Master Thesis

Formalising Model Coupling:

An XLRM Framework for Integrating Flood and Transport Simulations in Rotterdam

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“Floods are ‘acts of God’, but flood losses are largely acts of man.”

- Gilbert F. White

Father of modern flood-risk science (1945)

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by

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Finally, to Rotterdam, the city that motivates this work and the decisions it informs. May the ideas here help keep the city moving and its people safe when it matters most.

Ashwin Rajeev Pillai
Delft, August 2025

Executive Summary

Rotterdam faces increasingly complex flood risks, with climate-driven hazards posing significant threats to both urban infrastructure and citywide mobility. The intersection of flood and transport disruptions has become a critical focus for the city's adaptation strategy. However, practical methods for systematically integrating high-resolution flood models with dynamic transport models remain limited, and a formalised approach for model coupling is absent in both academic literature and policy guidance.

This thesis develops and validates an XLRM (eXogenous uncertainties, Levers, Relationships, Metrics) framework tailored to Rotterdam's context, with a particular emphasis on specifying the Relationships (R) layer that enables flood–transport model integration. Using the Laan op Zuid corridor as a policy-relevant toy case, the study demonstrates how a rule-based coupling of the 3Di hydrodynamic flood model with the MATSim agent-based transport simulation can capture the operational impacts of flooding on urban mobility. The methodology combines systematic literature review, technical model analysis, and expert interviews to elicit depth–speed thresholds, scenario logic, and implementation rules. Model behaviour and rule feasibility were validated through a technical workshop with domain specialists.

The main findings reveal that a formally specified R-layer, employing rule-based triggers like closure of road links at 0.3m water depth, enables operationally realistic and timely translation of flood impacts to transport network states. Furthermore, the framework's modular structure allows adaptation to evolving risks, facilitating robust scenario analysis and digital-twin readiness for the municipality. Practical recommendations include prioritising real-time raster-to-network translation workflows, institutionalising empirically calibrated depth–speed relationships, and advancing open, synchronised data standards for seamless model exchange.

Nonetheless, several limitations remain. The research focuses on conceptual specification and technical validation; implementation as a live digital-twin demonstrator was outside the scope. Broader stakeholder validation was limited due to time constraints, and technical challenges persist regarding spatial and temporal misalignments between models. While the XLRM framework and R-layer specification are transferable to other cities with high-resolution modelling capabilities, empirical calibration of thresholds and operational protocols must be localised for context-specific adoption.

This work provides Rotterdam and similar delta cities with an evidence-based, operational template for flood–transport integration in digital-twin environments, advancing adaptive mobility planning in the face of climate uncertainty.

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Chapter 1

Introduction

Urban resilience refers to a city's ability to survive, adapt, and thrive amid chronic stresses and acute shocks. In practice, this means the capacity of a city's people, institutions, and systems to withstand disruptions and maintain function in the face of challenges (Figueiredo et al., 2018). In the 21st century, this concept has moved from abstract ambition to an operational imperative, as climate change intensifies hazards and exposes new interdependencies across urban systems. Rotterdam has embraced this concept through a comprehensive resilience strategy. As one of the first members of the 100 Resilient Cities network, Rotterdam moved beyond its traditional focus on water management to address broader resilience issues (e.g. cybersecurity, social cohesion) in its planning. The city's approach builds on a legacy of innovative climate adaptation, famous for water squares, green roofs, and a flexible storm surge barrier (Maeslantkering), while also fostering social and economic resilience (Gemeente Rotterdam, 2016).

Flood resilience is a central pillar of Rotterdam's urban resilience efforts. Given its deltaic location, the city faces flood risks from river surge, sea level rise, and heavy rainfall. Flood events can trigger cascading impacts across urban systems, far beyond the immediate inundation. For example, floodwaters may knock out electrical substations or overwhelm pumping stations, leading to power outages that compound the crisis. Critical services and infrastructure are tightly interlinked, so the failure of one can disrupt others (Nofal & Van de Lindt, 2022). A particularly vulnerable domain is urban transportation. Even if flood defences protect most assets, intense rainfall or a dike breach can inundate roads, tunnels, and rail lines. This strains the transport network by causing road closures, detours, and delays. Studies show that flooding can severely disrupt mobility in both the short term (e.g. travellers stuck in congestion) and long term (infrastructure damage), with ripple effects on the economy (Rebally et al., 2021). In Rotterdam, pluvial flooding in low-lying neighbourhoods could stall traffic on major arteries and stop public transit, hampering emergency access and daily commerce. Notably, even when direct physical damage to roads is minimal, flood-induced traffic delays and diversions create significant indirect losses (e.g. lost time, productivity, and economic output) (Nicklin et al., 2019). These cascading transport impacts underscore why integrating flood and transportation planning is crucial for urban resilience. These dynamics underscore the need to move beyond traditional, siloed risk assessments. Integrating flood and transportation planning is now widely recognised as essential for building robust urban resilience in delta cities.

Digital Twin technology offers a promising way to achieve this integration. A digital twin is essentially "a dynamic representation of a physical system using interconnected data, models, and processes to enable access to knowledge of past, present, and future states to manage action on that system" (Abdelrahman et al., 2025). In the context of cities, a digital twin can serve as a live, virtual model of urban infrastructure and environment, continuously calibrated with real data. This enables planners to simulate disruptive events and their cross-sector effects in a systems approach. For Rotterdam, a digital twin that couples flood models with transport models could become a powerful decision-support tool. It would allow city officials to visualise how a flood propagates through the urban environment and simultaneously see how traffic flows respond in real time. By integrating these models, the digital twin can reveal interdependencies (like which flooded road segments cause citywide gridlock) and test the efficacy of various interventions. Such a tool aligns with Rotterdam's innovative ethos and would build resilience by informing long-term adaptation strategies across departments (water management, transport, urban planning) in a unified platform.

1.1 Rotterdam's Climate Adaptation and Resilience Strategies

Rotterdam, as a low-lying delta city, has long been at the forefront of climate adaptation planning, developing a strategy that emphasises both robust flood protection and broader urban resilience. The *Rotterdam Climate Change Adaptation Strategy* (2013) established the foundation for a multi-layered approach, integrating structural and non-structural measures:

- **(a) Robust flood defences**: Including infrastructure such as the Maeslantkering storm surge barrier, reinforced sea dunes, and an extensive network of river dikes to protect against extreme water levels
- **(b) Transforming urban spaces**: Treating the city as a "sponge" with innovative features like water squares, infiltration zones, and green roofs to absorb, store, and slow runoff, thus reducing pluvial flood peaks
- **(c) Spatial planning for damage control**: Encompassing designated evacuation routes, flood-proof building design, and even floating structures to mitigate damage when flooding does occur.

This holistic approach—often described as making Rotterdam "climate proof"—acknowledges that flood safety cannot be achieved by defences alone. Instead, adaptive spatial measures and continuous preparedness are essential. Crucially, the "damage control" function of urban adaptation explicitly highlights the importance of evacuation and transport continuity, underlining the tight coupling between flood risk management and transport network planning (C40 Cities Climate Leadership Group, 2016).

Subsequent policies have reinforced and expanded these principles. The *Rotterdam Resilience Strategy* (2016) and its update as *Resilient Rotterdam 2022–2027* integrate climate adaptation with social, economic, and infrastructural resilience objectives. These strategies recognise that urban systems face multiple, often interacting, stresses—from flooding to infrastructure failure to social or economic shocks (Municipality of Rotterdam, 2022). Within these documents, safeguarding critical infrastructure and ensuring urban connectivity during disruption are positioned as top priorities. For example, maintaining the functionality of arterial roads and key transit lines during and after flood events is seen as essential for both routine operations and emergency response.

Despite this, most policy documents set high-level ambitions but stop short of prescribing detailed, operational models for how to keep these assets functional under multi-hazard or compound-event scenarios. This gap is particularly acute when considering interactions between water management and transport planning—two sectors that have traditionally operated independently.

A unique feature of Rotterdam's adaptation context is the sharp distinction between areas within the primary dike ring ("inner-dike")—which encompasses the city centre and port, protected by national flood defences—and "outer-dike" neighbourhoods, which are at higher elevation but exposed to direct storm surge and riverine floods. For these outer-dike and port areas, the city has pioneered adaptive measures tailored to the specific risks of these zones. The *Rotterdam Port Adaptation Strategy*, for example, includes:

- Elevating critical roads to double as flood barriers,
- Installing flood gates at tunnel entrances,
- Creating compartmentalised flood zones to prevent cascading failures,
- Deploying removable or small-scale barriers at strategic points.

These actions blur the distinction between flood infrastructure and transport infrastructure, with highways, boulevards, and even parking garages increasingly serving dual purposes as water management assets and mobility corridors. This multi-functional infrastructure is now central to Rotterdam's adaptation agenda, combining robust engineering with adaptive urban design, such as waterproofing vital facilities and pursuing strategic land use planning (European Environment Agency, 2025).

In summary, Rotterdam's adaptation strategies blend engineered defences with innovative urban design and spatial policy to address evolving flood risks. However, these advances bring new modelling and planning challenges: city planners must be able to evaluate how these complex, multi-functional interventions perform under a wide range of future scenarios, and especially how interdependent systems like flood management and transport interact during extreme events. As recent events—such as the July 2021 cloudburst, which temporarily overwhelmed drainage and transport systems—have shown, integrating flood and transport resilience is no longer optional, but an urgent operational priority.

1.2 Significance of Flood–Transport Interactions

Flood events not only threaten property and safety through direct physical inundation, they can also cause far-reaching disruptions across urban systems, most notably in mobility and accessibility (Nicklin et al., 2019). In dense urban environments like Rotterdam, even minor flooding can stall critical roadways, interrupt public transit, and isolate neighbourhoods from essential services. These indirect impacts often amplify the overall consequences of a flood, resulting in delays to emergency response, interruptions to economic activity, and prolonged recovery periods for affected communities (Pregnolato et al., 2017).

The transport network, serving as the city's circulatory system, is especially vulnerable to cascading effects. Road and rail closures caused by water on key links can quickly create citywide congestion, strand commuters, and disrupt supply chains (Pregnolato et al., 2017). For vulnerable populations, such as those dependent on public transit or with limited mobility, these disruptions can lead to acute hardship and increased social inequality (Nofal & Van de Lindt, 2022). The experience of Rotterdam and other delta cities has shown that the costs associated with lost accessibility and traffic disruption often exceed direct flood damages, especially as urban systems become more interconnected and dependent on real-time mobility (Nicklin et al., 2019).

Effective flood and transport management, therefore, requires not just strengthening defences or improving drainage, but also anticipating and managing how people, goods, and services move during extreme events. Integrated modelling of flood and transport interactions supports more robust planning by enabling city officials to identify critical infrastructure, prioritise adaptation investments, and develop strategies for maintaining urban function under a range of future scenarios. In the context of accelerating climate risk and urban complexity, the ability to simulate these interactions is essential for ensuring both immediate response capability and long-term resilience (Ciullo et al., 2019).

In summary, the growing complexity and interdependence of urban systems demand that flood risk and transport resilience be addressed not in isolation, but as inherently linked challenges. To develop practical, evidence-based approaches for coupling flood and transport models, it is essential to first understand the state of knowledge across each domain and critically examine previous attempts at model integration. The following chapter provides a comprehensive literature review of flood risk modelling, transport resilience modelling, and the evolving field of coupled flood–transport systems, laying the conceptual and methodological foundation for this thesis.

Chapter 2

Literature Review

This chapter provides a comprehensive review of the scientific and practical literature at the intersection of flood risk modelling, transport resilience, and coupled system analysis. The aim is to synthesise current knowledge, clarify methodological approaches, and identify critical gaps that motivate the research undertaken in this thesis. Flooding and transport disruption are increasingly recognised as deeply interlinked challenges in urban resilience planning, particularly for delta cities such as Rotterdam. This chapter systematically examines the following:

1. Evolution and capabilities of state-of-the-art flood risk models
2. Evolution and capabilities of state-of-the-art transport resilience models
3. Emerging field of coupled flood–transport systems, including international case studies

By critically examining this literature, the chapter establishes the conceptual and technical foundation for the methods and case study that follow.

2.1 Flood Risk Modelling

Flood risk modelling plays a foundational role in urban resilience planning, providing the analytical basis for understanding, managing, and reducing the impacts of flooding on cities. At its core, flood risk modelling aims to simulate the occurrence and consequences of flood events, whether from coastal surges, riverine overflow, or intense rainfall, so that planners and decision-makers can assess both present vulnerabilities and future risks.(Nofal & Van de Lindt, 2022)

Key terms include flood hazard (the probability and intensity of flood events), exposure (the presence of people, assets, and infrastructure in potentially affected areas), vulnerability (the susceptibility of these elements to harm), and risk (the likelihood and magnitude of adverse consequences, often conceptualized as the product of hazard, exposure, and vulnerability).(Restemeyer et al., 2018) Robust flood risk modelling provides quantitative estimates for these components, enabling scenario analysis, economic impact assessment, and prioritisation of adaptation measures.

For cities like Rotterdam, facing increasing hazards due to climate change, sea-level rise, and urban densification, advanced flood risk modelling is central to effective resilience strategies.(Gemeente Rotterdam, 2016) The city's complex deltaic geography, dense infrastructure, and critical economic assets make it essential to deploy sophisticated modelling approaches that can inform both long-term adaptation pathways and real-time emergency response. In this way, flood risk modelling becomes not just a technical exercise, but a strategic tool for safeguarding urban function and well-being in the face of 21st-century challenges.

2.1.1 Technical Principles of Flood Modelling

Flood modelling is the simulation of how water moves across landscapes in response to rainfall, storm surges, or river flows, considering the effects of topography, land use, and infrastructure. Flood models capture the complex interactions between hydrological processes such as rainfall-runoff and hydraulic processes such as the movement of water through channels, floodplains, and urban environments.(Teng et al., 2017) Conceptually, these models translate meteorological or hydrological inputs like rainfall intensity, river discharge, or tidal surges into spatial and temporal patterns of flooding on the ground.

Modern flood models typically comprise several core components. The hydrodynamic module solves mathematical equations such as the shallow water equations to simulate water depth, velocity, and flow direction over time and space. (Hunter et al., 2007) Rainfall-runoff models estimate how much precipitation becomes surface runoff, factoring in soil type, land cover, and impervious surfaces. Boundary conditions, such as upstream river inflows or downstream water levels, and input data, such as high-resolution digital elevation models and infrastructure maps, provide the physical context for simulation.(Horritt & Bates, 2002)

Typical outputs from these models include maps and time series of water depth, inundation extent, flow velocities, and duration of flooding. These outputs explain risk assessments by identifying exposed assets, quantifying potential damages, and supporting the development of adaptation strategies.(Horritt & Bates, 2002)

2.1.2 Evolution from 1D to 2D/3D Flood Modelling

Flood modelling has advanced considerably over the past several decades, evolving from simple, one-dimensional (1D) channel-based models to sophisticated two and three-dimensional (2D/3D) systems capable of capturing the complexity of urban environments. Early flood models primarily represented rivers and channels as 1D networks, simulating water levels and flows along predefined sections but lacking the ability to depict water spreading over floodplains or interacting with urban features.(Horritt & Bates, 2002) While effective for broad-scale riverine risk assessments, these approaches could not resolve critical processes such as overland flow, surface ponding, or interactions with stormwater drainage.

The transition to 2D models represented a significant leap, allowing the simulation of water movement across detailed topography and built environments using grid- or mesh-based approaches. This increase in spatial resolution is essential for accurately modelling how floods propagate through streets, buildings, and infrastructure networks, especially in dense cities. More recently, the integration of 3D capabilities and sub-grid techniques has enabled models to account for micro-topography and dynamic interactions with drainage infrastructure, further enhancing predictive accuracy.(Hunter et al., 2007)

These advances are particularly important for urban resilience, enabling real-time flood forecasting, detailed risk mapping, and integration with digital twin platforms for decision support.(Teng et al., 2017) The ability to represent urban detail and dynamic interactions makes high-resolution 2D/3D modelling indispensable for effective flood risk management.

2.1.3 Risk Assessment and Scenario Analysis in Flood Modelling

Modern flood models extend far beyond basic hazard mapping, serving as core tools for comprehensive risk assessment in urban resilience planning. These models quantify not only the probability and extent of inundation but also the resulting impacts on people, infrastructure, and the broader urban economy.(Nofal & Van de Lindt, 2022) By overlaying flood hazard outputs with spatial data on assets and populations, practitioners can estimate direct damages, identify critical facilities at risk, and evaluate the exposure and vulnerability of urban systems.

Scenario analysis is central to this process, allowing planners to simulate a range of possible futures, including varying rainfall intensities, extreme sea level rise, or potential failures of flood defences. This approach supports stress testing of urban resilience strategies, revealing vulnerabilities and informing the prioritisation of adaptation investments. The Dynamic Adaptive Policy Pathways (DAPP) framework is particularly influential in the Netherlands, offering a structured method to map sequences of adaptation actions and decision points under deep uncertainty.(van Veelen, 2013) By coupling scenario analysis with pathway approaches, planners can design robust, flexible strategies that remain effective across a wide range of uncertain futures.(Haasnoot et al., 2013)

2.1.4 Limitations in Flood Risk Modelling

Despite significant progress in flood risk modelling, several limitations persist that constrain the operational value and integration of these models within broader urban resilience frameworks. A fundamental challenge is the high demand for accurate and up-to-date input data, such as high-resolution topography, land use, and drainage infrastructure. Acquiring and maintaining these datasets for large or rapidly changing urban areas can be resource-intensive and may introduce uncertainty when data are outdated or incomplete.(Teng et al., 2017) Furthermore, the computational demands of running advanced two- or three-dimensional models at fine spatial and temporal scales often limit their use for real-time forecasting or rapid scenario analysis, particularly in emergency contexts.

A persistent limitation lies in the representation of uncertainty. While scenario-based and probabilistic approaches have improved the ability to account for unknowns such as the magnitude and timing of extreme events, or the performance of flood defences, uncertainty remains difficult to communicate and operationalise in planning and policy decisions.(Restemeyer et al., 2018) Additionally, many models focus primarily on hydrological or hydraulic outputs like water depth, inundation extent, and economic damages, with less attention to metrics directly relevant for other urban systems, such as transport accessibility, emergency response times, or social vulnerability (Nofal & Van de Lindt, 2022).

Perhaps the most critical gap—especially for cities like Rotterdam—is the lack of integration between flood risk models and models for other urban infrastructures, most notably transport systems. Current flood models typically operate in disciplinary "silos," producing outputs that are not directly compatible with dynamic transport simulations or digital twin environments.(Kasmalkar et al., 2020) This siloed approach leads to challenges in semantic and temporal synchronisation; for example, flood models might output five-minute average water depths as gridded rasters, while transport models require link-based, near-instantaneous capacity changes. Real-time integration and feedback between flood and transport models are rare, limiting the capacity to assess cascading impacts, adaptive response options, or the full socio-economic consequences of flooding.

Finally, the literature highlights a lack of operational coupling frameworks that can reliably and transparently connect hydrodynamic models with other critical infrastructure domains.(Bernardini et al., 2017) Challenges remain not only in data and interface design, but also in model validation, stakeholder communication, and institutional readiness for adopting integrated approaches. Addressing these gaps is essential for enabling truly robust and adaptive urban resilience strategies in the face of deepening climate and infrastructure uncertainties.

While advanced flood risk models provide critical insights into hazard and exposure, they are rarely designed to capture the full range of disruptions that floods can cause to urban mobility. Understanding how transport systems respond to, and recover from, flood events requires dedicated modelling approaches that go beyond the traditional focus on hydrology or economic damage.

2.2 Transport Modelling

Urban transport systems are the circulatory networks of cities, enabling not only daily mobility and economic activity but also underpinning critical emergency response during disruptive events. As climate change and urbanisation intensify the frequency and severity of hazards such as flooding, the resilience of transport infrastructure has become a central concern in urban adaptation strategies. This section reviews the evolution and current state of transport resilience modelling, tracing the field's progression from traditional network science concepts through to advanced agent-based and dynamic simulation tools. It outlines the key metrics used to assess resilience, such as robustness, redundancy, and recovery, and highlights empirical findings from both Dutch and international contexts.

2.2.1 Network Science

Urban transportation networks are frequently conceptualised through the lens of network science, where intersections and terminals are represented as nodes and the connecting road, rail, or transit segments as links. This simplification allows the use of graph-theoretical metrics to analyse system structure and resilience. Early research on transport vulnerability employed these models to identify critical components, nodes or links whose failure would disproportionately disrupt network connectivity or capacity.(Jenelius & Mattsson, 2015)

Common metrics include betweenness centrality (the frequency with which a node or link lies on the shortest paths between all pairs of nodes), connectivity loss (the decline in network reachability after a failure), and critical link analysis (identifying links whose removal fragments the network or isolates demand centres).(Scott et al., 2006) These measures provide planners with first-order estimates of systemic risk and enable prioritisation of investment or protection strategies. Vulnerability analysis has been widely applied to urban road networks, rail systems, and multimodal transport, offering valuable insights for both day-to-day management and hazard preparedness.(Mattsson & Jenelius, 2015) However, while powerful for static analysis, traditional network science approaches are often limited in capturing dynamic, time-dependent disruptions and behavioural responses during real-world crises.

2.2.2 Agent-Based Simulation

While traditional network models provide valuable insights into system structure and vulnerability, they are fundamentally limited in their ability to represent the dynamic, adaptive behaviour of travellers during disruptions. In recent years, Agent-Based Modelling (ABM) and other dynamic simulation approaches have gained prominence in transport resilience research for their ability to explicitly simulate how individual travellers and vehicles adjust their routes, modes, or departure times in response to changing network conditions.(Balijepalli & Oppong, 2014)

Agent-based models represent each traveller as an autonomous agent with specific preferences, activity patterns, and behavioural rules. Tools such as MATSim (Multi-Agent Transport Simulation), SUMO (Simulation of Urban MObility), and OpenTrafficSim allow for large-scale, high-fidelity simulations in which thousands or millions of agents interact across complex transport networks.(Horni et al., 2016) These models can incorporate detailed representations of congestion dynamics, public transit, and even pedestrian flows, enabling the study of cascading impacts during extreme events.

One of the major strengths of ABM is its ability to simulate cascading disruptions—for example, how a single flooded road segment can trigger widespread congestion, alter travel demand, or delay emergency response across a city.(Kasmalkar et al., 2020) By capturing feedback loops between agent decisions and network performance, these models offer a nuanced understanding of both immediate and longer-term system responses to hazards. Additionally, ABM can represent heterogeneous traveller behaviours, such as risk aversion, route familiarity, or access to information, which are often critical in evacuation and crisis contexts.

In the Netherlands, dynamic simulation tools are increasingly used by government agencies and researchers for evacuation planning, stress testing of critical infrastructure, and resilience analysis under compound hazard scenarios.(van der Hurk et al., 2020) For example, Dutch studies have used MATSim and OpenTrafficSim to model flood-induced disruptions, optimise evacuation strategies, and test the robustness of urban networks under varying flood depths and durations.

Despite their strengths, ABMs remain computationally intensive and require extensive data for calibration and validation. Their capacity to model real-time adaptation and behavioural complexity makes them indispensable for advancing integrated flood–transport resilience analysis in modern cities.

2.2.3 Resilience Metrics in Transport Modelling

Assessment of transport system resilience increasingly centres on three interrelated metrics: robustness, redundancy, and recovery. Robustness refers to a system's capacity to maintain acceptable levels of service under stress, such as during road closures or increased demand. It is commonly evaluated by measuring the extent to which travel time, accessibility, or throughput degrade as disruptions occur.(Mattsson & Jenelius, 2015) Redundancy captures the availability of alternative routes or modes that can absorb displaced demand when primary links fail. Networks with higher redundancy tend to be less susceptible to fragmentation and exhibit smoother adaptation to disruptions.(Scott et al., 2006)

Recovery measures the speed and trajectory with which a transport network returns to normal operation following a disruptive event. This includes not only physical repairs but also the restoration of traffic flows and accessibility for users.(Bocchini & Frangopol, 2012) The interplay of these metrics provides a holistic view of resilience: robust systems can withstand shocks; redundant systems can re-route traffic efficiently; and systems with rapid recovery minimise socio-economic impacts.

Empirical studies validate the practical significance of these concepts. For instance, Kasmalkar et al. (2020)(Kasmalkar et al., 2020) demonstrated that urban areas with denser, more interconnected road networks in the San Francisco Bay Area exhibited faster recovery and less severe delays during flood events. Similarly, recent Dutch practice integrates these metrics into adaptation planning and infrastructure investments, using them to prioritise upgrades and emergency preparedness.(Argyroudis et al., 2022) As resilience thinking continues to inform transport policy, these metrics offer actionable criteria for evaluating and improving network performance under both routine and extreme conditions.

2.2.4 Flood Impacts on Urban Mobility Networks

Empirical case studies across diverse urban contexts highlight the complex and sometimes disproportionate impacts of network disruptions on urban mobility. In Boston, Suarez et al. (2005)(Suarez et al., 2005) demonstrated that overlaying flood maps on the metropolitan road network and removing submerged links led to substantial increases in citywide travel times, illustrating how even moderate flooding can trigger severe indirect impacts through lost connectivity and congestion. Similarly, Kasmalkar et al. (2020)(Kasmalkar et al., 2020) found in the San Francisco Bay Area that the closure of a small percentage of critical road links due to flooding could amplify total travel time by over 80%, with network density and redundancy proving more important than simple exposure in explaining delays.

