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Towards Holistic, Multifunctional and Sustainable Stormwater Management

Making Sense of Criteria, Indicators, and Evidence for Stormwater Decisions in Existing Urban Areas

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Abstract

Cities are shifting toward holistic, multifunctional, and sustainable stormwater management (SSWM), increasingly relying on nature-based solutions (NbS) that retain, convey, infiltrate, and treat water while delivering ecological quality, public value, and climate resilience. Given that NbS are spatially distributed and institutionally shared, their long-term delivery depends not only on hydrological performance but also on governance arrangements, including responsibilities, mandates, ownership, and maintenance, that shape legitimacy and outcomes. Critical challenges arise early, when goals are translated into criteria, indicators, and evidence that can be justified and used in planning and implementation.

This thesis examines that decision space through a sequential mixed-methods design. It traces how governance and other long-term delivery conditions are (1) represented in global decision-support tools, (2) articulated by practitioners as decisive factors in two Swedish cities, and (3) operationalized as context-anchored indicator prompts in two contrasting catchments. The findings reveal a persistent asymmetry: technical evidence is often rendered decision-ready, whereas governance and context-sensitive conditions remain under-specified, even though they are central to achieving holistic, multifunctional SSWM.

The thesis responds by applying a governance-aware sense-making step that makes these “silent” conditions and their assessability explicit. This approach provides a transparent basis for early-stage justification and for prioritizing what evidence is available now, what requires resourcing, and what demands coordination or mandate changes. By bridging technical evidence with institutional feasibility in early-stage assessment, the work supports more defensible decisions and more calibrated decision confidence for SSWM in existing urban areas.

Keywords: Sustainable stormwater management, Nature-based solutions, Sustainability assessment, Governance-aware assessment, Decision support, Indicators and criteria, Multifunctionality, Holistic, Sustainability, Decision-making

Mot en holistisk, multifunktionell och hållbar dagvattenhantering

Att skapa förståelse för kriterier, indikatorer och evidens i dagvattenbeslut i befintliga urbana områden

Sammanfattning

Städer ställer om mot en holistisk, multifunktionell och hållbar dagvattenhantering (SSWM) och förlitar sig i ökande grad på naturbaserade lösningar (NbS) som fördröjer, leder, infiltrerar och renar vatten samtidigt som de bidrar till ekologisk kvalitet, samhällsnytta och klimatanpassning. Eftersom NbS är rumsligt utspridda och institutionellt delade beror deras långsiktiga leverans inte bara på hydrologisk prestanda utan också på styrningsarrangemang, inklusive ansvar, mandat, ägande och underhåll, som formar legitimitet och utfall. Kritiska utmaningar uppstår tidigt, när mål översätts till kriterier, indikatorer och evidens som kan motiveras och användas i planering och genomförande.

Denna avhandling undersöker detta beslutsskede genom en sekventiell mixed-methods-design. Den följer hur styrning och andra långsiktiga leveransvillkor (1) representeras i globala beslutstödsverktyg, (2) formuleras av praktiker som avgörande faktorer i två svenska städer och (3) operationaliseras som kontextförankrade indikatorformuleringar i två kontrasterande avrinningsområden. Resultaten visar en bestående asymmetri: teknisk evidens görs ofta beslutsmogen, medan styrnings- och kontextkänsliga villkor förblir under-specificerade, trots att de är centrala för att uppnå holistisk, multifunktionell SSWM.

Avhandlingen bemöter detta genom att tillämpa ett styrningsmedvetet sense-making-steg som gör dessa ”tysta” villkor och deras bedömbarhet explicita. Tillvägagångssättet ger en transparent grund för motivering i tidiga skeden och för att prioritera vilken evidens som finns tillgänglig nu, vad som kräver resurssättning och vad som kräver samordning eller förändrade mandat. Genom att överbrygga teknisk evidens med institutionell genomförbarhet i tidig bedömning stödjer arbetet mer försvarbara beslut och en mer kalibrerad beslutstrygghet för SSWM i befintliga urbana miljöer.

Nyckelord: Hållbar dagvattenhantering, Naturbaserade lösningar, Hållbarhetsbedömning, Styrningsmedveten bedömning, Beslutsstöd, Indikatorer och kriterier, Multifunktionalitet, Holistisk, Hållbarhet, Beslutsfattande

Preface

I grew up in Chongqing, where the city is never flat and the horizon is rarely clear. Streets climb, turn, and drop out of sight around the next bend. The air is damp and heavy for most of the year, and sunlight can feel like a scarce resource. Rain is not an exception but a condition. In the warm season, downpours arrive suddenly. Water runs quickly over steep surfaces, gathers in the low points, sometimes spills, and turns a street corner into a stream. At the time, it felt normal. It was simply how the city behaved to a child. As that child, I enjoyed the rain. There was something comforting about it: the dim atmosphere, the damp air, the sound of drops against windows and rooftops. Rain also carries a particular aesthetic and cultural meaning in the city where I grew up. One of the lines many people know is 巴山夜雨涨秋池—night rain over the Ba Mountains, swelling the autumn ponds. The image is calm, poetic, even cozy. For me, rain is still associated with intimacy, pause, and tranquility. It feels gentle and familiar.

My academic path brought me to Sweden, where familiar things started to get renamed—and by being renamed, they also started to look unfamiliar. A street-corner "stream" became drainage overflow. The "autumn pond" became a detention basin. The endless "night rain" became a 20-year return period event. The rain had not changed in my memory, but the language had, and with the language came a different kind of attention: a demand to treat what felt familiar as something that could be assessed, measured, classified, and managed.

That shift intensified when I began working with stormwater management more directly at a Swedish national research institute. I found myself surrounded by unfamiliar concepts, new frameworks, and very skilled colleagues and international collaborators across disciplines. I visited pilot projects across countries that looked almost too reasonable: beautifully designed infrastructure, careful detailing, and multiple benefits promised by the landscape. Everything appeared convincing, everyone seemed enthusiastic, in the right order, for the right reasons. Sustainability and multifunctionality were no longer abstract slogans. I saw them in real stormwater projects, where they took concrete form and became procedures: functions to meet, templates to fill, categories to satisfy. Sometimes meaningful, sometimes mechanical.

And for the first time, I began to see what sits beneath these concepts: that stormwater management depends in reality, on coordination, shared understanding, and commitment sustained across actors and across time. It is not only about rain and infrastructures. It is also about responsibilities that are distributed, negotiated, and sometimes quietly avoided. This recognition did not arrive as a rupture. It came as a shift. I was working in applied settings, close to projects and deadlines, and I began to notice that the questions that mattered most in my mind were often the least reportable. When a city commits to a multi-million project meant to last for decades, "sustainability" cannot be reduced to what is easiest to document. To stay with that question, I moved into academia, and this thesis begins there.

Contents

List of publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I. **Sun, Z.,** Deak Sjöman, J., Blecken, G.-T. & Randrup, T. Decision support tools of sustainability assessment for urban stormwater management – A review of their roles in governance and management. *Journal of Cleaner Production* 447, 141646 (2024). https://doi.org/10.1016/j.jclepro.2024.141646

II. **Sun, Z.,** Randrup, T, Blecken, G.-T., Utkina, K. & Deak Sjöman, J. Decisive Factors in Sustainable Stormwater Management. (2025). https://doi.org/10.21203/rs.3.rs-6965519/v1 [In review for *npj Urban Sustainability*]

III. **Sun, Z.,** Deak Sjöman, J., Blecken, G.-T., Adhikari, U. & Randrup, T. Making Sense of Indicators for Nature-Based Solutions in Sustainable Stormwater Management: A Governance-Aware Approach. (2025). [Submitted to *Environmental Impact Assessment Review*]

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The contribution of Zhengdong Sun to the papers included in this thesis was as follows:

I. Zhengdong Sun led the conceptual development of the study, designed the review framework, conducted the systematic literature search and screening, and carried out the analysis. The author drafted the manuscript and led the revision process in close collaboration with the co-authors.

II. Zhengdong Sun designed the empirical study, conducted and analyzed the interviews, developed the factor framework, and implemented the Best–Worst Method. The author led the interpretation of results and drafted the manuscript, with input and feedback from the co-authors.

III. Zhengdong Sun led the study design, developed the indicator set and context dossiers, and designed the expert elicitation survey. He coordinated data collection, conducted the analysis and interpretation, and drafted the manuscript. The work was carried out in close collaboration with the co-authors, who contributed to methodological discussion, and manuscript finalization.

Publications not appended

In addition to the work presented in this thesis, the author has contributed to the following publications, which are not appended to the thesis but are relevant to the broader research context:

Adhikari, U., Broekhuizen, I., Pons, V., **Sun, Z.**, Sjöman, J. D., Randrup, T. B., Viklander, M., & Blecken, G.-T. (2024). Comparing the hydrological performance of blue green infrastructure design strategies in urban/semi-urban catchments for stormwater management. *Water Science & Technology*, *90*(9), 2696-2712.

Randall, M., Jensen, M., van de Ven, F., Zevenbergen, C., Körber, J., **Sun, Z.**, Chen, S., & Zhang, S. (2025). The three points approach (3PA) applied to two Chinese and four European cities for knowledge exchange on stormwater challenges and strategies. *Urban Water Journal*, *22*(5), 526-536.

Utkina, K., Ashley, R. M., **Sun, Z.**, Adhikari, U., Kali, S. E., Deak Sjöman, J., Randrup, T. B., Viklander, M., & Blecken, G.-T. (2025). Valuing structured alternatives for retrofitting blue-green infrastructure at a catchment scale using the Benefit Estimation Tool (B£ ST). *Blue-Green Systems*, 7(1), 139-155.

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Abbreviations

BWM	Best-Worst Method
DST	Decision-Support Tool
MLP	Multi-Level Perspective
PAM	Policy Arrangement Model
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
SSWM	Sustainable Stormwater Management

1. INTRODUCTION

By now we are all beginning to realize that one of the most intractable problems is that of defining problems … and of locating problems…

— Rittel & Webber, 1973

1.1 Background

For more than a century, urban drainage was designed to move runoff away as fast as possible, hidden beneath streets in a world of pipes. This logic reflected a period in which cities sought mastery over their environments, treating natural processes as disturbances to be tamed rather than partners to be understood (Gandy, 2004; Kaika, 2012). In truth, this mindset is far older: the conceptual model guiding most urban drainage today has changed little since Roman times, when water was channeled out of settlements to preserve hygiene, order, and human dominance over the natural world (Butler et al., 2024; Chocat et al., 2007; Novotny et al., 2010). What began as a triumph of engineering: a centralized, technocratic approach that prioritizes control, efficiency, and predictability, gradually became an unquestioned norm, an invisible infrastructure of thought as much as of concrete.

Yet the twenty-first century tells a different story. As cities densify and climates destabilize, this centuries-old logic reveals its limits. The same systems that once embodied progress now struggle to keep pace with the realities they helped create—rapid urbanization, sealed surfaces, biodiversity loss, and rising public expectations for equitable and livable environments (Depietri & McPhearson, 2017), what was once efficient has become brittle; what was once invisible now floods our streets. This recognition marks a broader paradigm shift in urban water management, from command-and-control systems toward adaptive and integrated approaches that combine technical, ecological, and social perspectives (Wong, 2006).

In many parts of the world, cities are beginning to look beyond the grey networks beneath their streets toward landscape-integrated, blue–green and other nature-based forms of stormwater management that embrace water as a living element of urban life. These ideas are encapsulated in the evolving discourse on sustainable stormwater management (SSWM), an approach that seeks not simply to drain but to retain, reuse, and regenerate, aligning technical performance with ecological function and social value (Fletcher et al., 2015). SSWM builds upon a family of related international paradigms such as Water Sensitive Urban Design (Australia), Low Impact Development (United States), and Sustainable Urban Drainage Systems (United Kingdom), Sponge City (China) all of which emphasize decentralized management and the co-benefits of stormwater integration across scales (Brown et al., 2009; Veal, 2021; Woods-Ballard et al., 2007).

At the heart of this shift lies the rise (re-recognition) of Nature-based Solutions (NbS). Once considered peripheral green amenities, NbS have become one of the central strategies for climate adaptation and urban transformation (Wild et al., 2017). As defined by the International Union for Conservation of Nature (IUCN), NbS aim to work with natural processes, to retain, store, convey, infiltrate, and purify water while simultaneously delivering co-benefits for biodiversity, microclimate, and human well-being (Cohen-Shacham et al., 2016). In stormwater contexts, NbS blur the boundaries between infrastructure and landscape, engineering and everyday life (Orta-Ortiz & Geneletti, 2022). The appeal is apparent, a rain garden or green roof is now no longer a decorative accessory but part of a broader urban socio-ecological system, one that requires not only hydrological performance but social legitimacy and institutional continuity to endure (Porse et al., 2022).

However, the more ambitiously multifunctional these systems are asked and expected to deliver, the harder they are to fully capture with the very tools designed to evaluate them, at least in a single, comprehensive representation (Adams et al., 2024; Van Der Jagt et al., 2023). Traditional quantifiable performance metrics, such as peak flow reduction, pollutant removal, or cost efficiency, while well established and necessary, illuminate only part of the picture. They quantify the visible, performative outputs of design, not the underlying relationships among people, institutions, cultures and places that give measures meaning and allow them to endure over time (Deak Sjöman, 2016; Eckert, 2025). Recent reviews have highlighted that most assessment frameworks for NbS in SSWM remain dominated by hydrological, pollutant or economic metrics, with limited integration of social or governance dimensions (Sarwar et al., 2025; Zhou et al., 2024). In effect, a systematic knowledge gap persists: what is easiest to count still too often substitutes for what is most critical to understand, particularly the socio-institutional processes that determine the long-term legitimacy and functionality of NbS (Wild et al., 2024).

The limitations in understanding, assessing and evaluating NbS are not merely a technical shortfall but also a challenge to stormwater governance. As NbS for SSWM are spatially distributed and institutionally shared; they cross departmental boundaries, implicate multiple mandates, and depend on mutual commitments and co-governance among authorities, managers, communities, and private owners (Andrews et al., 2010; Kabisch et al., 2017). In such settings, the question is not only how NbS interventions perform on hydrological outcomes, pollutant-removal efficacy, and cost-effectiveness; attention shall also turn to how decisions are made and how they are supported, whose values are surfaced, how trade-offs are negotiated, how responsibility is cultivated, and how evidence is interpreted at the moment of choice when dealing with such complex data and information (Fung, 2006; Pahl-Wostl, 2015). Bridging technical credibility with institutional legitimacy (Gibson, 2016; Hacking & Guthrie, 2008), therefore becomes central to decision-making here.

Two related gaps in current research and practice on SSWM in urban areas have emerged: 1) How to evaluate the social and cultural integration of NbS beyond technical performance, and 2) How to facilitate decision-making for lasting SSWM involving NbS in organizations and among various stakeholders. Much of the assessment architecture, especially in sustainability assessment that informs decisions, still privileges what can be modelled and priced (e.g., flows, pollutant loads, cost benefits), while the social, experiential and institutional life of NbS in SSWM remains thinly represented. Questions of how responsibilities are shared, how land is negotiated, how residents encounter and value NbS, and how long-term maintenance is secured are often either absent or treated as background context rather than as criteria in their own right (Blecken et al., 2017; Muller et al., 2022).

At the same time, the step where criteria and indicators are chosen and interpreted, often within decision-support tools (DSTs), is rarely made explicit. Criteria and indicator list for NbS and SSWM proliferate (leBrasseur, 2022; Sowińska-Świerkosz & García, 2021; Sörensen et al., 2024; van Lierop et al., 2025), but the underlying judgements about which aspects of governance, collaboration or social value are worth including, and on what grounds, tend to remain implicit, shaped by what is easiest to measure rather than by what is most decision-relevant (Hugé et al., 2013; Waas et al., 2014). There is little simple, context-attuned support for making sense of governance and qualitative-oriented indicators in different existing urban fabrics, or for relating such qualitative judgements to the hydrological and economic evidence that still anchors most decisions (Walker et al., 2024). Together, these gaps point to a need for assessment frameworks and decision support that are not only governance-aware but also relevant in concrete decision contexts. This entails a more transparent sense-making process for indicators, one that explicitly considers their perceived relevance to decision-makers and the practical feasibility of their application within specific institutional and spatial contexts (Eckert, 2025; Wild et al., 2024).

These considerations motivate the present thesis. It takes up the problem of how holistic and multifunctional aspirations in SSWM can be matched by decision-support in sustainability assessments that make governance visible and usable, linking modelled performance with the social and institutional conditions that sustain it. Situated in two Swedish city contexts, the work follows the pathways by which concepts, responsibilities, and evidence move across actors and levels, and explores how indicator frameworks might support clearer sense-making and strengthen both the quality and the confidence of decisions in SSWM.

1.2 Research questions, aim and objectives

The limited understanding of how governance and institutional conditions shape what counts as usable evidence, and which criteria and indicators are taken forward in concrete SSWM decisions, is the starting point of this thesis. As SSWM is increasingly expected to be holistic and multifunctional (Goonrey et al., 2009), the challenge becomes more acute. More of “what matters” sits outside what can be readily modelled, priced, or monitored. This raises a central question: How can governance-aware processes complement DSTs and assessment frameworks to strengthen decision quality and confidence in transitioning existing cities to holistic, multifunctional SSWM?

