impact areas across the scenarios. This analysis assesses the changes in the spatial distribution of flood source and impact areas under conditions with and without levees and in various rainfall scenarios. Additionally, this analysis includes overlaying data on land use map and land development map (Figure 5b) to identify the main and undeveloped flood source locations. Finally, a composite flood source area map will be created (Figure 5c), which will serve as the basis for formulating responsibilities for flood responsibility in primary flood source areas.

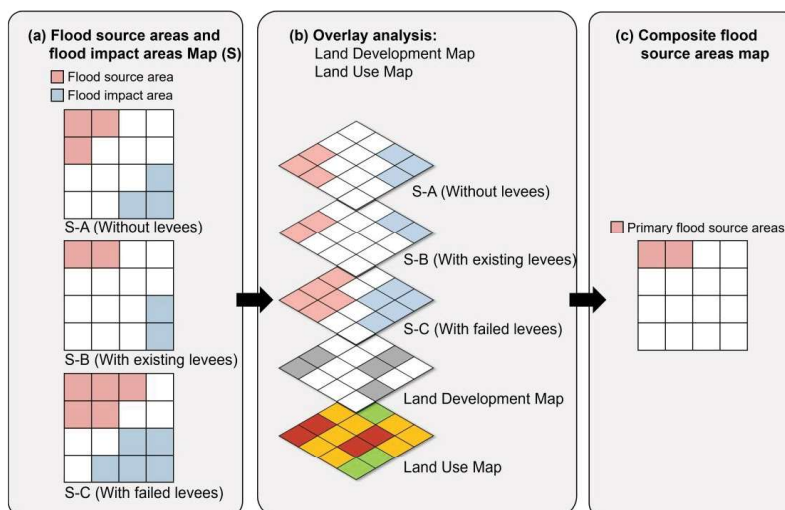


Figure 5. Flood Source-to-Impact Analysis research design

2.4 Formulate Flood Risk Management Strategies

The Composite flood risk zone map considers areas facing potential flood threats during climate change rainfall scenario or extreme rainfall events; the composite flood source area map identifies primary flood source areas likely to develop in the future. To implement strategic spatial planning based on flood risk, this study will formulate appropriate land management strategies for different flood risk zones: high flood risk areas will be designated as prohibited zones (to prevent new development), medium flood risk areas as restricted zones (allowing new developments but with specified development intensities and required flood mitigation measures), and low flood risk areas as development zones (encouraging concentrated new developments). Additionally, principal flood source areas will be assigned responsibilities for managing the excess runoff, which involves implementing measures to mitigate flooding impacts, thus ensuring equity in managing flood risks in the river basin management. Consequently, this research adopts land use policy for flood risk zone and responsibilities for flood source areas as crucial strategies in spatial flood risk management.

2.5 Simulate the Implementation of Flood Risk Management Strategies

To investigate the variations in flood risk under different flood risk management strategies, this study establishes four flood management strategy scenarios: Scenario 1 "No change" which retains current flood management practices; Scenario 2 "Land use management policy based on flood risk zone," prohibits development in high flood risk zones and restricts development intensity in medium flood risk zones while implementing flood mitigation measures; Scenario 3 " Flood responsibility in primary flood source areas," involves setting flood mitigation measures in primary flood source areas, taking responsibility for excess runoff; Scenario 4 " A Combination of land use management policy and flood responsibility " integrates flood risk zones with flood responsibilities under river basin management. The SOBEK model is used to simulate flooding under these four flood risk management scenarios, comparing changes in flood risk across scenarios to assess the most effective flood risk management strategies in response to flood threats under climate change.

3. Results

This study utilises the SOBEK model to simulate three flood scenarios: without levees, with existing levees, and with failed levees, and conducts flood hazard analysis to simulate flooding for each scenario. This approach offers a more comprehensive inclusion of land flood hazard levels prior to levee construction, as well as considers areas facing potential flood threats from climate change-driven rainfall scenarios or extreme rainfall events. It also considers land use and future major development plans to produce a Composite flood risk zone map, which categorizes areas into high, medium, and low flood risk zones. Additionally, through flood source-to-impact analysis, the spatial relationship between flood source and impact areas within the river basin is re-examined, with consideration of land use and land development to produce a composite flood source area map, identifying primary flood source areas responsible for excessive runoff.