Dutch studies reinforce these findings in the European context. Dai et al. (2017)(Dai et al., 2018) used simulation and network analysis to map critical road segments for emergency services in Amsterdam, revealing that strategic redundancy and proactive planning are essential to maintain accessibility during flood events. Recent work in Rotterdam and other Dutch cities increasingly integrates empirical network metrics with dynamic simulation tools—such as MATSim and OpenTrafficSim—to inform adaptation investments, evacuation planning, and day-to-day traffic management.(Andriessen et al., 2024) These examples underline the importance of both detailed empirical data and flexible modelling approaches in building resilient transport systems, supporting decision-makers as they prioritise interventions for critical assets and robust recovery.

2.3 Coupled Flood–Transport System

Flood hazards and urban mobility disruption have increasingly prompted researchers and practitioners to seek integrated modelling frameworks that can capture the cascading impacts of extreme weather on transport systems.(Pregnolato et al., 2017) While advances in both hydrodynamic and transport modelling have significantly improved our ability to analyse each system independently, translating flood events into transport outcomes—or vice versa—remains methodologically challenging. Conventional approaches typically operate in disciplinary silos, often overlooking feedback, time dependencies, and the complex behavioural responses of travellers and system operators during flood events.

The integration of flood and transport models can be approached through several conceptual and technical frameworks, each reflecting different assumptions about data flow, feedbacks, and system interdependencies. The choice of coupling type has important implications for operational feasibility, computational demand, and the range of phenomena that can be explored.

2.3.1 Unidirectional vs. Bidirectional Coupling

At the most fundamental level, coupling strategies can be divided by the direction of information flow between models:

Unidirectional (One-way) Coupling: In this approach, one model (typically the flood model) runs independently and provides outputs—such as time-varying water depths or inundation extents—that are subsequently used to modify the input or state of the transport model. For example, links in a road network may be closed or have reduced capacity if water depth thresholds are exceeded, as in the rule-based coupling approaches widely used in both research and practice.(Pregnolato et al., 2017)(Suarez et al., 2005) The key characteristic is that there is no feedback from the transport model to the flood model: the hydrodynamics are unaffected by transport system behaviour, which simplifies implementation but risks missing important interactions, such as the effect of traffic congestion on evacuation efficiency.

Bidirectional (Two-way) Coupling: Bidirectional approaches allow for feedback loops between the two systems. Here, not only do flood model outputs affect the transport network, but transport model states, such as congestion, vehicle routing, or blockages, can influence flood risk and propagation, especially in urban settings where traffic management actions like the blocking of intersections, activation of pumps, or prioritisation of emergency routes can alter drainage or risk exposure.(Lv et al., 2025) Bidirectional coupling provides a richer and more realistic representation of dynamic interactions but comes with greater demands for model synchronisation, data harmonisation, and validation.

2.3.2 Soft vs. Hard Coupling

Another key distinction is the degree of integration between the models:

Soft Coupling: Soft coupling involves separate model simulations connected via intermediate data exchanges—often manual or scripted exchanges without deep integration of the models' computational structures. Typically, one model completes a simulation run and generates outputs (e.g., flood extent maps), which are then fed into the other model. Soft coupling is easier to implement and more modular, allowing separate maintenance and updating of individual models. It is, however, less capable of handling intricate real-time interactions or feedback loops and is prone to errors introduced through data translation and interpolation.(Fewtrell et al., 2008)

Hard Coupling: Hard coupling, by contrast, involves real-time, iterative data exchange between models—often within a unified simulation environment or using middleware that coordinates their execution. In these setups, each model's state can be updated in response to outputs from the other model at every simulation time step, supporting the representation of tightly coupled feedbacks (e.g., when traffic jams impede emergency access, which in turn affects flood mitigation effectiveness)(Dawson et al., 2011). Hard coupling is essential for realistic digital twin applications or live incident management, but it poses challenges in terms of software compatibility, time-step alignment, and computational load.(Andriessen et al., 2024)

2.3.3 Synchronous vs. Asynchronous Coupling

The timing of data exchange is another critical aspect:

Synchronous Coupling: Both models operate on the same simulation clock, exchanging data at fixed intervals. This tight synchronisation ensures that changes in one domain are immediately reflected in the other, supporting real-time feedback and fine-grained scenario analysis.(Lv et al., 2025) Synchronous coupling is best suited for operational decision-support, such as real-time traffic management during flood events, but requires careful coordination to avoid instability or deadlocks.

Asynchronous Coupling: Models operate on different clocks or time-steps, exchanging information only when pre-defined events or thresholds are reached. This is more flexible and may better reflect real-world delays, but can introduce mismatches in data granularity and potentially overlook rapid cascades.(Hossain et al., 2017)

2.4 XLRM Framework

Cities worldwide face escalating challenges from climate-driven hazards and urban complexity, compelling planners to make high-stakes decisions under deep uncertainty (Walker et al., 2013). Traditional risk management approaches, rooted in deterministic forecasts and static assumptions, are often insufficient for dealing with the multiplicity of future scenarios in domains such as flood risk and urban mobility. As a result, decision frameworks that explicitly acknowledge uncertainty, accommodate adaptation, and support robust, flexible planning have become central to resilience research and practice.(Lempert et al., 2006)

The XLRM framework, an acronym for Exogenous Uncertainties (X), Policy Levers (L), Relationships (R), and Metrics (M), is one of the most widely adopted structures for systematically analysing decision problems under uncertainty. Originally developed in the context of robust decision-making (RDM) and later embedded within adaptation policy pathways (APP/DAPP), XLRM provides a logical architecture to link uncertain external drivers, intervention strategies, system dynamics, and performance evaluation in complex urban settings.(Lempert et al., 2003)

The XLRM framework traces its roots to the RAND Corporation's work on RDM, which was initially applied to water resource management in the face of climate uncertainty.(Lempert et al., 2003) In this context, XLRM was used to guide scenario discovery and to stress-test adaptation options across thousands of plausible futures. The framework was soon adopted and expanded by adaptation scholars (Kwakkel et al., 2016) and now underpins approaches such as Dynamic Adaptive Policy Pathways (DAPP) and Robust Decision Making (RDM), which are central to Dutch and international climate adaptation planning.(Kwakkel et al., 2016)

2.4.1 Components of XLRM

Each quadrant of the XLRM framework corresponds to a specific dimension of the decision problem (as seen in Fig. 2.1):(Lempert et al., 2006)

- **Exogenous Uncertainties (X):** Factors outside the immediate control of decision-makers, such as climate change trajectories, socio-economic trends, or extreme rainfall events. In urban flood–transport contexts, these include variables like rainfall intensity, sea-level rise, and land-use change.

- **Policy Levers (L):** The interventions or strategies that can be manipulated by planners and policymakers, ranging from infrastructural upgrades (e.g., flood defences, pump stations) to non-structural measures (e.g., evacuation protocols, adaptive traffic management).
- **Relationships (R):** The formal, often model-based, mechanisms that link uncertainties and policy levers to system outcomes. The R-layer encodes causal relationships, feedbacks, and model interactions, which are especially critical for coupled systems such as flood transport.
- **Metrics (M):** The performance indicators used to assess the desirability or effectiveness of different strategies under uncertainty. These may include quantitative measures (e.g., expected annual damages, accessibility loss, recovery time) or qualitative criteria (e.g., stakeholder acceptability).

This structured approach enables planners to systematically explore "what-if" scenarios, test the sensitivity of strategies to uncertainties, and identify robust adaptation pathways.(Haasnoot et al., 2013)

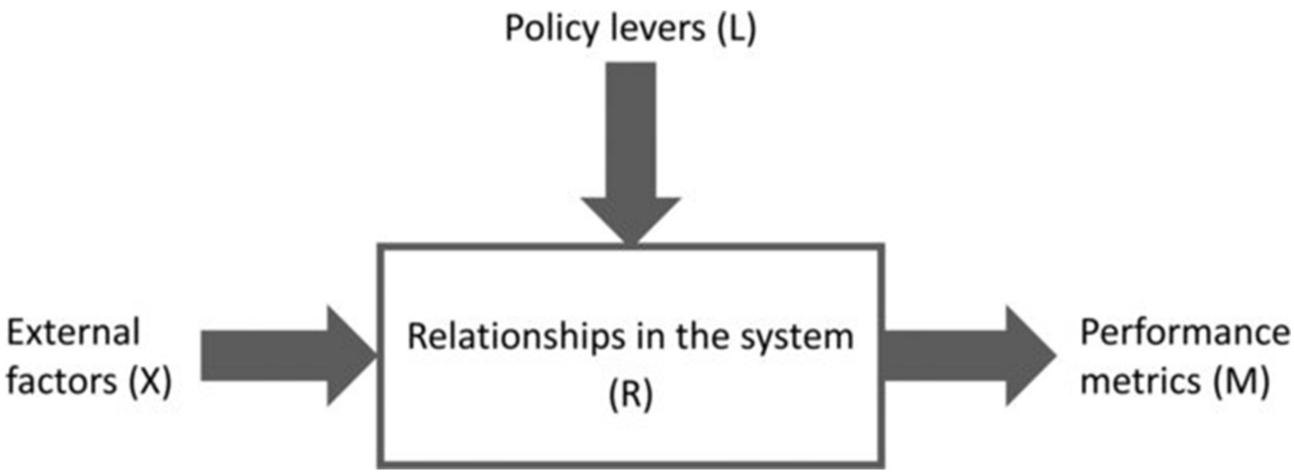

Figure 2.1: The XLRM framework for model-based policy analysis. (Lempert et al., 2006)

2.4.2 The Role of the R-Layer

Among the four XLRM quadrants, the R-layer is increasingly recognised as pivotal—especially for integrating multiple models and capturing system interactions in urban resilience planning. In flood–transport applications, the R-layer formalises how changes in climate drivers (X) and adaptation strategies (L) propagate through complex urban systems to affect outcomes such as accessibility, safety, and economic loss (M).

For example, in a coupled flood–transport scenario, the R-layer may encode:

- How a rainfall event leads to surface flooding (via a hydrodynamic model)
- How flood depths translate to road closures or speed reductions (via lookup tables or thresholds)
- How transport agents re-route or delay trips in response (via an agent-based traffic model)
- How mobility disruptions feed back to emergency response or evacuation outcomes

Developing an operational R-layer involves specifying model interfaces, data exchange protocols, time-step synchronisation, and semantic harmonisation.

2.5 Research Gap

The review of existing literature clearly illustrates that, despite significant advances in flood risk modelling and transport resilience analysis, critical gaps persist—especially regarding their integration.

Flood modelling traditionally concentrates on hydraulic, hydrological, and economic impacts, with limited explicit consideration of the cascading disruptions to urban transport networks. Conversely, transport resilience studies frequently treat flood hazards simplistically, employing static road-closure rules that neglect dynamic interactions, behavioural responses, and system feedback loops.

Current coupling approaches remain largely fragmented, typically implemented in ad-hoc or case-specific contexts rather than through operationally robust frameworks. While techniques like soft, hard, synchronous, and asynchronous coupling offer promising pathways, challenges remain related to computational complexity, semantic consistency, real-time synchronisation, and model interoperability. Additionally, few existing frameworks provide the semantic and operational clarity required for deployment in dynamic digital twin environments or emergency decision-support systems.

Consequently, there is an evident need for a structured, operationally scalable framework explicitly designed for coupling flood and transport models—one that can reliably inform decision-making in real-time crisis scenarios and strategic urban planning. This thesis addresses this critical research gap by formalising the relationships (the R-layer) within the XLRM framework for coupled flood–transport interactions, specifically tailored for the Rotterdam context but designed for transferability to other deltaic and flood-exposed urban areas.

The next chapter, therefore, presents the research methodology, detailing the conceptual approach, research questions, and methods used to systematically develop and validate this integrated coupling framework.

Chapter 3

Research Methodology

This chapter details the methodological approach taken to develop and validate a framework for coupling flood-inundation and transport models in the context of Rotterdam. The chapter begins by mentioning the scope of the research. The research questions are then presented. The subsequent sections describe the methodology for the research. A detailed account of the data sources, expert selection criteria, and strategies to ensure reliability and validity is provided, including a literature review and thematic coding. Developing each component of the XLRM framework is explained in detail. The rationale for employing a toy case application in Rotterdam's Laan op Zuid corridor is also explained, highlighting its value for proof-of-concept demonstration and stress-testing of the framework. Finally, the validation plan is presented.

This chapter provides a systematic account of the research strategy, ensuring that the development and assessment of the XLRM framework is fit for operational use in urban flood–transport planning.

3.1 Research Questions

Building on the identified gap, the study is guided by one overarching research question:

How can the Relationships (R) layer in an XLRM framework be formally specified to integrate flood models with transport models for Rotterdam's flood–transport interactions?

3.1.1 Sub Research Questions

1. What adaptation levers in Rotterdam require cross-domain flood transport analysis?

   This sub-question identifies which climate adaptation or infrastructure strategies in Rotterdam necessitate linking flood and transport outcomes. For example, road elevation projects, pump installations, or land-use changes might only reveal their full benefits or trade-offs when evaluated with an integrated flood and traffic model. By reviewing Rotterdam's adaptation plans and stakeholder priorities, we will pinpoint key policy levers (L) that span both domains.

2. What are the technical requirements of existing flood and transport models (data structures, formats, and time steps)?

   This sub-question inventories the input-output specifics of the models to be linked. We will document how a state-of-the-practice flood model like 3Di represents spatio-temporal flood dynamics (e.g. water depth grids, update intervals, file formats) and how transport models represent network performance (e.g. link capacities, traffic flow simulation time-steps). By comparing these, we establish the requirements for interoperability – for instance, whether the flood model can output water depths at road locations, how to translate those depths into road capacity reductions, and what temporal resolution is needed so that both models "speak" on synchronised timesteps.

3. What are the pros and cons of candidate interaction strategies for linking flood and transport models?

   This sub-question evaluates different modelling paradigms for the R-layer. The outcome of this sub-question will be a rationale for the interaction mechanism used in our R specification, grounded in the trade-offs identified (e.g. simplicity vs. fidelity, transparency vs. adaptiveness).

3.2 Research Scope

This study is focused on the operational and methodological challenges of coupling flood-inundation and transport models within the urban context of Rotterdam. While the framework and findings are designed to be broadly relevant for climate adaptation planning in delta cities, the research is empirically grounded in the Rotterdam metropolitan area.

The Laan op Zuid corridor, a critical mobility artery situated in a flood-prone district of Rotterdam, is used as a toy case for demonstrative purposes. This corridor was selected due to its high exposure to both pluvial and riverine flooding and policy relevance. The toy case serves as a controlled environment for illustrating the proposed XLRM framework, allowing for transparent exploration of model interactions and scenario logic without the complexity of citywide simulation.

The research is strictly methodological in orientation: it develops and validates a formal specification of the Relationships (R) layer within an XLRM framework, focusing on conceptual interfaces, data exchange logic, and operational rules for model coupling. Full-scale digital twin implementation, citywide evacuation modelling, or real-time operational forecasting are explicitly excluded from the scope. However, the artefacts produced—including the XLRM register and coupling specifications—are designed to be transferable, providing a template for planners and digital-twin developers in Rotterdam and other flood-prone cities.

In summary, the study is city-focused, but leverages the Laan op Zuid corridor as a demonstrative toy case to operationalise, test, and communicate the core concepts of the proposed methodological framework.

3.3 Research Design

This study's methodology is crafted to address the complex task of integrating flood and transport models for climate adaptation in Rotterdam. It combines exploratory-explanatory inquiry, design science, and mixed methods, enabling the creation of a validated, operational artefact, the XLRM register and R-layer specification, ready for digital-twin implementation in urban planning.

The research begins with an exploratory perspective. Prior work on flood–transport integration presents diverse but fragmented approaches, rule-based triggers, lookup tables, or co-simulation, yet no coherent procedure for policy-relevant settings. This exploration is particularly relevant for pinpointing adaptation levers that demand cross-domain analysis.

Parallel to this, the inquiry is explanatory, investigating how different model interaction strategies function in practice. By examining trade-offs, the study clarifies which paradigms best fit Rotterdam's operational needs.

Adopting a design science framework, the study prioritises artefact creation and iterative refinement. The artefact, comprising registers, interface definitions, and rules, is developed in successive cycles, incorporating stakeholder feedback and practical calibration. This aligns with established design science principles (Gregor & Hevner, 2013) and ensures the framework is both structurally sound and practically useful.

A mixed-methods approach integrates quantitative calibration with qualitative inquiry through manual expert elicitation and thematic analysis. Such triangulation strengthens the artefact's validity and helps uncover practitioner insights that raw data alone cannot reveal. (Creswell & Plano Clark, 2018)

This multi-layered methodology ensures that the framework is informed by empirical needs, grounded in technical feasibility, and validated through structured stakeholder engagement.

3.3.1 Methods Overview

The methodological workflow unfolds in five stages, as shown in Fig. 3.1. Each stage builds on insights from the previous one.

Stage 1: Systematic Document Analysis and Literature Review This phase identifies adaptation levers and catalogues model requirements. A targeted review—drawing on Rotterdam climate and adaptation plans, flood–transport integration literature, and technical documentation for different models is conducted. Sources are selected based on empirical relevance, operational focus, and methodological clarity. A structured matrix captures:

- Adaptation levers like pump installations and road elevation
- Technical model attributes like water-depth outputs and traffic simulation time steps

These insights lay the groundwork for locating coupling opportunities and constraints later addressed through expert interviews and artefact design.

Stage 2: Semi-Structured Expert Interviews Building on the document phase, interviews provide context and clarity. Six experts from flood modelling, transport simulation, and digital-twin modelling were chosen based on their involvement in Rotterdam projects. The interviews explore:

- Adaptation levers that require integrated modelling.
- Technical workflows and data-transfer challenges.
- Practical experience with coupling mechanisms.

Interviews were conducted face-to-face, recorded, and transcribed. They were manually coded following thematic analysis principles, allowing deep engagement with practitioners' nuanced insights. This manual coding helps align abstract design considerations with real-world feasibility.

Stage 3: Iterative XLRM Artefact Development Combining evidence from earlier stages, a draft XLRM register is developed. Stakeholders are invited to review intermediate versions, giving feedback on semantic consistency (file formats, data scales, time steps), sufficiency of adaptation levers, and coupling transparency. Alternative interaction strategies like rule-based, lookup, co-simulation, etc., are evaluated in terms of simplicity, performance, and planner usability.

Stage 4: Toy Case Application and Scenario Translation To operationalise the XLRM framework, a toy case application was developed in Rotterdam's Laan op Zuid corridor, a dense, mixed-use artery prone to surface water accumulation. This corridor served as a proof of concept for translating abstract XLRM elements into tangible spatial and temporal variables.

Stage 5: Focus Group Workshop and Validation To validate the artefact's integrity and practical utility, a focused group workshop was held. Participants from earlier interviews and additional domain professionals convened to review the framework, toy case assumptions, and interface rules. Using structured discussion prompts, the session captured user feedback on usability, completeness, and

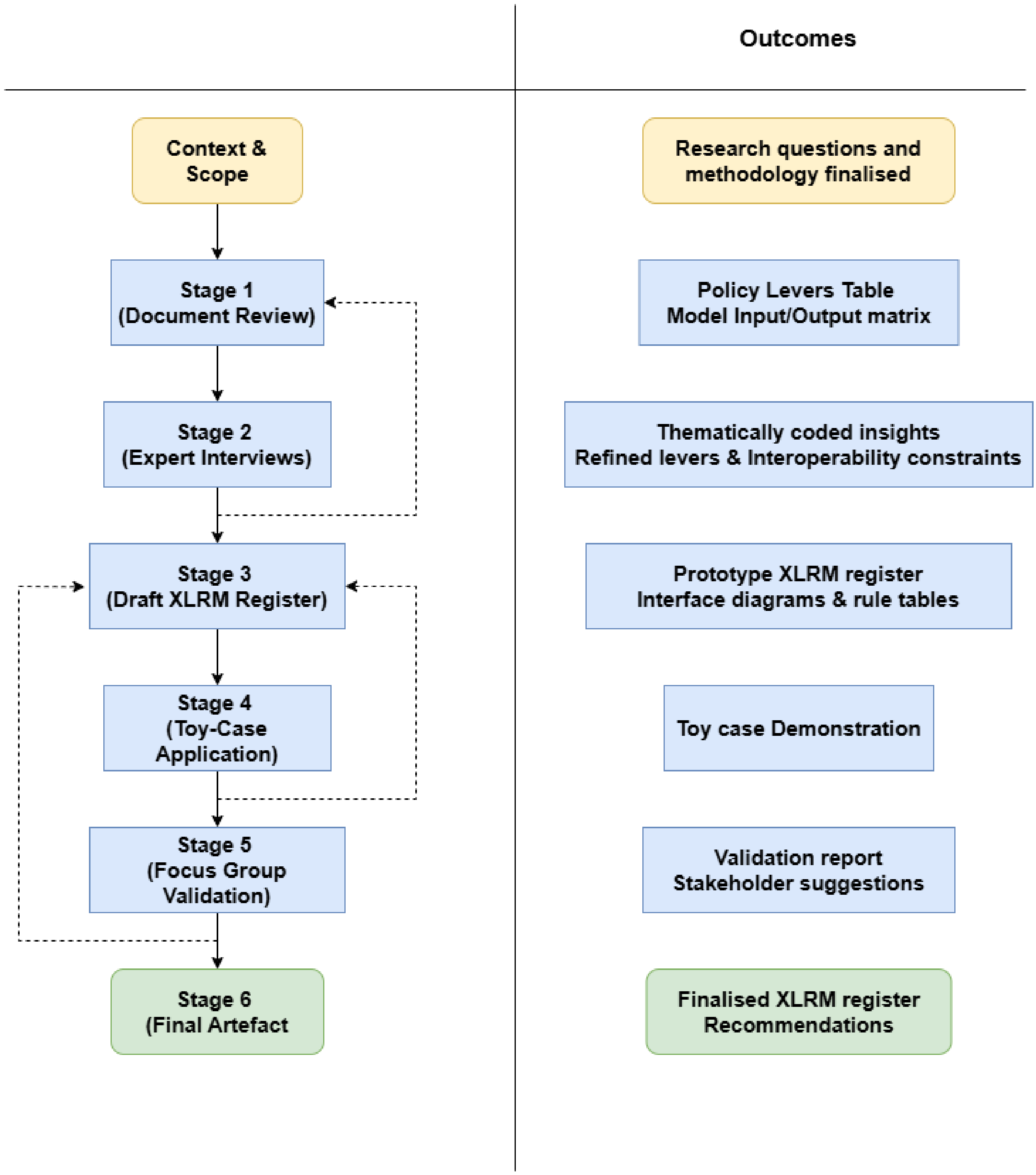

Figure 3.1: Research Design

scenario realism.

Feedback was recorded and manually coded, revealing three areas for refinement:

- Need for clearer specification of data exchange frequency.
- Adjustments to lookup thresholds based on real-world operational priorities.
- Simplified articulation of interaction logic for non-technical stakeholders.

Each method stage builds toward answering the sub-research questions:

1. Identifying adaptation levers (Stages 1 & 2) informs which policy measures require integrated modelling.
2. Document and interview insights (Stages 1 & 2) clarify the technical interoperability needs of different flood and transport models.
3. Artefact iteration and expert review (Stages 3 & 4) evaluate and justify interaction strategies through practical demonstration and validation.

3.4 Data Sources

This study integrates multiple data sources and rigorous strategies to ensure credible and high-quality findings.

3.4.1 Literature Review

A systematic literature review was conducted to ensure comprehensive coverage and transparency. Academic databases such as Scopus and Web of Science were queried alongside grey literature (Rotterdam Adaptation Strategies). Search terms included:

- "XLRM framework"
- “Rotterdam flood transport coupling,”
- “urban flood transport integration,”
- “digital twin flood transport.”
- "flood impact on road networks"
- "network resilience flood impacts"
- "digital twin transport planning"
- rule-based coupling
- co-simulation

Inclusion criteria prioritised empirical content, operational relevance to Rotterdam, and model-specific documentation. Exclusions were drawn for conceptual-only studies, non-urban settings, and unrelated domains.

3.4.2 Expert Selection and Interview Protocol

Six domain experts were selected via purposeful sampling, spanning flood modelling, transport systems, and digital-twin applications within Rotterdam’s planning environment. Selection criteria included hands-on experience with flood and transport modelling and digital twin modelling. Ethics procedures were followed, with informed consent secured. Data was collected through 45–60 minute semi-structured interviews and one focus-group session. Questions probed operational levers, model interoperability issues, and practical coupling constraints. Audio recordings were transcribed for analysis, which was later anonymised for privacy reasons.