The overarching aim of this thesis is thus to advance and operationalize governance-aware decision-support for SSWM in existing urban areas. It seeks to explore how technical, social, cultural and institutional dimensions can be jointly evaluated and communicated to guide more legitimate, adaptive, higher-quality and more confident stormwater decisions. To achieve this aim, the thesis pursues three interrelated objectives:

- To systematically review existing DSTs and identify conceptual and practical gaps in how sustainability and governance dimensions are represented in SSWM assessment research (**Paper I**).
- To examine which factors have been decisive in past and present stormwater transitions in two Swedish cities, and which of these are perceived as most critical for future SSWM (**Paper II**).
- To empirically explore how a broad set of indicators are judged on relevance and resources in two catchment case studies, and to demonstrate how such judgements can be used in a simple, transparent sense-making process to support indicator selection and interpretation for NbS-related SSWM decisions (**Paper III**).

1.3 Scope of the work

The scope of this thesis is to advance the understanding and practice of holistic, multifunctional and SSWM in existing urban areas. It builds on, rather than replaces, existing quantitative and hydraulic studies that have clarified how stormwater systems perform and why some NbS installations fail to deliver as intended. Rather than focusing on hydraulic design or technical optimization of NbS, the research approaches SSWM through the lenses of governance, criteria and indicators in sustainability assessment, and decision support (Figure 1). It examines how these perspectives can help translate such ambitions into practice. Specifically, the thesis addresses how social, cultural, institutional and technical dimensions can be jointly understood and assessed in order to strengthen the quality, legitimacy and confidence of SSWM decisions.

Conceptually, the thesis is positioned within stormwater governance and sustainability assessment, emphasizing coordination, responsibilities and decision support across actors, sectors and scales. Empirically, it focuses on two Swedish cities and the associated catchments as complementary learning cases: Malmö exemplifies urban inner-city, while Östersund represents a residential suburban. Studying both cases enables exploration of how different context-attuned governance structures and institutional arrangements shape the implementation of multifunctional NbS in SSWM.

Methodologically, the thesis follows a sequential mixed methods design that moves from global mapping to local operationalization and integrated across the three studies across the three studies and subsequent papers. As presented in Figure 1, **Paper I** included a systematic review of DSTs to surface conceptual and practical gaps, especially the under-representation of social and governance aspects in current sustainability assessment framework of SSWM. **Paper II** examined which decisive factors have shaped past and present transitions toward SSWM in Malmö and Östersund, and prioritized these for future SSWM using the Best–Worst Method. **Paper III** explored how factors from Paper II can be translated into indicators and, through a structured expert elicitation survey using Relevance and Resources criteria, how such indicators are judged in terms of decision relevance and resource feasibility. Together, the three studies form an integrated inquiry into how holistic and multifunctionality NbS can be understood and embedded in SSWM decision processes.

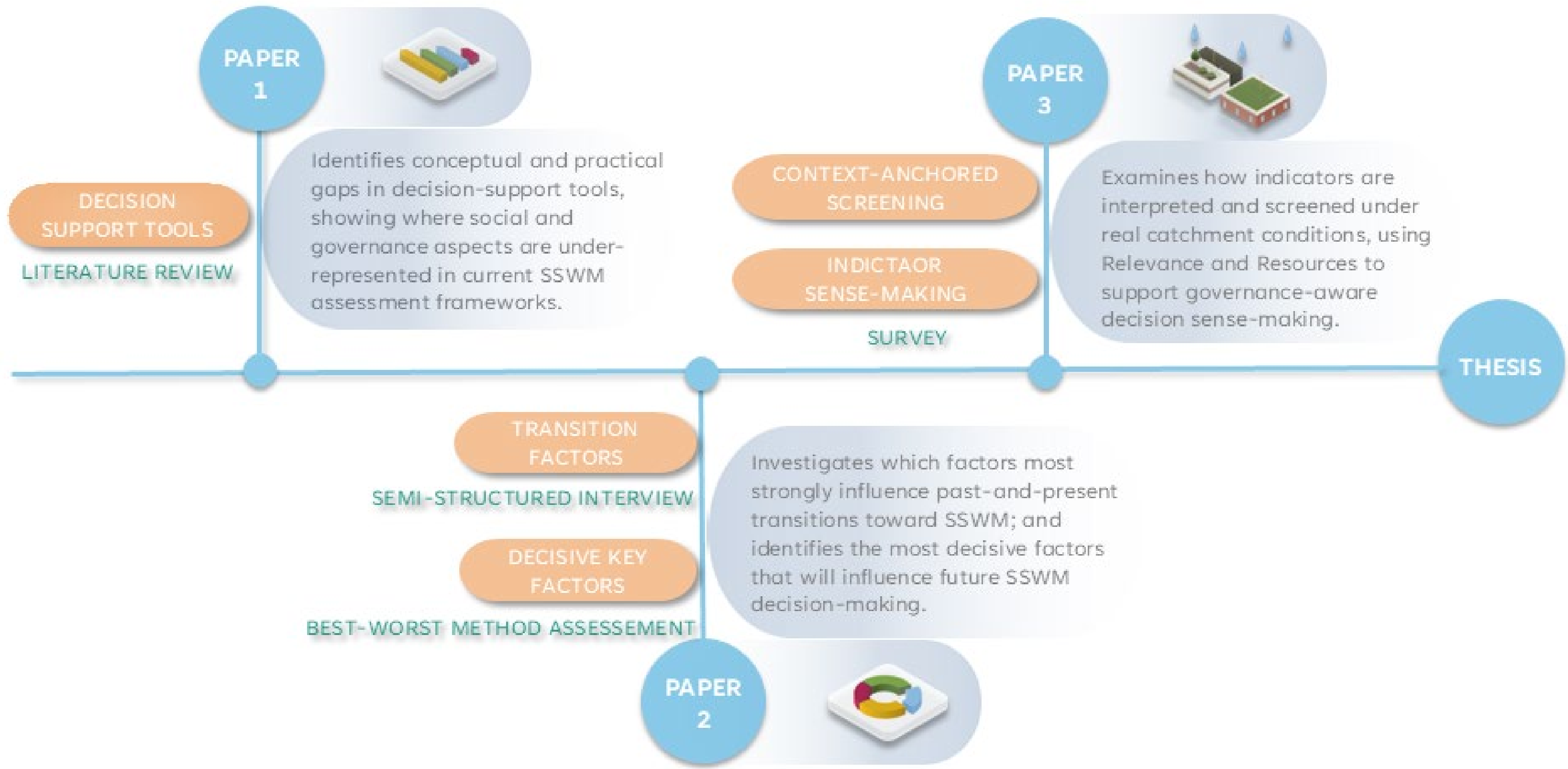

Figure 1. Thesis roadmap: the overview of the thesis design

1.4 Thesis structure

This thesis is organized as a compilation dissertation consisting of a comprehensive summary and three appended papers. The thesis is structured into six main chapters:

1. Introduction: outlines the background, research gaps, central research questions, aim, scope and overall structure of the thesis.

2. Theoretical Background: presents the conceptual foundations of holistic, multifunctional and SSWM, NbS, sustainability assessment, governance and decision-support.

3. Research Design and Methods: describe the case contexts, methods, empirical materials and analytical frameworks.

4. Results: summarizes the key findings of the three papers and synthesizes them in relation to the overarching research question.

5. Discussion: interprets the results in light of the theoretical and methodological frameworks. Reflects on the contributions and limitations of the research, and highlights implications for future research and practice

6. Conclusions: summaries of the thesis.

The three appended papers are referred to in the text as **Papers I–III**.

2. THEORETICAL BACKGROUND

2.1 Holism, multifunctionality, and sustainability

Words are always simpler than the phenomenon to which they refer.

— Ellinor Ostrom, 2009

The concepts of holistic, multifunctional, and SSWM together articulate the intellectual foundation (conceptual worldview) of this thesis. They represent, conceptually, the way of thinking, the way of designing, and the purpose of transitioning stormwater practice toward integrated, equitable, and long-term resilient systems.

2.1.1 Holistic: a systemic and integrated way of thinking

The term holistic originates from holism, denoting the view that systems, whether ecological, technical, or social, must be understood as interconnected wholes rather than isolated parts (Keller, 2019). A holistic approach recognizes that the performance of any NbS depends on its relationships within the larger socio-ecological and infrastructural system (Viti et al., 2022).

In the context of SSWM, holistic implies an integrated, multi-disciplinary approach where hydrology, ecology, landscape planning, governance, and social well-being are treated as interdependent dimensions rather than separate domains. It requires moving beyond the purely hydraulic focus of conventional drainage to include environmental quality, urban livability, and institutional capacity as equally decisive dimensions of success (Brown et al., 2009).

Holistic stormwater management therefore operates on the principle that the whole is greater than the sum of its parts, and shall entail 1) integration across SSWM infrastructure types (grey–green–blue), governance levels, and professional disciplines (Rijke et al., 2012), 2) interdependence between ecological processes, technical functions, and social legitimacy, long term functionality, and cultural and experiential relevance (Wild et al., 2017), and 3) coherence across planning scales from site-level design to catchment-level policy (Stahre, 2002). This perspective aligns with systems theory

(Meadows, 2008), which emphasize feedback, adaptation, and multi-level interactions in complex systems. It provides a conceptual backdrop for the thesis's analytical lens, linking technical considerations with social and governance-related conditions through a transparent, context-based approach to criteria and indicators

2.1.2 Multifunctional: translating holism into design practice

If holistic thinking helps framing the mindset, multifunctionality translates this framing into design expectations for NbS and SSWM in urban environments (Croeser et al., 2021). A multifunctional approach deliberately designs stand-alone NbS or integrated NbS systems to perform several functions within the same physical area, thereby achieving multiple co-benefits from the same spatial footprint (Hölting et al., 2019). Traditionally, stormwater systems were engineered for a single objective, rapid conveyance and flood control underground or out of the place, in contrast, multifunctional stormwater infrastructure (e.g., NbS) integrates hydrological, ecological, and social functions on the surface and within the place (Cettner et al., 2014). The principle of multifunctionality thus operationalizes holism by embedding stormwater functions within public space, landscape design, and urban life, rather than isolating them in concealed technical facilities.

In real-world contexts, multifunctional designs also create cross-sectoral synergies: a green corridor can serve as flood detention, biodiversity habitat, and pedestrian infrastructure simultaneously, while some functions are more episodic, becoming critical only in particular events (e.g. temporary storage during cloudbursts) (Hansen & Pauleit, 2014). The key point is that the capacity for multiple hydrological, ecological and social functions is built into the same NbS or NbS systems in the catchment area, even if not all functions are equally prominent at every moment (Depietri & McPhearson, 2017). Such synergy forms the spatial and operational foundation for NbS that advance both environmental and social goals in SSWM (Barbosa et al., 2012). In the empirical chapters of this thesis, one criterion is therefore labelled "Multifunctionality" to capture practitioners' views on these combined hydro–eco–cultural–experiential functions at the site scale.

2.1.3 Sustainability: the overarching purpose

While holistic thinking frames the mindset, and multifunctionality translates it into design, sustainability sets the horizon, clarifying why we act. However, sustainability is a powerful yet ambiguous concept, its meanings and interpretations have evolved alongside societal aspirations and environmental awareness. From the Brundtland Commission's call to meet present needs without compromising future generations (Brundtland, 1987), to the triple bottom line emphasis on balancing environmental, social, and economic objectives (Elkington & Rowlands, 1999; Hacking & Guthrie, 2008), sustainability has become a shared yet contested language for pursuing a more balanced future. Rather than a single definition, it represents an evolving dialogue on how human activities can coexist within ecological limits while enabling well-being, equity, and continuity (Köhler et al., 2019).

In this thesis, sustainability is understood through Gibson's integrative perspective as "*the current language for lasting well-being and for exploring what pursuing lasting well-being entails*" (Gibson, 2016, p. 3). This view emphasizes that sustainability is not a static goal but a continual process of reconciliation between human aspirations and ecological realities. It recognizes that the biosphere's capacity to sustain human prosperity is finite, demanding stewardship within planetary limits; that human well-being depends on secure material and social foundations, including health, livelihood, and justice; that progress toward sustainability requires profound and often difficult transformations in institutions, behaviors, and values; and that such transformations unfold within a world of complexity and uncertainty, where knowledge is partial and outcomes unpredictable (Gibson, 2016).

From this perspective, sustainability in this thesis is not treated as a checklist of discrete pillars but as a relational equilibrium that integrates environmental integrity, social equity, and institutional accountability across scales, and especially the time horizons. It serves as both a normative goal—defining what is to be sustained; and an evaluative lens—shaping how progress toward that goal is understood and assessed (Pope et al., 2004; Pope et al., 2017). This interpretation links directly with the thesis's broader conceptual triad of holistic, multifunctional, and sustainable approaches: how we think, how we design, and why we act (Table 1).

Table 1.Summary of how the thesis uses the concepts of holistic, multifunctional and sustainable.

Dimension	Essence	In the context of this thesis
Holistic	How we think: *integrated, systemic perspective*	Forms the conceptual basis for linking technical, social, cultural, and institutional dimensions of SSWM.
Multifunctional	How we design: *NbS in one space, with many benefits*	Translates holism into practice by designing NbS and stormwater spaces to deliver hydrological performance together with ecological, social, and other qualitative benefits, and by making governance, trade-offs and co-benefits explicit.
Sustainable	Why we do it: *lasting well-being over time, in a finite world*	Represents the normative horizon and assessment lens for SSWM, integrating environmental, social and institutional goals, and framing what counts as a "good enough" decision in the long term.

Although the three papers were not framed *a priori* around the three dimensions of holism, multifunctionality, and sustainability, their insights converge around these three interdependent dimensions. In the remainder of the thesis, I use this triad as a synthesizing lens for reading the papers together and for structuring the subsequent analysis.

2.2 Nature-based solutions in sustainable stormwater management

When we try to pick out anything by itself, we find it hitched to everything else in the Universe.

— John Muir, 1911

Conceptually, SSWM reframes stormwater from a waste stream to a socio-ecological resource, advancing an integration logic that seeks concurrent hydrological, ecological, and societal performance within shared urban space (Fletcher et al., 2015; Brown et al., 2009). It bridges disciplinary and institutional silos by linking infrastructure types (grey–green–blue), governance levels, and planning scales into coherent systems (Depietri & McPhearson, 2017). Its theoretical value lies in showing that technical design, ecological function, and social legitimacy must co-exist and co-evolve, rather than be pursued in isolation.

NbS, rooted in ecosystem-based management and resilience thinking, denotes a family of measures that deliberately mobilize ecological processes in urban open space (Sowińska-Świerkosz & García, 2022). In stormwater engineering and management, this largely overlaps with what is often described as green and blue infrastructure: vegetated, soil-based or open-water systems that can retain, convey, or treat runoff while also contributing to biodiversity and human well-being (Depietri & McPhearson, 2017). Within the SSWM frame, NbS is thus used mainly to denote those surface-oriented measures that sit alongside, and can be combined with, more conventional grey or hybrid infrastructure (Wild et al., 2017).

At the same time, NbS is not a single category. It spans a grey–green continuum from minimal intervention to highly engineered "created" ecosystems. Eggermont et al. (2015) describe this range as three NbS types that differ in how much engineering or management is applied to ecosystems, and in how many ecosystem services and stakeholder groups are targeted. As targets expand, trade-offs become more likely and "win-win" outcomes become rarer, which shifts decision-making from optimization to judgement under uncertainty (Eggermont et al., 2015). In SSWM contexts, this continuum is visible in how measures range from the protection or restoration of existing ecosystems, including water and riparian systems (Type 1), to actively managed urban green–blue spaces that steer hydrological and ecological functions, such as managed parks, swales, and vegetated corridors (Type 2), and further toward engineered ecological systems designed and maintained to deliver specific stormwater functions, such as constructed wetlands, green roofs, and bioretention features including rain gardens, biofilters, and stormwater tree pits (Type 3). Boundaries are not clear-cut, and hybrids can emerge and change character over time (Eggermont et al., 2015), which further reinforces the need to treat performance and management as dynamic rather than fixed.

In this thesis, SSWM and NbS are used in a complementary way. SSWM provides a domain-specific integration logic for urban stormwater management that can encompass both nature-based and grey elements. While NbS sharpens the focus on the green and blue measures that rely on ecological processes to deliver multiple benefits. Empirically, the thesis uses NbS primarily in the sense of engineered stormwater-control measures (Type

3), in particular bioretention systems (rain gardens and biofilters) and stormwater tree pits, rather than broader urban green space (e.g., parks in Type 2) where stormwater benefits are more diffuse and management logics differ. The analysis spans an inner-city and a residential suburban catchment, where ownership, space constraints, and management interfaces differ (Section 3.3). This focus on engineered stormwater NbS, together with differing interface conditions across the two settings, clarifies why governance becomes decisive. Many NbS for SSWM are hybrid infrastructures that combine grey engineering with living components such as vegetation and substrates (Boogaard, 2024). Because performance depends on both hydraulic function and ecological condition, these measures require both technical competence and ecological stewardship (Przestrzelska et al., 2024). This hybridization often disrupts existing management regimes: planning, delivery, and long-term operation and maintenance are split across municipal departments and external contractors that do not share established routines or a history of collaboration, especially for maintenance (Knapik et al., 2025). In practice, this creates blurred accountability and coordination gaps that can undermine performance even when the design is sound. As solutions expected to become more multifunctional, decentralized, and hybrid, decision quality increasingly depends on clear role and responsibility interfaces, coordinated maintenance arrangements, and legitimacy for long-term care (Howe et al., 2014). This motivates the governance perspective in the next section.

