

A conceptual foundation for community-centric decision support through soft adaptation in urban climate resilience

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1 INTRODUCTION & SCOPE OF WORK

Flooding is among the most damaging natural hazards worldwide, with both frequency and severity projected to increase under climate change (IPCC, 2021). Urban areas are particularly vulnerable due to dense populations, aging infrastructure, and increasing exposure of critical infrastructures. In this context, there is a growing need for decision-support approaches that place communities and end-users at the center of resilience planning, recognizing their role in shaping risk outcomes. Traditionally, flood risk management has emphasized hard adaptation measures, such as levees, dikes, flood barriers, and engineered drainage systems, designed to physically control or redirect floodwater (Aerts et al., 2014). While hard measures remain essential, recent flood disasters have demonstrated their limitations. Extreme events exceeding the design return periods of flood protection structures can lead to catastrophic consequences, particularly when social and institutional preparedness is weakened by a false sense of security induced by flood protection infrastructure, a phenomenon widely referred to as the levee effect (Collenteur et al., 2015). Risk awareness, preparedness, and contingency planning tend to be neglected, as observed in recent European flood events (Kreibich et al., 2017). These events highlight the risks of relying solely on engineered protection and emphasize the need to move beyond purely infrastructure-based solutions.

In contrast, soft adaptation measures focus on strengthening societal capacity to anticipate, respond to, and recover from floods through regulatory, organizational, educational, and behavioral strategies (Hegger et al., 2016). These measures are inherently community-centric, as they rely on behavioral change, local knowledge, and stakeholder engagement, making them critical components of decision-support systems aimed at enhancing infrastructure resilience. Despite their potential, soft measures remain underrepresented in formal resilience planning, partly due to difficulties in quantification, dependence on human engagement, and limited integration with infrastructure-focused approaches.

The Resilient HydroTwin Project addresses this gap by developing a methodological framework to support decision-making, assessing evacuation dynamics integrating both physical infrastructure and human actors. The scope of this work is: (i) to clarify and systematize the concept of soft adaptation measures through a consolidated definition and categorization; (ii) to assess their effectiveness both independently and in combination with hard measures; and (iii) to demonstrate how integrated (hybrid) strategies enhance flood resilience, particularly for urban systems.

By focusing on the city of Rotterdam (the Netherlands), where hydrological extremes, dense populations, complex infrastructures converge with a high levee effect, this research supports more people-centered and actionable flood resilience strategies, contributing to decision-support

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frameworks that enable communities and authorities to better anticipate and respond to flood hazards.

2 METHODOLOGY

In this work, soft adaptation measures are classified into seven categories: warning systems, zone management, evacuation, administrative coordination, regeneration mechanisms, educational initiatives, and evaluation processes. This classification is derived from a structured review of flood risk management literature and policy practice. The measures are grouped according to their primary function and mechanism of action within the system, i.e., each category therefore represents a distinct intervention strategy, e.g., influencing warning timing, regulating exposure, enabling evacuation, or shaping behavior, which reduces conceptual overlap between groups.

These measures are assessed using a set of criteria to evaluate their performance across different dimensions, including economic cost, political cost, social engagement, cost-effectiveness, and flexibility. The evaluation is based on semi-structured expert interviews across policy, engineering, and emergency management domains. Experts were asked to qualitatively rank soft adaptation measures relative to hard infrastructure measures for each criterion. Based on this comparative assessment, scores were assigned as follows: better performance than hard measures (2), similar performance (1), and worse performance (0). The resulting scores therefore represent a structured synthesis of expert judgment rather than a statistical aggregation, allowing for a transparent comparison of the perceived strengths and limitations of soft versus hard adaptation measures in the context of The Netherlands (Colijn, 2025). Figure 1 compares hard and soft adaptation measures based on this expert-informed multi-criteria assessment. Note that economic cost refers to the absolute investment required to implement a measure, whereas cost-effectiveness captures the ratio between achieved risk reduction and the associated cost, reflecting the efficiency of the intervention.