Six domain experts (coded E1–E6, as shown in Appendix A) participated in semi-structured interviews. The panel comprises three academic experts, two applied-research specialists, and one post-doctoral researcher. Their collective expertise spans high-resolution flood modelling, depth–speed road disruption analysis, co-simulation latency management, municipal open-data licensing, drainage operations practice, and digital-twin orchestration. First-line emergency responders and public-transport operators were not interviewed; this coverage gap is acknowledged as a limitation and is flagged for future validation work.

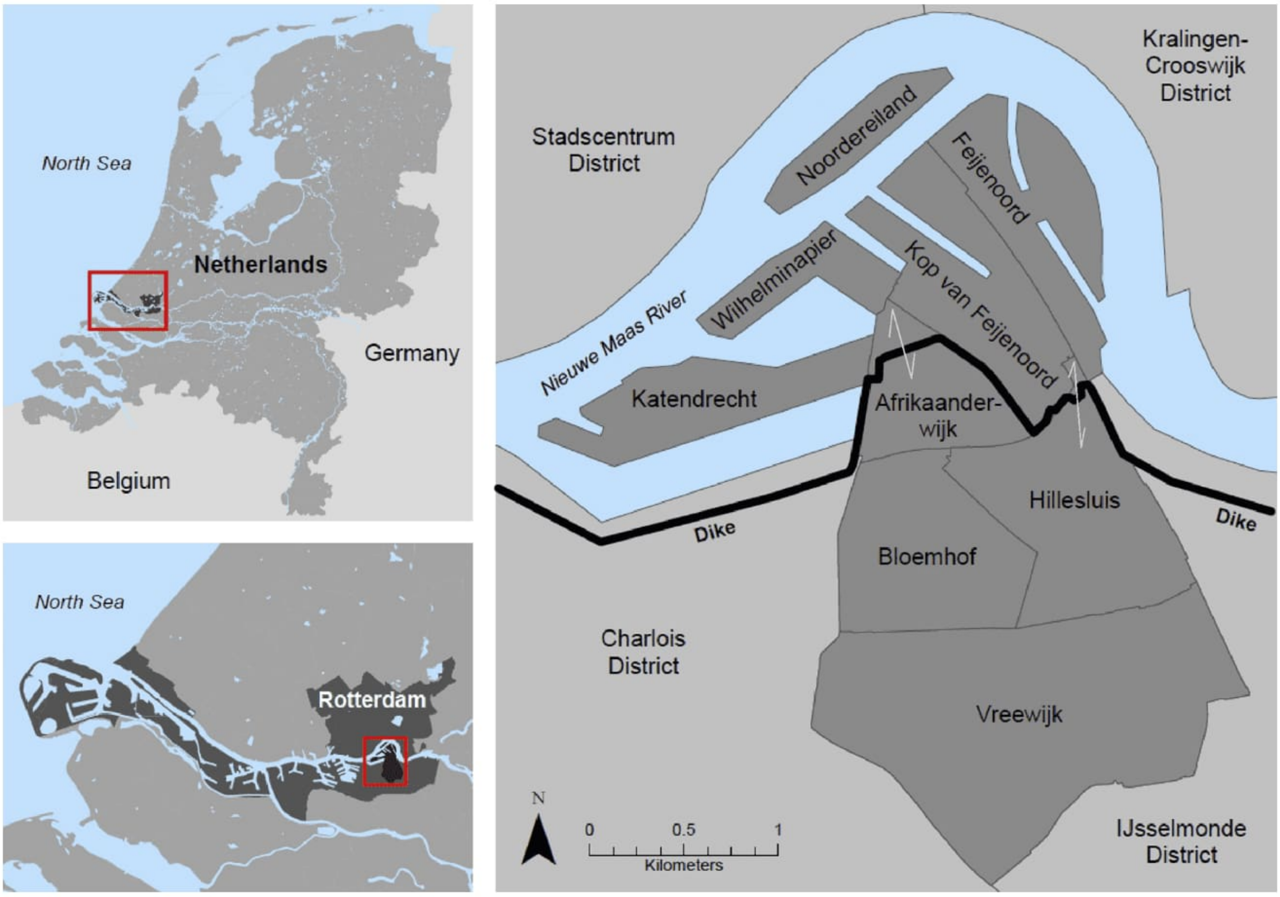

Figure 3.2: Map of the Kop van Feijenoord District in Rotterdam, Netherlands (Plan Integration for Resilience Scorecard, 2018)

3.5 Toy Case

The Laan op Zuid corridor, located in the Kop van Feijenoord district of Rotterdam, serves as the demonstration area for this toy case. This corridor forms the primary southern approach to the Erasmus Bridge and functions as a vital artery connecting Rotterdam-Zuid with the city centre. Despite its importance to citywide mobility and emergency response, Laan op Zuid lies outside the primary dike system ("buitendijks"), making it particularly prone to both riverine flooding from the Nieuwe Maas and pluvial flooding during heavy rainfall.

The selection of Laan op Zuid is therefore rooted in policy relevance. Rotterdam's climate adaptation agenda consistently flags Kop van Feijenoord as an area requiring integrated resilience investment, particularly in arterial road corridors. Gemeente Rotterdam, 2013 Plans emphasise the need for dual-use infrastructure—elevated roads serving both flood resistance and mobility continuity. This corridor also possesses a complex institutional and governance profile: lying outside the main dikes, adaptation responsibility is diffused across municipal services and private stakeholders, reflecting national encouragement of bottom-up resilience strategies, as documented in studies of Feijenoord governance and resilience initiatives.

From a scenario-alignment perspective, Laan op Zuid offers a rich mix of flood dynamics, land use, and transport functions. Pluvial flooding during intense cloudbursts coincides here with fluvial backwater conditions, creating compound stress scenarios ideal for testing coupling frameworks. The corridor's mixed urban character—featuring residential zones, tram lines, and high-volume roadways—provides the heterogeneity needed to stimulate meaningful calibration of depth, speed and route-closure rules. Additionally, Feijenoord's status as a diverse, evolving district closely aligns with Rotterdam's resilience planning priorities, emphasising governance innovation and physical-network enhancement to support resilience goals. (Plan Integration for Resilience Scorecard, 2018)

Strategically, the Laan op Zuid toy case offers two strategic insights: first, applying the XLRM framework here allows for both empirical and institutional validation in a recognised high-risk zone. Second, the integration of flood modelling outputs with transport model parameters in this corridor emphasises technical feasibility and scenario communication value, making results tangible and compelling for stakeholders.

The Laan op Zuid corridor embodies an ideal toy case setting as a policy-significant, scenario-rich, and institutionally complex environment for demonstrating how a formally specified R-layer can bridge flood hazards and transport impacts in digital-twin planning.

3.6 Roadmap for Addressing the Research Questions

This section explains how each research question (RQ) is answered in the remainder of the thesis and points to the relevant artefacts (X, L, R, M).

- RQ1: Which adaptation levers matter for flood–transport integration in Rotterdam? Chapter 4 specifies the X and L layers (uncertainties and levers) and links them to policy-relevant scenarios.
- RQ2: What are the technical requirements and constraints of existing flood and transport models? Chapter 5 maps I/O structures, formats, and time steps (3Di to MATSim/SUMO) and describes spatial/temporal alignment and exchange rules.
- RQ3: What are the pros/cons of candidate coupling strategies, and how should they be specified? Chapter 5 compares rule-based, co-simulation, and mediated approaches and formalises the R-layer; Chapter 6 consolidates metrics (M) and the validated coupling specification.

Validation and synthesis: Chapter 7 reports external, qualitative validation via a structured focus-group workshop. Chapters 8–9 discuss implications for digital-twin pilots, provide recommendations for practice and research, and outline limitations.

Chapter 4

Exogenous Uncertainties (X) and Policy Levers (L)

This chapter develops the "X" (exogenous uncertainties) and "L" (policy levers) components of the XLRM framework, within the specific context of Rotterdam. This chapter establishes the logic by systematically defining, classifying, and quantifying uncertainties and levers, preparing them for integration into model coupling and validation stages.

First, we introduce clear operational definitions for X and L, explaining how external factors like extreme rainfall or subsidence (X) and planner-controlled interventions, such as temporary barriers or adaptive traffic management (L), shape scenario outcomes. We then classify uncertainties using a practical typology and quantify them using empirical sources, including KNMI projections and Rotterdam's adaptation statistics.

Next, we present a structured X-L register, mapping each uncertainty to relevant levers appropriate for the Laan op Zuid corridor. This register, grounded in local adaptation strategies and expert input, ensures clarity in how specific interventions respond to real-world risks. Following this, we outline the scenario-building process, detailing the logic for combining multiple Xs and Ls into coherent, manageable scenario sets, including representative, stress-test, and extreme event configurations.

4.1 Exogenous Uncertainties (X)

Exogenous uncertainties refer to factors external to the direct control of decision-makers, yet fundamentally shaping system dynamics and risk profiles. In the XLRM framework, these uncertainties, denoted as "X", represent environmental, climatic, infrastructural, and societal drivers whose trajectories, magnitudes, and interactions cannot be predetermined or manipulated by planners. They differ from endogenous variables, which can be influenced by policy levers or adaptive actions. Instead, exogenous uncertainties define the scenario space within which adaptation strategies must operate, and their explicit representation is essential for robust decision-making under conditions of deep uncertainty. (Lempert et al., 2006)

In the context of Rotterdam's flood–transport coupling, exogenous uncertainties encompass the full range of physical and socio-economic processes that influence both flood hazard and transport system vulnerability. This includes, for example, the frequency and intensity of extreme rainfall events, long-term sea-level rise, changing patterns of river discharge, rates of urban subsidence, and evolving transport demand due to population or economic growth. Each of these drivers has the potential to trigger, amplify, or modulate disruptive cascades affecting both flood and transport domains. In a delta city like Rotterdam, with its intricate system of dikes, polders, and interconnected mobility networks, the interplay of these uncertainties is particularly consequential for both immediate crisis management and long-term adaptation planning.

Exogenous uncertainties are treated through a combination of conceptual and parametric approaches. In this framework, X encompasses all factors that lie beyond the direct control of decision-makers, such as extreme rainfall events along with river discharges, sea level rise, and broader climate change projections. Practically, these uncertainties are defined using scenario logic and parameter ranges, for example, varying rainfall intensities, frequencies, or water levels. These definitions are anchored in authoritative sources, including Dutch national climate scenarios and local adaptation plans.

To systematically identify and characterise exogenous uncertainties for this study, we rely on a triangulation of data sources. These include:

- Peer-reviewed literature on flood risk and urban resilience
- National and regional climate projections (e.g., KNMI'23 climate scenarios)
- Official policy and adaptation plans (e.g., Resilient Rotterdam 2022–2027, Delta Programme reports)

By synthesising insights from these sources, we construct a register of exogenous uncertainties that is both empirically grounded and directly relevant to Rotterdam's operational and policy context. This register forms the basis for the scenario logic and lever selection detailed in subsequent sections.

Category	**Uncertainty variable**	**Range**	**Unit**
Climatic	Extreme rainfall intensity	Historic up to 78 mm h^{-1}; projected +30% by 2100	mm h^{-1}
	Seasonal precipitation variability	±10–30 % seasonal change by 2100	% change
	Storm-surge frequency	Increased incidence under SLR	events yr^{-1}
Hydrological	Sea-level rise	0.3–0.8 m by 2050	m
	River-discharge extremes	+5–25% annual max by 2100	% change
	Groundwater rise/subsidence	2–8 mm yr^{-1}	mm yr^{-1}
Infrastructural	Pump/sewer capacity performance	80–120% of nominal under peak loads	% capacity
	Flood-defence integrity	Qualitative variability	–
Behavioural	Driver compliance with closures/detours	0–100% across scenarios	% compliance
	Transport-demand growth	+10–40% by 2050	% change

Table 4.1: Key exogenous uncertainties considered in the Rotterdam X-layer.

4.1.1 Classification of Exogenous Uncertainties

A structured classification of exogenous uncertainties (X) is fundamental for robust scenario development in coupled flood–transport modelling. For Rotterdam, we can employ a fourfold typology:

1. **Climatic Uncertainties:** Climatic drivers constitute the backbone of flood hazard scenarios for Rotterdam, where shifts in rainfall and temperature regimes directly influence urban pluvial and fluvial risk profiles.
    - Extreme rainfall intensity and duration: Recent analyses underscore a robust upward trend in short-duration, high-intensity rainfall, as evidenced by both observed events and climate projections. KNMI'23 scenarios project a significant increase in 1-hour and 3-hour rainfall extremes for the Dutch lowlands, with urban flood peaks potentially rising by over 30% this century. (van Oldenborgh et al., 2021)

- Seasonal and interannual variability: Projections from CMIP6 highlight substantial uncertainty in annual precipitation patterns for Northwest Europe, with wetter winters and drier summers, but more frequent extreme summer downpours. (van Aalst et al., 2023)
- Storm surge and tidal events: While average storm frequency may not increase, higher baseline sea levels mean a greater probability that even moderate storms will cause damaging surges. (Sterl et al., 2009)

2. **Hydrological Uncertainties:** Hydrological uncertainties cover changes in riverine, coastal, and groundwater regimes, compounded by geophysical processes.
   - Sea-level rise (SLR): Projections for the Dutch coast, including Rotterdam, indicate a plausible SLR range of +0.26 m to +1.24 m by 2100 under different emission scenarios.(Haasnoot et al., 2020) Accelerated Antarctic melt may drive even higher endpoints.
   - River discharge extremes: Projected Rhine–Meuse winter discharges are expected to increase by 10–30% by 2100, while summer flows may decrease, raising the likelihood of compound flood events. (Deltares, 2023)
   - Groundwater rise and land subsidence: Land subsidence in parts of Rotterdam (notably the south) proceeds at 2–8 mm/year, cumulatively raising effective flood risk by reducing drainage gradients. (Municipality of Rotterdam, 2023)
3. **Flood Infrastructural Uncertainties:** Infrastructural uncertainties focus on the performance, maintenance, and adaptive limits of Rotterdam's urban water and transport systems.
   - Pump and sewer capacity and reliability: Extreme rainfall can overwhelm current drainage and pumping capacity, leading to road closures and transit disruption. (Pregnolato et al., 2017)
   - Integrity and adaptability of flood defences: Variability in dike quality, compartment barriers, and flexible protection (e.g., mobile walls) introduces non-trivial uncertainty in the extent and duration of urban flooding. (Municipality of Rotterdam, 2022)
   - Operational and institutional response: The efficiency of infrastructure management—scheduled maintenance, emergency deployment—remains a critical uncertainty, especially during concurrent events. (van der Brugge & de Graaf, 2010)
4. **Behavioural and Socioeconomic Uncertainties:** Human responses and socioeconomic trajectories add a further layer of uncertainty in both exposure and system performance. (Gemeente Rotterdam, 2016) Impact of behavioural uncertainties was discussed during the interviews.
   - Population growth and spatial development: Shifts in urban density, spatial planning, and asset distribution directly influence who and what is exposed in future flood events.
   - Economic activity and transport demand: Rotterdam's role as a critical port hub means any change in trade volumes, logistics patterns, or baseline mobility has a disproportionate effect on flood-induced disruption.
   - Behavioural adaptation and compliance: Public compliance with evacuation and detour protocols, modal shifts during warnings, and changes in travel demand due to remote work or risk perception are difficult to forecast but crucial for scenario robustness.

4.2 Policy Levers (L)

In the XLRM framework, policy levers (L) are defined as planner-controlled strategies, interventions, and actions designed to adapt to, mitigate, or respond to flood–transport risks. Unlike exogenous uncertainties, which lie beyond the control of decision-makers, levers represent the adjustable features in the urban adaptation scenario, including infrastructural, spatial, operational, and emergency measures. (Lempert & Groves, 2021)

For Rotterdam, there are many policy levers like dike reinforcement, the Maeslantkering storm-surge barrier, water squares, green roofs, the innovative tidal park at Keilehaven, traffic signal adaptation, smart detours, infrastructure resilience at transport nodes, early-warning systems, road-closure protocols, and public alert mechanisms.

Policy levers (L) in this framework are treated both conceptually and parametrically, with a direct operational mapping to the underlying models. These levers encompass the adaptation strategies and interventions available to planners, including measures such as elevating critical roads, installing flood gates, adjusting the timing of evacuations, or modifying traffic management protocols. The identification of relevant policy levers is grounded in a detailed analysis of Rotterdam's official adaptation strategies, such as the Rotterdam Climate Change Adaptation Strategy and Resilient Rotterdam 2022–2027.

These levers align with Rotterdam's Resilient Rotterdam Strategy 2022–2027 and its adaptation-driven planning approach, which combines flood-proof infrastructure, multi-functional urban space, and crisis preparedness to build resilience and livability.

4.2.1 Classification of Policy Levers

A structured classification of policy levers (L) is fundamental for robust scenario development in coupled flood–transport modelling. For Rotterdam, we can employ a fourfold typology:

1. **Structural/Hard Engineering Levers:** Structural levers comprise traditional civil engineering interventions aimed at physically controlling water, reducing exposure, or preventing system failure. These interventions are long-term, capital-intensive, and often central to Dutch flood risk management. By directly modifying the hydrodynamic environment, these measures reduce the likelihood or severity of urban inundation, maintaining or restoring transport system operability during extreme events.

    - Dike Heightening and Reinforcement: Continuous reinforcement and elevation of primary flood defences, such as the Nieuwe Maas dike, protect both residential areas and critical transport arteries from breach and overtopping. (Aerts et al., 2008)
    - Storm Surge Barriers: The Maeslantkering barrier is a flagship structure, shielding Rotterdam from coastal surges; its timely closure is vital for the uninterrupted operation of bridges and tunnels. (Gemeente Rotterdam, 2016)
    - Compartmentalisation: Creation of secondary embankments or compartment dikes within port areas to localise flood impacts and protect key infrastructure corridors.
    - Pump Upgrades and Drainage Enhancements: Expansion and modernisation of urban pump stations and drainage canals, as exemplified by the city's post-2021 upgrades, reduce pluvial flood impacts on road networks. (Pregnolato et al., 2017)

2. **Nature-Based & Spatial Adaptation Levers:** These levers employ ecosystem-based approaches, utilising natural processes and multifunctional design to absorb, store, and delay floodwaters. Nature-based solutions moderate runoff and peak flows, directly lessening street-level flooding and maintaining passability for emergency vehicles and commuters. Spatial planning levers

Lever Category	Policy Lever	Operational Definition	Flood–Transport Relevance
Structural/Hard	Dike Heightening/Compartmentalization	Raising/reinforcing dikes; adding secondary dikes to limit flood extent	Reduces direct exposure of infrastructure; keeps critical links dry
	Storm Surge Barriers	Movable barriers at river mouth or harbours to prevent storm surges	Blocks North Sea surges, protects city and transport networks
	Pump Upgrades/Drainage	Enhanced pumps and drainage systems to remove floodwater faster	Shortens duration/extent of road inundation
Nature-Based & Spatial	Water Squares & Green Roofs	Temporary water retention in public squares; green roofs increase infiltration	Reduces runoff to streets; delays peak flows
	Tidal Park	Urban parks that store tidal and stormwater temporarily	Buffer for pluvial/tidal surges, relieve the adjacent road network
	Spatial Planning & Zoning	Directing critical infrastructure away from high-risk flood zones	Reduces exposure of key transport/evacuation routes
Transport & Infrastructure	Elevated Roads/Viaducts	Raising transport corridors above flood thresholds	Maintains emergency & logistics routes under flood conditions
	Redundancy/Alternate Modes	Multiple transport modes/routes to ensure mobility	Ensures connectivity if primary links fail
	Flood-Proofing Vital Nodes	Waterproofing/raising entrances, vital nodes, tunnels, or power supplies	Faster recovery; avoids network "bottleneck" failures
Operational & Emergency	Dynamic Traffic Management	Real-time detours, closures, ITS using sensor data and communication	Minimises congestion, reroutes traffic, increases safety
	Early Warning/Crisis Protocols	Municipal alert systems, flood warnings, emergency evacuation plans	Timely action by public and authorities
	Public Awareness & Preparedness	Campaigns, drills, communication for risk awareness and compliance	Increases compliance, reduces casualties and disruption

Table 4.2: Typology of Policy Levers for Flood–Transport Adaptation in Rotterdam

reduce transport system exposure by guiding development toward safer locations.

- Water Squares: The Benthemplein water square exemplifies a multifunctional public space that temporarily retains stormwater, protecting adjacent roads and tram lines. (de Urbanisten, 2022a)
- Green Roofs and Infiltration Zones: Rotterdam's "Green Roof Programme" has added over 400,000 m² of green roofs, increasing infiltration and reducing overland flow onto streets. (Municipality of Rotterdam, 2023)
- Urban Retention Ponds and Parks: The Keilehaven tidal park, with its oscillating water levels, integrates ecological and flood-buffering functions, directly supporting local transport resilience. (de Urbanisten, 2022b)
- Adaptive Spatial Zoning: The "Water Sensitive Rotterdam" policy directs critical assets like hospitals and evacuation routes away from high-risk flood zones. (Municipality of Rotterdam, 2023)

3. **Transport & Infrastructure Measures:** These levers involve direct modification or management of transport infrastructure to improve system robustness and maintain mobility under flood

conditions. Targeted elevation, redundancy, or flood-proofing of transport assets ensures that key corridors and nodes remain operational during or after flood events.

- Elevated Roads and Viaducts: The Port of Rotterdam adaptation plan highlights raising roadbeds and key junctions above flood thresholds to maintain critical supply chains and emergency access. (European Environment Agency, 2025)
- Network Redundancy: Developing alternate routes, such as waterbus services along the Maas, ensures connectivity if primary roads are flooded. (Gemeente Rotterdam, 2016)
- Flood-Proofing Vital Nodes: Investments in sealing metro station entrances and elevating control centres are underway to ensure that public transport can resume rapidly after flooding. (Pregnolato et al., 2017)

4. **Operational & Emergency Levers:** These are dynamic, often technology-enabled measures and protocols activated before, during, or after flood events to minimise impact, protect lives, and maintain mobility. Operational levers can be triggered in real-time as flood hazards emerge, directly influencing system response and public safety.

   - Dynamic Traffic Management: Adaptive closure and detour protocols based on real-time flood sensor data (e.g., smart road signs, dynamic route guidance). (Municipality of Rotterdam, 2022)
   - Early Warning and Forecasting: The city's integration of KNMI alerts into municipal communication platforms ensures timely public warnings and transit system adjustments. (Municipality of Rotterdam, 2022)
   - Crisis Response and Evacuation: Pre-planned evacuation corridors, vertical evacuation sites, and dedicated emergency service deployment routes. (van Veelen, 2013)

Uncertainty (X)	**Relevant Policy Levers (L)**	**Rationale / Mechanism**
Extreme rainfall	Water squares, green roofs, pump upgrades, dynamic traffic management	Reduces runoff; increases drainage capacity; manages real-time road closures
Sea-level rise	Dike heightening, surge barriers, spatial planning, compartmentalization	Prevents overtopping; protects critical assets; moves vital links out of risk zones
Storm surge	Surge barriers, dike reinforcement, early warning systems	Physical protection and advanced closure, plus alerts for operational preparedness
River discharge extremes	Compartment dikes, retention ponds, spatial zoning	Localised impacts, stores excess water, and reduces infrastructure exposure
Groundwater rise	Green infrastructure, pump upgrades, building elevation	Increases infiltration/storage; ensures drainage and raises assets above risk
Pump/sewer capacity stress	Pump station modernisation, redundancy, emergency protocols	Increases system resilience under peak loads; ensures continuity with backup plans
Transport demand growth	Spatial planning, redundancy, elevated roads, flood-proof nodes	Moves critical infrastructure, adds alternative routes, flood-proofs bottlenecks
Behavioural compliance	Public awareness, dynamic management, early warning	Improves response, compliance with detours/closures, and reduces exposure during events

Table 4.3: Register Table mapping Ls to Xs

4.3 Mapping of Exogenous Uncertainties (X) to Policy Levers (L) in Rotterdam

Table 4.3 above provides a structured mapping between key exogenous uncertainties and targeted policy levers for Rotterdam's flood–transport adaptation. Each uncertainty is linked to the most effective interventions, with a clear rationale for their application. This register not only ensures transparency in scenario construction but also anchors the XLRM framework in real-world adaptation practice.

The register table systematically connects each major exogenous uncertainty (X) identified for Rotterdam with the most relevant policy levers (L) available to city planners and stakeholders. For each uncertainty, such as extreme rainfall, sea-level rise, or pump capacity stress, the table lists one or more levers that can effectively address or mitigate its impacts. The rationale column explains the mechanisms by which these levers act, for example, how green roofs reduce surface runoff or how surge barriers protect against storm surges, ensuring that the connections are evidence-based and operationally meaningful. This table thus serves as a practical roadmap for scenario development in the XLRM framework, making explicit how Rotterdam's adaptation strategies can be matched to specific climate and system risks.

This chapter developed the exogenous uncertainties and policy levers layers of the XLRM framework in the context of Rotterdam's flood–transport challenges. Through a structured typology, the principal sources of uncertainty that shape risk profiles for flood and transport systems in the city were identified. Each uncertainty has been mapped to a set of policy levers, reflecting both Rotterdam's adaptation strategies and internationally recognised best practices. The X–L register ensures transparency and operational relevance in scenario design by explicitly connecting uncertainties to targeted interventions. This linkage is critical for robust adaptation planning: it allows decision-makers to test how specific measures can mitigate the impacts of plausible extreme events.