2.3 Governance in SSWM

No single center of authority can solve the problems of complex systems.

— Ellinor Ostrom, 2017

Governance is commonly understood as the processes through which multiple actors, institutions and knowledge systems shape collective decisions about shared problems (Kooiman, 2004; Ostrom, 1990). In water and environmental governance, this has generated extensive work on how authority and responsibility are organized across levels of government and between sectors, utilities, planners, developers and residents (Lemos &

Agrawal, 2006; Pahl-Wostl, 2015). Studies of urban water, open space and NbS have documented different kinds of challenges, such as fragmented mandates, where jurisdictions, responsibilities, and management criteria are split or overlapping across organizations with misaligned priorities; vertical and horizontal coordination, where alignment is needed both across levels of government (e.g., national, reginal, municipal) and across sectors at the same level; and emerging forms of co-governance and stewardship, where public, private and civic actors share roles in planning, delivery and long-term care (Farrelly & Brown, 2011; Fratini et al., 2012; Kabisch et al., 2017; Randrup et al., 2021; Van Der Jagt et al., 2023). Existing studies have produced a rich and detailed picture of who is involved in stormwater-related decisions and how formal responsibilities and roles are distributed, including recent work on Swedish urban open space and SSWM (Glaas et al., 2025; Qiao et al., 2019; Storbjörk et al., 2025; Sunding et al., 2024; Sörensen & Hanson, 2024; Wihlborg et al., 2019)

This thesis builds on that foundation and is indebted to it, but it does not aim to re-map or compare stormwater governance structures, nor to propose a "better" governance model for the case studies. Instead, it complements this work by shifting attention from governance as institutional architecture to governance as the conditions under which stormwater decisions are formed, supported and justified. In other words, rather than focusing only on *who is at the table*, the thesis asks *what is on the table* when decisions about SSWM are made: which dimensions are recognized as relevant, which are rendered visible as "evidence" in assessment and decision-support, and where actors themselves feel confident, or hesitant, about their judgments.

This perspective of what becomes actionable in decision situations is particularly important for SSWM, where technical performance, financial and spatial constraints, and long-term responsibilities intersect (Goulden et al., 2018; Zandersen et al., 2021). Implementing NbS requires coordination across departments, landownerships, tenure arrangements and time horizons (Grigg, 2024). Decisions are often taken under uncertainty about future climate, maintenance capacity and public acceptance (Van Der Jagt et al., 2023). In this thesis, governance is understood as the ensemble of institutional and relational conditions that shape how problems are framed, which considerations are treated as legitimate, and how responsibility is distributed over time. These governance conditions shape how trade-offs between hydrological, ecological, social, economic and institutional aims are interpreted and handled. They also determine what can be brought into decision situations as assessable evidence, and what remains uncertain or contested.

Against this definition, the thesis examines how governance conditions appear, or fail to appear, in DSTs (**Paper I**), in practitioners' accounts of what has actually mattered for SSWM transitions (**Paper II**), and in the Relevance–Resources screening of indicators under concrete catchment contexts (**Paper III**). In doing so, this thesis approaches governance in SSWM as inseparable from the ways evidence is assembled and used, and from the degree of confidence that actors can place in decisions intended to be holistic, multifunctional SSWM.

2.4 Decision-making and decision-support in SSWM

Not everything that can be counted counts, and not everything that counts can be counted.

— William Bruce Cameron, 1963

2.4.1 Decision making in stormwater governance

While governance defines the institutional structures and actor relationships that shape how stormwater is managed, these arrangements ultimately materialize through the decisions that different actors make: how priorities are set, values and interests negotiated, and evidence applied in practice (Brown & Farrelly, 2009; Flynn & Davidson, 2016; Qiao et al., 2018). Understanding decision-making is therefore essential for linking stormwater governance frameworks to on-the-ground implementation and for evaluating the sustainability of outcomes (Barbosa et al., 2012; Dhakal & Chevalier, 2016). Decision-making is the mechanism through which the objectives of SSWM are translated into practice, it determines how sustainability is framed, whose knowledge and values inform priorities, and how trade-offs are handled when technical, ecological, social, and institutional goals intersect (Pascual et al., 2023; van Oudenhoven et al., 2018). In this sense, decision-making represents the *procedural expression* of governance, the point where collective intentions become concrete choices (Pahl-Wostl, 2017).

2.4.2 Decision quality and decision confidence

This thesis examines decision-making processes based on two related ideas. The first is decision quality. This concerns the quality of reasoning that leads to action. It rests on decision-relevant evidence, explicit value judgements, and transparent handling of trade-offs under uncertainty (Gregory et al., 2012; Howard, 1988; Raghunathan, 1999). The second is decision confidence. It concerns whether actors see a decision as defensible and actionable in their institutional setting. It relates to credibility, legitimacy, and practical usability of the assessment and process (Peters, 2022). In SSWM, these can diverge. An assessment can be technically rigorous but still fail to build confidence if key governance and social conditions are treated as add-ons or outside the assessment boundary (Eckert, 2025).

2.4.3 Decision-support and sustainability assessment

In SSWM, decisions on NbS planning are inherently complex because they cross disciplinary and administrative boundaries, linking engineers, planners, ecologists. In this sense, decision-making represents the procedural expression of governance, the point where collective intentions become concrete choices citizens, while reconciling heterogeneous forms of evidence (van Lierop et al., 2024). Historically, stormwater decisions have been dominated by engineering rationalities emphasizing quantifiable performance criteria such as hydraulic efficiency or pollutant removal (Grigg, 2024). Yet holistic and multifunctional approaches and political agendas require decision processes that also recognize qualitative and relational values of NbS, such as aesthetics, place attachment, social equity, and governance capacity (Finewood et al., 2019). Consequently, decision-making in SSWM is not only a matter of selecting the "optimal" NbS but of balancing multiple, often incommensurable and sometimes conflicting, forms of value across actors, and across temporal and spatial scales.

Because such decisions are complex and contested, they depend on decision-support that can integrate evidence, deliberation, and legitimacy (Halla et al., 2022; Pope et al., 2013). Decision-support refers not only to analytical tools or models but also to broader frameworks, such as sustainability assessment from the impact assessment domain, that structure how evidence, values, and trade-offs are interpreted in decision-making (Morrison-Saunders et al., 2015). As defined by Halla et al. (2020), sustainability assessment is a purposeful process that facilitates engagement with the concept of sustainability and aims to advance sustainability-based objectives in decision-making. The sustainability assessment frameworks help make the reasoning behind the sustainable choices transparent and allow different forms of knowledge to be compared and justified (Bond & Pope, 2012).

In sustainability-oriented planning fields, such as NbS, sustainability assessment provides an overarching framework for linking decision-making and decision-support, and it is a decision-oriented assessment that improves how we perform, and what we do, so choices advance sustainability, integrating evidence, values, and explicit criteria with transparent trade-off rules to avoid shifting burdens across places, groups, or generations (Gibson, 2016; Gibson, 2006). Sustainability assessment principles thus have informed this thesis as a whole, both in its theoretical framing and in the analytical frameworks used in the three studies, guiding the review of decision support tools (**Paper I**), guiding the thematic analysis of the decisive indicators (**Paper II**), and underpinning indicator validation and sense-making process (**Paper III**).

2.4.4 Criteria, indicators and factors

Furthermore, in sustainability assessment, criteria and indicators are indispensable components for assessment and decision-making. Criteria are the standards or principles used to judge or evaluate something against a goal, they act as benchmarks against which performance, processes, or outcomes are assessed (Gibson et al., 2013). Criteria are often organized in a bundle manner, such as the triple bottom line - environmental, social, and economic criteria (Elkington, 2013). Conversely, indicators are specific variables, metrics, or prompts that provide evidence of whether criteria are being met. Indicators operationalize criteria, and they make criteria assessable by specifying what can be observed and judged (Nedyalkova, 2020). Criteria and indicators are both tied to goals and tasks, but they play different roles: criteria define the judgement space, and indicators define what evidence can enter it (Gibson et al., 2013; Nedyalkova, 2020).

This thesis also uses the term "factor". In assessment studies, factors often refer to attributes or conditions that influence a process or condition (Gibson, 2016). The study described in **Paper II** does not appraise NbS alternatives in SSWM, rather explores the transitional attributes that influence SSWM from a longitudinal perspective. Here in **Paper II**, a "factor" is a neutral label as it is inductively retrieved from the narratives of participating stormwater managers and engineers and help support an overarching thematization of subsequent decision criteria.

This thesis uses the concepts of criteria, indicators and factors as a working vocabulary for what is worth including in governance and decision-making, and what can be judged in practice by practitioners with subsequent clarification:

- Criteria: decision dimensions to a high-level goal.
- Indicators: assessable prompts linked to criteria.
- Factors: neutral term used during elicitation before formalization.

3. RESEARCH DESIGN AND METHODS

An approximate answer to the right question is worth a great deal more than a precise answer to the wrong question

— John W. Tukey, 1962

3.1 Overall approach

The thesis follows a sequential mixed-methods design that translates insights from a global review of DSTs, into empirically grounded factors and, finally, into a context-sensitive indicator screening for decision support (Table 2). This sequencing follows from the thesis problem framing and case-based logic. It combines interpretive approaches that capture situated meaning with structured elicitation and comparison that make trade-offs and judgements explicit, without implying population inference or false precision (Creswell & Creswell, 2017). The overarching aim was to develop and empirically ground a framework for assessing governance-related decision conditions in SSWM. The research includes three interlinked stages:

I. Conceptual mapping through a systematic literature review (**Paper I**);

II. Empirical Identification of past-and-present transition factors and prioritization for future SSWM using interviews and Best–Worst Method (**Paper II**);

III. Indicator sense-making and screening of candidate indicators using Relevance and Resources judgements in a structured expert elicitation survey (**Paper III**).

Each stage informed the next, allowing iterative refinement of both the conceptual understanding and the operational approach, consistent with a progressive focusing logic (Miles et al., 2014). Credibility is supported through triangulation across sources and analytical perspectives, treated here as a check for coherence under difference rather than a requirement of full convergence (Carter, 2014; Vaughan, 1992; Yin, 2017).

Table 2. Overview of **Papers I–III**, summarizing focus, scale, material, methods, analytical lenses, and outputs

Research focus	Governance dimensions in decision-support tools	Past-and-present transition factors, and future decisive factors shaping SSWM	Indicator sense-making and screening for decision support
Scale	Global	Local, city scale *(Malmö & Östersund)*	Local, catchment scale *(Davidshallstorg, inner-city Malmö; Ångbryggeriet, residential suburban Östersund).*
Materials / Data	50 peer-reviewed papers (DSTs)	17 interviews (Malmö & Östersund); 10 BWM participants.	Catchment documents and field observations; Context dossiers; Survey responses (n = 14): Qualitative comments.
Methods	Systematic literature review (PRISMA)	Case study; Semi-structured interviews; Best–Worst Method (BWM).	Case study; Document analysis; Structured expert elicitation survey; Descriptive statistics; Directed content analysis.
Analytical lens	Policy Arrangement Model (PAM)	Multi-Level Perspective (MLP); MLP-guided thematic analysis; sustainability assessment - informed interpretation.	3Rs-informed screening, operationalized as 2Rs (Relevance–Resources) with NA%/dispersion as uncertainty signals; Strategic management framing.
Output	**Paper I**	**Paper II**	**Paper III**

3.2 Systematic literature review

Paper I applied a systematic literature review to examine how international DSTs were applied in sustainability assessment for SSWM. A systematic review was chosen as it provides a transparent and reproducible method for synthesizing existing knowledge, minimizing researcher bias, and identifying conceptual and empirical gaps (Grant & Booth, 2009). The review followed the PRISMA protocol (Page et al., 2021), with searches in

Scopus and Web of Science using combinations of terms related to stormwater, urban drainage, governance, assessment, and decision-support. After screening 1 432 records, 11 tools from 50 peer-reviewed papers met the inclusion criteria.

3.2.1 Analytical Framework: Policy Arrangement Model

Each tool was coded and analyzed using the Policy Arrangement Model (PAM) (Arts et al., 2006). PAM was selected as it enables structured analysis of how decision-making systems are institutionalized through the interplay of actors, resources, rules, and discourses (Figure 2). PAM conceptualizes policy domains through the interplay of four dimensions—actors, resources, rules, and discourses—that together stabilize governance arrangements (Arts et al., 2006). In **Paper I**, PAM was used to interpret DSTs as institutional artefacts, examining how they embed specific actor configurations (who is involved or excluded), resource logics (data, expertise, funding), formal and informal rules (legislations, standards, procedures), and dominant discourses (stormwater quantity control, quality treatment).

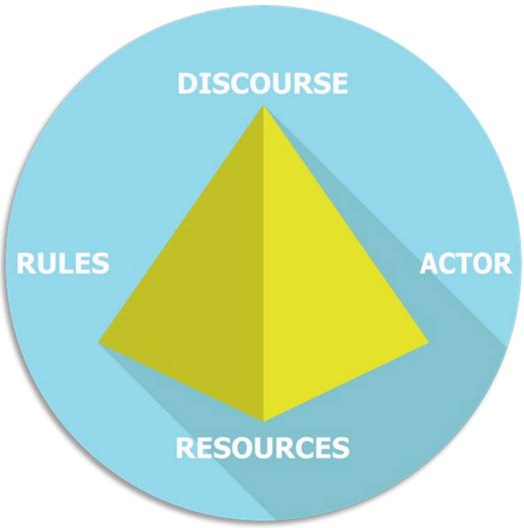

Figure 2. Visualization of the Policy Arrangement Model (PAM). The four dimensions of a governance arrangement: actors, resources, rules and discourse, are represented as the faces of a pyramid, indicating that they are mutually shaping and need to be understood together.

3.3 Case study

A case study is an empirical investigation of a contemporary phenomenon in depth and within its real-world context, especially when the boundaries between phenomenon and context may not be clearly evident (Yin, 2017). Two Swedish municipalities: Malmö and Östersund, were selected as contrasting case studies (Figure 3). **Paper II** treats Malmö and Östersund as contrasting city-scale cases. While **Paper III** zooms in the comparison to two embedded catchment-scale cases: Davidshallstorg in Malmö (inner-city) and Ångbryggeriet in Östersund (residential suburban) (Figure 4).

Figure 3. Location of the two study municipalities in Sweden: Malmö (southern Sweden) and Östersund (central–northern Sweden).

Malmö is a coastal city in southern Sweden. It includes a spatially dense inner-city core with high imperviousness and recurrent pluvial flooding.

Davidshallstorg in Malmö represents the inner-city catchment, with mixed commercial and residential land uses. Stormwater responsibilities in Malmö are distributed across municipal planning, public space and street management, environmental functions, and the regional water utility (VA SYD, the regional water and sewer utility in southwest Scania).

Östersund is an inland city in northern Sweden, with a more dispersed urban form and stormwater priorities closely linked to receiving-water protection. Ångbryggeriet in Östersund represents a residential suburban catchment dominated by housing areas. In Östersund, stormwater responsibilities similarly span municipal planning and environmental functions and the water and waste services.

Governance arrangements differ slightly between the cases: Malmö's water and wastewater services are managed through the regional utility VA SYD, whereas Östersund's water and wastewater service is housed within the municipal technical administration, with corporatization plans discussed and revisited in recent years. The cities share similar policy ambitions for nature-based and multifunctional stormwater management but differ in climatic, spatial, and institutional conditions. Both cities participate in the FORMAS funded research project *Achieving multifunctional, holistic and SSWM in existing developments*, which enabled close collaboration between universities and municipal partners.

The empirical work integrates field visits, document analysis (Table 3), interviews, workshops, and survey data across the two municipal contexts. Such integration allows vertical triangulation (linking conceptual, empirical, and evaluative layers) and horizontal triangulation (combining different data types within each case) (Carter, 2014; Flick, 2018; Yin, 2017).

Collaboration with Luleå University of Technology (LTU) further enhanced this triangulation by contributing the hydrological and spatial dimension through modelling of NbS alternatives under an engineered–decentralized (ENG–DEC) configuration in the same case studies (Adhikari et al., 2024; Utkina et al., 2025). These works were essential for anchoring governance indicators in real-world design settings and for linking social-institutional analysis with physical performance modelling (Figure 4).