Furthermore, based on the Composite flood risk zone map, the study formulates appropriate land use management strategies to guide suitable land use, preventing high-density development in areas of high flood risk to minimize potential loss of life and economic damage. Preliminary strategies include prohibiting new developments in high flood risk areas, restricting development and implementing flood mitigation measures in medium flood risk areas, and promoting intensive development in low flood risk areas. According to the composite flood

source area map, primary flood source areas should take flood responsibilities, due to their excessive runoff contributing to flooding in impacted areas. Finally, the study simulates flooding under four flood risk management strategy scenarios, assessing the impact of flood risk zones and flood responsibilities, and formulates strategic spatial planning responsive to climate change, effectively reducing flood hazards and equitably distributing excessive runoff.

4. Conclusion

This paper is grounded in a spatial planning perspective, aiming to overcome the constraints imposed by traditional flood inundation maps used for land management in flood-prone areas. It assesses alterations in flood hazard levels under scenarios with and without levees, and in the event of levee failures, redefining the spatial dynamics between flood source areas and flood impact areas from the perspective of river basin management. Three flood simulation scenarios—without levees, with existing levees, and with failed levees—have been established using the SOBEK model for flood simulation. Initially, this research analyses changes in the spatial distribution of flood hazard levels through flood hazard analysis. It identifies areas at potential flood risk, culminating in a Composite flood risk zone map that categorises regions into high, medium, and low flood risk zones. Moreover, flood source-to-impact analysis investigates spatial variations between flood sources and affected areas across these scenarios, resulting in a composite flood source area map that pinpoints primary flood origins. Concurrently, flood risk management strategies are developed based on land use considerations. New developments are prohibited in high flood risk zones; development is constrained, and flood mitigation measures are mandated in medium flood risk zones; responsibilities for managing excess runoff are allocated in primary flood source areas to address the equitable distribution of runoff. This study also evaluates variations in flood risk among different flood risk management strategies.

In conclusion, in response to the severe threats and uncertainties posed by climate change, this research integrates residual flood risks and the spatial relationships between flood sources areas and flood impact areas into comprehensive flood risk management. It advocates for strategic spatial planning based on land flood risk and water management responsibilities. From a land-use management perspective, this strategy aims to prohibit development in high-risk areas, guide appropriate spatial development, and ensure fairness in river basin management by assigning flood responsibility to flood source areas. The objective is to harmonise land development imperatives with flood risk management, thereby establishing a resilient spatial planning framework that is responsive to climate change.

References

Associated Programme on Flood Management (2017) *Selecting Measures And Designing Strategies For Integrated Flood Management*. World Meteorological Organization.

Chang, H.-S., & Hsueh, P.-R. (2023) 'Exploring Flood Characteristics of Source and Impact Areas for Runoff Management - A Case of Yanshuei River Basin', *City and Planning*, 50(4). Available at: [https://doi.org/10.6128/CP.202312_50\(4\).0003](https://doi.org/10.6128/CP.202312_50(4).0003).

Di Baldassarre, G. *et al.* (2018) 'Hess Opinions: An interdisciplinary research agenda to explore the unintended consequences of structural flood protection', *Hydrology and Earth System Sciences*, 22(11), pp. 5629–5637. Available at: <https://doi.org/10.5194/hess-22-5629-2018>.

Ding, M. *et al.* (2023) 'Reversal of the levee effect towards sustainable floodplain management', *Nature Sustainability*, 6(12), pp. 1578–1586. Available at: <https://doi.org/10.1038/s41893-023-01202-9>.

Hartmann, T., Slavíková, L. and Wilkinson, M.E. (2022) *Spatial flood risk management: Implementing catchment-based retention and resilience on private land*. Cheltenham, UK: Edward Elgar Publishing. Available at: <https://doi.org/10.4337/9781800379534>.

O'Donnell, E.C. and Thorne, C.R. (2020) 'Drivers of future urban flood risk', *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 378(2168), p. 20190216. Available at: <https://doi.org/10.1098/rsta.2019.0216>.

Scher, W. and Löschner, L. (2018) 'Balancing upstream–downstream interests in flood risk management: experiences from a catchment-based approach in Austria', *Journal of Flood Risk Management*, 11(1), pp. 56–65. Available at: <https://doi.org/10.1111/jfr3.12266>.

Serra-Llobet, A. *et al.* (2022) 'Managing residual flood risk behind levees: Comparing USA, France, and Quebec (Canada)', *Journal of Flood Risk Management*, 15(2), p. e12785. Available at: <https://doi.org/10.1111/jfr3.12785>.

Vercruyse, K. *et al.* (2019) 'Developing spatial prioritization criteria for integrated urban flood management based on a source-to-impact flood analysis', *Journal of Hydrology*, 578, p. 124038. Available at: <https://doi.org/10.1016/j.jhydrol.2019.124038>.