The foundation laid in this chapter prepares the ground for subsequent technical work, particularly the specification of the Relationships (R) layer, which will formalise how these uncertainties and levers interact within coupled flood and transport models.

Chapter 5

Model Landscape and Coupling Approaches

The ability to robustly couple high-resolution flood-inundation models with dynamic urban transport models lies at the heart of operational resilience planning for cities like Rotterdam. As flood risk and mobility disruptions increasingly interact under conditions of climate change, planners and modellers require transparent, interoperable frameworks to simulate, anticipate, and manage cascading impacts on critical infrastructure.(Kasmalkar et al., 2020) Achieving this goal is as much a technical as a methodological challenge: flood and transport models have evolved along separate disciplinary lines, each with distinct data structures, spatial and temporal scales, and underlying assumptions. Bridging these divides demands not only careful selection and configuration of modelling tools, but also explicit protocols for harmonising variables and synchronising time-steps.

This chapter provides a detailed technical review of the model landscape, setting the foundation for the XLRM framework developed for Rotterdam's flood–transport coupling. It begins by understanding the state-of-the-art flood and transport models used in Dutch urban resilience planning, highlighting their input/output structures, operational interfaces, and key assumptions. The chapter then systematically classifies coupling strategies as identified in the scientific literature before evaluating their suitability for operational integration in Rotterdam's digital-twin context. Finally, it details the empirical and operational rationale for specific coupling choices, closure rules, and lookup tables applied to the Laan op Zuid corridor, the toy case.

5.1 Flood Models

In this section, we will explore the different flood models and their characteristics.

5.1.1 3Di

The 3Di hydrodynamic model represents a state-of-the-art tool for simulating urban flood dynamics in the Netherlands, with growing adoption among municipalities and waterboards seeking operational and planning insight into complex inundation events. Developed in the Netherlands and built on the two-dimensional shallow water equations, 3Di employs a unique subgrid modelling technique: fine-scale topographic detail (down to 0.5–5 m resolution) is stored within larger, flexible computational grid cells, enabling the simulation of urban water movement with high accuracy but without prohibitive computational costs.(Tibben, 2015) This approach is particularly valuable in Dutch urban contexts, where subtle variations in elevation and infrastructure can drive significant differences in flood behaviour.

3Di's architecture is cloud-native, allowing for web-based access, collaborative scenario building, and near real-time simulation. Its RESTful API and support for standard data formats such as NetCDF and

Figure 5.1: Geographical map overlay showing a 3Di flood model simulation with terrain elevation and hydraulic network elements (3Di Documentation Team, 2024)

GeoTIFF facilitate easy integration with external analysis tools, GIS software, and other simulation models. For example, 3Di exposes time-varying water depth rasters and flood extent polygons that can be queried, processed, and mapped onto transport networks—a key enabler for flood–transport coupling. (Nelen & Schuurmans, 2023)

A typical 3Di workflow begins with high-resolution input data: digital elevation models (DEM), land use and surface roughness maps (Manning's n values), rainfall forcing (in gridded or time series form), and boundary conditions (tidal or river hydrographs). The hydrodynamic core operates at adaptive time-steps (usually 1–10 seconds), producing outputs such as water depth, velocity, and flood extent at user-defined intervals (commonly 5 minutes), with results stored in NetCDF or GeoTIFF format for downstream use. (Tibben, 2015) This fine temporal and spatial granularity is especially advantageous for urban flood modelling, where rapid changes in inundation must be captured to inform emergency management and transport impact assessments.

Crucially, 3Di's flexibility and technical openness make it suitable for integration with dynamic transport models. In Rotterdam, for instance, 3Di is routinely used by local waterboards to maintain up-to-date schematics of the city and to support operational water management. The model's capacity to deliver minute-by-minute water-depth rasters via its open API enables direct coupling with agent-based or microscopic transport simulators, allowing road-level flood impacts (such as link closures or speed reductions) to be dynamically triggered as the simulated flood evolves.(Pregnolato et al., 2017) In this thesis, 3Di serves as the flood model of reference for the toy case, chosen for its proven accuracy, open integration, and operational relevance for the Rotterdam context.

5.1.2 Delft3D Flexible Mesh (D-Flow FM)

Delft3D Flexible Mesh (D-Flow FM) is an advanced hydrodynamic modelling suite developed by Deltares, widely used for simulating surface water dynamics in riverine, estuarine, coastal, and increasingly, urban environments. D-Flow FM extends the legacy of the Delft3D modelling system by enabling flexible, unstructured grids—supporting triangles, quadrilaterals, and curvilinear elements within a single computational domain. (Deltares, 2022) This flexibility allows modellers to achieve fine spatial resolution in areas of interest, such as urban floodplains or critical infrastructure corridors, while maintaining coarser grids in less sensitive regions, optimising both computational efficiency and simulation accuracy.

D-Flow FM solves the one-dimensional, two-dimensional, and three-dimensional forms of the shallow water equations, incorporating detailed representations of hydraulic structures, overland flow, and

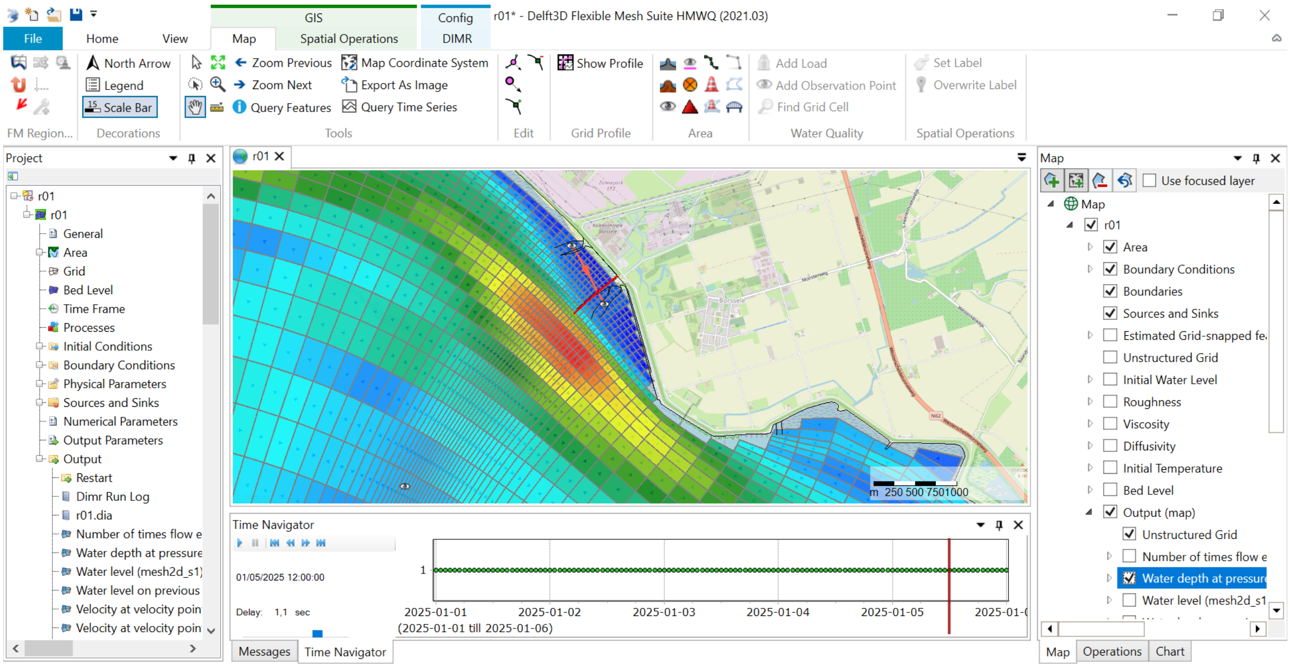

Figure 5.2: Delft3D Flexible Mesh model interface (Deltares, 2024)

dynamic boundary conditions. Its robust numerical schemes have been validated against real-world flood events in the Netherlands and internationally, making it suitable for both design studies and operational forecasting. (Deltares, 2022) The model is fully open-source, with an active development community and extensive documentation, ensuring transparency and adaptability for research and planning needs.

Input requirements for D-Flow FM include high-resolution digital elevation and bathymetry data, land use and roughness parameters, rainfall and discharge time series, and specifications for hydraulic structures such as weirs, pumps, and sluices. Outputs are provided as time-varying water depth, velocity, and flood extent maps, typically stored in NetCDF or GeoTIFF formats. The model supports scripting and automated workflows through Python and MATLAB interfaces, and can be integrated into larger modelling chains or digital twin environments.

5.1.3 LISFLOOD-FP

LISFLOOD-FP is an open-source, raster-based hydrodynamic model developed by the University of Bristol, widely used for simulating floodplain inundation at local, national, and continental scales. (Bates et al., 2022) Designed for efficiency and scalability, LISFLOOD-FP enables rapid simulation of flood propagation across complex topographies, making it suitable for both detailed urban studies and large-scale flood risk mapping under uncertainty.

At its core, LISFLOOD-FP solves the local inertial form of the shallow water equations on a regular or variable-resolution grid, allowing for the representation of both one-dimensional (1D) channel flow and two-dimensional (2D) overland flow. This grid-based approach offers significant flexibility, with typical cell sizes ranging from a few meters in dense urban environments to several hundred meters for regional or national studies. (Bates et al., 2022) The model supports adaptive time-stepping, wetting and drying processes, and efficient handling of hydraulic structures such as weirs, culverts, and levees.

Inputs to LISFLOOD-FP include high-resolution digital elevation models (DEMs), land surface roughness coefficients (Manning's n), river inflow hydrographs, and spatially or temporally distributed rainfall. Outputs are generated as time-varying rasters of water depth, flood extent, and velocity, commonly exported in ASCII or NetCDF formats for integration with GIS and downstream analysis. (Bates et al., 2022) The model's open architecture and comprehensive documentation facilitate adaptation to a wide range of scenarios, including pluvial, fluvial, and compound flood events.

A particular strength of LISFLOOD-FP is its computational efficiency, which enables the simulation of thousands of flood scenarios for probabilistic risk assessments and uncertainty analyses. The model has been validated in numerous case studies across Europe, including high-profile urban flood events, and supports integration with exposure and impact modules for rapid damage estimation. (Bates et al., 2022)

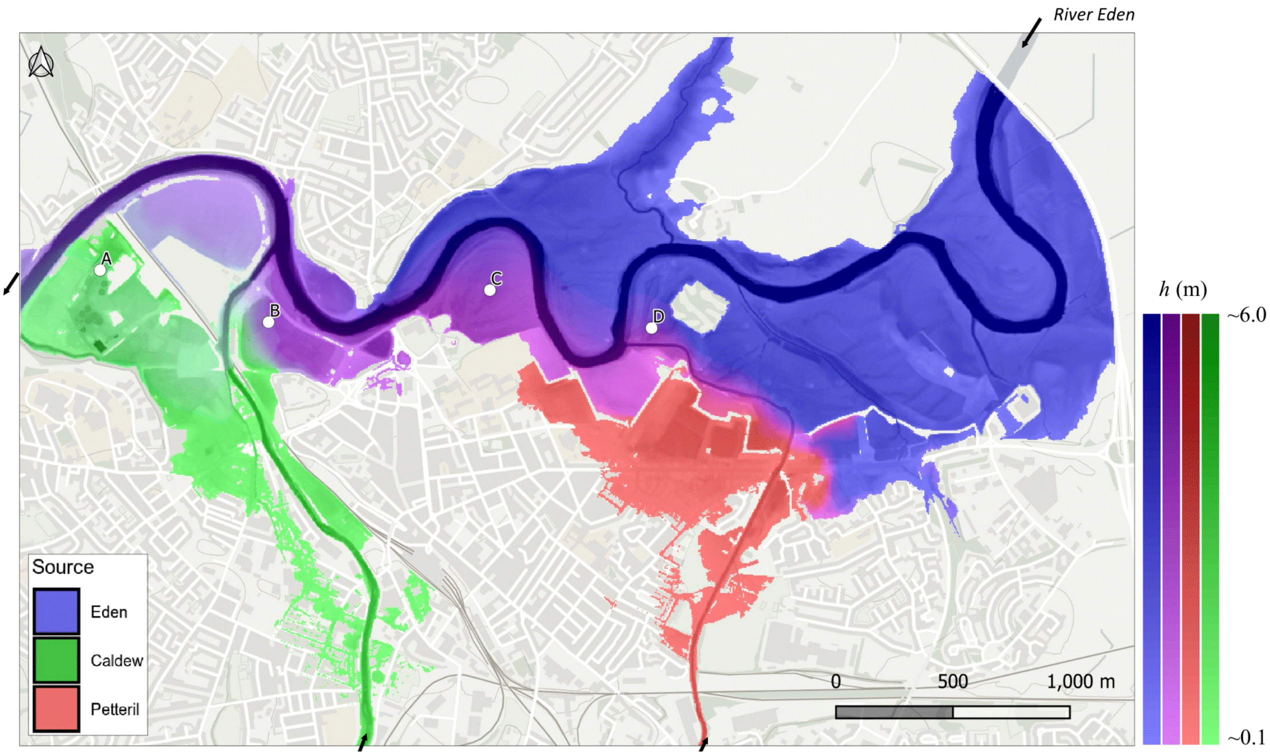

Figure 5.3: Sample output from LISFLOOD-FP model (Shaw et al., 2023)

5.1.4 Comparison of Flood Model Inputs and Outputs

Tables 5.1 and 5.2 summarise the key input and output characteristics of the three reference flood models considered for this research.

In terms of model inputs, all three platforms require high-resolution digital elevation models (DEMs) as a foundation, but differ in the granularity and format supported. 3Di and Delft3D FM accept GeoTIFF and NetCDF files, with 3Di leveraging a subgrid approach to represent fine-scale urban topography, while LISFLOOD-FP is optimised for adaptive raster grids spanning from several metres in urban areas to over 90 metres in regional settings. The representation of surface roughness also varies: 3Di and Delft3D FM allow for detailed polygon or element-based roughness assignment, whereas LISFLOOD-FP uses uniform or raster-based Manning's n values specified in parameter files.

Rainfall forcing and boundary condition handling further distinguish the models. 3Di and Delft3D FM ingest gridded or time series rainfall via NetCDF, supporting dynamic storm events and climate scenarios. LISFLOOD-FP reads rainfall from DEM-aligned stacks and channel inflow hydrographs, consistent with its emphasis on large-scale floodplain dynamics. Across all models, flexible handling of boundary conditions enables the simulation of both fluvial and pluvial events relevant to Rotterdam's compound risk landscape.

From an output perspective (Table 5.2), all models produce gridded maps of water depth and velocity, but their temporal resolution and export formats differ. 3Di delivers high-frequency (5 min) rasters accessible via its REST API, supporting real-time integration and visualisation. Delft3D FM outputs are typically grouped in NetCDF or GeoTIFF at user-defined intervals, while LISFLOOD-FP, known

Input item	3Di	Delft3D FM	LISFLOOD-FP
Terrain / DEM	GeoTIFF or ASCII; metres (NAP); sub-grid elevation array (0.5–5 m cell detail)	NetCDF/GeoTIFF mesh attributes; metres (NAP); 5 m urban → 250 m river	ASCII grid / GeoTIFF; metres (NAP); 5–90 m adaptive raster
Roughness / land use	Polygons in GeoPackage; Manning n 0.015–0.08	Element attribute table; Chezy or Manning n 0.02–0.06	Uniform or raster n map in .par; typical 0.025–0.07
Rainfall forcing	Gridded NetCDF; mm h^{-1}; 100 m / 5 min cloudburst	NetCDF grid or uniform series; mm h^{-1}; mesh Δx / 5 min	NetCDF stack; mm h^{-1}; DEM Δx / 15 min
Boundary conditions	CSV/NetCDF hydrographs; m^3 s^{-1} or m; 5 min	CSV/NetCDF tide & discharge; m, m^3 s^{-1}; 10 min	.bdy text hydrograph; m^3 s^{-1}; 15 min
Core time-step	Semi-implicit, adaptive; 1–10 s typical	Semi-implicit; 0.5–5 s typical	Explicit local-inertia; 1 s (GPU)
Typical output interval	5 min rasters via NetCDF API	1–10 min NetCDF groups	10 min binary rasters
Primary outputs	Depth, level, velocity rasters; max-depth GeoTIFF; 1-D link flows CSV	Depth, velocity, discharge NetCDF; flood-extent GeoTIFF	Depth, velocity rasters; max-depth GeoTIFF; cell hydrographs CSV
Data-exchange formats for coupling	NetCDF-4 (+ REST JSON), GeoTIFF, CSV	NetCDF-CF, GeoTIFF, CSV	Binary/ASCII rasters, NetCDF, CSV

Table 5.1: Comparison of Flood Model Inputs

for its computational speed, generates 10-minute binary or ASCII rasters suitable for ensemble runs and sensitivity analysis.

3Di supports NetCDF-4, GeoTIFF, and CSV, with the added advantage of a RESTful API for direct querying. Delft3D FM aligns with NetCDF-CF and GeoTIFF standards, while LISFLOOD-FP exports in both binary/ASCII and NetCDF formats.

5.2 Transport Models

In this section, we will explore the different transport models and their characteristics.

Output item	3Di	Delft3D FM	LISFLOOD-FP
Primary outputs	Depth, level, velocity rasters; max-depth GeoTIFF; 1-D link flows CSV	Depth, velocity, discharge NetCDF; flood-extent GeoTIFF	Depth, velocity rasters; max-depth GeoTIFF; cell hydrographs CSV
Typical output interval	5 min rasters via NetCDF API	1–10 min NetCDF groups	10 min binary rasters
Data-exchange formats for coupling	NetCDF-4 (+ REST JSON), GeoTIFF, CSV	NetCDF-CF, GeoTIFF, CSV	Binary/ASCII rasters, NetCDF, CSV

Table 5.2: Comparison of Flood Model Output

5.2.1 MATSim – Multi-Agent Transport Simulation

MATSim (Multi-Agent Transport Simulation) is an open-source, agent-based modelling framework that has become a standard tool for simulating large-scale urban transport dynamics and traveller behaviour. (Horni et al., 2016) Unlike aggregate or static assignment models, MATSim explicitly represents each traveller as an autonomous agent endowed with an individual daily activity plan. These agents interact with the network and with each other, making independent choices regarding departure times, routes, and modes—thereby enabling the simulation of adaptive responses to dynamic system changes such as flooding, congestion, or road closures.

The data workflow in MATSim is structured around a set of modular XML files, which define the transport network (nodes, links, link attributes), the synthetic population (with activity chains and travel demands), vehicle and mode specifications, and scenario parameters. Each simulation iteration consists of agents executing their plans, experiencing network feedback (e.g., congestion delays or detours), and updating their choices through a co-evolutionary learning process.

A key strength of MATSim for this thesis is its flexibility for dynamic network adaptation. After each simulation iteration, the network can be programmatically altered—edges can be closed, link capacities reduced, or speeds changed—based on external hazard information such as flood rasters.(Horni et al., 2016) This enables high-fidelity testing of scenario interventions, such as the cascading effects of progressive road closures during a flood event, and the impact on agent rerouting, accessibility, and evacuation times.

The platform's open architecture and Java/Python APIs allow integration with flood models, GIS, and digital-twin platforms. In the Dutch context, MATSim has been used for stress-testing Rotterdam's mobility under hazard scenarios, evaluating adaptation strategies, and supporting urban evacuation planning. For the toy case in this thesis, MATSim serves as the reference transport model, enabling a direct link between evolving flood conditions and real-time transport disruption.

5.2.2 SUMO – Simulation of Urban Mobility

SUMO (Simulation of Urban MObility) is a microscopic, open-source traffic simulation suite developed and maintained by the Eclipse Foundation and the German Aerospace Centre (DLR). SUMO is designed for high-fidelity modelling of individual vehicles, pedestrians, public transport, and multimodal logistics flows on road networks of virtually any size—from individual corridors to entire metropolitan regions.(Alvarez Lopez et al., 2018) SUMO's agent-based approach enables detailed representation of traffic dynamics, congestion, intersection control, and the operation of traffic management systems under both normal and disrupted conditions.

One of SUMO's principal innovations for hazard and adaptation research is the TraCI (Traffic Control Interface) API, which allows real-time, bidirectional communication between the simulation environment and external applications. (Eclipse Foundation, 2024) Through TraCI, users can dynamically alter the network state during simulation runtime: links or edges can be opened, closed, or capacity-modified based on external data feeds, such as evolving flood rasters or sensor observations. This capability makes SUMO particularly attractive for real-time flood–transport coupling, enabling immediate translation of flood model outputs into operational traffic responses and allowing scenario testing of adaptive strategies.

SUMO's input data are structured in a modular XML format, defining road network geometry, node/link attributes, demand files (trip and route definitions), vehicle types, and simulation parameters. OpenStreetMap and GIS data can be imported to streamline network creation for real-world cities like Rotterdam. SUMO supports advanced features such as public transport scheduling, traffic signal control, emissions modelling, and multi-modal integration—extending its utility beyond private vehicle flows to capture the full spectrum of urban mobility.

Outputs from SUMO are equally rich and granular: per-link and per-vehicle data can be exported at sub-second intervals in XML or CSV format, allowing post-processing of flows, speeds, delays, travel times, and network accessibility. The flexibility of the platform, its open-source nature, and its established community have driven its adoption in numerous Dutch and European research projects focused on transport resilience, real-time operations, and digital-twin applications. (Alvarez Lopez et al., 2018)

5.2.3 OpenTrafficSim (OTS)

OTS is a TU Delft–led open-source platform that unifies micro-, meso- and macro-traffic simulation in a single Java codebase. The same network file can be run in microscopic detail for a flood-affected district or in aggregate form for the wider Randstad, enabling consistent multi-scale testing. OTS's architecture exposes a rich event bus and units-aware data model, making it straightforward to plug in non-traffic hazards such as flood-depth rasters or infrastructure failures. Because it is developed by researchers who also work on Rotterdam's digital-twin pilots, OTS offers direct access to academic support and example code for infrastructure-coupling experiments.

Input item	**SUMO**	**OpenTrafficSim (OTS)**	**MATSim**
Road-network geometry	XML .net.xml (converted from OSM/ GIS); coords in WGS 84 or RD New; length m	XML/Java objects; unit-aware, can import OSM or GIS shapefiles	XML .network.xml; coords in any CRS (often WGS 84)
Demand / trips / agents	Trip/route XML (.trips.xml, .rou.xml) or OD CSV; veh s^{-1}	Population objects or OD matrices; Java/CSV	Plans XML (.plans.xml) with full activity chains
Vehicle / mode definitions	XML vehicle types (length m, v_{max} $m\,s^{-1}$, accel $m\,s^{-2}$)	Java classes or XML; multi-modal	Vehicle type XML plus mode choice parameters
Dynamic control / API	**TraCI** TCP socket; set speed, capacity, close edge at 1 s steps	Event bus / listeners; Java calls each simulation tick	Java listeners; after each iteration, network attributes can be updated
Basic simulation step (Δt)	1 s default (configurable to 0.1–10 s)	0.1–1 s micro; 1–5 s meso/macro	Sub-second internal; external iteration ≈ 60 s simulated

Table 5.3: Comparison of Transport Model Inputs

Output item	**SUMO**	**OpenTrafficSim (OTS)**	**MATSim**
Primary link outputs	Edge states XML/CSV: flow veh h^{-1}, speed $m\,s^{-1}$, travel-time s	Per-link statistics via CSV or Java callback	Link stats per iteration CSV: flow, TT, capacity
Vehicle-trajectory outputs	Per-vehicle XML/CSV (positions every Δt)	Java logs or CSV	Events XML: depart, enter link, arrive

Table 5.4: Comparison of Transport Model Outputs

5.2.4 Comparison of Transport Model Inputs and Outputs

Tables 5.3 and 5.4 provide a systematic comparison of the primary input and output specifications of the three transport models.

In terms of model inputs (Table 5.3), all three platforms accept high-resolution network geometries, but differ in format and spatial referencing. SUMO networks are typically generated as XML files converted from OpenStreetMap (OSM) or GIS data, while OTS uses unit-aware Java objects or standard shapefiles, and MATSim leverages XML network files in various coordinate systems (often WGS 84). Demand modelling is equally flexible. SUMO and MATSim use XML files to specify trips, routes, or activity chains, with support for CSV-based population data in OTS. The specification of vehicle and mode definitions also varies, with SUMO and MATSim employing detailed XML configuration, and OTS supporting both XML and Java class-based, multi-modal definitions.

A distinguishing feature of dynamic hazard integration is each platform's control interface. SUMO's TraCI API enables real-time network manipulation, allowing link states, speeds, and capacities to be updated every simulation second based on external data feeds, such as evolving flood conditions. OTS uses event-driven listeners to process hazard events and control simulation ticks, while MATSim offers Java listeners that allow network attributes to be altered after each iteration. The underlying simulation time-steps reflect their focus: SUMO and OTS support micro- and meso-level simulation steps (as low as 0.1 s), while MATSim operates on sub-second intervals within each simulated minute, providing the flexibility needed for real-time flood–transport coupling.