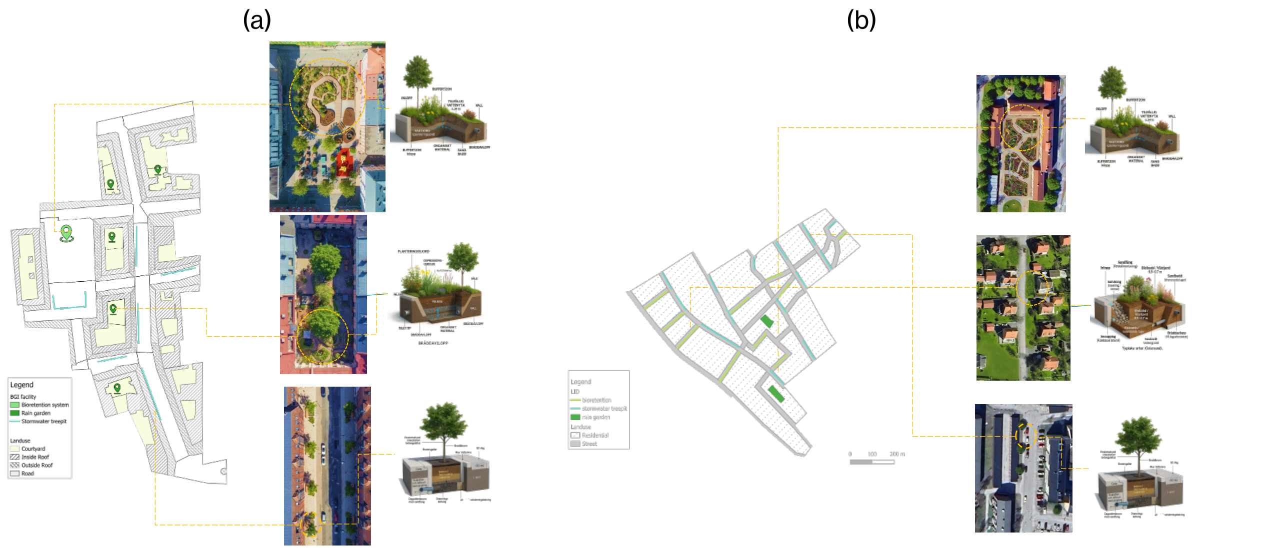

Figure 4. Case study catchments and NbS configuration. Panels (a) and (b) show the inner-city (Davidshallstorg, Malmö) and residential suburban (Ångbryggeriet, Östersund) catchments. The maps show a shared ENG–DEC configuration, including biofilters, rain gardens, and stormwater tree pits.

Both inner-city catchment (Davidshallstorg, Malmö) and residential suburban catchment (Ångbryggeriet, Östersund) adopted a comparable ENG–DEC NbS configuration. The configuration consists of a distributed package of small-scale measures, including biofilters, rain gardens, and stormwater tree pits, corresponding to engineered Type 3 NbS (Eggermont et al., 2015). Here, "decentralized" in ENG-DEC refers to the spatial distribution of measures across the catchment. The semi-distributed layout combines engineered retention and infiltration, with localized pre-treatment and outlet control, and targets water-quality improvement and volume reduction during small, frequent rainfall events while remaining feasible within existing urban morphology (Adhikari et al., 2024; Utkina et al., 2025; Randall et al., 2025). Using the same ENG–DEC NbS configuration in both sites enabled controlled cross-case comparison while keeping key hydrological design variables aligned. This concrete NbS configuration provided a shared spatial and technical reference for indicator judgements (Section 3.5.2)

3.4 Research techniques and data collection

3.4.1 Semi-structured Interview

Semi-structured interviews formed the qualitative foundation of empirical research in **Paper II** (Kvale & Brinkmann, 2015). This approach allows participants to articulate their own experiences and interpretations while providing enough structure to ensure coverage of key themes (Adeoye - Olatunde & Olenik, 2021; Yin, 2017). **Paper II** applied a longitudinal perspective. Interviews were designed to elicit how stormwater management priorities, responsibilities, and decision routines in Malmö and Östersund have evolved from the late 1960s to the present, and which factors interviewees consider decisive for future transition toward SSWM. Seventeen interviews were conducted between February and April 2024 with municipal officials, consultants, and practitioners directly engaged in stormwater management in Malmö and Östersund, including two professionals whose experience spans from the 1960s to the 2020s. Participants represented departments of spatial planning, street/park management, environment, housing, and the regional water utility, and the longitudinal approach aimed to identify recurring factors that interviewees considered decisive in past and present stormwater management toward sustainability. The interview protocol was informed by transition theory (Section 3.5.1) and explored institutional settings, actor interactions, decision-making routines, and coordination challenges related to stormwater governance retrospectively. All interviews were recorded, transcribed verbatim, and anonymized in accordance with SLU's data-protection guidelines. The transcripts were systematically coded and thematically interpreted to identify recurring transition factors across actors and time periods, following the analytical approach described in Section 3.5.1.

3.4.2 Best-worst method

Following the retrospective qualitative phase, a Best–Worst Method (BWM) (Rezaei, 2015) workshop was conducted to prospectively prioritize the factors derived from interview analysis. BWM, a structured multi-criteria decision method, was chosen for its transparency, consistency checking, and relatively low cognitive demand compared to full pairwise comparison techniques like Analytic Hierarchy Process. It allows participants to express preferences using "best" and "worst" anchors, producing ratio-scaled weights and a consistency ratio that quantifies internal reliability (Rezaei, 2016), and also reduces time and cognitive burden.

Ten of the interview participants took part in this BWM workshop (Malmö: n=6; Östersund: n = 4). Each selected the most and least decisive factors for SSWM transition and rated the others relative to these anchors. Consistency ratios (≤ 0.2) were verified to ensure data quality. The resulting weights were aggregated by case, yielding rankings of decisive factors and cross-case comparison. This structured elicitation combined practitioner expertise with mathematical transparency, offering both empirical robustness and legitimacy through stakeholder involvement.

3.4.3 Structured expert elicitation survey

The final data collection step in **Paper III** applied a structured expert elicitation survey (Bhattacherjee, 2012), to operationalize and validate the factors as context-related indicators. Structured elicitation is widely used in sustainability assessment and environmental decision-making when empirical data are limited but expert judgment is well-founded (Cooke, 1991), and this standardized approach can gather informed professional judgements from domain-knowledgeable participants (Martin et al., 2012).

Forty indicators (Appendix 1), translated from the earlier 40 factors, were organized under nine overarching criteria (e.g., Collaboration, Organizational Capacity, Policy and Legislation, etc.). Respondents rated each indicator for both case cities (Malmö and Östersund) under two criteria derived from the 3Rs framework: Relevance (importance and contextual fit) and Resources (feasibility and data accessibility) (Section 3.5.2.).

The survey was implemented in Netigate and distributed during October and November 2025 to 23 invited practitioners and researchers familiar with the two cases. Twenty individuals initiated the questionnaire, and fourteen completed ratings for both catchments and both criteria. The final sample included eight researchers and six municipal practitioners. A "Do not know / cannot judge" response option and open comment fields accompanied each indicator. Comments were used to support interpretation of rating patterns and to flag ambiguity and feasibility constraints.

3.4.4 Field study

Field studies were conducted in both case contexts: Davidshallstorg in Malmö and Ångbryggeriet in Östersund, to complement the interview and survey data with first-hand observation and contextual grounding. This research technique is used for understanding how actors, infrastructures, and spatial configurations interact in practice (Hammersley & Atkinson, 2019). It allows the researcher to capture tacit dimensions of governance, such as collaboration routines, site-specific constraints, and experiential aspects of NbS implementation, that are often difficult to elicit through interviews alone (Cloke & Crang, 2004; Yin, 2017).

Field visits were performed continuously throughout **Papers II** and **III** in close collaboration with project partner and local practitioners. Observations focused on the spatial configuration of implemented and planned stormwater interventions (including NbS), maintenance practices, and real-world public interactions during site inspections. This method supported the identification of context-sensitive factors that influenced the perceived feasibility and legitimacy of NbS projects, and to ensure that the indicator identification (**Paper II**) and indicator sense-making (**Paper III**) reflected conditions observable in practice rather than abstract or modelled assumptions.

3.4.5 Document analysis

To complement interview and survey data, a document analysis (Bowen, 2009; Yin, 2017), was undertaken in **Paper III** to investigate the formal governance structures and NbS owners within each catchment. This research technique offers a systematic means of examining how institutional intentions, responsibilities, and coordination mechanisms are articulated in grey literature, such as planning and policy documents. It is particularly valuable in governance research, where official texts reveal both formal mandates and underlying discourses (Silverman & Patterson, 2021).

Table 3. Summary of the planning, policy, and technical documents reviewed (titles translated into English), including year, document type, and stage.

City	Document name	Year	Document type
Östersund	Audit report on revision of the Municipal Comprehensive Plan Östersund 2040	2022	Audit / review report
Östersund	Environmental Impact Report for revision of the Municipal Comprehensive Plan Östersund 2040	2022	Environmental impact report (SEA/EIA)
Östersund	Guidelines for Stormwater Management	2020	Guidelines
Östersund	Water and Wastewater Program	2014	Program / strategic plan
Östersund	Background Report to the Water and Wastewater Program	2018	Report
Östersund	Water Plan for Lake Storsjön	2016	Water plan
Malmö	Stormwater Policy for Malmö	2000	Policy
Malmö	Stormwater Strategy	2008	Strategy
Malmö	Cloudburst Plan for Malmö	2017	Plan (cloudburst / emergency)
Malmö	Blue–Green Fingerprints in the City of Malmö: Malmö’s way towards sustainable urban drainage	2008	Report

As presented in Table 3, for each case city, the related municipal documents was reviewed, including local stormwater strategies, guidelines, environmental programs, detailed development plans, and interdepartmental steering documents. These materials were used to identify the distribution of responsibilities, cross-sectoral coordination mechanisms, and integration of multifunctionality principles (further verified by local practitioners via interviews). The analysis provided an institutional map of the governance arrangements surrounding the two catchments and served as a base for the strategic management interpretation (Section 3.5.2). Combining these textual insights with the empirical data from field study and interview responses strengthened the reliability and triangulation of the overall evidence.

3.5 Analytical frameworks for case studies

3.5.1 Transition theory and Thematic Analysis

Paper II applied the Multi-Level Perspective (MLP) from the transition theory (Geels, 2002), to design the semi-structured interview guide and to interpret factors that have influenced the shift toward SSWM since the 1960s. The three analytical levels, niche innovations, socio-technical regimes, and landscape pressures, were used to structure the interview prompts and ensure coverage of influences operating at different levels over time.

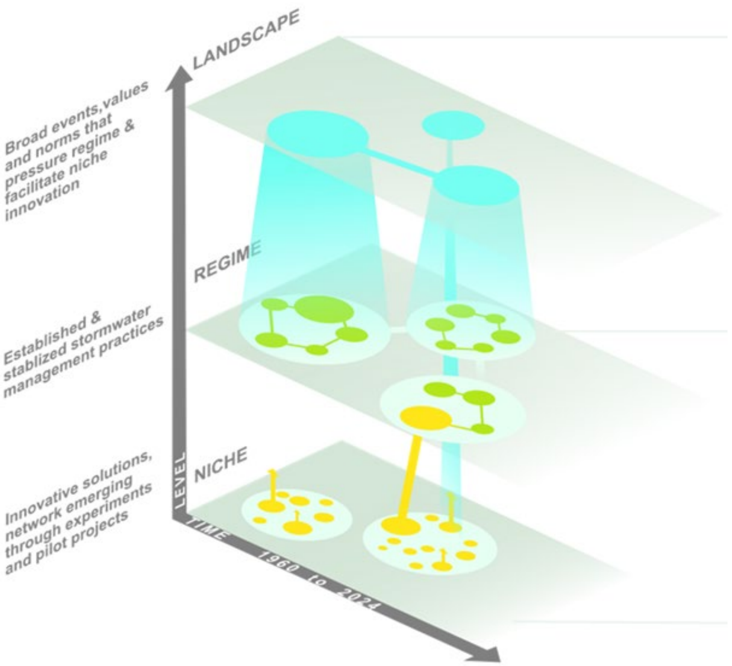

Figure 5. Multi-Level Perspective (MLP). The vertical axis distinguishes three levels: niche (innovative solutions and emerging networks), regime (established and stabilized

stormwater management practices), and landscape (broader events, values and norms that put pressure on regimes and enable niche innovation). The diagonal axis represents time. circles depict factors, while the shaded cones indicate how niche developments can scale up and interact with regime configurations under landscape influences.

Interview transcripts were further analyzed using thematic analysis (Braun & Clarke, 2006), which combines flexibility with theoretical rigor and is particularly well-suited to exploring patterns of meaning across qualitative datasets. We used a hybrid strategy. Deductive coding was guided by the MLP, to organize statements across niche, regime, and landscape levels. Inductive coding captured additional themes and cross-cutting interdependencies, including how institutional, technical, environmental, economic, social, and temporal and spatial considerations interacted in stormwater decision-making. The thematic analysis yielded 40 factors influencing SSWM transitions, which were subsequently mapped to the MLP levels and prioritized through the BWM exercise (Section 3.3.3). This combination of qualitative patterning and quantitative weighting enabled both interpretive depth and methodological robustness (Creswell & Creswell, 2017).

3.5.2 Analytical frameworks

Relevance, Robustness, and Resources

To elicit the survey judgements in **Paper III**, we use the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) "3Rs" framing for valuation choices as an analytical lens for trading off Relevance, Robustness, and Resources in applied indicator use (Termansen et al., 2022). In this framing, Relevance concerns whether information captures what matters across socio-ecological contexts, Robustness concerns reliability and fair representation of diverse values, and Resources concerns the time, budget, data availability, human inputs, and technical capacity required for application (Pascual et al., 2023).

In **Paper III**, the 3Rs lens was operationalized as a two-question screening focused on Relevance and Resources, as scoring Robustness as a third dimension would require specifying and validating indicator measurement approaches. That sits beyond the scope of a judgement-based screening step. Robustness was therefore examined indirectly using signals embedded in the instrument and its outputs. These include rating dispersion (median and interquartile range), the share of “Don’t know / cannot judge” responses (NA%), and convergence in qualitative comments across the two catchment cases. Accordingly, the survey screening uses two dimensions:

- Relevance: whether an indicator captures what matters for SSWM decision-making in the specified decision context.

- Resources: the perceived feasibility and assessability of using the indicator in practice within that context, considering data access, time, financial and technical requirements, and local knowledge capacity.

The lens is used for sense-making, not for performance measurement. Relevance and Resources scores, together with NA% and comments, are treated as signals that help interpret how decision context shapes indicator judgements, where feasibility constraints arise, and where trade-offs emerge between perceived importance and perceived practicality. This sense-making purpose distinguishes it from formal indicator selection protocols like RACER (European Commission, 2023). Those protocols finalize indicators for performance monitoring; the 2Rs screening in **Paper III** serves as a diagnostic and upstream logic, surfacing the contextual judgements and feasibility constraints that must be addressed before robust monitoring can be established.

Strategic Management

The document analysis described in Section 3.4.5 was used to reconstruct the institutional setting in which the indicators would be judged. Drawing on a strategic management perspective that emphasize planning, design, implementation and long-term maintenance as distinct and iterative development phases (Randrup & Jansson, 2020), the analysis traced how responsibilities, ownership structures and coordination mechanisms around stormwater and NbS were distributed in each catchment. The reconstruction was based on municipal policy documents, planning reports (Table 3), and earlier stakeholder analyses and interviews. Situating the indicators within these site-specific NbS configurations enabled respondents to assess their contextual relevance and practical feasibility, rather than their abstract desirability, thereby bringing the screening exercise closer to actual decision-making conditions.

3.6 Integrative perspective of used methods

This thesis treats transitions toward holistic, multifunctional SSWM as a socio-technical and institutional phenomenon that requires empirical inquiry and explicit attention to how decision support is grounded in practice. Empirically, it examines context-sensitive decision conditions, such as socio-organizational arrangements and temporal, spatial, and resource constraints, shape decisions in real settings across the studied cases and research stages. It also examines how judgements about what is decisive, decision-relevant, and practically assessable are formed and used when translating decision conditions into factors and candidate indicators. These questions cannot be addressed with a single method without either losing contextual meaning or producing false precision (Yin, 2017). The sequential mixed-methods design therefore follows from the thesis problem framing and case-based logic. It allows different kinds of evidence to be made with appropriate warrants, both interpretive (e.g., interviews) and structured comparative (e.g., BWM), while keeping each form of evidence within its valid scope (Creswell & Creswell, 2017).

Moreover, the methods used across the three papers form a deliberate, sequential chain of knowledge production, where the output of one paper informs the focus and design of the next, consistent with a *progressive focusing* logic (Miles et al., 2014). Triangulation is addressed in the case study design (Section 3.3) and is used here as a check for coherence under difference rather than a requirement of full convergence (Carter, 2014). Together, these heuristic design logics respect the integrity of each method, using it for what it can do well without stretching it beyond its strengths. Specifically, **Paper I** uses a systematic review to map how governance is represented in international DSTs and to locate recurring blind spots and boundary choices in sustainability assessment of SSWM. **Paper II** then shifts from representation to practice using semi-structured interviews to capture the retrospective trajectory of how SSWM is coordinated and justified across actors, cases, and time. The BWM then shifts the focus forward by structuring prospective judgements about decisiveness. Building on these empirically grounded factors, **Paper III** translates them into candidate indicators and examines them through practitioner and researcher judgements elicited via a structured expert survey under specified catchment conditions.