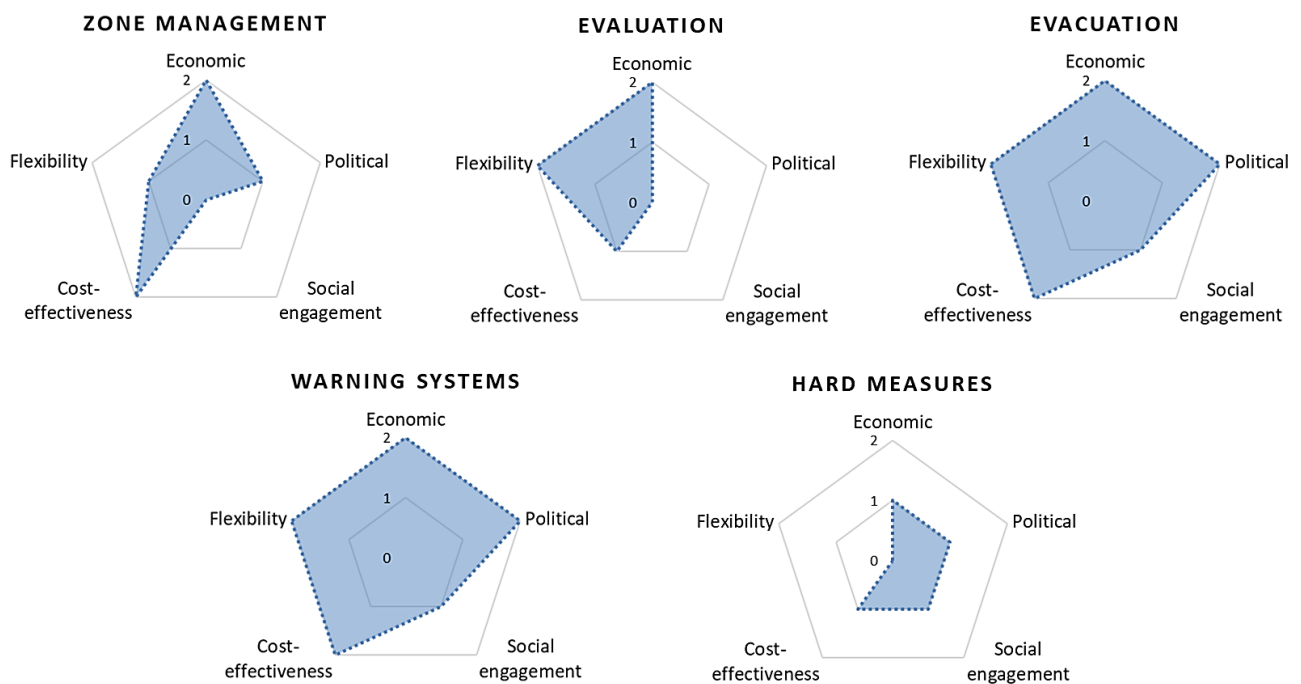


Figure 1. Comparative performance of hard and soft adaptation measures across key decision criteria. Scores: Better = 2, Neutral = 1 and Worse = 0.

While no single measure excels across all criteria, the figure highlights how different measures complement each other, suggesting that coordinated implementation can enhance urban flood resilience. In this context, soft measures can be understood as force multipliers, enhancing the performance of physical infrastructure by improving evacuation efficiency, increasing compliance with official guidance, and supporting coordinated emergency response (Aerts et al., 2018). Their contribution is closely linked to that of hard measures but operates through different

mechanisms. Hard measures act on the physical hazard, whereas soft measures shape behavioral response and system adaptability. This distinction becomes particularly relevant under stress conditions, when system performance increasingly depends on how individuals and institutions respond. This complementarity highlights the need to evaluate both types of measures jointly when designing resilient urban flood strategies.

3 RESEARCH OUTCOMES

The research yields several outcomes relevant to both academic research and practical flood risk management. The following conclusions are drawn: (i) soft adaptation measures play a critical yet underutilized role in enhancing urban flood resilience. When clearly defined and systematically evaluated, soft measures provide measurable reductions in vulnerability and exposure that complement structural protection (Hegger et al., 2016). (ii) Combination of both types are needed to enhance resilience, hard infrastructure provides baseline protection against frequent floods, while soft measures increase adaptability and societal preparedness when structural limits are exceeded (Aerts et al., 2014). (iii) Soft measures offer significant advantages in terms of economic efficiency, flexibility, and adaptability. Unlike structural interventions, policies, warning systems, and evacuation protocols can be updated rapidly as climate projections evolve, with lower implementation costs (Kreibich et al., 2017).

At the same time, there are still persistent challenges, including reliance on public engagement, political preference for visible infrastructure, and difficulties in monetizing social benefits. By embedding soft adaptation measures within a structured analytical framework, these challenges can be addressed more transparently, supporting evidence-based and people-centered resilience planning.

To overcome some of the mentioned challenges, modeling tools are needed capturing both types of adaptation and their combined effect. This challenge can be addressed using agent-based models allowing to assess the impact of different soft adaptation measures on agent behavior such as, decision timing, and system constraints. For example, warning systems influence agents' reaction times and likelihood of initiating evacuation. Evacuation planning and zone management shape route choice, shelter availability, and destination selection. Administrative coordination affects system-level capacities, such as shelter operation and traffic management. Educational measures modify behavioral archetype distributions by increasing the share of coordinated agents. Evaluation and learning mechanisms enable iterative updates to model parameters, reflecting institutional learning over time. Implementing such models requires detailed data on socio-demographic, economic, infrastructure capacity, behavior, and response times. The effectiveness of these adaptation measures can be assessed in terms of evacuation time, reduced exposure, improved people's safety during emergencies, as well as recovery times.

This behavioral representation allows both hard and soft adaptation measures to be assessed within a unified modeling framework. Structural interventions modify the physical hazard and accessibility conditions, while soft measures influence how individuals and institutions perceive, interpret, and respond to those conditions. Although this study does not present a specific numerical experiment yet, the framework demonstrates strong potential to systematically test adaptation strategies, explore trade-offs, and identify synergistic combinations of measures.

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