Regarding model outputs (Table 5.4), each tool provides detailed traffic state and trajectory information at multiple aggregation levels. SUMO exports edge-based link flows, speeds, and travel times in XML or CSV, with the ability to track individual vehicle positions at every simulation step. OTS offers per-link statistics and per-vehicle logs accessible via Java callbacks or CSV, while MATSim generates comprehensive link-level statistics and event logs that capture agent departures, arrivals, and route choices. This granularity is essential for quantifying flood-induced disruptions, such as increases in travel times, bottleneck formation, or changes in accessibility for vulnerable populations.

5.3 Coupling Flood and Transport Models

To accurately model flood–transport interactions, one needs to connect two very different simulation domains. Several approaches have emerged in the literature for linking flood models with transport models.

5.3.1 Rule-Based Coupling

Rule-based coupling is the most widely adopted method for integrating flood models with transport simulations. (Jafari Shahdani et al., 2023) It is a loose, asynchronous, and unidirectional integration method. In this framework, outputs from a flood model—typically spatially distributed water depth—are overlaid on a transport network, and a simple "depth-disruption" rule is applied: if the water depth on a road exceeds a threshold (e.g., 10–30cm), that link is either closed or assigned a reduced speed/capacity. (Pregnolato et al., 2017)

The appeal of rule-based coupling lies in its simplicity, transparency, and modularity. The logic is explicit: road closures or slowdowns are mechanically driven by a depth threshold. This approach is computationally efficient and model-agnostic—flood and transport models need only exchange basic raster or tabular data. It also lends itself well to stakeholder communication and scenario exploration, particularly during early planning phases or rapid assessments.

Empirical validation reinforces its real-world relevance. Pregnolato et al. (2017) fitted a polynomial function linking flood depth to vehicle speed using real traffic observations, showing a strong correlation ($R^2 = 0.95$) during a 2012 urban flood in Newcastle, UK. Similarly, Gangwal et al. (2023) applied the same function to define dynamic delays for flood-affected road segments.

Despite its strengths, rule-based coupling has limitations. It assumes unidirectional influence, ignoring how traffic redistribution or behavioural changes might feed back into flood exposure or response strategies. It further relies on accurate temporal discretisation, often misaligned between high-frequency flood dynamics and lower-resolution traffic models, resulting in possible under-representation of transient but impactful disruptions. While effective for response-level insights, it lacks support for capturing complex socio-technical dynamics or emergent system feedback loops.

Within the Rotterdam XLRM framework, rule-based coupling offers a transparent, operational foundation for scenario-based analyses. Its empirical grounding in depth-disruption functions supports the formulation of credible lookup tables and threshold rules in the R-layer. By providing a clear baseline, it enables layering on more sophisticated methods, such as co-simulation, at later stages of model validation and operational refinement.

5.3.2 Co-Simulation

Co-simulation offers a tight, synchronous and bidirectional, real-time integration of flood and transport models, allowing both systems to dynamically respond to each other during simulation. Unlike rule-based coupling, co-simulation retains the integrity of both models by orchestrating simultaneous execution and data exchange.

One example is found in urban transportation research by adjusting flood-related road closures in SUMO via MIKE FLOOD outputs. (Pyatkova et al., 2019) This method dynamically pauses or slows traffic on affected links as flooding occurs, and evaluates the downstream effects on trip times, fuel consumption, and emissions, demonstrating the feasibility of operationalising co-simulation in real-world urban contexts. By synchronising both simulations at one-minute intervals, they captured how flood-induced gridlock impeded emergency vehicle movement and examined how alternate routes affected flood exposure. This setup typically requires middleware to manage sync, data conversion, and iteration control.

Co-simulation excels in revealing temporal interdependencies. It captures cases where a flood might not immediately inundate a major road, but subsequent congestion from earlier closures causes later-stage disruptions. These dynamics are impossible to observe when flood and transport models are run sequentially. It also enables richer scenario testing—examining how varying start times of rainfall, evacuation orders, or ramping up of emergency services interact with evolving traffic states. (Wu et al., 2023)

However, the method is technically demanding. Key challenges include carefully synchronising time steps between models (e.g., flood model at 1–5 min intervals, transport at sub-minute steps), spatial matching (raster-to-network mapping), and error boundary management (to avoid drift or overflow). Computational load is another concern. Running two high-resolution, synchronised models in parallel significantly increases processing time and resource needs.

Operationally, co-simulation is best suited for high-fidelity scenario testing, digital-twin prototypes, or emergency planning tools where timing, feedback loops, and cascading effects matter. Its complexity and cost make it less suitable for routine scenario screening, where rule-based coupling still offers efficiency and clarity. In the context of the Rotterdam XLRM, co-simulation provides a valuable second layer of analysis: building on rule-based foundations to interrogate timing-sensitive questions, evacuation strategies, and response sequences with greater systemic realism.

5.3.3 System Dynamics

Another approach is to use a system dynamics model or another abstract representation to capture interactions between flood and transport systems at a higher level. It is typically loose, asynchronous, and bidirectional in nature. Instead of simulating individual roads and floodplains, this might involve stock–flow relationships and feedback loops. For instance, Hossain et al. (2017), in their framework for the Bangladesh delta, described qualitatively how transportation accessibility might deteriorate with increasing flood frequency, which in turn could affect socio-economic variables. Such models could include equations linking flood duration to, say, reduction in traffic flow, and then linking reduced mobility to economic loss or to the effectiveness of emergency response, which loops back to flood impact. These are essentially conceptual or analytical couplings – they are useful for understanding the big picture and testing policy levers in a broad sense (e.g. if we improve transport infrastructure, do overall flood impacts reduce?), especially under deep uncertainty. However, they lack spatial detail and precision. In Rotterdam's case, a system dynamics model might indicate that better transport connectivity improves resilience, but not tell you which street to raise or where to place shelters. Thus, system dynamics is often a first step or a complementary tool to more granular models.

5.3.4 Bayesian Network Mediator

A Bayesian Network (BN) Mediator provides a probabilistic framework for integrating flood and transport models by expressing their interdependencies through conditional probability distributions (CPDs), enabling explicit modelling of uncertainty in flood–transport impacts. (Joo et al., 2019) It is a loose, asynchronous, and generally unidirectional approach. In this approach, relevant variables—such as flood depth, infrastructure condition, and transport disruption—are represented as nodes linked by directed edges, with CPDs derived from empirical data, expert judgment, or dimensionality reduction techniques. (Joo et al., 2019) The multi-tiered BN methodology introduced by Liu et al. (2025) demonstrates how hierarchical structures can capture both broad system-level hazards and detailed local effects, supporting scalable analysis and efficient scenario updating. This mediation approach is particularly well-suited for strategic-level planning, where quantifying the probability of disruption or resilience under varying flood scenarios supports robust policy evaluation. However, the main limitations are its lack of fine spatial–temporal detail and the often subjective nature of CPD calibration, making it less practical for operational, real-time management. Within the Rotterdam XLRM, a BN mediator complements rule-based or co-simulation methods by providing an uncertainty-aware layer for risk-informed scenario ranking and decision support.

5.3.5 Justification for Selecting Coupling Methods

Rule-Based Coupling and Co-Simulation are chosen as the most relevant approaches for the Rotterdam flood-transport XLRM research because of their complementary strengths in operational feasibility, transparency, and capability for nuanced real-time interaction modelling. Rule-based coupling, due to its clear and easily communicable rules, directly supports rapid prototyping, stakeholder engagement, and initial validation of model interactions. This simplicity allows immediate usability within existing urban management processes, aligning with the practical objectives of city planners and emergency managers.

Co-simulation complements this simplicity by enabling detailed, real-time, and interactive simulation of complex feedback loops that are critical for operational decision-making and digital twin implementation. Given the project's aim to build a robust and operationally deployable integration for flood and transport management in Rotterdam, the co-simulation's ability to reflect precise timing and spatial-temporal dynamics ensures that critical operational questions can be accurately represented and managed.

Conversely, the System Dynamics, despite its effectiveness in representing aggregate system-level feedback and conceptual relationships, was excluded because it lacks the required spatial granularity and temporal precision critical for the Rotterdam flood-transport scenario. Its highly aggregated and conceptual approach does not match the project's need for detailed, location-specific operational planning.

The Bayesian Network Mediator, while robust in uncertainty management and probabilistic reasoning, was deemed less suitable due to its limited spatial-temporal detail and operational complexity. This approach is better aligned with strategic assessments rather than operational decision-making, which demands direct, clearly defined interactions between flood and transport dynamics without significant probabilistic abstraction.

5.4 Toy Case

This toy case demonstrates how high-resolution flood and transport models can be coupled to analyse critical infrastructure resilience in Rotterdam. Focusing on the Laan op Zuid corridor in the Kop van Feijenoord district, an unembanked, flood-prone area that forms a vital link between Rotterdam-Zuid and the city centre, the scenario simulates how riverine and pluvial flooding could disrupt urban mobility during extreme weather events. Laan op Zuid is explicitly identified in Rotterdam's adaptation strategies as a critical mobility artery for both daily commuters and emergency evacuation, and is notably vulnerable due to its location outside the city's main flood defences. As climate-driven hazards increasingly threaten low-lying urban infrastructure, safeguarding such corridors has become a core priority for city planners. This toy case directly addresses the research question: How can integrated flood–transport modelling frameworks support adaptation and maintain accessibility along critical corridors under severe flood conditions?

Flood dynamics are modelled using 3Di, which provides detailed, time-varying water depths across the urban landscape. These outputs are translated to the MATSim agent-based transport model by overlaying flood maps with the city's road network. Road segments that exceed safe water depth thresholds are assigned reduced speeds or closures in MATSim, which then simulates the resulting impacts on traffic flow, congestion, and detours.

Two coupling approaches are explored: a one-way interaction, where flood results inform transport disruptions, and an iterative feedback loop, where traffic outcomes (e.g., jams or evacuation needs) influence subsequent adaptation measures such as earlier road closures or traffic management interventions.

The toy case exposes key data integration challenges (such as spatial and temporal resolution mismatches), but also provides a concrete, visual narrative for decision-makers. Using an XLRM framework, it identifies the external drivers (flood severity, traffic demand), levers (road closure timing, adaptation measures), model relationships (flood depth impacts on capacity), and resilience metrics (total delay, number of stranded vehicles). The scenario illustrates, in a transparent and scalable way, how coupled modelling supports Rotterdam's climate adaptation and mobility strategies.

5.4.1 Relevant Flood Types and Policy Alignment

According to city adaptation documents, three main flood risks converge on Laan op Zuid:

- Riverine (fluvial) flooding from storm surges and high river discharge, with hazard maps showing predicted overtopping in the area under 10 to 100 year scenarios.
- Pluvial (rainfall) flooding, with events up to 70mm/hr (Weatherwise 2019) cited as likely to cause surface ponding and transport disruption.
- Compound events, where river surges and heavy rainfall coincide, are recognised as high-impact, low-probability events in local adaptation plans.

Rotterdam's strategy explicitly aims to safeguard critical mobility corridors and maintain city accessibility under these flood conditions. Laan op Zuid, as both an evacuation route and daily commuter link, is a prime demonstration case for assessing the effectiveness of coupled flood–transport adaptation measures.

5.4.2 Model Choices and Justifications

Flood Model: 3Di

3Di is a high-resolution, two-dimensional hydrodynamic model widely used in Dutch urban flood risk management. It accurately simulates surface water movement and flood depth on a fine grid, supporting detailed, street-level impact assessment. Its proven use in Rotterdam and flexible API make it ideal for real-world coupling studies.

Transport Model: MATSim

MATSim is an agent-based transport simulation platform capable of representing thousands of individual travellers, their routes, and how they adapt to network changes (such as road closures). It operates at the road/link level and with second-level time steps, making it well-suited for simulating traffic dynamics and rerouting in response to sudden flood-induced disruptions. Its open data compatibility aligns with Rotterdam's available network data.

The two models are thus selected for their fine spatial and temporal resolution, open data compatibility, and precedent use in both research and practice.

5.4.3 Scenario Logic and Coupling Strategies

One-Way Coupling

3Di first simulates a flood event, generating time-varying water depths on a regular grid. These outputs are overlaid on the city's road network. Each road link is assigned a status (open, reduced speed, or closed) based on empirical depth thresholds (e.g., >15cm = closed). This modified network is fed to MATSim, which simulates the impact on mobility, including delays, detours, and network congestion. This approach quantifies the direct, first-order impacts of flooding on city traffic and highlights critical vulnerabilities.

5.4.4 Model I/O Tables and Data Transfer

3Di (Flood Model)

Input/Output	Type/Units	Resolution	Format
Digital Elevation Model	Elevation (m NAP)	1–5 m grid	GeoTIFF
Land Use/Roughness	Manning's n	Grid/Polygon	Shapefile
Rainfall Forcing	Intensity (mm/hr, time series)	5 min steps	CSV/JSON
Boundary Conditions	Water level (m), flow (m^3/s)	10 min steps	CSV/JSON
Output: Water Depth	Depth (m, grid)	5 min, per cell	NetCDF/GeoTIFF
Output: Flood Extent	Polygon (wet/dry)	Matches grid	Shapefile

Table 5.5: 3Di Input/Output - Toy Case

MATSim (Transport Model)

Data Component	Type/Units	Resolution	Format
Road Network	Nodes/links (length, speed, cap.)	Each link	XML (network)
Agent Plans	O/D, time, mode, trip sequence	Each agent	XML (plans)
Input from flood: Link status	Open/reduced/closed (event)	Per link, per time	CSV/XML/events
Output: Trajectories	Entry/exit events (sec, link ID)	Per vehicle, per link	CSV/XML
Output: Link stats	Flow, speed, delay per interval	Per link, 5–15 min bins	CSV

Table 5.6: MATSim Input/Output - Toy Case

Step	3Di Output	Processing/Translation	MATSim Input
Flood → Traffic	Water depth grid	GIS overlay: max/mean per link	Link closure/reduction events
Timing	Flood depth series	Assign event time stamps	Closure/opening in MATSim

Table 5.7: Coupling Data Transfer Table - Toy Case

5.4.5 Coupling Workflow

The coupling workflow in this toy case is designed for transparency, reproducibility, and empirical grounding. The process begins with 3Di simulating urban flooding across Laan op Zuid, producing high-resolution water depth rasters at five-minute intervals. These outputs are mapped onto the MATSim road network using an automated grid-to-link overlay. For each road segment and time step, the maximum water depth encountered is recorded.

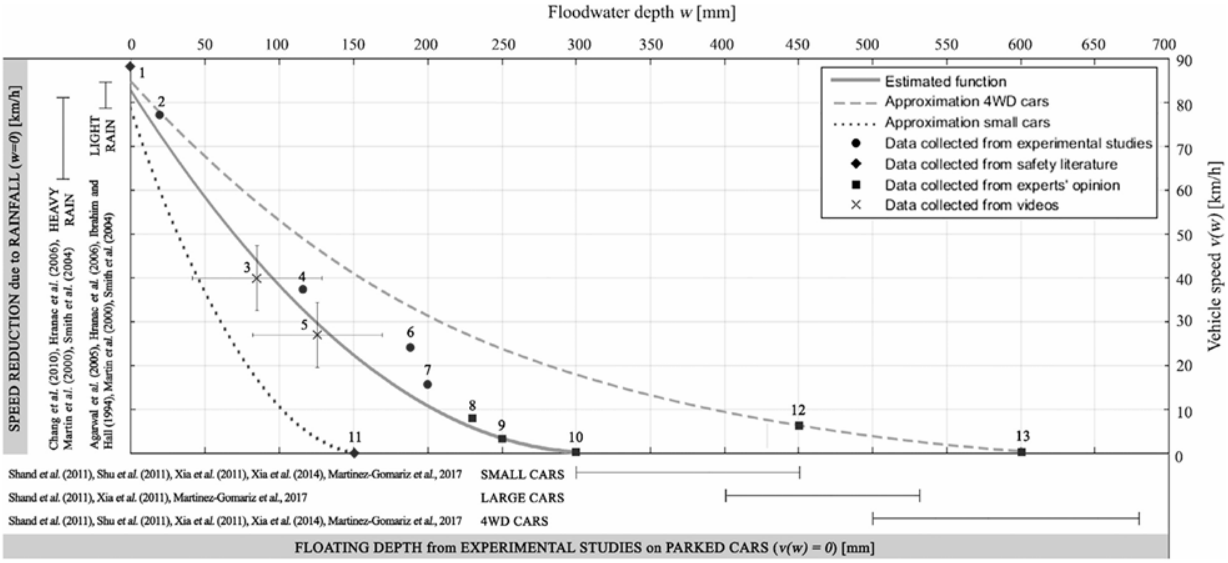

Figure 5.4: The depth-disruption function that relates flood depth on a road with vehicle speed (Pregnolato et al., 2017)

The translation from flood depth to transport impact is governed by the empirically validated depth–disruption curve from Pregnolato et al. (2017), as shown in Figure 5.4. This function, derived from experimental data, safety literature, and expert opinion, quantifies the expected reduction in vehicle speed at increasing water depths. In the workflow, if the flood depth on a road segment remains below 50 mm, only a modest reduction in speed is applied in MATSim. For depths between 50 mm and 150 mm, speed is progressively reduced according to the curve, reflecting the growing hazard and uncertainty. If the water depth on a segment exceeds 150 mm, the critical threshold identified for small cars in Pregnolato et al. (2017), the link is treated as fully closed to vehicular traffic in the transport simulation. These thresholds are encoded as automated rules in the data transfer pipeline.

At each five-minute interval, MATSim receives the updated network status table (with speed and closure states per link) and simulates agent routing, congestion, and network-wide delays.

5.4.6 Data Integration Challenges

Data integration between 3Di and MATSim presents several technical challenges that must be carefully managed to ensure the reliability of the coupled simulation. First, there is a spatial mismatch; while 3Di produces flood depth outputs on a gridded surface, MATSim operates with road network links that often span multiple grid cells. As a result, each road segment must be assigned a representative depth value—either the maximum or an average from the intersecting grid cells, which can potentially overestimate or underestimate the true local impact of flooding. Second, a temporal mismatch arises from differences in model output frequencies. 3Di typically generates results at five-minute intervals, whereas MATSim simulates agent movements at a much finer, second-level time step. This necessitates precise synchronisation to ensure that road closures and reopenings in the transport model accurately reflect the evolving flood conditions. Finally, data format conversion is another issue. Seamless integration requires robust scripting and workflow automation to translate between the NetCDF, GeoTIFF, or shapefile formats produced by 3Di and the XML or CSV input structures required by MATSim. Addressing these challenges is essential for the flood–transport coupling framework.

This chapter has mapped out the technical landscape for modelling flood–transport interactions in Rotterdam. By reviewing the main flood and transport models, we have seen how each model's data structure, operational logic, and resolution shape their suitability for city-scale resilience planning. In practice, effective coupling depends as much on the clarity and openness of model I/O as on the underlying physics.

The comparative discussion of coupling approaches has been done, especially the contrast between rule-based and co-simulation methods. Rule-based coupling offers operational simplicity and transparency, while co-simulation opens the door to more nuanced, dynamic feedback, but at the cost of technical complexity. For the Rotterdam context, both approaches have distinct roles: rule-based integration is invaluable for rapid prototyping and scenario exploration, while co-simulation is better suited for digital-twin environments and detailed operational testing.

The Laan op Zuid toy case brings these considerations into focus, showing concretely how flood impacts can be mapped onto the transport network, how closure rules (grounded in empirical research like the Pregnolato depth–disruption curve) can be implemented, and where practical integration bottlenecks may arise. Real-world coupling will always require some degree of compromise—whether in spatial or temporal alignment, scripting for data conversion, or in the level of automation that is feasible given available resources.

Thus, this chapter builds the groundwork for the XLRM framework and the R-layer specification to follow.

Chapter 6

XLRM Model and Demonstration

In chapters 4 and 5, the exogenous uncertainties (X) and policy levers (L) within the Rotterdam context and the technical assessment of flood–transport coupling approaches were developed. This chapter presents the operational core of the thesis, which is the XLRM framework. The XLRM (eXogenous uncertainties, Levers, Relationships, Metrics) framework is widely recognised as a robust, evidence-based approach for structuring decision-making under deep uncertainty, especially in climate adaptation and critical infrastructure domains. (Lempert et al., 2006)

In this chapter, the XLRM register is formalised and applied to the coupled flood–transport modelling challenge for Rotterdam. The aim is to translate the conceptual advances of previous chapters into a tangible, operational tool for scenario-based planning and a demonstration scenario set in the Laan op Zuid corridor.

The chapter is structured as follows. Section 6.1 presents the completed XLRM register, mapping key uncertainties and policy levers to explicit model relationships and performance metrics relevant for Rotterdam's urban resilience agenda. Section 6.2 provides a stepwise walk-through of how a representative scenario is processed within the XLRM structure, illustrating how spatial and temporal data are harmonised and how system interactions are captured. Section 6.3 documents the empirical calibration of critical thresholds and coupling rules, drawing on peer-reviewed literature, Rotterdam adaptation plans, and anonymised expert interviews. Section 6.4 outlines the main assumptions and simplifications underpinning the operationalisation of the framework, providing transparency for future adaptation and transferability. Finally, Section 6.5 includes visual diagrams and tables to clarify the structure of information flows and the integration between model components.

Through this integrated and evidence-based demonstration, the chapter not only addresses the research gap identified in earlier chapters but also provides a validated and transferable template for digital-twin integration in Rotterdam and comparable delta cities. The formalisation of the XLRM framework here serves as a practical reference for planners, model developers, and policy analysts aiming to strengthen resilience at the intersection of flood risk and urban mobility.

6.1 XLRM Register for Flood–Transport Integration

Table 6.1 presents a structured mapping of the most salient exogenous uncertainties (X), policy levers (L), model relationships (R), and performance metrics (M) for integrated urban adaptation planning. This register is designed to serve as a practical reference for scenario construction, model coupling, and multi-lever stress testing, and is fully aligned with robust decision-making literature.

6.1.1 Classification and Structure

Exogenous uncertainties (X) are grouped according to a fourfold typology (climatic, hydrological, flood infrastructural, and behavioural/socioeconomic), reflecting both empirical evidence and the unique risk profile of Rotterdam. This classification is already explained in section 4.1.

Policy levers (L) are organised into structural/hard engineering, nature-based and spatial adaptation, transport and infrastructure, and operational/emergency management domains. This classification is already explained in section 4.2.

Model relationships (R) specify how each lever is operationalised in the coupled flood–transport framework. These include direct changes to flood model parameters (e.g., defence height, drainage capacity), network modifications in the transport model (e.g., link elevation, capacity reduction, or closure protocols), and dynamic couplings through rule-based or time-stepped integration.

Key metrics (M) encompass direct measures of mobility and disruption (e.g., network delay, connectivity loss, trip completion), emergency response (e.g., clearance and response times), and broader resilience and recovery outcomes (e.g., passability hours lost, average speed reduction, exposure of critical links). These metrics are consistent with those used in Dutch adaptation policy and international flood–transport research. (Gemeente Rotterdam, 2016)

Exogenous Uncertainties (X)	**Policy Levers (L)**	**Model Relationships (R)**	**Key Metrics (M)**
Climatic: Extreme rainfall, storm surge, seasonal and interannual variability. **Hydrological:** Sea-level rise, river discharge extremes, land subsidence. **Infrastructural:** Pump/sewer capacity, flood defence integrity, operational/institutional response. **Behavioural & Socioeconomic:** Population growth, transport demand, behavioural adaptation/-compliance.	**Structural/Hard:** Dike heightening/compartment-alisation, surge barriers, pump upgrades. **Nature-Based & Spatial:** Green roofs, water squares, tidal parks, spatial planning/zoning. **Transport & Infrastructure:** Elevated roads/viaducts, redundancy/alternate modes, flood-proofing vital nodes. **Operational/Emergency:** Dynamic traffic management, early warning/crisis protocols, public awareness/preparedness.	**Flood model:** Adapt elevation/barriers, activate pumps, implement green infrastructure. **Transport model:** Rule-based closure (depth threshold), apply speed/capacity penalties, dynamic rerouting, prioritise emergency vehicles, redundancy in network graph. **Integration:** Synchronise via spatial overlays, time-stepped coupling, data exchange (e.g., NetCDF→CSV/XML/API).	Flooded area, duration of closure, percentage of network dry, economic loss avoided, total economic loss (direct & indirect) and Loss-of-Life. Residual throughput, delay, connectivity, trips completed, emergency response and clearance time, passability hours lost, average speed reduction, and exposure of critical links.

Table 6.1: XLRM Register: Flood–Transport System Interactions in Rotterdam

6.1.2 Interaction of Uncertainties and Levers through the Relationships Layer

The interaction between exogenous uncertainties (X) and policy levers (L) is operationalised through the Relationships (R) layer of the XLRM framework. While Table 4.3 provides a clear mapping of which levers are relevant for each major uncertainty, the R-layer formalises how each lever influences system outcomes under varying scenarios—effectively translating both hazard and intervention into measurable changes in flood and transport performance.

At its core, the R-layer is the set of rules, thresholds, and model linkages that determine how the system solves any given combination of uncertainties and active levers. We can see a few instances.