Furthermore, methodological integration in this thesis rests on sequenced translation across scales and context boundaries, rather than forcing commensurability between different data forms. This reflects that credible claims at different analytical scales rely on different forms of evidence and different standards of warrant (Maxwell, 2013; Yin, 2017). At each step, the analytical lens (Sections 3.2.1 & 3.5) and empirical material are selected to match the scale of the claim, and constraints are used as anchoring devices, such as case boundaries, structured elicitation formats, and shared context materials, to keep interpretations grounded when moving from one scale to the next.

Lastly, the method design is shaped by an engaged, co-productive research–practice setting (Lang et al., 2012; Norström et al., 2020). The research commenced from an analytical, literature-based foundation to map how governance is represented in DSTs (**Paper I**). To engage SSWM practical realities, participant selection in **Paper II** followed purposive reputational and positional logic, prioritizing key actors with deep case familiarity and direct involvement in stormwater planning, delivery, or coordination (French, 1969; Knoke, 1993). This helped ground the identified transition key factors (criteria) and the subsequent factors (indicators) in implementation-relevant perspectives. In **Paper III**, to balance practice-based and applied-science perspectives and support robust indicator interpretation, the respondent pool was expanded to include researchers with relevant expertise alongside practitioners, consistent with engaged scholarship and collaborative inquiry (Van de Ven, 2007).

4. RESULTS

The most serious problem is that we come to value what we measure rather than measure what we value.

– Jerry Z. Muller, 2018

The results unfold in four steps in this section. **Paper I** examines how existing DSTs used for urban stormwater sustainability assessment treat different sustainability dimensions. **Paper II** reconstructs which conditions practitioners themselves see as decisive for transitions towards SSWM, and how these are prioritized for future SSWM. **Paper III** explores how these conditions can be translated into indicators and how practitioners and researchers judge their decision relevance and resource feasibility as a simple sense-making step for indicator selection. The final step synthesizes the three papers in relation to the thesis aim of moving towards holistic, multifunctional and SSWM.

4.1 Missing the whole: challenges in current SSWM assessment

Paper I reviewed fifty peer-reviewed studies applying DSTs in sustainability assessment for urban SSWM. A clear pattern emerged. Assessments are rich in technical, environmental and economic analysis, but governance and social conditions are weakly operationalized. Multi-criteria analysis dominated the DST landscape, and almost all DSTs focused on ex-ante option comparison rather than deliberation, implementation follow-up, or learning over time. Only one paper documented the direct decision uptake beyond the assessment exercise itself.

Using the PAM (Section 3.2.1), governance dimensions were examined across four components: actors, resources, rules and discourses (Figure 6). Across the sample, hydrology-centered framings were most common, and actor engagement was typically unaddressed. Municipal agencies, utilities, and technical specialists were the most frequently envisioned decision actors, while residents, property owners, and other affected groups were rarely included in an explicit way. In several papers, "end users" referred to municipal decision-makers or experts rather than those living with or benefit from the NbS. Institutional resources, mandates, and responsibility interfaces were often treated as background context, not as assessable decision conditions.

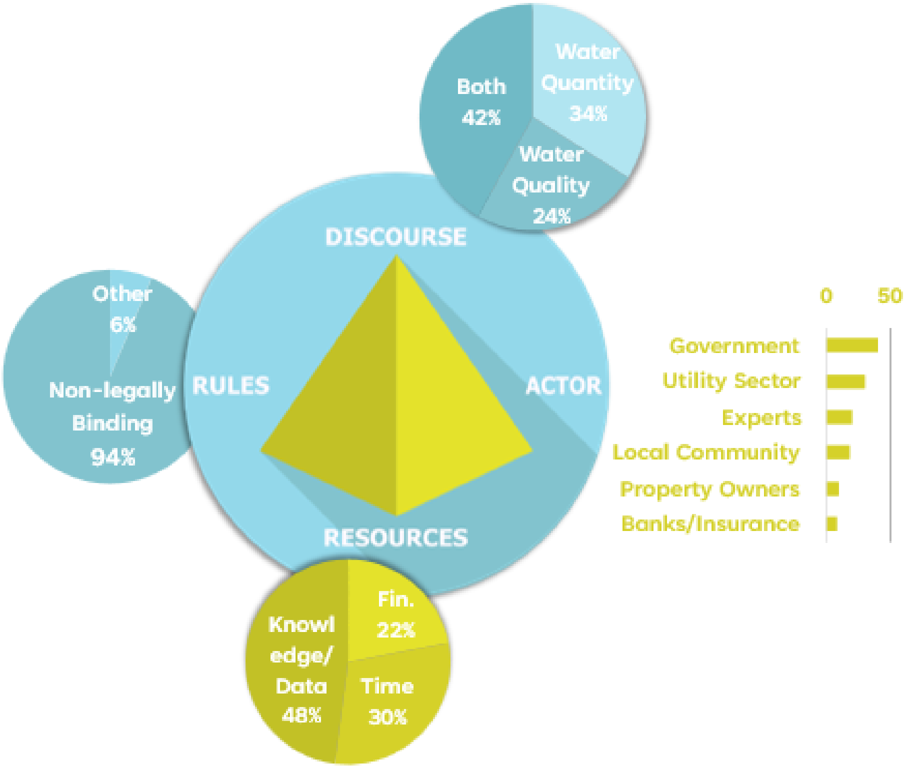

Figure 6. Summary of governance dimensions captured in reviewed DST applications, organized with the Policy Arrangement Model (PAM).

Multifunctionality was frequently invoked in discourse, but less consistently translated into criteria, indicators, or decision rules. Three recurring gaps were identified:

- Only seven recurring social criteria were identified (e.g., recreation, education, accessibility, aesthetics, well-being), but they were typically treated as headline labels. Their definitions, indicators/metrics, data sources, and selection rules in DSTs were seldom specified.

- Decision process and actor engagement were weakly specified: assessments were usually performed by a small expert or research team, stakeholders were hypothetically presented, with limited description of who they are, how trade-offs were negotiated between them, or whether results informed formal decisions.

- Governance arrangements were rarely operationalized. Coordination demands, responsibility splits, and long-term ownership and maintenance interfaces were seldom represented in DSTs, nor as part of the sustainability assessment logic.

Thus, the review identified a fundamental disconnect: DSTs measure what SSWM systems do (flows, pollutants, costs) far more rigorously than the institutional and social conditions through which holistic and multifunctional ambitions are delivered and sustained. This diagnostic gap motivated the subsequent empirical studies. **Papers II** and **III** therefore move from DST representation to real-world evidence, by eliciting which factors practitioners regard as decisive for SSWM and then testing how they can be judged as decision-relevant and feasible under specified decision contexts.

4.2 Understanding what matters: decisive factors in SSWM

To address the gaps identified in **Paper I**, **Paper II** examined which conditions are regarded as decisive for holistic and multifunctional SSWM in real-world settings. Drawing on practitioners from Malmö and Östersund, the study identified 40 dynamic decisive factors (Figure 8). The interview guide was informed by the MLP as a heuristic framing (Section 3.5.1), prompting interviewees to reflect on change since the 1960s across landscape pressures, regime-level routines, and niche-level experiments in stormwater practice.

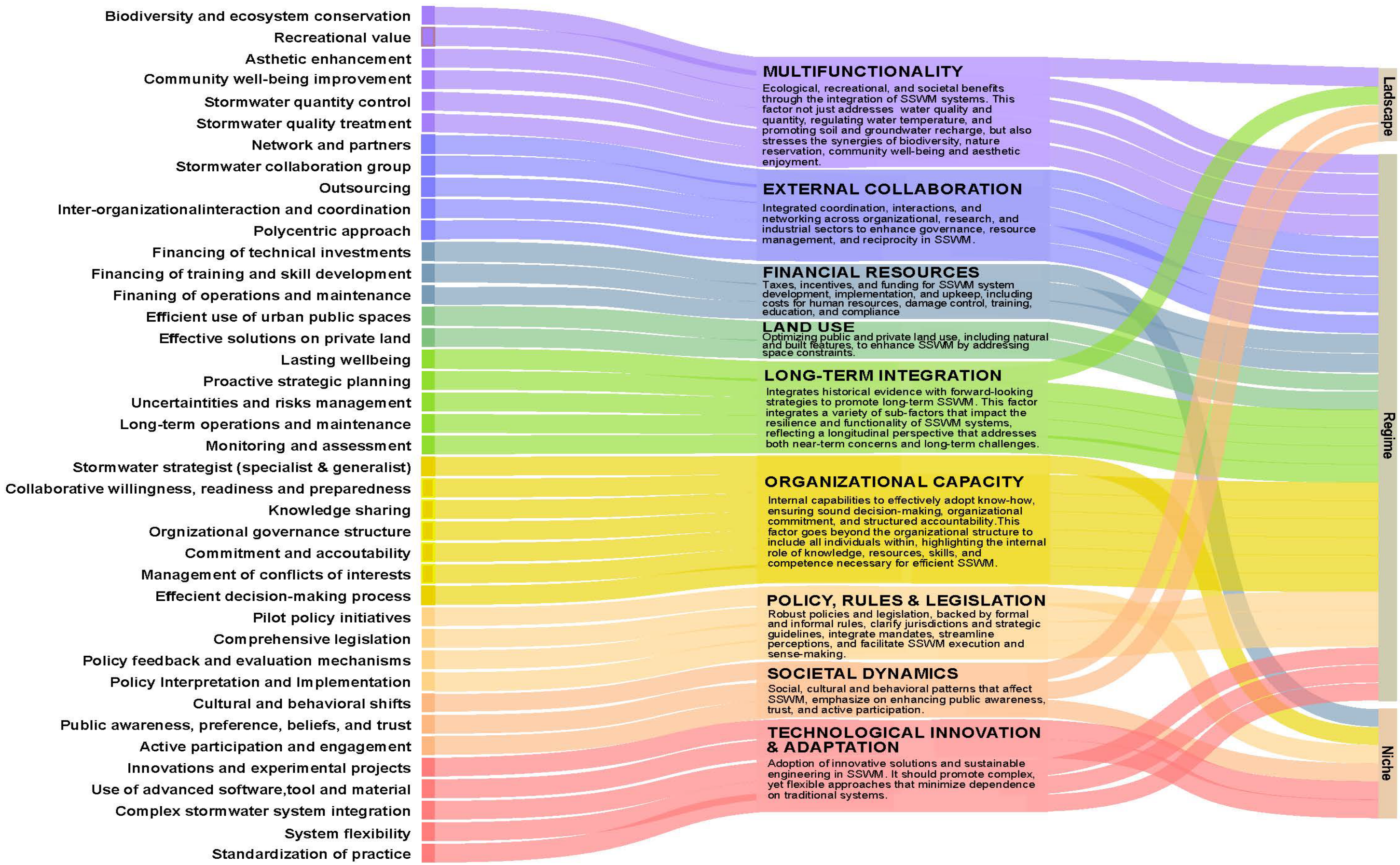

Figure 7. Forty factors (left) are consolidated into nine decisive bundles (center) and linked to the MLP heuristic levels (right) to illustrate how SSWM depends on interacting conditions from broad context to local innovation. Full forty factor descriptions are provided in Appendix 1.

At the landscape level, drivers such as climate adaptation, environmental awareness, and urban densification repeatedly acted as triggers for change. At the regime level, long-standing divisions of responsibility between utilities, planning, and environmental departments—combined with short funding cycles—continued to hinder coordination. At the niche level, experimental NbS provided opportunities for innovation but remained largely confined to pilot status due to weak institutional anchoring, unclear maintenance routines, and limited learning across projects.

These factors were then consolidated into nine decisive bundles that capture the recurring conditions shaping SSWM across the two city cases: *External Collaboration; Policy and Legislation, Land Use; Organizational Capacity; Financial Resources, Long-Term Integration; Multifunctionality; Societal Dynamics; and Technological Innovation and Adaptation*. Together, they encompass governance-related, spatial, temporal, and experiential aspects, reflecting the inherent complex and systemic in SSWM. Rather than acting as fixed "barriers" or "drivers", these factors interact dynamically as adaptive levers that can be strengthened or weakened over time.

A structured BWM workshop (Section 3.4.2) was then used to elicit prospective judgements about which bundles are most decisive for future transition. Across participants, *External Collaboration* emerged as the highest-weighted criteria bundle, followed by *Policy and Legislation* and *Land Use*, indicating that coordination capacity, rule clarity, and landownership and responsibility interfaces are perceived as decisive for future SSWM in both municipalities. *Organizational Capacity* and *Financial Resources* were also consistently emphasized, reflecting the practical dependence of implementation and maintenance on staffing, competence, budget cycles, and routines.

While Malmö and Östersund differ in urban form, institutional arrangements, and stormwater priorities, the overall pattern was similar. Participants in both cities described SSWM as hinging less on the availability of new technical measures than on institutional readiness and relational capacity. In this sense, **Paper II** provides a structured account of what practitioners perceive as decisive at the city scale, and it also specifies the very socio-institutional dimensions **Paper I** found missing in sustainability assessment of SSWM. This set of decisive factors served as the direct empirical foundation for **Paper III,** which zooms in to catchment contexts by translating the factor pool as indicator and using a structured sense-making and screening exercise to examine how they are judged as decision-relevant and practically feasible in concrete catchment conditions.

4.3 Making sense of indicators: governance-aware assessment for multifunctional NbS

Paper III examines how practitioners and researchers make sense of the 40 candidate indicators when these are anchored in two contrasting catchment contexts. The contribution is to distinguish what is judged decision-relevant from what is judged practically feasible to use in real governance-aware decision contexts. Each indicator was described in plain language (Appendix 1), and embedded in two catchment context dossiers: inner-city (Davidshallstorg, Malmö), and residential suburban (Ångbryggeriet, Östersund). The dossiers combined maps, photos, and short narratives of the stormwater situation with a shared NbS configuration, summarized hydrological modelling outputs, and mapped actor role and responsibility interfaces across planning, design, construction, ownership and use rights, operation and maintenance, and follow-up and monitoring (Table 4). This design allowed respondents to anchor their judgements in specified NbS design and governance settings rather than responding to abstract indicator statements.

Table 4. Actor responsibilities for selected NbS in Malmö and Östersund and their respective catchment areas.

NbS measure	Case	Planning	Design	Construction	Ownership & use rights	Operation & maintenance	Follow-up & monitoring
Rain gardens (private courtyards)	Inner-city	Housing cooperatives / private property owners; City Planning Office; Real Estate and Streets Department.	External design consultants; Real Estate and Streets Department.	Private contractors	Housing cooperatives / private property owners (use rights on private land managed by the owner)	Housing cooperatives / private property owners; private contractors (as needed)	Housing cooperatives / private property owners; Real Estate and Streets Department (advisory); Universities / Research partners
Rain gardens (school yards)	Residential suburban	Department of Children and Education; school (principal and school management); City Planning Office; Real Estate and Streets Department	External consultants; Real Estate and Streets Department; Department of Children and Education; school	Private contractors; Real Estate and Streets Department (procurement / oversight); water and sewer utility	Department of Children and Education (formal / administrative ownership); School (use rights)	School (day-to-day maintenance); private contractors (as needed)	School (teachers and pupils, environmental education); Real Estate and Streets Department (advisory); Universities / Research partners
Stormwater tree pits (street)	Inner-city	Real Estate and Streets Department; City Planning Office; Regional water and sewer utility (e.g., VA SYD)	Real Estate and Streets Department; external design consultants; Regional water and sewer utility	Private contractors (procured by the City of Malmö)	Real Estate and Streets Department, City of Malmö (municipal ownership; permits handled by the City of Malmö)	Regional water and sewer utility; Real Estate and Streets Department; private contractors	Regional water and sewer utility; Real Estate and Streets Department; Universities / Research partners
Stormwater tree pits (street)	Residential suburban	Real Estate and Streets Department; water and sewer utility; City Planning Office; external consultants	Real Estate and Streets Department; external consultants; water and sewer utility	Private contractors	Real Estate and Streets Department (municipal ownership; permits handled by Östersund municipality)	Parks and Nature Department; private contractors	Water and sewer utility; Real Estate and Streets Department; Universities / Research partners
Biofilters (public square)	Inner-city	Real Estate and Streets Department; City Planning Office; Regional water and	Real Estate and Streets Department; external design	Private contractors (procured by	Real Estate and Streets Department (municipal ownership); general	Parks and Nature Department; Regional water and sewer utility (as needed);	Real Estate and Streets Department; Regional water and sewer utility; Local

		sewer utility; Local businesses (restaurants, cafés, shops)	consultants; Regional water and sewer utility	the City of Malmö)	public; Local businesses (fronting premises / use rights for outdoor seating)	Private contractors; Local businesses	businesses (fault reporting); Universities / Research partners
Biofilters (private land)	Residential suburban	Real Estate and Streets Department; City Planning Office; water and sewer utility; Local property owners (use rights along corridors)	Real Estate and Streets Department; external consultants; water and sewer utility	Private contractors	Real Estate and Streets Department (municipal ownership); Local property owners (use rights along corridors)	Parks and Nature Department; water and sewer utility (as needed); Private contractors; Local property owners (use rights along corridors)	Real Estate and Streets Department; water and sewer utility; Local property owners (use rights along corridors); Universities / Research partners

Using a structured survey, respondents rated each indicator under two judgement dimensions: Relevance (decision relevance and contextual fit) and Resources (practical feasibility to apply, given data access, time, competence, routines, and coordination demands), with “Do not know / cannot judge” treated as meaningful information. Across the full indicator set, nineteen indicators showed cross-catchment convergence as high-Relevance, indicating broad agreement on what should matter for multifunctional NbS in SSWM. In contrast, Resources judgements were lower and more dispersed, and the share of “Do not know” responses increased markedly, particularly for socio-organizational and land-use related indicators. To make this sense-making logic visible, the indicators were further interpreted in a Relevance–Resources matrix (Figure 9), which separates indicators that appear both relevant and feasible from those that are judged relevant but currently constrained in implementation and follow-up. Overall, the matrix highlights broad convergence on Relevance, but a more uneven and uncertain on Resources, especially for indicators that depend on cross-actor coordination and long-term responsibility interfaces.

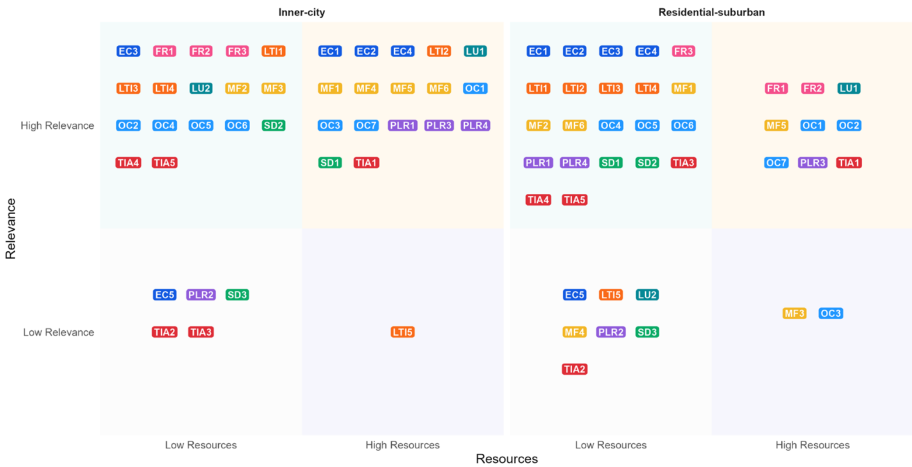

Figure 8. Relevance–Resources quadrants for indicators in two cases (categorical placement). Each square represents one indicator, labelled by its abbreviation. Vertical line = Relevance threshold and horizontal line = Resource. The thresholds separating low and high Relevance-Resources, dividing the space into four quadrants.

Therefore, **Paper III** shows a clear operationalization gap. Factors that are judged decisive at the city scale (**Paper II**) also display their divergence between perceived relevance and perceived feasibility when translated into indicator prompts and judged under specified catchment contexts. **Paper III** extends the thesis's diagnostic chain by making visible where perceived relevance aligns with, or diverges from, practical feasibility in SSWM decision-making contexts. It provides an explicit sense-making and screening step that clarifies which candidate indicators appear straightforward to use and where implementation and follow-up conditions remain least settled in decision contexts.

4.4 Synthesis of results

Across **Papers I–III**, the results trace a coherent line from published sustainability assessment in SSWM, to what practitioners describe as decisive for transition, and finally to what happens when these conditions are expressed as candidate indicators for NbS in concrete catchment contexts. The progressing sequence makes one pattern hard to ignore. In sustainability assessment of SSWM, what is most consistently operationalized tends to be what is easiest to model and quantify in DSTs. In practice, however, moving toward holistic, multifunctional SSWM repeatedly hinges on conditions that are harder to formalize as indicators.

Paper I shows that sustainability assessment studies using DSTs for urban SSWM are generally strong on technical, environmental, and economic performance dimensions, while governance and social conditions are less consistently operationalized and more often treated as contextual background. **Paper II** responds by reconstructing, from practitioners' own accounts, the "missing" conditions and critical principles that actually shaped past-and-present and continues to affect future SSWM. Practitioners articulate a broader set of dynamic decisive factors and prioritize them, showing that decisive conditions include responsibility interfaces, coordination and organizational capacity, land-use and ownership constraints, and long-term delivery and maintenance conditions alongside hydrology and cost.

Paper III applies a sense-making process to these factors, translating them into indicator prompts for multifunctional NbS in SSWM. The prompts are anchored in two governance-aware catchment dossiers and judged under two dimensions, Relevance and Resources. The results separate two kinds of judgement. Convergence is strong on what is seen as decision-relevant across the two catchments, whereas practical feasibility is more uneven. In other words, there is broad agreement on what should count for holistic, multifunctional SSWM, but a more fragmented picture of what can currently be supported through indicator use in everyday decision contexts. The synthesis thus reveals a persistent challenge: while the ambition for holistic and multifunctional SSWM is rising, the available evidence remains split between what is technically robust (e.g., hydrology) and what is practically decisive but difficult to capture (e.g., governance).

5. DISCUSSION

We do not act because we know, but we know because we are destined for action; practical reason is the root of all reason.

– Johann Gottlieb Fichte, 1800

5.1 Rethinking what holistic, multifunctional and sustainable stormwater management requires

In this thesis, "holistic, multifunctional and SSWM" is not a set of combined buzzwords but a shorthand for a particular kind of decision. It refers to decisions that integrate hydrological and ecological performance with social and governance conditions; that treat NbS as multifunctional systems embedded in concrete land-use, ownership and organizational settings (Hölting et al., 2019). Such decisions also have to remain defensible over time, in terms of maintenance, path dependence and legitimacy (Blecken et al., 2017; Randrup et al., 2020). Holism here is therefore less about adding more criteria and indicators in principle, and more about whether the criteria and indicators that actually shape decisions that capture the institutional realities, and determine whether multifunctional NbS can be implemented and sustained in existing urban areas.

Empirically, the thesis intervenes upstream of design and implementation, at the planning stage where alternatives are framed and assessment criteria are set. It does not re-run or compare hydraulic model performance, nor does it select NbS alternatives in different SSWM strategies. Rather, it draws on hydrological modelling developed in collaboration with LTU to ground the catchment dossiers, and examines the missing link in current decision-making: the governance and context-related conditions that determine whether multifunctional ambitions can be implemented and sustained. This is framed in terms of decision quality and decision confidence in early-stage SSWM decisions (Section 2.4.2).

Across the three studies, a consistent pattern emerges: hydrological and economic aspects are often formalized and decision-ready, while governance and socio conditions remain thin, implicit, or treated as background. **Paper I** makes this asymmetry visible in existing DSTs. **Paper II** shows that what practitioners perceived as decisive can be articulated as a structured bundle of interlinked factors rather than left as diffuse "context". **Paper III** then makes the indicator selection step more legible under concrete catchment and responsibility settings, by using a transparent sense-making/screening logic that surfaces feasibility constraints, trade-offs, and where judgments become uncertain rather than silently dropping "difficult" dimensions.

Seen together, this thesis suggest that moving towards holistic, multifunctional and SSWM is as much about rebalancing what counts as decision-relevant evidence as it is about refining technical designs (Wild et al., 2017). If governance-related capacities, land-use arrangements and long-term integration are central to whether multifunctional NbS can work in the long term, then omitting them from sustainability assessment architecture can undermine substantive decision quality, even when hydrological and economical modellings are sophisticated. Conversely, making these conditions visible as assessable content, and adopting explicit sense-making steps that clarify feasibility and uncertainty, is a necessary precondition for decisions that can credibly claim to be holistic (Andrews et al., 2010; Rijke et al., 2012).

This thesis therefore does not offer a new governance "model" or a complete design framework for SSWM. Its contribution lies in clarifying, and beginning to operationalize, a governance-aware assessment layer that can be added to existing DSTs and sustainability assessment frameworks. This can help cities take more defensible steps towards holistic, multifunctional and SSWM by aligning stated ambitions in NbS with the conditions required for long-term delivery.

5.2 Governance-aware decision support for multifunctional NbS in SSWM

Building on the governance framing in Section 2.3, this thesis treats governance as the conditions under which stormwater decisions are formed, supported, and justified, including what becomes actionable as assessable evidence in decision situations. Governance-aware decision support therefore depends on whether these conditions are made visible in SSWM, rather than remaining as narrative context around them.

Across current DSTs used in sustainability assessment for SSWM (**Paper I**), the assessment is still dominated by hydrology, pollutants, and cost, sometimes supplemented with environmental co-benefits. Social and governance dimensions are absent, inconsistently defined, or relegated to qualitative narrative, which means they are rarely weighed and traded off in the same way as peak-flow reduction or cost (Croeser et al., 2021; Rijke et al., 2012). The consequence is not only that governance is “missing”, but that institutional feasibility and long-term responsibility are difficult to handle within the same evaluative grammar that structures technical performance evidence.

This challenge is particularly consequential for multifunctional NbS in SSWM. Multifunctionality is not only a set of co-benefits, but a design and delivery ambition that must hold under real land-use constraints and over long-time horizons (Section 2.1). NbS in SSWM are hybrid interventions where engineered functions and vegetated components interact with site conditions, maintenance regimes, and institutional responsibilities (Eggermont et al., 2015). This implies that knowledge requirements and responsibilities are distributed across actors and phases, from planning and design to operation and long-term stewardship. In already built-up areas, where NbS must be negotiated into existing land-use patterns and fragmented ownership arrangements, these governance and implementation conditions can be decisive for whether multifunctional ambitions can be realized at all (Halla et al., 2022).

From practice, **Paper II** identifies a structured bundle of decisive factors (Section 4.2). These factors refer to concrete challenges such as negotiating limited space with private landowners, aligning stormwater ambitions with zoning and building regulations, coordinating across departments with different mandates, and maintaining competence over time (Newig & Fritsch, 2009; Ostrom, 2017; Pascual et al., 2023; Van Winden & Van den Buuse, 2017). In other words, what practitioners describe as central to decision quality aligns closely with the dimensions that remain marginal in the DSTs identified in **Paper I**.

Read in sequence, **Papers I** and **II** motivate a reframing of governance in SSWM assessment: from contextual background to assessment content in its own right. Governance-related dimensions that often appear in sustainability assessment studies as background assumptions, such as institutional context, stakeholder engagement, or maintenance capacity, are experienced in practice as concrete conditions that function much like criteria or indicators for whether multifunctional NbS can be implemented and sustained (Keech et al., 2023). The **Paper II** decisive factors can therefore be read as a holistic guiding bundle of criteria for multifunctional NbS in SSWM: a structured articulation of additional factors that decisions in existing urban catchments need to consider, alongside hydrological performance and cost. This does not imply that the bundle is universal, but it makes visible how decision quality for multifunctional NbS is tied to institutional and relational conditions, echoing wider transition and NbS governance literature that treats these dimensions as core rather than secondary (Adams et al., 2024; Knapik et al., 2025; Köhler et al., 2019).

For sustainability assessment research and practice in SSWM, this has two implications. First, DSTs that claim to support holistic or multifunctional SSWM need to move beyond treating governance as narrative backdrop (Farahdel et al., 2024; Rijke et al., 2012). If criteria related to collaboration, land-use authority, regulatory flexibility and organizational capacity remain off the formal scorecard, assessments will continue to privilege what is easiest to model rather than what practitioners regard as most decisive (Keech et al., 2023; Moreau et al., 2022). Second, there is no need to reconstruct existing DSTs used in SSWM. Instead, the governance criteria and indicators developed in this thesis can be used as a complementary lens to interrogate how such tools handle decision conditions that affect feasibility and long-term functioning, particularly in multi-criteria decision support. By examining whether and how each of the nine factors is represented, operationalized, and weighted within a given framework, proponents and decision makers can start to align assessment grammar and architectures with the governance realities that shape the feasibility and long-term performance of multifunctional NbS.

5.3 Sense-making the criteria and indicators

If **Papers I and II** argue that governance needs to be treated as assessment content, **Paper III** shows what happens when this move is attempted in real cases. As described in Section 4.3, **Paper III** translates governance-related conditions into a context dossier and indicator prompts, and examines how they are interpreted under concrete NbS catchment contexts. Across the two catchments, the results reveal a consistent pattern. Indicators linked to coordination, long-term integration, organizational practices, and land-use negotiation are frequently judged as highly relevant for SSWM decisions. Yet they are also associated with high resource requirements or high proportions of “do not know / cannot assess” responses. In other words, many of the factors that practitioners described as decisive for transitions toward SSWM in **Paper II** prove difficult to resource, measure, or even judge when expressed as assessable indicators in **Paper III**. This pattern appears across both cases, despite differences in land use and governance arrangements, suggesting that it reflects a more general operationalization challenge rather than a case-specific anomaly.

Importantly, this operationalization gap should not be interpreted as a failure of expert judgment or as evidence that such indicators are poorly formulated. Rather, it reflects the institutional and epistemic conditions under which judgments are made (Hanea et al., 2022). Some indicators depend on locally specific arrangements, such as who owns which land, how responsibilities are distributed across departments and organizations, or which coordination forums are active in practice (Meerow & Newell, 2019). Others refer to capacities that are widely recognized as important but only weakly institutionalized, such as stable arenas for negotiating multifunctional NbS across mandates, or routines for monitoring social and organizational outcomes over time (Dhakal & Chevalier, 2016; Kabisch et al., 2017; Wild et al., 2024). In these cases, high NA responses and low resource scores signal uneven access to information, data, authority, or experience, rather than lack of importance. This signals a structural scalar mismatch. While decisive factors like organizational culture or broad political support are identified at the strategic municipal level (**Paper II**), they become difficult for local actors to assess or influence within the scope of a specific catchment project (**Paper III**). The High NA scores therefore reveal the limit of local agency: decision-makers often lack the mandate to judge the very governance conditions that constrain their work (Finewood et al., 2019; Hölting et al., 2019).

The sense-making approach used in **Paper III** is designed to work with this situation rather than to smooth it away. By pairing judgments of Relevance and Resources, and by treating NA responses as informative rather than as noise, the screening logic turns the indicator set into a diagnostic device rather than a checklist. The resulting quadrant patterns do not prescribe which indicators should be selected or discarded. Instead, they surface the trade-off where indicators are both decision-relevant and feasible to work with under current conditions, and where they are decision-relevant but under-resourced. This creates a structured basis for discussing what can reasonably be included in a given sustainability assessment at a particular point in time, and what would require changes in data availability (Walker et al., 2025), mandates, or with deliberative governance (Hendriks, 2009), before it can be operationalized.

The emphasis therefore lies less in the specific indicators and their scores *per se* than in making the indicator selection step itself legible under decision context. Rather than assuming that all relevant dimensions can be treated symmetrically within assessment frameworks, the sense-making highlights where evidence is strong, where it is fragile, and where it is missing. Decision confidence, in this framing, does not come from forcing commensurability across all dimensions, but from understanding the conditions under which judgments are made and the limits of the available evidence (Gregory et al., 2012; Peters, 2022). For decisions about multifunctional NbS in existing urban areas, where trade-offs around land use, responsibilities, and long-term maintenance are unavoidable (Eckert, 2025; Van Der Jagt et al., 2023), this form of structured transparency can be as consequential for decision confidence as further refinement of technical performance assessments.

5.4 Strengthen decision quality and confidence for holistic, multifunctional SSWM

What emerges from the discussion so far is that the difficulty towards holistic, multifunctional and SSWM is not primarily a shortage of tools, criteria, or indicators (Renfrew et al., 2024; Waas et al., 2014). It is a decision problem about what becomes actionable as evidence in early-stage planning, and how actors can justify choices under uncertainty and distributed responsibility. Viewed through the definitions established in this thesis (Section 2.1–2.4), the thesis contribution is therefore less about proposing new ends and more about strengthening the means through which decisions are made defensible.

For holistic SSWM, the core implication is that decision quality cannot be reduced to technical completeness within a narrow assessment grammar. As holism depends on whether institutional and relational conditions that shape feasibility and long-term delivery are made explicit and discussable alongside hydrological performance and cost (Brown et al., 2013; Rijke et al., 2012). For multifunctionality, "benefits on paper" are insufficient unless the conditions for delivery are addressed upfront, including land-use constraints, responsibility interfaces, and long-term stewardship requirements. For sustainability, understood as a normative and evaluative lens rather than a checklist of pillars (Gibson et al., 2013; Gibson, 2016), the defensibility over time depends on accountability for what is known, what is uncertain, and what is institutionally under-specified. In this sense, strengthening decision confidence is not about forcing commensurability across all dimensions, but about making the limits of evidence visible and negotiable in decision situations with decision makers (Hölting et al., 2019; Stirling, 2010).

Operationally, this thesis contributes a governance-aware assessment layer that can be added to existing DSTs and sustainability assessment workflows rather than replacing them. The nine-factor bundle provides a structured way to interrogate whether decisive governance and feasibility conditions are explicitly addressed in an assessment architecture, or left as background assumptions. The Relevance–Resources–NA screening logic, provides a flexible sense-making step that supports transparent indicator selection under context: it distinguishes between what is judged decision-relevant, what is currently feasible to operationalize, and where judgments remain uncertain due to uneven mandates, information, or experience. Used in this way, the layer does not deliver decision closure. It supports more defensible decisions by *keeping complexity open* where it must remain open (Stirling, 2010), and by making explicit where confidence is warranted and where it rests on fragile or contested grounds.