- When "pump upgrades" are deployed as a lever (L) in the presence of an "extreme rainfall" event (X), the flood model dynamically increases drainage capacity and shortens inundation

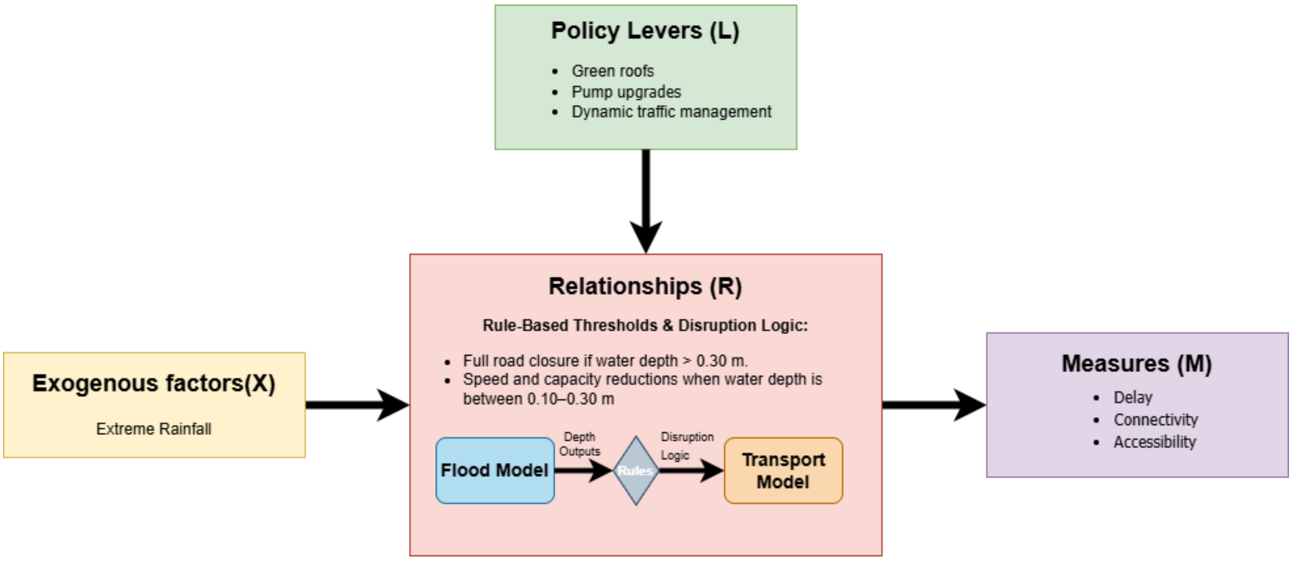

Figure 6.1: Conceptual visualisation of the XLRM framework

duration, thus directly reducing the extent and duration of road closures.

- Similarly, if "sea-level rise" (X) is realised in a scenario, but "dike heightening" (L) is activated, the model raises defence elevations, shifting overtopping thresholds upward and maintaining network operability except under higher, less frequent events.
- For storm surge scenarios (X), the activation of "surge barriers" (L) is implemented as a boundary condition in the flood model, such that surge water levels are contained. The timing and reliability of this closure (modelled in R) are crucial for preventing urban inundation and downstream transport disruption.
- In the case of "transport demand growth" (X), the operationalisation of "spatial planning" and "redundancy" (L) within the R-layer ensures that critical transport infrastructure is spatially shifted or duplicated, maintaining connectivity even as exposure grows.
- The R-layer encodes empirical disruption curves, such that each policy lever alters either the hazard by limiting maximum water depth or the exposure by elevating roads. For example, green infrastructure levers decrease local surface runoff in response to rainfall extremes, resulting in fewer and shallower flooded road segments in the transport model.

The interaction is not one-directional. Certain uncertainties may reduce or amplify the effectiveness of levers, and some levers provide cross-cutting benefits. For example, improved public awareness and compliance (L) are modelled as modifying agent behaviour in the transport domain, reducing risky driving during flood events (X) and thus reducing secondary incidents or delays.

Figure 6.1 presents a conceptual visualisation of this XLRM interaction, clearly illustrating how exogenous uncertainties and policy levers converge within the relationships layer, driving the modelled response and resulting in measurable performance metrics. This figure is a simplified representation, and the actual model implementations involve more complex, detailed interactions.

6.2 Performance Metrics (M)

In the XLRM framework, the Measures (M) layer serves to evaluate how effectively different adaptation strategies perform under diverse scenarios of uncertainty and intervention. (Lempert et al., 2003) Performance metrics are essential for interpreting the practical implications of model results and supporting robust decision-making for urban resilience planning. However, in this thesis, the primary research question centres on formalising the R-layer, the relationships and integration logic that couple flood and transport models, rather than conducting a comprehensive analysis of outcome metrics.

For the toy case demonstration in the Laan op Zuid corridor, a selection of key metrics is defined to illustrate the operational value of the framework. These include total network delay (vehicle-hours lost due to flooding), trip completion rate, duration and extent of road closures, and accessibility to emergency services. Such metrics have been widely applied in both resilience and transport literature to benchmark disruption and recovery. (Chang & Nojima, 2001)

Metrics are computed directly from the coupled simulation outputs. Transport model generates detailed records of agent travel times, route choices, and congestion patterns in response to dynamic road closures triggered by flood depths. These metrics can be compared across scenarios to highlight the effects of activating different levers or under varying exogenous uncertainties.

It is important to emphasise that, while these measures support the demonstration of the XLRM framework's practical value, the design, selection, and interpretation of metrics are not the main focus of this research. The principal contribution lies in the rigorous specification and operationalisation of the R-layer, establishing the foundation for future studies to explore outcome metrics in greater depth and variety.

6.3 Scenario Demonstration using Toy Case

To illustrate the practical operation of the XLRM framework, this section presents a representative scenario for the Laan op Zuid corridor in Rotterdam.

Exogenous Uncertainties (X)

- **Extreme Rainfall:** A cloudburst delivering 78 mm of rain in 1 hour over Rotterdam, representing an event with an approximate 100–300 year return period, based on KNMI'23 projections. (van Oldenborgh et al., 2021)
- **Peak Traffic Demand:** The event occurs on a weekday morning during the commuter rush, meaning the Laan op Zuid corridor is heavily loaded with both private vehicles and public transport.
- **Baseline Drainage Capacity:** Assume no pump upgrades have yet been implemented.

Policy Levers (L):

- **Green Infrastructure:**Water squares and permeable pavements have been installed in adjacent public spaces, increasing local infiltration and temporary storage.
- **Pump Upgrade:** A recent investment has doubled the pump capacity for the catchment, reducing drainage time for surface water.

Relationships Layer (R): Model Integration and Operational Logic

In this scenario, the R-layer defines how the models interpret and operationalise the above X and L:

- **Flood Model Configuration:** The rainfall input is imposed over the Laan op Zuid corridor using the high-resolution hydrodynamic model. The green infrastructure lever reduces effective runoff coefficients, resulting in less and slower surface accumulation. The pump upgrade is modelled by increasing the drainage discharge rate parameter, meaning that, once rainfall ceases, standing water is removed more rapidly.
- **Transport Model Configuration:** As the flood model outputs water depths over time for each

grid cell, these are mapped to individual road segments using the critical-cell approach. The following disruption logic (R) is applied, based on Pregnolato et al. (2017):

  - If water depth is more than 0.30m: The road link is closed to all vehicles except emergency services.
  - If depth is between 0.10 and 0.30m: Speed is reduced to 50% of the free-flow speed, and link capacity is reduced accordingly.
  - If depth is less than 0.10 m: No significant impact on traffic.

- **Integration Rules & Coupling Logic:** The models are run in a time-stepped, sequentially coupled manner. The flood model produces water depth rasters every 5 minutes. At each time step, the most recent flood depth data is mapped onto the road network. The transport model updates road status and reroutes agents as needed. This continues throughout the storm event and recovery phase until all roads are reopened.

Metrics (M): Outcome Evaluation

Performance is assessed using several quantitative and qualitative metrics:

- **Total Network Delay:** Calculated as the sum of all additional vehicle-hours incurred due to closures and detours, relative to baseline (no-flood) travel times.
- **Trip Completion Rate:** Percentage of trips successfully completed during the event window.
- **Critical Route Accessibility**: Minimum and average travel time from the flooded district to emergency facilities.
- **Duration of Corridor Closure:** Total time (in minutes) that Laan op Zuid is impassable to regular traffic.
- **Passability for Emergency Vehicles:** Whether (and for how long) the route remained open to ambulances and fire trucks.
- **Recovery Time:** Time elapsed from rainfall end until normal network function is restored.

These metrics are directly computed from the agent-based transport model outputs, post-processed for each scenario variant. Comparative analysis can be performed between different policy lever scenarios.

We use this particular combination because it is both policy relevant for Laan op Zuid and technically transparent for exercising the R-layer. It stresses exactly the parts the framework is meant to show. This keeps the demonstration aligned with the thesis's specification focus to show the interface and rules while remaining recognisable to Rotterdam practitioners.

Minor tweaks within the same XLRM/R-rules that expand the scenario set, like Amplitude, persistence, timing, system state, behavioural settings, and lever variants. This is in line with Robust Decision Making (RDM): the X–L register defines a structured space of futures and levers, and the fixed R-layer applies the same transparent rules across them; ensembles are created by small, explicit changes to X and L rather than by altering the coupling logic.

6.4 Model Interaction Scenarios

Flood to Traffic Update:

This is the primary one-way coupling from 3Di to MATSim. At each flood time step, 3Di provides an updated map of water depths. The processing step translates this geospatial flood data into traffic-relevant information, determining which specific road links are affected and to what degree. The result is fed into MATSim as network update events. In essence, this function answers, “Given the current flood conditions, what is the status of each road?”. An important assumption here is how we assign a single depth to a road link. Since a road segment may span multiple grid cells, we chose to use the maximum water depth along the link (a conservative approach) to decide its status. This could overestimate the impact if only a small portion of the link is flooded, but it ensures safety by not underestimating flood effects. We utilise high-resolution data and the sub-grid detail of 3Di to capture fine variations, and we apply a clear rule that any significant inundation closes the link to avoid ambiguity. The output to MATSim is structured as a time-stamped events list. MATSim’s engine, upon reading this list, will enforce road closures or speed reductions at the specified times. This method leverages MATSim’s existing event-handling. The format used is MATSim’s standard Events XML schema, which includes fields for time, event type, and link identifier.

Temporal Alignment:

This is not an exchange of physical variables like depth or speed, but of timing information, ensuring that the “when” of events is consistent. Here, the 3Di output timestamps (which might be in simulation minutes or a real datetime) are mapped onto MATSim’s timeline. We assume both models start simultaneously at t_0 (for example, the flood starts at the same time the morning traffic simulation starts). Each flood output interval is known, so we schedule the corresponding MATSim events at those same intervals. If a flood threshold is crossed between output times, it might be registered only at the next output (introducing a slight lag). We mitigate this by potentially interpolating, for example, if a road floods at 7.5 minutes, 3Di would report it at 10 minutes, but we can estimate and trigger closure in MATSim a bit earlier if critical. The important assumption is that a 5-minute update frequency is sufficient to capture the major dynamics of interest. This was informed by the flood rise rate and traffic sensitivity. Interviews suggested that sub-minute precision was unnecessary for strategic decisions (Interview with Flood Modeller). In MATSim, these closure and reopen events alter the network state only for the duration of flooding. By explicitly scheduling reopening times, we can avoid keeping a road closed longer than necessary in the traffic model. The temporal exchange thus keeps a tight correspondence; every flood change has a timestamp, and that same timestamp is used in the traffic simulation.

Feedback loop:

In our one-way physical coupling, MATSim does not send any variables into 3Di. We do not attempt to have MATSim alter flow rates or anything in the hydraulic model. However, there is valuable information from the transport side that can be used to adjust decisions. For example, MATSim might reveal that when Road A is closed, Road B becomes heavily congested, leading to long delays. A planner might react by closing Road B as well (to prevent traffic from overwhelming a flooded area) or by installing a temporary traffic management measure. In our framework, such decisions are implemented by modifying the inputs and rules in a subsequent simulation run, rather than dynamically. The feedback exchange thus involves taking MATSim’s output (like link travel time or total delay on detour routes) and using it to tweak the scenario. This is represented in the matrix as an output of performance metrics, some processing/analysis, and an adjusted input. Concretely, after running the flood-traffic simulation once, we examine metrics like maximum queue length on flooded route approaches, average delay per link, number of agents stuck or rerouting frequency, etc. The next run might then include an a priori closure of a road that we saw was problematic. Another example of feedback is if MATSim shows that vehicles are still attempting to use a road that is technically closed, we could adjust driver behaviour assumptions. All these adjustments are external to the core models and are implemented by changing configuration or input files. This manual feedback loop is consistent with a "what-if" analysis approach. In summary, the feedback row of the matrix is about learning and iteration rather than a direct data feed into the flood model. The assumption is that any significant two-way dependencies are handled through this iterative planning. Our core results focus on the first-run one-way coupling, and the feedback loop is an extension to test adaptive strategies.

6.5 R-Layer Components

The Relationships (R) layer in the XLRM framework is the operational bridge that translates flood model outputs into actionable updates for the transport model. Its design must reflect both technical and practical realities and preferences identified by domain experts in Rotterdam. This section formalises the R-layer by detailing the variables exchanged, information mapping, translation rules, semantic consistency, and integration of behavioural and operational feedback, determined from literature and interview analysis.

- **Rule-Based Interaction Logic:**

  The coupling follows predefined if-then rules to translate flood impacts into transport network changes. Specifically, when the flood model simulates inundation, any road link with water depth exceeding a threshold is marked as impaired (speed reduction or closed). This straightforward logic mirrors approaches used in prior studies, for example Suarez et al. (2005) overlaid flood maps on a road network and closed any submerged links. This approach is transparent and easy to implement, allowing us to couple existing models without modifying their core code. As noted in the literature, the bottleneck is that purely rule-based coupling neglects some behavioural feedback, a point that is addressed with a feedback step.

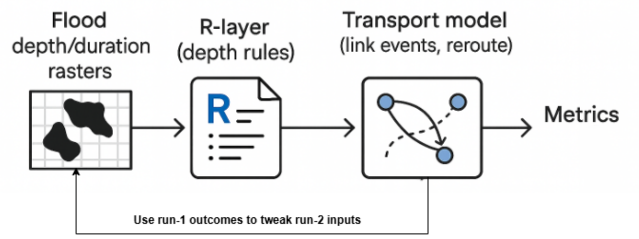

Figure 6.2: End-to-End coupling pipeline: One-way, rule-based integration of flood outputs with a transport model via R-layer rules

- **Variables Exchanged**

  Several variables are systematically exchanged in the coupling between the flood and transport models to ensure that the integration accurately captures real-world dynamics. From the flood model to the transport model, the primary variable transferred is the maximum water depth for each transport link, derived directly from high-resolution flood rasters. In some cases, the velocity of floodwaters is also included, especially where risk to roadbeds or fast-moving flood events is a concern. In addition to water depth, the R-layer tracks the duration of flooding on each link, specifically recording how long water levels remain above critical thresholds—a key parameter for operational and structural closure decisions. Each of these updates is accompanied by a precise timestamp, documenting the simulation time at which the flood status is assessed. Where necessary, risk status flags are appended, indicating particular concerns such as potential embankment failure or other fragility conditions arising from extended inundation or high velocities. Conversely, feedback from the transport model to the flood model, while optional and generally not affecting hydrodynamic calculations at the street scale, can include link closure events for operational purposes (such as pre-emptive closure for safety or detour management) and, if behavioural dynamics are modelled, dynamic updates to the origin-destination (OD) matrix to reflect demand shifting in response to flooding. Practitioner interviews strongly emphasise that an effective R-layer must account not only for static water depth but also for flood duration and, where relevant, floodwater velocity, as these factors critically affect both physical infrastructure risk and operational decision rules. Several experts highlighted the importance of capturing "flood persistence", the length of time a road remains inundated, as well as the often-neglected influence of velocity in risk assessments, particularly for flash floods or on major arterials, which can compound both damage and disruption.

- **Data-Exchange Interfaces:**

  Model communication is facilitated via a custom data exchange pipeline. Rather than a fully unified platform, the models communicate by passing files and events through an interface layer. After each flood simulation step, flood models output water depth data (gridded rasters or GIS files). A Python script then processes these outputs into a format transport models can input, essentially translating a flood raster into a list of road link status updates. This requires format conversion, unit conversion, and identifier matching. Ensuring seamless I/O exchange requires ad hoc scripting to convert between the flood model's geospatial data and the transport model's network events. The interface should be designed to be run in near-real time. It polls the flood model outputs at defined intervals, performs transformations, and then inputs the corresponding events (road closures or re-openings) into the transport model.

- **Real-Time Synchronisation Constraints:**

  A critical aspect of the R-layer is synchronising the flood and traffic simulation clocks. The two models operate on different temporal resolutions – flood models might produce outputs every few minutes, while transport models simulate vehicle movement every second. We must impose a common timeline so that flood-driven events occur in transport models at the correct simulation times. In practice, this means each 5-minute flood model update is mapped to a series of transport model events at the corresponding simulation second, for example, a road closure at $t = 15$ min in 3Di translates to a closure event at $t = 900$ s in the transport model. Maintaining this alignment prevents temporal mismatches where a road might be closed in the traffic model either too early or too late relative to the flood. Interviewees had mentioned that choosing an appropriate sync interval is crucial; if the flood evolves on a 5-minute step but traffic peaks on an hourly scale, important dynamics can be missed. We can address this by using the smallest practical time-step for exchange (on the order of minutes) and ensuring both models speak on synchronised time steps. However, we also assume that flood conditions change only at the chosen interval, essentially holding water depths constant in between updates.

- **Depth–Capacity Translation Rules:**

  At the core of the R-layer implementation is a transparent, documented, and threshold-driven rule-based coupling logic, which has emerged as a clear practitioner preference for both credibility and operational uptake. The depth based thresholds structure the decision rules as follows: for standard vehicles, any road link with a flood depth below 0.15 meters is classified as fully open with normal speed; if the water depth lies between 0.15 and 0.30 meters, a speed reduction is imposed, calculated according to the continuous depth–speed relationship established by Pregnolato et al. (2017); and once the water depth reaches or exceeds 0.30 meters, the affected link is considered fully closed and is removed from traffic assignment. For emergency vehicles, an alternative scenario is available in which closure only occurs at 0.50 meters, acknowledging the higher tolerance and priority assigned to such services. In addition, the framework can optionally incorporate velocity or depth–velocity compound metrics as risk triggers, particularly in corridors subject to high-velocity flash flood conditions, which several experts have identified as critical for robust scenario coverage. Furthermore, the rule set extends beyond instantaneous depth by including duration-based triggers. If the water depth above a threshold persists longer than a critical period (for example, two hours), then infrastructure fragility rules may automatically trigger link closure, simulating roadbed or embankment failure due to prolonged inundation, thus addressing the theme that "duration is the forgotten variable" in flood risk, as highlighted by a transport expert. Finally, the R-layer specification includes a behavioural overlay such that, when flood depths exceed approximately 0.30 meters, the model should inject demand-shift responses in the transport model simulation. For example, a specified proportion of agents using that link may switch to walking, cancel their trip entirely, or redefine their destination, thereby reflecting empirically observed and expert-flagged behavioural changes in response to impassable or unsafe road conditions. This was a refinement strongly recommended by a resilience expert.

- **Feedback Design and Iterative Coupling:**

  The integration so far is essentially one-way (flood impacts traffic). True two-way feedback, where traffic conditions, in turn, influence flood dynamics, is generally negligible; traffic doesn't significantly alter flood water flow. However, there is operational feedback to consider on the human side: for example, drivers might pre-emptively avoid areas expected to flood, or authorities might close roads proactively before they are fully inundated for safety. Our framework allows an iterative feedback loop at the scenario level to capture some of these effects. In practice, this means after an initial simulation (flood to traffic), we analyse the traffic outcomes like extreme congestion on certain detour routes or unsafe conditions as floodwaters rise. We can then adjust the input rules for a second simulation, for instance, introducing a pre-emptive closure for a critical tunnel 10 minutes before it's flooded, to reroute traffic early, or adding a detour routing plan for emergency vehicles. This kind of feedback is implemented not as continuous real-time co-simulation, but as a scenario adjustment between runs. It serves as a proxy for adaptive traffic management. By using the traffic model's output to modify the next flood scenario or road management strategy, we mimic how authorities might respond in reality, if a first run shows gridlock, a revised plan is run with certain roads closed earlier. This design is informed by both literature and interviews – for example, interviewees noted that completely dynamic two-way coupling is complex for an initial prototype, but that incorporating some feedback logic (like planned detours or early closures) would greatly enhance realism (Interview with Transport Modeller 2). In summary, the R-layer is designed with a feedback option: the default run uses static rules, and an iteration uses the outcomes to tweak those rules.

  In this study, iterative feedback is recommended for digital-twin (DT) pilots but is not part of the validated baseline pipeline. At the city scale, traffic conditions do not materially alter flood hydraulics, so we do not couple transport dynamics back into the hydrodynamic equations. This is not continuous real-time co-simulation; it is a between-runs adjustment that serves as a practical proxy for adaptive traffic management. The concept was specified and discussed with experts, who noted that fully dynamic two-way co-simulation is complex for first deployments, while limited feedback greatly improves realism. Debris transport and inlet/culvert blockage are not modelled here; representing them credibly would require additional process modules and calibration effort that is disproportionate to the expected benefit for this specification-level framework.

Chapter 7

Validation

Chapter 6 formalised the XLRM artefact for flood–transport integration, specifying the X-layer uncertainties, actionable levers, and detailing the R-layer coupling logic alongside the performance metrics. This chapter examines whether the artefact is credible and decision-useful to domain specialists before any implementation effort. Consistent with the thesis scope, the validation here is qualitative and advisory: it assesses face validity (does the framework look right to experts?) and content validity (does it cover what practitioners expect), and translates the resulting advice into implementation notes for pilot projects. The validation method used is a structured focus-group workshop in which experts reviewed the XLRM register, the R-layer rules, the toy case narrative, and candidate performance metrics.

The chapter proceeds as follows. It describes how the workshop was run and how feedback was captured, and then mentions what the experts mentioned and what they advised documenting or considering in pilots. Finally, it brings the practical implications of those advisories and reflects on limitations and next steps.

7.1 Validation Methodology

The validation is external and qualitative, aimed at establishing face validity, that the artefact looks right to domain specialists and content validity, that it spans the constructs practitioners expect when coupling flood and transport models for Rotterdam. The outcomes of the validation are framed as advisory recommendations and implementation notes for pilots; they do not revise the XLRM specification developed in the previous chapter. The validation instrument is a structured focus-group workshop with domain experts, as is common for pre-implementation conceptual models (Sargent, 2011).

For conceptual frameworks, expert-judgment methods are appropriate because they test plausibility, coverage, and communicability prior to any quantitative calibration. (Sargent, 2011) Therefore, a face validation, typically used in simulation model development, and a content-validation (are X, L, R, M sufficiently complete and relevant?) were combined.

The workshop reviewed four artefacts: (i) a one-page XLRM register, (ii) the R-layer rule flow, (iii) a short toy case narrative (Laan op Zuid), and (iv) a candidate performance metrics list. These materials were chosen to elicit comments on completeness (X, L, M) and interpretability and realism of the coupling logic (R).

Experts were chosen to cover complementary competencies: hydrology/hydraulics, transport/traffic modelling, and digital-twin/integration. A single group of 8 participants was convened, which sits within recommended sizes for focus groups. (Morgan, 1997) Participants were provided a short pre-read of the artefacts to reduce cognitive load during the session.

The session followed the following sequence: artefact walk-through, targeted prompts and plenary synthesis and was scheduled for 40 minutes. A moderator led the discussion, with a separate voice recording being captured, which was then transcribed. Prompts were designed to uncover both endorsement and coupling logic (is a unidirectional flood to traffic baseline adequate; when would feedback add value?), timing (what update interval is sensible for flood→transport exchange?) and Metrics (which metrics are decision-useful for municipal operations?). To enhance credibility, the moderator encouraged minority views, asked for concrete rationales, and summarised interim agreements for participant confirmation.

Field notes and the session transcript were analysed using thematic analysis. Participants were informed about the study purpose, the advisory nature of validation, and the non-attributive reporting of quotes for which they provided informed consent. Identifiers are anonymised in notes and any reproduced statements, consistent with standard qualitative research practice.

7.2 Results of the Validation

The expert focus group produced a coherent set of affirmations and advisories. In keeping with the chapter's purpose, these results are advisory: they confirm that the artefact is plausible and decision-oriented while offering guidance for pilot implementation and documentation.

7.2.1 Affirmations (face/content validity)

Participants concurred that the lookup-style R-layer is an appropriate baseline for a first deployment. Expressing flood impacts as transparent depth-to-disruption rules was judged realistic and easy to communicate to operational stakeholders. Experts described the expected model behaviour, modest speed reductions at shallow depths, escalating to closures at higher depths, and subsequent restoration as waters recede, as consistent with practice and with published vulnerability relationships for flooded carriageways. In particular, the use of a continuous depth–speed effect at low inundation levels combined with a closure threshold at higher depths was seen as faithful to empirical evidence and suitable for municipal planning. The group also endorsed the framework's modularity: separating uncertainties (X), levers (L), relationships (R), and metrics (M) was viewed as aiding governance, auditability, and stakeholder communication by making explicit where policy choices sit relative to physical processes and performance indicators. Finally, the emphasis on decision-oriented metrics—such as accessibility, delay, network availability, and emergency access time—was welcomed as appropriately focused on service outcomes rather than simulator-internal statistics.