Practically, this layer can be used to structure early-stage discussions around a specific NbS project in SSWM: to clarify which governance conditions need attention before detailed design, to surface capacity and responsibility gaps across departments and actors (end users), and to provide a transparent basis for dialogue about what long-term delivery would require in constrained urban conditions. The value is not a universal indicator set. It is a transferable way of making the selection and justification of criteria and indicators more legible under real institutional conditions.

5.5 Limitations and future directions

The limits of this thesis follow directly from the scope and research design. The empirical base is grounded in Swedish municipal contexts, representing a relatively high-capacity governance arrangement (Torfing et al., 2020). The governance-related indicator prompts were used diagnostically within this institutional setting to elicit expert judgement. Transferability to other governance paradigms, more resource-scarce contexts, or less stable institutional environments was not tested. Moreover, the participant scope was limited to professionals (municipal practitioners, utility managers), and researchers. The thesis captures an institutional view of SSWM, but does not yet incorporate end-users, residents, or private property owners who may ultimately carry long-term stewardship responsibilities for decentralized NbS on private land. Furthermore, the studies follow decision-support practices up to the point of assessment and sense-making, not through implementation, long-term operation and maintenance, or ex-post evaluation of delivered performance. Finally, the thesis does not claim that a governance-aware assessment layer will automatically improve hydrological performance or reduce flood risk under specific rainfall regimes. What it does show is that assessment practices can undermine decision quality when decisive conditions remain under-specified, and that making these conditions explicit can strengthen decision confidence in ways that matter for long-term delivery. Future work can extend this thesis along four practical directions that follow the "governance-aware layer" logic:

I. **Use the sense-making step in real SSWM assessment projects**. Applying the Relevance–Resources–NA screening and context dossiers in live NbS planning processes would show how it shapes SSWM framing, NbS alternative comparison, and the handling of feasibility constraints before plans or designs are locked.

II. **Test and refine the factor bundles with end users and private actors.** Since decentralized NbS often depends on private land and long-term stewardship , using different participatory approaches (Boogaard & Arellano Jaimerena, 2025), deliberative governance approaches (Hendriks, 2009), with residents and property owners can help identify where feasibility and responsibility are understood differently from the institutional view, and which bundles and prompts need adjustment to remain meaningful beyond the research-practice settings.

III. **Move from diagnostic prompts to decision-support integration.** Future work could test context-sensitive ways of structuring qualitative judgement (Walker et al., 2024), so that governance indicators can be measured without forcing them into fully quantifiable parameters. This would support transparent documentation of governance evidence and its careful integration into assessment grammar alongside modelling outputs (e.g., in multi-criteria decision support), while treating qualitative and quantitative inputs as complementary layers and keeping uncertainty explicit rather than hidden.

IV. **Explore case transferability and learning through ex-post assessment**. Future work could apply the approach in cases with different governance paradigms and institutional capacity settings, and examine how the governance-aware sense-making logic performs in ex-ante assessment. Complementarily, use it in ex-post assessment by tracking delivery and operation over time, surfacing how roles, coordination, maintenance, and monitoring actually unfolded. This would support iterative improvement of the approach, by showing how flexible rules and indicator prompts perform across settings and over time.

6. CONCLUSION

...to make the familiar unfamiliar .

— Zygmunt Bauman, 2020

The thesis examines SSWM in existing urban areas through three interrelated layers. At the level of assessment architectures, DSTs that present themselves as sustainability assessment for multifunctional NbS still rest on a narrow evidence base. At the level of what practitioners experience as decisive, institutional, spatial, temporal and organizational conditions have to align for NbS to work in already-built settings. At the level of criteria and indicators, many of these conditions are compelling in principle yet difficult to translate into feasible, assessable prompts under concrete catchment and responsibility settings.

The aim of this thesis is to support the movement towards holistic, multifunctional SSWM by strengthening the conditions for decision support. It targets the upstream assessment space where goals are translated into criteria, indicators, and evidence requirements, and where responsibilities, coordination, land-use interfaces, and long-term maintenance capacity conditions are feasible to implement and sustain. The central argument is that if governance and context-sensitive conditions are left implicit, assessment may over-privilege quantifiable metrics and under-represent the conditions that determine whether multifunctional NbS can be delivered and maintained.

Within this boundary, the thesis treats decision quality and decision confidence as the two critical attributes shaped by this evidence landscape. The thesis demonstrates how both are currently constrained by a persistent asymmetry: technical dimensions are rendered decision-ready, while governance and social conditions remain thin, implicit, or contested. The governance-awareness and the sense-making logic developed in this work provide a lightweight way to make that imbalance visible and discussable, transforming these "silent" context factors into actionable evidence for more defensible decisions.

Finally, the research process itself represents the value of transdisciplinary inquiry at the research-practice interface, bringing together practitioners and researchers from stormwater management, landscape planning, and governance perspectives. Working across tools, catchments and actor interfaces reinforced a simple lesson: many obstacles to “better” SSWM are not a lack of holistic goals or multifunctional NbS, but a lack of ways to see, talk about and justify the institutional work those options require. If this thesis helps researchers and practitioners ask different questions of their decision routines and assessment tools, give feasibility conditions a clearer place in early-stage evaluation, and be more precise about where confidence is warranted and where it is not, then it has taken a small but meaningful step toward making holistic and multifunctional SSWM more achievable.

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Popular science summary

Cities are increasingly turning to nature-based solutions (NbS), such as rain gardens, biofilters and tree pits, as part of sustainable stormwater management. These measures are associated not only with flood mitigation and water quality improvement, but also with greener streets, more attractive public spaces and greater climate resilience. Considerable progress has been made in understanding how such systems function from a technical and hydraulic perspective. Yet experience from practice suggests that performance alone rarely determines success.

Many of the most influential decisions in sustainable stormwater management are made well before implementation begins. At this early stage, broad ambitions for multifunctional NbS are translated into criteria, indicators and forms of evidence that shape planning, design and construction. In practice, this translation is uneven. Technical and economic aspects tend to be clearly specified and readily incorporated into assessment frameworks. Governance and social aspects, by contrast, often remain implicit, treated as background context rather than as part of what is actively assessed.

Looking across different urban settings brings this pattern into sharper focus. Whether in dense inner-city environments or more residential suburban settings, practitioners working with NbS in stormwater management often express similar views on what enables sustainable outcomes. Coordination across organizational boundaries, alignment with policy and land-use, and sufficient institutional capacity are repeatedly described as influential. These conditions shape how NbS are realized, operated and maintained over time, rather than how they perform in isolation.

Difficulties emerge when such conditions are translated into indicators intended for use in real decision contexts. While there is broad agreement on their relevance for sustainable stormwater management, assessments of feasibility are more varied. Questions related to data availability, budget, effort and responsibility are frequently accompanied by uncertainty. This does not reflect a lack of importance. These conditions sit within organizational practices, institutional arrangements and long-term horizons. They do not translate easily into standard indicators and metrics.

This helps explain why assessment research and practice in sustainable stormwater management often gravitates toward what is easier to formalize. When governance, institutional and other context-dependent conditions remain weakly specified, decisions about NbS may appear robust on technical grounds while overlooking factors that influence real-world and long-term delivery. The result is less a failure of assessment frameworks or modelling than a narrowing of what counts as decision-relevant and feasible.

Approaches that give greater visibility to governance-related and other context-dependent conditions offer a different starting point for sustainable stormwater management. By articulating these conditions more explicitly, and acknowledging feasibility constraints and uncertainty, assessment can support earlier and more transparent reflection on NbS alternatives. This matters most when sustainable stormwater management priorities are set and trajectories take shape, long before outcomes become visible on the ground.

Populärvetenskaplig sammanfattning

Städer vänder sig i allt högre grad till naturbaserade lösningar (NbS), såsom regnbäddar, biofilter och trädgropar, som en del av hållbar dagvattenhantering. Dessa åtgärder förknippas inte bara med minskad översvämningsrisk och förbättrad vattenkvalitet, utan också med grönare stadsmiljöer, mer attraktiva offentliga platser och ökad klimatanpassning. Under senare år har betydande framsteg gjorts i förståelsen av hur sådana system fungerar ur ett tekniskt och hydrauliskt perspektiv. Erfarenheter från praktiken visar dock att teknisk prestanda i sig sällan är avgörande för långsiktig framgång.

Många av de mest avgörande besluten inom hållbar dagvattenhantering fattas långt innan genomförandet påbörjas. I detta tidiga skede översätts övergripande ambitioner om multifunktionella naturbaserade lösningar till kriterier, indikatorer och former av evidens som styr planering, utformning och byggande. I praktiken sker denna översättning ojämnt. Tekniska och ekonomiska aspekter är ofta tydligt specificerade och lätta att integrera i bedömningsramverk. Styrningsrelaterade och sociala aspekter förblir däremot ofta underförstådda och behandlas som bakgrund snarare än som något som aktivt bedöms.

Jämförelser mellan olika urbana miljöer gör detta mönster tydligare. Oavsett om det gäller täta innerstadsmiljöer eller mer bostadsdominerade områden uttrycker praktiker som arbetar med naturbaserade lösningar inom dagvattenhantering ofta liknande uppfattningar om vad som möjliggör hållbara resultat. Samordning över organisatoriska gränser, samstämmighet med policy och markanvändning samt tillräcklig institutionell kapacitet beskrivs återkommande som avgörande. Dessa förutsättningar påverkar hur naturbaserade lösningar realiseras, drivs och förvaltas över tid, snarare än hur de presterar isolerat.

Svårigheter uppstår när sådana förutsättningar ska översättas till indikatorer avsedda att användas i faktiska beslutsprocesser. Även om det råder bred enighet om deras relevans för hållbar dagvattenhantering varierar bedömningarna av genomförbarhet. Frågor om datatillgång, budget, arbetsinsats och ansvar präglas ofta av osäkerhet. Detta speglar inte bristande betydelse. Dessa förutsättningar är inbäddade i organisatoriska arbetssätt, institutionella arrangemang och långa tidshorisonter. De låter sig därför inte enkelt fångas i standardiserade indikatorer och mått.

Detta bidrar till att förklara varför bedömningsforskning och praktik inom hållbar dagvattenhantering ofta tenderar att fokusera på det som är lättare att formalisera. När styrningsrelaterade, institutionella och andra kontextberoende förutsättningar är svagt specificerade kan beslut om naturbaserade lösningar framstå som tekniskt välgrundade, samtidigt som faktorer som påverkar faktisk och långsiktig funktion förbises. Resultatet är mindre ett misslyckande i bedömningsramverk eller modellering, och mer en begränsning av vad som betraktas som beslutsrelevant och genomförbart.
Angreppssätt som ger större synlighet åt styrningsrelaterade och andra kontextberoende förutsättningar erbjuder en annan utgångspunkt för hållbar dagvattenhantering. Genom att tydligare formulera dessa förutsättningar och samtidigt erkänna begränsningar i genomförbarhet och osäkerhet kan bedömningar stödja tidigare och mer transparent reflektion kring olika alternativ för naturbaserade lösningar. Detta är särskilt viktigt när prioriteringar inom hållbar dagvattenhantering fastställs och utvecklingsbanor formas, långt innan resultaten blir synliga i den byggda miljön.

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Appendix 1. Full indicator set used in the Paper III survey

Appendix 1. Codes, criteria bundles, indicator prompts, and descriptions.

CRITERIA	INDICATOR & CODES	INDICATOR DESCRIPTION
External Collaboration	**Interdepartmental Coordination (EC1)** ***breaking silos in municipal routines***	Coordination between municipal departments and municipally owned companies (e.g., VA-bolag) on stormwater issues. This captures internal, horizontal collaboration within the same municipal organization, ensuring that planning, street/parks management, and environmental regulation work together rather than in silos.**(actual coordination process &practices)**.
External Collaboration	**Partnerships & Networks (EC2)**	Active collaboration with external partners (e.g., universities, NGOs, businesses, housing companies) that **bring knowledge, expertise, data, sites or funding** for stormwater projects in the catchments.
External Collaboration	**Shared Governance (Polycentric) (EC3)** ***Bridging legally distinct mandates.***	Coordination across multiple, semi-autonomous authorities and governance levels in stormwater management. This captures external, cross-organizational and vertical collaboration, where municipalities, regional utilities (e.g., VA Syd), county/regional agencies, and consulting firms each hold their own mandates but shall collectively shape stormwater outcomes.
External Collaboration	**Stormwater Team/Group (EC4)**	A standing cross-disciplinary working group or team that meets, communicates, tracks progress, and unblocks issues for stormwater actions in the catchments.
External Collaboration	**Outsourced Expertise (EC5)**	The extent to which municipalities/VA-bolag rely on external consultants or contractors to fill knowledge or capacity gaps (e.g., advanced modelling, design, monitoring). Outsourcing can provide needed expertise and flexibility, but high structural dependence may also create risks if in-house competence to evaluate or follow up is lacking.
Organizational Capacity	**Knowledge Sharing (OC1)**	Regular internal sharing of lessons, tools, processes and training across units and colleagues (e.g., joint workshops, site walks, mentoring) to spread good practice, experiences etc.)
Organizational Capacity	**Collaboration Culture & Readiness (OC2)**	Organizational(internal) attitudes, mindset and routines that welcome joint work, info sharing and co-ownership of outcomes (e.g., early involvement across units, open data).
Organizational Capacity	**Expertise Balance (Specialist & Generalist) (OC3)**	NBS scenarios require both specialists (e.g., hydrology, ecology, engineering, social science) and generalists (e.g., project management, facilitation). Specialists secure the quality, while generalists connect disciplines and actors. Both are needed to make solutions work.

Organizational Capacity	**Clear Governance Structure (OC4)**	Clear roles, decision rights, and escalation paths for stormwater (who decides what, when), reducing (role & responsibility) duplication.
Organizational Capacity	**Commitment & Accountability (OC5)**	Named owners(responsibilities) for deliverables, KPIs and timelines for catchment actions; **follow-up and follow-through** on agreed tasks. Clear accountability is essential to prevent gaps in maintenance and technical performance when stormwater/NbS responsibilities are fragmented across multiple actors.
Organizational Capacity	**Conflict Management (OC5)**	Ways to surface and manage competing project conflicts(interests (**e.g., long- vs. Short-terms; NbS vs. Pipes etc.**) to reach workable solutions.
Organizational Capacity	**Efficient Decision-Making (OC6)**	Timely decisions with transparent criteria (**e.g., design standards, cost caps, performance targets**) to keep projects moving.
Policies, Legislations & Rules	**Clear & Enabling Regulations (PLR 1)**	Local/regional rules and guidelines that enable NBS (**e.g., clear standards for infiltration near buildings, regulations on the service level**).
Policies, Legislations & Rules	**Pilot Policies & Trials (PLR 2)**	Use of **temporary policies**/agendas/zoning/permits to test new stormwater solutions (e.g., floating curtain, permeable pavements) at site scale.
Policies, Legislations & Rules	**Policy Feedback & Evaluation (PLR 3)**	Routine review of what worked/failed (**e.g., mid, ongoing, and post-project reviews/policy briefs**) to update specifications, guidance and policy.
Policies, Legislations & Rules	**Policy Implementation in Practice (PLR 4)**	How consistently the project, field work and contracts follow the intent of policies/design guides (**from drawings to delivery , and to operation and maintenance**).
Financial Resources	**Financing of training and skill development (FR1)**	Allocating dedicated funds to build human-resource capacity through education and training for effective stormwater management.
Financial Resources	**Financing of technical investments (including capital costs) (FR2)**	Providing funding (investment) for new infrastructure, modelling tools, and innovative technologies, while accounting for capital costs to improve stormwater management strategies and systems. Sources of funding typically include municipal budgets, property owners, and businesses. Indirect financial actors such as insurance companies may not fund projects directly, but their risk assessments, premiums, and support for pilot studies (with IVL, or Svenst Vatten) can influence the uptake of resilient NbS solutions.
Financial Resources	**Financing of operations and maintenance (FR3)**	Securing reliable, long-term funds for operation, maintenance, and upgrades to sustain NBS performance.
Long-Term Integration	**Monitoring & Assessment (LTI1)**	Continuous (**post-project**) documentation, evaluation, and data collection on stormwater management performance, enabling evidence-based improvements.
Long-Term Integration	**Proactive Strategic Planning (LTI2)**	**Plans that identify** future challenges, opportunities, and uncertainties, ensuring stormwater management/systems (NBS) resilience and preparedness.