7.2.2 Advisories (suggestions for pilots and documentation)

Alongside these endorsements, the workshop generated a set of non-prescriptive advisories intended to make pilot implementations smoother and more interpretable. First, experts recommended representing behavioural heterogeneity through scenario toggles or parameters rather than introducing bespoke behavioural sub-models in this version. Flood situations elicit diverse traveller responses—from early rerouting to risk-taking or non-compliance—and simple scenario levers (e.g., compliance rates, early-reroute shares) allow sensitivity analysis without sacrificing transparency. Second, the group advised adopting a clear flood to traffic update interval of about five minutes. Exchanges that are too sparse risk missing evolving conditions; exchanges that are too frequent add complexity with limited decision benefit. A five-minute cadence was judged a pragmatic default that balances responsiveness with runtime and reflects typical pluvial dynamics and traffic adaptation times.

Third, participants asked that spatial and temporal harmonisation choices be made explicit. In practice, this means documenting the grid to link aggregation rule (e.g., maximum or percentile depth intersecting a link), the clock mapping between models (e.g., 3Di outputs at five-minute steps applied at the next MATSim time slice), and any format conversions (GeoTIFF/NetCDF to CSV/XML). Packaging these items as a one-page checklist reduces integration ambiguity. Fourth, the group suggested recording an optional semantic hook—variable identifiers, units, and future-proof interoperability in a digital-twin context, while keeping it optional for first pilots. They recommended stating out-of-scope dependencies (e.g., power supply, public-transport operations, repair-crew logistics) as assumptions wherever results are shown, to avoid over-claiming model coverage. Finally, two forward-looking notes were recorded for the roadmap rather than this specification: (i) consider surrogate/AI inundation forecasting to enable near-real-time twin operation; and (ii) broaden participation in a follow-on validation round to include operators and first responders, improving external validity and operational insight.

7.3 Limitations of External Validation

The validation presented here is conceptual and qualitative, designed to test credibility and coverage rather than predictive performance. As such, it establishes face and content validity but does not yet demonstrate construct or criterion-related validity in the statistical sense. Expert judgements can show that the artefact looks right and includes the right elements; they cannot, by themselves, prove that simulated relationships reproduce real-world behaviour or correlate with observed outcomes. (Sargent, 2011) This limitation is appropriate to the thesis scope (framework, not implementation).

A second limitation concerns external validity and generalisability. The focus group brought together a purposive but necessarily small set of experts, skewed toward technical modellers. Perspectives from operators and first responders (e.g., traffic control centres, emergency services, public transport operations) were under-represented, and the discussion was grounded in a Rotterdam use context. These features, typical of early-stage focus groups, constrain the breadth of inference that can be drawn from the results. The advisory outputs should therefore be read as practice-informed guidance rather than claims that are universally applicable without adaptation.

Third, the group process itself can introduce bias. Focus groups are efficient for eliciting consensus and surfacing tacit knowledge, but they are also susceptible to groupthink, conformity pressures, and moderation effects, especially in time-boxed sessions with clear artefacts and prompts (Krueger, 2014). This study mitigated such risks through structured turn-taking, explicit solicitation of minority views, and end-of-session member checking. The resulting affirmations and advisories should thus be interpreted as credible but provisional, pending triangulation with additional stakeholder groups and contexts.

Fourth, the validation does not test operational validity, that is, how the specification performs when instantiated in software, integrated across tools, and used by practitioners. The workshop could not reveal runtime issues, data harmonisation pitfalls, or user-interface challenges in reading and acting on outputs. These are material risks that only a pilot implementation can expose. (Sargent, 2011) The chapter therefore records implementation notes precisely to de-risk such later stages, while acknowledging they remain untested here.

Finally, measurement limitations remain. Several advisories anticipate pairing simulated and observed metrics for future criterion validation, but suitable observational datasets (e.g., road passability logs, high-resolution depth sensors, incident records aligned in space and time) were not brought to this qualitative exercise. Until such data are assembled and analysed, statements about accuracy, bias, or calibration of depth–disruption functions will remain untested hypotheses grounded in literature and expert judgement rather than in local evidence.

Taken together, these limitations do not undercut the chapter's purpose, establishing that the XLRM artefact is credible, intelligible, and decision-oriented, but they describe the boundary of what has been shown. The present validation should be read as a necessary first step in a broader validation pathway: qualitative expert review to secure face/content credibility now, followed by pilot implementation, empirical benchmarking, and wider stakeholder engagement to establish construct, criterion, and external validity in subsequent work.

Chapter 8

Discussion

8.1 Situating the XLRM Framework in Existing Literature

This research developed an XLRM-based flood–transport integration framework, and findings confirm several patterns noted in prior studies while introducing novel elements. First, the study reinforces well-documented empirical relationships between flood hazards and transport disruption. For example, consistent threshold effects were observed: approximately 0.15 m of water depth tends to induce significant traffic slowdowns, and around 0.5 m causes complete road closure. These critical values were directly embedded into our model's road capacity rules. Likewise, our results underscore the importance of network redundancy over simple exposure measures in explaining mobility outcomes. This mirrors the literature: studies have shown that the availability of alternate routes ("network density" or reachability) better predicts delay impacts than the sheer number of flooded roads. By incorporating an accessibility-loss metric that accounts for alternate path availability, the XLRM framework confirmed this pattern – a finding consistent with both Pregnolato et al. (2017) and (Kasmalkar et al., 2020), who demonstrated that network connectivity metrics outperform raw flood exposure in predicting regional delay.

Second, the framework builds on existing coupling approaches while addressing their limitations. Many previous flood–transport studies employed one-way, rule-based coupling as a straightforward method to estimate impacts. In such approaches, a flood model produces inundation maps which then inform a transport model by closing or slowing any roads exceeding a water-depth threshold (often 10–15 cm). This method, used by Suarez et al. (2005) and numerous subsequent works, provides clarity and modularity: it is easy to implement and any traffic model can accept the modified network. Our study adopted a similar rule-based coupling for the initial analysis, applying flood depth thresholds to generate road closure events, and achieved results in line with those of classical studies. However, consistent with the literature, we also encountered the known shortcomings of this approach. Notably, purely one-way coupling neglects feedback from the transport side. Human behavioural adjustments, such as travellers avoiding areas pre-emptively when flood warnings are issued, or the effect of congestion on accessing flood-prone zones, are typically not fed back into flood progression models in rule-based frameworks. Our interviews with experts echoed this concern: model simplifications that ignore dynamic feedback might miss important behaviours. For example, one interviewee noted that drivers often slow down or divert at the first sign of water on the road, well before a road becomes fully impassable – a nuance that a simple binary closure rule would overlook. This study acknowledges such nuances. This research incorporated a speed-reduction curve (gradually reducing vehicle speed as flood depth increases) in addition to binary closures. This enhancement confirms suggestions by Pregnolato et al. (2017) that a depth–speed function can better represent reality than a binary threshold. It also illustrates the trade-off noted by experts, adding detail improves fidelity but at the cost of complexity in calibration.

Third, our framework introduces novel elements that expand the current understanding of coupled modelling systems, particularly through cross-domain interactivity and feedback loops. A key innovation is the inclusion of an iterative feedback mechanism between the flood and transport models, something that most prior studies did not implement. Traditional one-way coupling assumes a unidirectional influence – floods impact transport – but our XLRM framework explored a two-way interaction in which transport outcomes can inform flood management responses. In practice, while traffic dynamics were not coupled back into the hydrodynamic equations (since, in general, traffic has a negligible direct effect on flood water levels), we did simulate operational feedback: using transport model outcomes to adjust the timing or deployment of flood interventions in a subsequent simulation run. This reverse feedback (transport conditions influencing flood outcomes via management actions) is a novel element in our framework. It expands the typical coupled modelling paradigm by acknowledging that the transportation system state can alter the consequences of flooding and thus should inform adaptive response. As a concrete example, the interviews highlighted niche scenarios where transport can even influence flood dynamics: one expert mentioned that heavy vehicles on a dike road might marginally suppress overtopping, or cars blocking a storm drain could worsen localised flooding. Such effects are usually negligible at the city scale, but recognising them is conceptually important. Our framework's design leaves room for incorporating this feedback, for instance, by reducing drain capacity if a road is jammed with stalled vehicles, although in the present study, we treated them qualitatively due to their minor impact. Overall, by introducing a feedback loop, this work moves beyond the prevailing "flood-to-transport only" paradigm and demonstrates the value of cross-domain interactivity. It shows that coupled systems are not one-way streets where transport networks can influence outcomes in the flood risk domain, particularly through the mediation of human decisions like evacuation timing, road closure policies. Finally, the XLRM framework situates these technical contributions within a broader decision-making context, thereby extending current understanding of how to integrate models for resilience planning. Past integrated modelling efforts often lacked a unifying decision framework; they provided impact assessments but not a structured way to explore uncertainties and strategies. In contrast, the use of the XLRM structure (eXternal factors, Levers, Relationships, Metrics) explicitly links the flood–transport model interactions (the R in XLRM) with policy levers and uncertainties. This is informed by robust decision-making literature (Lempert et al., 2003) and by prior applications of XLRM in climate adaptation contexts, such as Hossain et al. (2017), which qualitatively mapped flood and transportation interactions in the Bangladesh delta. Hossain and colleagues' conceptual framework identified how increasing flood frequency could erode transportation accessibility, feeding into socio-economic outcomes.

In summary, the developed XLRM flood–transport framework both affirms established knowledge (common depth thresholds, importance of redundancy, efficacy of rule-based coupling for first-order analysis) and expands the envelope by incorporating feedback loops and a decision-centric structure. It bridges the gap between empirical findings in the literature and practical planning tools by embedding those findings into a modular, dynamic framework.

8.2 Implications of Coupling Strategies in the Toy Case

The Rotterdam toy-case, focusing on the Laan op Zuid corridor, was used to compare two coupling strategies: (i) a rule-based one-way coupling, and (ii) an iterative feedback (adaptive co-simulation). Both were assessed for operational realism, barriers to implementation, and policy relevance.

1. **Rule-Based One-Way Coupling** The first strategy establishes a static linkage: the flood model issues depth maps at 5-minute intervals, and the transport model applies IF–THEN rules to reduce link speeds or close roads once depths exceed a predefined threshold. This method

mirrors approaches in other static integrations, such as those described by Jafari Shahdani et al. (2023), which applied flood-induced hindrance to mesoscopic traffic models using similar logic (speed reductions or closures).

Advantages:

- Technically simple to implement via scripting, like depth grid overlay, CSV link attribute updates.
- Transparent and communicable to stakeholders like traffic engineers who can readily interpret rules like "close road if water >15cm."
- No simulation runtime required, enabling rapid scenario drafting and stakeholder elucidation.

Limitations:

- Spatial misalignment: flood grids versus long link extents requires conservative aggregation logic.
- Temporal granularity: 5-minute depth updates may miss brief inundation events, affecting realism, as noted in existing literature. (Jafari Shahdani et al., 2023)
- Rigid one-way information flow fails to capture adaptive policy adjustments or dynamic traveller behaviour.

Despite these problems, the rule-based coupling supports emergency drills and preliminary planning by enabling rapid scenario exploration with understandable outcomes.

2. **Iterative Feedback (Adaptive Coupling)** The framework also envisions a second, more sophisticated coupling method: adaptive co-simulation. After an initial rule-based run, model outcomes—such as emerging traffic congestion or stranded vehicles—inform adjusted interventions (e.g., early closure signals) in a subsequent iteration. This is conceptually analogous to proactive strategies identified in flood-traffic research, where pre-emptive interventions reduce exposure but bring efficiency costs. (Rebally et al., 2021)

   Key Insights:

   - Safety–Mobility Trade-off: Earlier closures prevent vehicle stranding but may increase total network delay due to rerouting impact.
   - Temporal sensitivity: Adaptive timing—closing roads ahead of rush-hour flare-ups—unveils non-linear dynamics across scenarios, necessitating iterative coupling.
   - Supporting targeted interventions: Adjustments like bus rerouting and adaptive signal timing can attenuate but not eliminate congestion without additional capacity investment.

   This iterative design, although resource-intensive, offers policymakers a structured way to test adaptive measures and rehearse decision sequences prior to real-world deployment.

3. **Practical Barriers & Policy Relevance**

   - Integrating 3Di and MATSim required data translation scripts, which demand data-processing expertise beyond typical municipal capabilities. In real applications, such integration prerequisites may challenge organisational capacity. However, the incremental adoption of open formats like NetCDF, GeoTIFF, and CSV can help overcome these hurdles.
   - Scalability is another concern. Adaptive co-simulation on city-wide scales may require high-performance computing or surrogate models, an option identified by Jafari Shahdani

et al. (2023). We avoided machine-learning emulators to preserve model transparency.

The toy-case revealed important implications that rule-based, one-way coupling is fast, transparent, and actionable; it supports routine scenario planning but requires careful handling of spatial and temporal mismatches. The iterative feedback coupling enhanced realism by capturing adaptive dynamics. A hybrid approach, using simple couplings for routine drills and targeted iterative runs for critical events.

8.3 XLRM Framework for Adaptive Transport Planning

The XLRM framework provides a structured, modular framework for decision-making under climate uncertainty. By compartmentalising uncertainties, policy actions, modelled dynamics, and performance outcomes, it enables planners to systematically identify high-impact interventions, weigh trade-offs, and pursue robust, adaptive strategies.

XLRM clarifies what can be influenced. The X component enumerates uncontrollable factors like flood intensity, timing, and future demand. while L lists potential interventions like drainage upgrades, road closure thresholds, and flood warnings. This decomposition assists planners in understanding which levers yield the greatest benefit across flood futures. In the Rotterdam case, two levers stood out:

- Timing of road closures, which significantly affects both safety and traffic efficiency.
- Network redundancy, such as alternate routes or secondary crossings—shown in recent research to be critical for resilience. (Yadav et al., 2020)

Since it is derived from Robust Decision Making (RDM) principles (Lempert et al., 2003), XLRM supports evaluating strategies over a wide set of future conditions rather than relying on a single prediction. For example, drainage improvements in the Laan op Zuid corridor consistently performed well across all flood scenarios, making them a no-regret option, while reactive-only strategies degenerated under stronger floods. The explicit structure allows identification of vulnerable futures and targeted mitigations, aligning with RDM workflows.

By tracking multiple metrics (e.g., travel delay, stranded vehicles), the XLRM setup exposes trade-offs in very clear terms. A decision to close roads early might eliminate stranded vehicles but add travel time—quantitatively making the decision-making explicit. This trade-off framing supports transparent policymaking when balancing mobility and safety.

XLRM is also designed for evolution. As new flood projections emerge (X changes), new policies become available (L), or observed performance deviates (M), components can be updated and re-evaluated. This structure supports the development of a dynamic decision-support system, such as a transport resilience digital twin, continuously ingesting data, updating simulations (R), and suggesting optimal levers (L). Cities like Rotterdam could periodically revisit the framework to manage changing risks.

Chapter 9

Conclusions and Recommendations

This chapter synthesises the key outcomes of this research, which was to formalise and validate an XLRM framework, specifically, the Relationships (R) layer, for coupling flood models with transport models in an urban context. The work was anchored in a policy-relevant setting in Rotterdam. By integrating evidence from literature, Rotterdam policy documents, and targeted expert interviews, the study constructed a validated register of exogenous uncertainties (X), adaptation levers (L), relationship rules (R), and performance metrics (M) that planners can embed within digital-twin environments. The subsequent sections answer the central research questions and provide practical recommendations for Rotterdam's digital-twin strategy, and reflect on the generalisability, limitations, and future directions of the proposed framework.

9.1 Answers to the Research Questions

In this section, we will explore how the research answered the different research questions.

The **main research question** was how the Relationships (R) layer in an XLRM framework can be formally specified to integrate flood models with transport models for Rotterdam's flood–transport interactions. This research demonstrates that a formally specified R-layer enables systematic, transparent coupling of high-resolution flood models (such as 3Di) with dynamic agent-based transport models (such as MATSim), supporting real-time translation of flood impacts to transport network states. By defining operational rules for depth-to-capacity translation, synchronising simulation timesteps, and structuring data exchange (see Chapters 5 and 6), the R-layer facilitates timely road closures, adaptive rerouting, and scenario testing in digital-twin environments. This approach allows planners to evaluate the effectiveness of adaptation measures under deep uncertainty, with empirical thresholds and lookup functions underpinning practical application in Rotterdam.

The **first sub research question** was what adaptation levers in Rotterdam require cross-domain flood transport analysis. Rotterdam's adaptation levers that necessitate integrated flood–transport analysis span structural, nature-based, transport, and operational domains. Structural levers include dike heightening, compartmentalisation, surge barriers, and pump upgrades—measures that directly influence both flood risk and road network operability. Nature-based levers, such as water squares, green roofs, and tidal parks, reduce surface runoff and moderate pluvial flooding, thereby maintaining transport continuity during extreme rainfall. Transport-specific levers, notably road elevation, redundancy (alternate routes), and flood-proofing of critical nodes (e.g., metro entrances), are essential for preserving network accessibility under inundation. Operational levers like dynamic traffic management and early-warning protocols further enable rapid response to flood events, minimising indirect losses from mobility disruption (see Chapter 4.2 and Table 4.2). Integrated modelling is indispensable for identifying levers that offer cross-domain benefits and for avoiding unintended consequences across urban systems.

The **second sub research question** was what are the technical requirements of existing flood and transport models (data structures, formats, and time steps). A comprehensive mapping of technical requirements reveals distinct, but reconcilable, model architectures (see Chapter 5.1–5.2 and Tables 5.1–5.4). Flood models like 3Di generate high-resolution, gridded outputs (NetCDF, GeoTIFF) at typical intervals of 5 minutes, reporting variables such as water depth and velocity per cell. Transport models such as MATSim and SUMO operate on link-based networks, requiring XML/CSV inputs with second-to-minute-level time-steps. Achieving interoperability involves robust spatial mapping (overlaying grid cells onto road links) and temporal alignment (synchronising 5-minute flood updates with transport simulation intervals). Data exchange is facilitated through automated scripts that convert model outputs to compatible formats and schedule network state updates (see 5.4.4–5.4.6). Limitations include spatial mismatches like links spanning multiple grid cells.

The **third sub research question** was what are the pros and cons of candidate interaction strategies for linking flood and transport models. Four main interaction strategies were reviewed and tested. Rule-Based Coupling, Co-Simulation, System Dynamics and Bayesian Network Mediation. This thesis operationalised rule-based coupling as the primary method, with iterative feedback for adaptive scenario refinement. The choice balances model transparency, ease of validation, and computational feasibility (see Chapter 5.3–5.5).

In summary, this thesis provides a rigorously specified R-layer for XLRM-based integration of flood and transport models in Rotterdam, grounded in both technical detail and practical policy relevance. The answers above are directly operationalised in the technical register, model input/output tables and demonstration scenarios described throughout Chapters 4–6.

9.2 Key Takeaways for Rotterdam Digital Twin Pilot

The evidence gathered in this research provides several actionable recommendations for advancing Rotterdam's digital twin ambitions at the intersection of flood and transport resilience. The digital-twin application follows directly from the artefact without changing its intent: the X and L registers frame futures and levers, the R-layer provides the interface rules that translate flood variables to transport network states, and M records performance. In a live setting the same rules operate under streaming inputs: gridded flood/observation updates are aggregated at approximately five-minute steps to align with the coupling design, while transport states refresh at sub-minute resolution with a sample-and-hold between flood updates; thresholds and triggers remain as specified (e.g., depth bands for speed penalties and closures, duration and velocity flags where relevant). This aligns with the thesis's existing coupling logic and feedback design, and with the practical takeaway to institutionalise empirically calibrated depth–speed relationships and prioritise robust raster-to-network translation workflows as the data spine for operations.

- Prioritise real-time raster-to-network translation: Adopt robust, script-based workflows for clipping high-resolution flood rasters to the city's road network in near real time. This is essential for providing timely, actionable inputs to traffic management and digital twin platforms, cutting preprocessing time and enabling operational readiness, as implied during the expert interviews.
- Institutionalise empirically calibrated depth–speed curves: Embed the depth–disruption relationship within transport models as a standard for translating flood depth to link speed and closure. This will prevent over-optimistic rerouting assumptions during extreme events and align scenario logic with observed risk thresholds. Implement car-lane closure protocols at 0.30m water depth and stricter thresholds for emergency vehicles only above 0.50 m, as validated

through both literature and Rotterdam drainage operations.

- Strengthen scenario-driven adaptive traffic management: Utilise digital twin pilots to test a spectrum of adaptive interventions, such as early warning signals, pre-emptive detours, or dynamic traffic signals, —using the rule-based coupling as a baseline, with iterative feedback for critical events. This supports both routine drills and real-world response planning.
- Adopt open, synchronised data standards and automation: Move towards open data formats (NetCDF, GeoTIFF, CSV) and automated data exchange pipelines to enhance interoperability between water and mobility domains and support scaling to city-wide digital twin applications.
- Candidate live feeds to drive the same R-rules include rainfall nowcasts (radar/gauges), hotspot water-depth probes, pump/sluice telemetry, and link speeds/occupancies (loops or floating-car data); update cadences should remain pragmatic—event-driven for control states and 1–5 min for hydrometeorological inputs—to match the specified flood–transport synchronisation.

Together, these steps will accelerate the integration of flood and transport domains in Rotterdam city with a vision like the Rotterdam Digital City Roadmap 2030, providing a transferable operational model for other delta cities.

9.3 Research Limitations

Although this research makes significant strides in specifying an operational R-layer for flood–transport model coupling in Rotterdam, several limitations must be acknowledged.

1. **Methodological limitations**

   The principal limitation of this study is its conceptual focus: the framework and R-layer logic were developed and validated at the design and specification level, without implementation as a working software tool or digital-twin demonstrator. Validation was conducted primarily through inputs from technical modellers and targeted expert interviews, ensuring methodological soundness and technical feasibility. However, broader stakeholder engagement, particularly from emergency services, municipal operations, or end-users, was not realised due to time constraints. This restricts the assessment of practical usability, institutional alignment, and the ability to capture emergent requirements from operational actors, which are critical for eventual adoption. (Gregor & Hevner, 2013)

2. **Model limitations**

   The research highlights persistent technical challenges in integrating high-resolution flood models and dynamic transport models. Chief among these are spatial mismatches, such as aggregating flood depths over network links, which can introduce conservative bias, and temporal misalignments between hydrodynamic and transport simulation steps, which may overlook short-duration impacts. The adopted rule-based coupling logic, while transparent and implementable, omits the feedback loops and adaptive behaviours that are possible in co-simulation environments or fully integrated digital twins. (Pyatkova et al., 2019) This study also does not model debris transport or blockage. In Rotterdam's low-gradient urban setting, capturing debris dynamics and resulting hydraulic/traffic effects would add substantial modelling complexity (additional processes, data, and calibration) for limited decision value at the framework stage, and is therefore outside the scope. Furthermore, the applicability of empirical depth–speed relationships may vary across different network morphologies and flood typologies, highlighting the need for site-specific calibration.

9.4 Transferability and Future Research Scope

9.4.1 Transferability

Several core elements of the XLRM framework and R-layer specification developed in this research are transferable to other urban contexts seeking to integrate flood and transport modelling within digital twin initiatives. The formal logic for coupling model outputs—particularly the use of rule-based triggers for translating flood depths to transport network disruptions—is directly applicable wherever high-resolution hydrodynamic models and agent-based transport simulations are available. The modular register structure (X, L, R, M) and the workflow for aligning model interaction via standardised data exchange provide a practical template for scenario analysis and resilience planning. Moreover, the methodology for constructing, documenting, and validating R-layer rules through expert elicitation and literature review can inform adaptation strategies beyond Rotterdam, especially in delta cities with similar risk profiles.

However, certain aspects of the approach require localisation and cannot be transferred without adjustment. The empirical calibration of depth–speed disruption relationships, operational thresholds for road closures, and prioritisation of adaptation levers are inherently context-specific. They must be tailored to the local hydrological regime, network topology, and operational practices, which differ substantially between cities and regions. Thus, while the structural framework is generalisable, operational deployment demands careful adaptation to local realities.

9.4.2 Future research scope

Several aspects of the current research can be further developed to enhance both academic insight and operational relevance. First, the conceptual R-layer specification can be implemented as a software prototype and tested with real-world data flows and event-driven scenarios. Second, the expert validation process can be broadened to include a wider array of stakeholders, such as emergency responders, public works, and citizens, to capture institutional requirements and user perspectives not addressed in this thesis. Finally, the entire XLRM register and workflow can be iteratively tested in additional case-study corridors or under different hazard scenarios, supporting the generalisation and incremental improvement of the framework.

References

3Di Documentation Team. (2024). Tutorial 6: Analysing simulation results [Accessed 29 June 2025]. Retrieved June 29, 2025, from https://docs.3di.live/e_results_analysis_tutorial.html

Abdelrahman, M., Macatulad, E., Lei, B., Quintana, M., Miller, C., & Biljecki, F. (2025). What is a digital twin anyway? deriving the definition for the built environment from over 15,000 scientific publications. *Building and Environment*, *274*, 112748. https://doi.org/10.1016/j.buildenv.2025.112748

Aerts, J. C. J. H., Botzen, W. J. W., van der Veen, A., Krywkow, J., & Werners, S. (2008). Dealing with uncertainty in flood management through diversification. *Ecology and Society*, *13*(1), 41. https://doi.org/10.5751/ES-02341-130141

Alvarez Lopez, P., Behrisch, M., Bieker-Walz, L., Erdmann, J., Flötteröd, Y.-P., Hilbrich, R., Lücken, L., Rummel, J., Wagner, P., & Wiessner, E. (2018). Microscopic traffic simulation using SUMO. *2018 21st International Conference on Intelligent Transportation Systems (ITSC)*, 2575–2582. https://doi.org/10.1109/ITSC.2018.8569938

Andriessen, L., Agugiaro, G., Borgers, A., & Pauwels, P. (2024). Semantic 3d city models as support for urban flood resilience: Experiences from rotterdam. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *X-4/W4-2024*, 5–12. https://doi.org/10.5194/isprs-annals-X-4-W4-2024-5-2024

Argyroudis, S. A., Mitoulis, S. A., Winter, M. G., & Kaynia, A. M. (2022). Resilience metrics for transport networks: A review and practical examples for bridges. *Proceedings of the Institution of Civil Engineers – Bridge Engineering*, *175*(3), 179–192. https://doi.org/10.1680/jbren.21.00075

Balijepalli, C., & Oppong, O. (2014). Measuring vulnerability of road network considering the extent of serviceability of critical road links in urban areas. *Journal of Transport Geography*, *39*, 145–155. https://doi.org/10.1016/j.jtrangeo.2014.06.025

Bates, P. D., Neal, J. C., Sampson, C. C., Smith, A. M., & Quinn, N. (2022). *Lisflood-fp user manual, version 5.9.6* [Retrieved 29 June 2025; code release 5.9.6]. School of Geographical Sciences, University of Bristol. Bristol, UK. Retrieved June 29, 2025, from https://www.bristol.ac.uk/media-library/sites/geography/migrated/documents/lisflood-manual-v5.9.6.pdf

Bernardini, G., Postacchini, M., Quagliarini, E., Brocchini, M., Cianca, C., & D'Orazio, M. (2017). A preliminary combined simulation tool for the risk assessment of pedestrians' flood-induced evacuation. *Environmental Modelling & Software*, *96*, 14–29. https://doi.org/10.1016/j.envsoft.2017.06.007

Bocchini, P., & Frangopol, D. M. (2012). Restoration of bridge networks after an earthquake: Optimization for resilience enhancement. *Earthquake Spectra*, *28*(2), 427–455.

C40 Cities Climate Leadership Group. (2016). C40 good practice guides: Rotterdam – climate change adaptation strategy [Case study in the C40 Good Practice Guides series]. https://www.c40.org/case-studies/c40-good-practice-guides-rotterdam-climate-change-adaptation-strategy/

Chang, S. E., & Nojima, N. (2001). Measuring post-disaster transportation system performance: The 1995 kobe earthquake in comparative perspective. *Transportation Research Part A: Policy and Practice*, *35*(6), 475–494. https://doi.org/10.1016/S0965-8564(00)00003-3

Ciullo, A., De Bruijn, K. M., Kwakkel, J. H., & Klijn, F. (2019). Systemic flood risk management: The challenge of accounting for hydraulic interactions. *Water*, *11*(12), 2530. https://doi.org/10.3390/w11122530

Creswell, J. W., & Plano Clark, V. L. (2018). *Designing and conducting mixed methods research* (3rd ed.). SAGE Publications. https://books.google.com/books/about/Designing_and_Conducting_Mixed_Methods_R.html?id=eTwmDwAAQBAJ

Dai, L., Wörner, R., & van Rijswick, H. F. M. W. (2018). Rainproof cities in the netherlands: Approaches in dutch water governance to climate-adaptive urban planning. *International Journal of Water Resources Development*, *34*(4), 652–674. https://doi.org/10.1080/07900627.2017.1372273

Dawson, R. J., Peppe, R., & Wang, M. (2011). An agent-based model for risk-based flood incident management. *Natural Hazards*, *59*(1), 167–189. https://doi.org/10.1007/s11069-011-9745-4

de Urbanisten. (2022a). Benthemplein water square [Accessed 29 June 2025]. Retrieved June 29, 2025, from https://www.urbanisten.nl/projects/benthemplein

de Urbanisten. (2022b). Tidal park keilehaven [Landscape–urbanism project in Rotterdam developed with the Municipality of Rotterdam and ARK Nature Development; project period 2018 – ongoing]. Retrieved June 29, 2025, from https://www.urbanisten.nl/work/tidal-park-keilehaven

Deltares. (2022). *Delft3d flexible mesh suite: User manual* [Technical user guide for the Delft3D Flexible Mesh hydrodynamic modelling suite]. Deltares. Retrieved June 29, 2025, from https://www.deltares.nl/en/software/delft3d-flexible-mesh-suite/

Deltares. (2023). Future discharges in the rhine and meuse: Lower in summer and higher in winter. Retrieved June 29, 2025, from https://www.deltares.nl/en/news/future-discharges-rhine-meuse-lower-summer-higher-winter

Deltares. (2024). Delft3d fm suite 2d3d [Product description and technical specifications for the Delft3D Flexible Mesh hydrodynamic modelling suite]. Retrieved June 29, 2025, from https://www.deltares.nl/en/software-and-data/products/delft3d-flexible-mesh-suite

Eclipse Foundation. (2024). Sumo documentation: Traci—traffic control interface [Accessed 29 June 2025]. Retrieved June 29, 2025, from https://sumo.dlr.de/docs/TraCI.html

European Environment Agency. (2025). Rotterdam port adaptation strategy for climate resilient transport and business activities [Climate-ADAPT case study]. https://climate-adapt.eea.europa.eu/en/metadata/case-studies/rotterdam-port-adaptation-strategy-for-climate-resilient-transport-and-business-activities

Fewtrell, T. J., Bates, P. D., Horritt, M. S., & Hunter, N. M. (2008). Evaluating the effect of scale in flood inundation modelling in urban environments. *Hydrological Processes*, *22*(26), 5107–5118. https://doi.org/10.1002/hyp.7148

Figueiredo, L., Honiden, T., & Schumann, A. (2018). *Indicators for resilient cities* (tech. rep. No. 2018/02). OECD Publishing. Paris. https://doi.org/10.1787/6f1f6065-en

Gangwal, U., Siders, A. R., Horney, J., Michael, H. A., & Dong, S. (2023). Critical facility accessibility and road criticality assessment considering flood-induced partial failure. *Sustainable and Resilient Infrastructure*, *8*, 337–355. https://doi.org/10.1080/23789689.2022.2149184

Gemeente Rotterdam. (2013). Rotterdam climate change adaptation strategy [Municipal policy document outlining the city's multi-layered flood-risk and climate-adaptation approach]. https://www.rotterdam.nl/wonen-leven/rotterdam-climate-change-adaptation-strategy-2013.pdf

Gemeente Rotterdam. (2016). Resilient rotterdam: Rotterdam resilience strategy – ready for the 21st century. https://assets.100resilientcities.org/wp-content/uploads/2017/07/Rotterdam-Resilience-Strategy-e.pdf

Gregor, S., & Hevner, A. R. (2013). Positioning and presenting design science research for maximum impact. *MIS Quarterly*, *37*(2), 337–355. https://doi.org/10.25300/MISQ/2013/37.2.01

Haasnoot, M., Kwakkel, J. H., Walker, W. E., & ter Maat, J. (2013). Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. *Global Environmental Change*, *23*(2), 485–498. https://doi.org/10.1016/j.gloenvcha.2012.12.006

Haasnoot, M., van Alphen, J., & Middelkoop, H. (2020). Policy design for a climate resilient dutch delta: A simulation–gaming approach. *Environmental Science & Policy*, *103*, 15–23.

Horni, A., Nagel, K., & Axhausen, K. W. (Eds.). (2016). *The multi-agent transport simulation matsim*. Ubiquity Press. https://doi.org/10.5334/baw

Horritt, M. S., & Bates, P. D. (2002). Evaluation of 1d and 2d numerical models for predicting river flood inundation. *Journal of Hydrology*, *268*(1–4), 87–99. https://doi.org/10.1016/S0022-1694(02)00121-X

Hossain, B. M. T. A., Kulsum, U., & Timmermans, J. (2017). A framework to analyze the complex dynamic delta system for adaptive decision making in bangladesh [Panel T07P02: Public Policy and Uncertainty]. *Proceedings of the 3rd International Conference on Public Policy (ICPP3)*. https://www.ippapublicpolicy.org/file/paper/593c3c59a322e.pdf

Hunter, N. M., Bates, P. D., Horritt, M. S., & Wilson, M. D. (2007). Simple spatially-distributed models for predicting flood inundation: A review. *Geomorphology*, *90*(3–4), 208–225. https://doi.org/10.1016/j.geomorph.2006.10.021

Jafari Shahdani, F., Matos, J. C., & Ribeiro, P. (2023). A systematic literature review of hybrid methodologies in assessing flood indirect impacts on transportation. *Applied Sciences*, *13*(9), 5595. https://doi.org/10.3390/app13095595

Jenelius, E., & Mattsson, L.-G. (2015). Road network vulnerability analysis: Conceptualization, implementation and application. *Computers, Environment and Urban Systems*, *49*, 136–147. https://doi.org/10.1016/j.compenvurbsys.2014.10.005

Joo, H. J., Choi, C. H., Kim, J. W., Kim, D. H., Kim, S. J., & Kim, H. S. (2019). A bayesian network-based integrated flood risk assessment (infra). *Sustainability*, *11*(13), 3733. https://doi.org/10.3390/su11133733

Kasmalkar, I. G., Serafin, K. A., Miao, Y., Bick, I. A., Ortolano, L., Ouyang, D., & Suckale, J. (2020). When floods hit the road: Resilience to flood-related traffic disruption in the san francisco bay area and beyond. *Science Advances*, *6*(32), eaba2423. https://doi.org/10.1126/sciadv.aba2423

Krueger, R. A. (2014). *Focus groups: A practical guide for applied research*. Sage publications.

Kwakkel, J. H., Haasnoot, M., & Walker, W. E. (2016). Comparing robust decision-making and dynamic adaptive policy pathways for model-based decision support under deep uncertainty. *Environmental Modelling & Software*, *86*, 168–183. https://doi.org/10.1016/j.envsoft.2016.09.017

Lempert, R. J., & Groves, D. G. (2021). Greater use of robust adaptation and resilience pathway decision frameworks under deep uncertainty. *Annual Review of Environment and Resources*, *46*, 175–196. https://doi.org/10.1146/annurev-environ-012220-011247

Lempert, R. J., Groves, D. G., Popper, S. W., & Bankes, S. C. (2006). A general, analytic method for generating robust strategies and narrative scenarios. *Management Science*, *52*(4), 514–528. https://doi.org/10.1287/mnsc.1050.0472

Lempert, R. J., Popper, S. W., & Bankes, S. C. (2003). *Shaping the next one hundred years: New methods for quantitative, long-term policy analysis*. RAND Corporation. https://www.rand.org/pubs/monograph_reports/MR1626.html

Liu, Z., Carr, M. L., Nadal-Caraballo, N. C., Aucoin, L. A., Yawn, M. C., & Bensi, M. T. (2025). A multi-tiered bayesian network coastal compound flood analysis framework [Preprint]. *arXiv*. https://doi.org/10.48550/arXiv.2505.15520

Lv, W., Deng, F., Wang, J., Han, Y., & Yang, S. (2025). Large-scale real-time evacuation modeling during urban floods: A coupled agent-based multi-model framework. *Simulation Modelling Practice and Theory*, *140*, 103075. https://doi.org/10.1016/j.simpat.2025.103075

Mattsson, L.-G., & Jenelius, E. (2015). Vulnerability and resilience of transport systems—a discussion of recent research. *Transportation Research Part A: Policy and Practice*, *81*, 16–34. https://doi.org/10.1016/j.tra.2015.06.002

Morgan, D. L. (1997). *Focus groups as qualitative research* (Vol. 16). Sage.

Municipality of Rotterdam. (2022). Resilient rotterdam strategy 2022–2027: From risk to resilience [City resilience strategy document]. https://www.resilientrotterdam.nl/en/download

Municipality of Rotterdam. (2023). Rotterdam weatherwise programme framework 2030: Implementation agenda 2023 – 2026 [City climate-adaptation programme that sets the actions and priorities for making Rotterdam climate-proof by 2050]. Retrieved June 29, 2025, from https://rotterdamsweerwoord.nl

Nelen & Schuurmans. (2023). 3di modelling suite: Technical documentation [Comprehensive user and developer documentation for the 3Di hydrodynamic modelling suite]. Retrieved June 29, 2025, from https://docs.3di.live/

Nicklin, H., Leicher, A. M., Dieperink, C., & van Leeuwen, K. (2019). Understanding the costs of inaction: An assessment of pluvial flood damages in two european cities. *Water*, *11*(4), 801. https://doi.org/10.3390/w11040801

Nofal, O. M., & Van de Lindt, J. W. (2022). Understanding flood risk in the context of community resilience modeling for the built environment: Research needs and trends. *Sustainable and Resilient Infrastructure*, *7*(3), 171–187. https://doi.org/10.1080/23789689.2021.1913878

Plan Integration for Resilience Scorecard. (2018). Feijenoord district, rotterdam, the netherlands [Online case study]. Retrieved June 28, 2025, from https://planintegration.com/case-study/feijenoord-district/

Pregnolato, M., Ford, A., Wilkinson, S. M., & Dawson, R. J. (2017). The impact of flooding on road transport: A depth–disruption function. *Transportation Research Part D: Transport and Environment*, *55*, 67–81. https://doi.org/10.1016/j.trd.2017.06.020

Pyatkova, K., Chen, A. S., Djordjević, S., Butler, D., Vojinović, Z., Abebe, Y. A., & Hammond, M. (2019). Flood impacts on road transportation using microscopic traffic modelling techniques. In M. Behrisch & M. Weber (Eds.), *Simulating urban traffic scenarios* (pp. 115–126). Springer. https://doi.org/10.1007/978-3-319-33616-9_8

Rebally, A., Valeo, C., He, J., & Saidi, S. (2021). Flood impact assessments on transportation networks: A review of methods and associated temporal and spatial scales. *Frontiers in Sustainable Cities*, *3*, 732181. https://doi.org/10.3389/frsc.2021.732181

Restemeyer, B., van den Brink, M., & Woltjer, J. (2018). Resilience unpacked: Framing of ‘uncertainty’ and ‘adaptability’ in long-term flood risk management strategies for london and rotterdam. *European Planning Studies*, *26*(8), 1559–1579. https://doi.org/10.1080/09654313.2018.1490393

Sargent, R. G. (2011). Verification & validation of simulation models. In S. Jain, R. R. Creasey, J. Himmelspach, K. P. White & M. C. Fu (Eds.), *Proceedings of the 2011 winter simulation conference (wsc)* (pp. 183–198). IEEE. https://www.informs-sim.org/wsc11papers/016.pdf

Scott, D. M., Novak, D. C., Aultman-Hall, L., & Guo, F. (2006). Network robustness index: A new method for identifying critical links and evaluating the performance of transportation networks. *Transportation Research Record*, *1964*(1), 48–56.

Shaw, L. R., Coulthard, T. J., Wilson, H. L., Neal, J. C., & Sampson, C. C. (2023). Tracing and visualisation of contributing water sources in the lisflood-fp model of flood inundation (within caesar-lisflood version 1.9j-ws). *Geoscientific Model Development*, *16*, 2415–2438. https://doi.org/10.5194/gmd-16-2415-2023

Sterl, A., Bakker, A. M. R., Beersma, J. J., van den Brink, H. W., Katsman, C., Kwadijk, J., Lammersen, R., & Hazeleger, W. (2009). *Sea-level rise projections for the netherlands* (KNMI Special Report No. WR 2009-05). Royal Netherlands Meteorological Institute (KNMI). De

Bilt, The Netherlands. https://cdn.knmi.nl/knmi/pdf/bibliotheek/knmipubWR/WR2009-05.pdf

Suarez, P., Anderson, W., Mahal, V., & Lakshmanan, T. R. (2005). Impacts of flooding and climate change on urban transportation: A systemwide performance assessment of the boston metro area. *Transportation Research Part D: Transport and Environment*, *10*(3), 231–244. https://doi.org/10.1016/j.trd.2005.05.002

Teng, J., Jakeman, A. J., Vaze, J., Croke, B. F. W., Dutta, D., & Kim, S. (2017). Flood inundation modelling: A review of methods, recent advances and uncertainty analysis. *Environmental Modelling & Software*, *90*, 201–216.

Tibben, F. F. M. (2015). *The introduction of interactive modelling by 3di in flood resilient urban spatial planning* [Master's thesis]. University of Twente [Civil Engineering and Management MSc programme]. https://essay.utwente.nl/66739/

van Aalst, M. K., Kew, S. F., & van Oldenborgh, G. J. (2023). Attribution of extreme weather events: Progress and challenges. *WIREs Climate Change*, *14*(2), e790. https://doi.org/10.1002/wcc.790

van Oldenborgh, G. J., Philip, S. Y., Kew, S. F., Arrighi, J., & others, 1. (2021). Rapid attribution of heavy rainfall events leading to the severe flooding in western europe, july 2021 [Technical report (accessed 29 June 2025)]. https://www.worldweatherattribution.org/rapid-attribution-of-heavy-rainfall-events-leading-to-the-severe-flooding-in-western-europe-july-2021/

van Veelen, P. C. (2013). *Adaptive strategies for the rotterdam unembanked area: Synthesis report* (tech. rep. No. KfC Report No. 89/2013). Knowledge for Climate. Rotterdam. https://edepot.wur.nl/326773

van der Brugge, R., & de Graaf, R. (2010). Linking water policy innovation and urban renewal: The case of rotterdam, the netherlands. *Water Policy*, *12*(3), 381–400. https://doi.org/10.2166/wp.2010.037

van der Hurk, E., van Lint, J., & Hoogendoorn, S. (2020). Data-driven and agent-based simulation of urban mobility: Lessons from the netherlands. *Transportation Research Procedia*, *47*, 186–193. https://doi.org/10.1016/j.trpro.2020.03.106

Wu, H., Wang, S., Fan, Y., & Liu, J. (2023). A tight coupling model for urban flood simulation based on SWMM and TELEMAC-2D and the uncertainty analysis [Preprint, posted 11 Oct 2023]. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.4598972

Yadav, N., Chatterjee, S., & Ganguly, A. R. (2020). Resilience of urban transport network-of-networks under intense flood hazards exacerbated by targeted attacks. *Scientific Reports*, *10*, 10350. https://www.nature.com/articles/s41598-020-66049-y

Note on AI assistance

During drafting, I used ChatGPT (OpenAI) to tighten prose and summarise sources I had already read. The tool was not used to generate or alter data, run models, or invent citations. All bibliographic entries correspond to materials I consulted and were checked for accuracy before inclusion.

Appendix A

Expert Interview Composition

Code	Organisation Type	Sector Focus	Interview Date	Primary Expertise
E1	University research group	Infrastructure resilience	14 May 2025	Pluvial 2-D modelling & network reliability
E2	University research group (Hydraulic Structures)	Flood-transport disruption	17 May 2025	Depth–speed functions
E3	University research group	Digital-twin co-simulation	22 May 2025	Co-simulation latency management
E4	Applied-research institute	Open-data & licensing	24 May 2025	Geo-data policy & APIs
E5	University post-doctoral project	Drainage operations	28 May 2025	Drainage rules & fragility thresholds
E6	University research group	Digital-twin orchestration	31 May 2025	Message-bus architecture

Table A.1: Interviewed Experts (anonymised)

Note: Personal identifiers have been removed in compliance with TU Delft ethics protocol. Interview recordings were transcribed and stored on an encrypted drive.

Appendix B

Interview Protocol and Question Guide

Objectives

O1. Elicit practitioner views on exogenous uncertainties (X) and actionable levers (L) relevant to flood–transport integration in Rotterdam.

O2. Probe coupling requirements and constraints to inform the R-layer (Relationships) specification.

O3. Identify decision-use metrics (M) used by planners and operators.

Consent, and Recording

Consent: informed consent obtained prior to recording; participants could decline any question.
Recording: 45–60 minutes, audio-recorded; verbatim transcription; manual thematic coding. Data stored on encrypted drive; anonymised in reporting (see Appendix A).[1]

Session Structure (60 min template)

1. **Opening (5 min):** introduce study scope; confirm consent; clarify confidentiality.
2. **Warm-up (5 min):** role, relevant projects, tools/models used.
3. **Core blocks (40 min):**
   - 3.a. **Model landscape & I/O mapping (8–10 min).**
   - 3.b. **Coupling strategies & constraints (8–10 min).**
   - 3.c. **Uncertainties (X) & Policy levers (L) (8–10 min).**
   - 3.d. **R-layer rule design (8–10 min).**
   - 3.e. **Metrics (M) & decision use (5–6 min).**
4. **Closing (5 min):** missing topics; willingness for follow-up/validation workshop.

Question Guide

Block A: Model landscape & I/O

- Which flood/transport models are most relevant locally, and why?
- What input–output structures (formats, spatial/temporal resolutions) do you typically see?
- *Probes:* raster to network mapping; time-step alignment; typical post-processing workflows.

Block B: Coupling strategies & constraints

- In your experience, what coupling approaches are feasible (rule-based, co-simulation, mediators)?
- Where do integrations usually fail (licensing, runtime, data fidelity)?
- *Probes:* synchronous vs. asynchronous; one-way vs. two-way; middleware needs.

Block C: Uncertainties (X) & Policy levers (L)

- Which exogenous uncertainties most influence outcomes (hazard timing/depth, demand, behaviour)?
- Which levers are realistically actionable (operations, infrastructure, information)?
- *Probes:* stress-testing ranges; scenario design; operational constraints.

Block D: R-layer rule design

- How should flood variables translate into transport states? What thresholds are defensible?
- Views on depth–disruption functions and closure triggers (e.g., link closed at depth 0.30 m)?
- *Probes:* pre-emptive closures; emergency routing; frequency of data exchange.

Block E: Metrics (M) & decision use

- Which KPIs best reflect performance under flood disruption?
- How should results be reported for planners vs. operators?

Analysis Plan

Manual thematic coding with code families aligned to X, L, R, M and *Governance/Data*.

Appendix C

Validation Workshop Protocol

This appendix summarises the validation session used to assess the XLRM artefact's face and content validity (with emphasis on the R-layer). The session followed the focus-group approach described in the Methods and Validation chapters. **Eight domain experts** participated. *No individual identifiers are reported.*

Objectives

V1. Face validity: do the R-layer rules and dataflow "look right" to specialists?

V2. Content validity: are X, L, R, and M sufficiently complete for intended decision use?

Composition (anonymised)

Eight experts spanning: *flood modelling*, *transport modelling*, *resilience modelling*, and *digital-twin integration*. The mix ensured technical depth on raster-to-network translation, coupling feasibility, scenario design, and decision-use metrics.

Agenda (30–40 minutes)

- **Opening & objectives** (3 min) — scope, consent reminder, ground rules.
- **XLRM overview (quick)** (5 min) — X/L registers; role of R-layer; non-goals.
- **R-layer walkthrough** (8–10 min) — raster to link mapping, thresholds (e.g., link closure at 0.30 m), exchange frequency.
- **Structured discussion** (12–15 min) — prompts below; scribe captures action points.
- **Wrap-up** (3–5 min) — confirm must-change vs. nice-to-have; next steps.

Discussion prompts

R-layer rules

- Are depth-based triggers (e.g., closure at 0.30 m) and timing windows appropriate? Where should thresholds vary by link type/criticality?

- Is the proposed data-exchange cadence adequate (e.g., 1–5 min raster updates) for the intended decision context?

Coupling feasibility

- Any gaps in raster to network mapping, partial inundation handling, or pre-emptive closures?
- For screening use-cases, is the one-way, rule-based approach sufficiently transparent vs. heavier co-simulation?

Uncertainties & levers

- Are the key X-layer uncertainties (hazard timing/depth, demand, behaviour) sufficiently covered?
- Which L-layer levers are realistically actionable (ops/infrastructure/information) under time constraints?

Metrics & reporting

- Which KPIs best reflect performance under disruption (e.g., accessibility, delay, emergency reach)?
- What summary outputs would planners/operators need for quick triage?

Materials provided

- One-page XLRM overview; R-rules decision flow.

Documentation and handling

Scribed notes captured comments and action items; feedback was coded into refinement areas (threshold calibration, exchange cadence, clarity of rule articulation) and mapped to edits in stated limitations. Consent reaffirmed at start; outputs reported in aggregate only.