Long-Term Integration	**Management of Uncertainties & Risks (LTI3)**	Preparedness to manage future variability - **Climate change (extreme rainfall, droughts); Urbanization & land-use change (competing land pressures, Economic shocks (budget cuts, recessions affecting maintenance, Emerging Contaminants (PFAS, Microplastics) Public health crises (pandemics limiting workforce capacity),** enabling adaptive and flexible scenario planning and risk mitigation. This also involves alignment with external risk management actors (e.g., insurance companies), whose policies and incentives can influence the uptake of adaptive and innovative solutions.
Long-Term Integration	**Long-Term O&M (routine upkeep) (LTI4)**	Sustained procedures and responsibilities guiding stormwater systems lifecycle management.
Long-Term Integration	**Lasting Well-Being (LTI5)**	The extent to which stormwater management supports long-term societal and ecological well-being — strengthening sustainability and resilience, safeguarding quality of life, and ensuring fairness across both current and future generations (**intra- and intergenerational**).
Multifunctionality	**Recreation & Use (MF1)**	Stormwater and NBS spaces support both **passive recreation** (e.g., yoga, mental restoration, relaxation) or **active recreation** (e.g., playgrounds, sports areas, gathering spaces), and **compatible public uses** (e.g., outdoor dining, markets), while continuing to perform their hydrological or treatment functions.
Multifunctionality	**Aesthetic Quality (MF2)**	Stormwater and NBS measures contribute positively to visual quality and placemaking, using materials, planting, lighting, and design elements that **respect and enhance the cultural and architectural character of the site** (e.g., 1920s heritage buildings in Davidshallstorg), or reflect the natural and landscape-oriented identity of Östersund (e.g., views to Storsjön lake, mountain backdrop, and use of local/northern vegetation).
Multifunctionality	**Community Well-Being (MF3)**	The contribution of stormwater and NBS solutions to residents' daily life and community values — including perceived safety, comfort, shade/cooling(**reduced energy demand** from home cooling/shading functions), and micro-climate benefits — while also considering potential social consequences or drawbacks (e.g., noise from active recreation affecting nearby residents, or conflicts with passive recreation), and misuse or vandalism of NBS.
Multifunctionality	**Biodiversity & Habitat (MF4)**	Enhance **desired urban biodiversity** and **ecosystem services** (e.g., carbon sequestration, reducing urban heat island, supporting street trees) by using native/diverse vegetation and habitat features (e.g., pollinator strips, bird boxes, insect hotels), while improving ecological connectivity and **limiting nuisance** (mosquitoes, rats) or invasive species.

Multifunctionality	**Stormwater Quantity Control (MF5)**	Encompasses retention, infiltration, and water reuse for non-potable purposes (e.g., irrigation, street cleaning), alongside other hydrologic processes that **harvest, reduce, or delay** runoff volumes and peak flows, thereby mitigating flooding, erosion, and pressure on downstream systems.
Multifunctionality	**Stormwater Quality Treatment (MF6)**	Treatment performance (e.g., sediment/oil removal) matched local sources and receiving water goals.
Land Use	**Efficient Use of Public Space (LU1)**	Ensuring that stormwater and NBS measures are integrated into limited urban areas in a spatially efficient way, considering both **surface uses** (accessibility; mobility: equity and inclusivity for different user groups-children, elderly, people with reduced mobility etc.; emergency/service access) and **underground space** (compatibility with utilities such as electricity, heating/cooling, and telecom). Also, potential archaeological heritage may require preservation or special treatment.
Land Use	**Measures on Private Land (LU2)**	Feasible stormwater measures on private land (e.g., rain gardens, green roofs) supported by incentives for implementation
Societal Dynamics	**Public Awareness & Trust (SD1)**	Public and Residents' awareness of stormwater solutions/NBS, and their trust in municipal/regional plans, delivery, and maintenance.
Societal Dynamics	**Cultural & Behavioral Change (SD2)**	Willingness (e.g., society, local community) to adopt new practices (e.g., accepting less parking, rainwater reuse etc.).
Societal Dynamics	**Public Participation & Engagement (SD3)**	Quality of engagement (**co-plan/design/creation**) and **deliberative participation** with diverse groups (e.g., businesses owners and schools).
Technological Innovation & Adaptation	**Innovation & Pilots (TIA1)**	Testing and trialing new stormwater/NbS **solutions, designs, or governance & management approaches** in pilot projects or small-scale experiments, with the aim of learning and adapting before wider implementation.
Technological Innovation & Adaptation	**Advanced Tools & Materials (TIA2)**	Adoption of advanced or cutting-edge technologies and materials (**e.g., AI, sensors, new digital modelling tools, durable or eco-friendly construction materials**) that enhance the performance and efficiency of stormwater/NbS systems.
Technological Innovation & Adaptation	**Standardized Practices (TIA3)**	Consistent standards/details/specs that reduce rework and speed delivery across projects.
Technological Innovation & Adaptation	**Complex Stormwater System Integration (TIA4)**	**1. On-site integration** – strategically combining grey infrastructure with green-blue solutions (or NbS) into one cohesive, multifunctional system (e.g., bioswales linked with underground storage and controlled overflow). **2. Catchment-scale integration** – connecting multiple NbS projects and technical systems across the wider catchment so they work together as part of one coordinated stormwater network in the city scale.

Technological Innovation & Adaptation	**System Flexibility (TIA5)**	The inherent ability of stormwater systems (grey or NBS) to adjust to evolving environmental conditions, operational demands, and urban development pressures, with flexibility for design adaptation, retrofitting, and scaling to meet future needs.

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Review

Decision support tools of sustainability assessment for urban stormwater management – A review of their roles in governance and management

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ABSTRACT

Urban areas face growing sustainable challenges arising from stormwater issues, necessitating the evolution of stormwater management concept and practice. This transformation not only entails the adoption of a multi-functional, holistic, and sustainable approach but also involves the integration of water quality and quantity considerations with governance and management aspects. A means to do so is via decision support tools. However, whilst existing studies using the tools by employing sustainability assessment principles or as indicators to plan blue-green infrastructures and strategies, uncertainties remain regarding how decision support tools encompass governance and management dimensions. The aim of this review study is to provide much-needed clarity on this aspect, in doing so, a systematic review of decision support tools used in sustainability assessment within the stormwater management context is conducted, focusing on their abilities to include governance and management. Findings encompass governance aspects, such as actors, discourses, rules, and resources considered, and explore how these relate to long-term management. The results reveal the recognized potential of decision support tools in facilitating governance and management for sustainable stormwater management, however, future research and efforts need to be allocated in: (i) Exploring practical challenges in integrating all sustainability assessment pillars with consistent criteria into decision support tools, to determine the optimal use of all criteria in fostering open and informed stormwater governance and management. (ii) Understanding how to engage diverse stormwater actors with future decision support tools, to secure ownership and relevance. (iii) Using retrospective (ex-post) sustainability assessments to provide more tangible knowledge and to support long-term management.

1. Introduction

1.1. Sustainable stormwater management

The concept of sustainable development is at the core of urban stormwater management (SWM) by designating that this task is not exclusively underscoring the traditional engineering approach of runoff retention, conveyance, flood control, and quality treatment. Rather, SWM is increasingly considered a holistic and integrated approach to complex urban challenges. As such, SWM addresses environmental concerns of ecological, socio-technological, and social-economical magnitudes where technical means to abate flooding, stormwater discharges, and pollution control are integrated into a wider and comprehensive sustainable context and adopted as sustainable SWM (Flynn and Traver, 2013; Mell and Clement, 2020; Porse, 2013). Such demands are creating an ever-challenging task, as the already complicated existing hyetographic, topographic, hydrological, and engineering information for stormwater control, needs to be added with quantitative and qualitative data from technological, social, environmental, and economic perspectives to be fully acknowledged as sustainable SWM (Depietri and McPhearson, 2017; Makropoulos et al., 2008).

To comprehend such complexities, several concepts have been developed over the past decades, *e.g.*, Water Sensitive Urban Design (Wong, 2006), Low Impact Development (USEPA, 2000), and Sustainable Urban Drainage Systems (Fletcher et al., 2015). These concepts have been ascribed not only to mitigate pluvial flooding and water quality treatment but also to support heat mitigation, biodiversity, health, recreation, *etc.* (Cettner et al., 2014). As such, these concepts are to varying degrees including nature processes in the development of specific measures to tackle stormwater, such as Nature-based Solutions

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(NbS), which is still perceived as having a broad view of nature, and an emphasis on participatory processes in the creation and management (Sowińska-Świerkosz and García, 2022).

1.2. Challenges in stormwater governance and management

Sustainable SWM needs collective actions and cannot be achieved within existing governance structures. At least within industrialized countries, governance generically refers to the process of decision-making by which society defines and handles its pressing concerns (Iribarnegaray and Seghezzo, 2012; Jansson et al., 2018; van Zeijl-Rozema et al., 2008). The notion of governance in sustainable SWM is gaining more and more attention in the EU, from the embedded concept in the supranational regulation such as the European Water Framework Directive (Todo and Sato, 2002), and to the governance modes per se in national sustainable SWM practices such as the urban decentralized management in Sweden and Germany (Bohman et al., 2020; Geyler et al., 2019)

Governance arrangements or policy arrangements have been defined to comprise both resources and actors whose roles and relations define the outcome of a planning or management decision (Arnouts and Arts, 2012). A wider understanding of a policy arrangement as a conceptual framework was developed in environmental policy studies to assist the understanding of the content and organization of a given policy domain, namely, the policy arrangement model (Arts et al., 2006). The model can be used to describe the state in which the interaction between actors, discourses, resources and rules of the game solidifies in a temporary stable structure before socio-environmental changes force them to readjust their interdependency (Qiao et al., 2019). Management of stormwater comprises multi-actor processes between the local government and the public, by which decisions are developed and communicated. Such initiatives may come from the government itself but are also sometimes driven by an increasing demand from the public to participate (Münster et al., 2017). Thus, while the traditional and conventional piped drainage systems mainly was organized and managed within one department (*e.g.,* the water department), sustainable SWM need to be aligned with more complex governance structures, including decentralized management by cooperation across a variety of departments, *e.g.*, water, planning, parks, and environmental departments, as well as involving a multitude of actors from outside the government organization (Qiao et al., 2019). This governance approach further epitomizes how sustainable SWM is neither a single discipline nor a sole proposition that can provide comprehensive and sustainable solutions.

1.3. Decision support tools for sustainability assessment of stormwater management

To address complex decision-making processes, various Decision Support Tools (DSTs) have been developed for the sustainability assessment of urban SWM. Such tools can aid decision-makers to evaluate the potential impacts of different stormwater control measures or management strategies on the environment, technology, economy, and society, to elicit trade-offs and opportunities for improvement (George, 1999; Gibson et al., 2005). Additionally, it can provide a framework for integrating sustainability considerations into the decision-making process and for measuring progress over time (Sheate, 2011). Unlike other assessment approaches, such as risk assessment, that analyze the potential disaster or events (Duan et al., 2022), sustainability assessment is derived from the domain of impact assessment, capturing a decision-making process of identifying, measuring, and evaluating the potential impacts of alternatives against the sustainability domains of economy, environment, technology, and social aspects (Devuyst, 2000; Gibson, 2006; Hacking and Guthrie, 2008; Millennium ecosystem assessment, 2005).

Sustainability assessment is also considered one of the most intricate assessment approaches, as it not only entails any discipline underpinned by the concept of sustainability but can also be applied in all levels of decision-making from projects to strategic policies, plans, and programs. Moreover, it can be formal or informal, legally prescribed, voluntarily applied, policy-driven, or science-driven (Pope and Grace, 2006; Sala et al., 2015). The richness, fuzziness, and complexity of sustainability are becoming an open concept that allows different interpretations dependent on the user's perception, background, knowledge, and experience (Pope et al., 2017). For example, Bixler et al. (2020) developed a dynamic assessment framework for green infrastructure, while Castro (2022) introduced a system thinking framework for environmental policymaking. Denjean et al. (2017) proposed an NbS framework emphasizing insurance value, and Ghafourian et al. (2021) established an economic assessment framework for NbS in circular water.

While existing sustainability assessment studies conform fundamentally by utilizing sustainability principles (pillars hereinafter) as indicators to explore optimal stormwater control measures and sustainable SWM strategies with DSTs, extensive reviews and comparative studies (Jayasooriya and Ng, 2014; Kumar et al., 2021; Qureshi and Rachid, 2021) have scrutinized input parameters, resultant data, strengths, applicability, performance, and limitations of DSTs. However, despite this extensive exploration, the extent to which DSTs in sustainability assessment incorporate dimensions to support governance and management in the decision-making process for sustainable SWM remains unclear.

With this review, we aim to understand how DSTs can support decision-making for holistic and integrated governance and management of sustainable SWM. To drive the review process, we have formulated the following three objectives:

Objective 1: How are decision support tools used in sustainability assessment of stormwater management?
Objective 2: What stormwater management themes are decision support tools applied for?
Objective 3: How do existing decision support tools assist sustainable stormwater governance and management perspectives based on the policy arrangement model?

2. Methods

We conducted a systematic review (Grant and Booth, 2009), and followed the PRISMA approach (Fig. 1.) to extract our findings (Page et al., 2021). Using the search engines Web of Science (Core), Scopus, and EBSCOhost we followed an iterative process of search strings under the category of "title-abstract-keywords". We grouped our search into three main strands, relating to (i) decision-making tools in sustainability assessment, based on the description of sustainability assessment tools in (St Flour and Bokhoree, 2021), (ii) decision-making, and (iii) stormwater management, based on various concepts which have been developed and used worldwide for sustainable SWM practices. Delimitations were made to the assessment scale of sector-based and project-based tools only. The following search strings were applied in conjunction with each other:

- **Sustainability assessment decision-making tools:** "multi-criteria decision analysis" OR "multi-criteria decision making" OR "multi-criteria analysis" OR "Dow Jones Sustainability Index" OR "Environmental Impact Assessment" OR "Strategic Environment Assessment" OR "Composite Sustainable Development Index" OR "Full Cost Accounting" OR "Integrated Value Model for Sustainable Assessment" OR "Cost-Benefit Analysis" OR "System Dynamics" OR "Sustainability Assessment Model" OR "Sustainability Assessment by Fuzzy Evaluation" OR "Fuzzy Logic Approach for Sustainability Assessment based on the integrative Sustainability Triangle" OR "Adaptive Neuro-Fuzzy Inference System";
- **Decision-making:** "decision making" OR "decision support" OR "policy" OR "policy making".

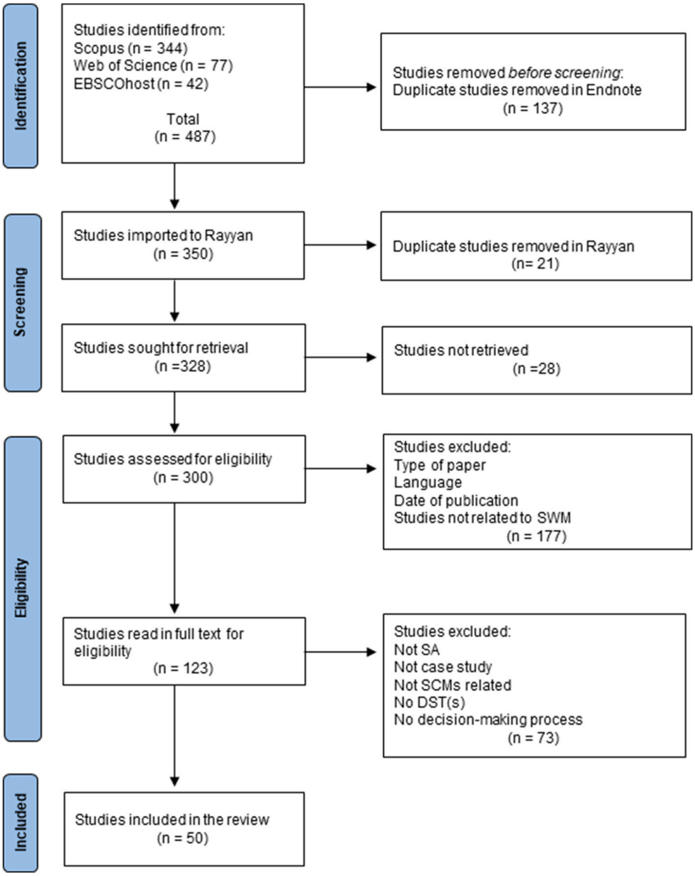

Fig. 1. Flow diagram of the selection process based on PRISMA (Page et al., 2021).

- **Stormwater management:** "stormwater management" OR "low impact development" OR "sustainable urban drainage system" OR "best management practice" OR "water sensitive urban design" OR "nature-based solution" OR "green infrastructure" OR "stormwater control measure*" OR "Sponge City".

The search was conducted in October 2022 and resulted in a total of 487 papers. From these, duplicates, irrelevant papers (based in reading abstract and titles), papers inaccessible in full-text, non-original research papers, papers not in English language, papers not published in peer-reviewed journals (*i.e.,* no conference proceedings, book chapters, technical reports, and government documents) were excluded, resulting in a total number of 123 papers published between 2010 and 2022. These were included in the full-text reading and skimmed through for eligibility in line with the objective of this review. Based on this, another 73 papers were excluded and, thus, a total of 50 papers were comprised as the final sample of this review.

In order to analyze the selected papers, we applied the Policy Arrangement Model to our analysis (Arts et al., 2006). The model is a conceptual framework, developed in environmental policy studies to assist understanding stability of content and organization of a policy domain. Arts et al. (2006) defines a policy arrangement as the state in which the interaction between political actors and resources and rules of the game solidifies in a temporary stable structure (institutionalization), before the driving force of evolution forces them to readjust their interdependency. The model comprises four profoundly interconnected dimensions: actors, resources, rules of the game, and discourses. Each of these dimensions affects the others and changes the shape of the entity, such as new actors' appearance may lead to division of resources, new rules of the game and/or new discourses. Previous reviews related to SWM and urban forest management have used policy arrangement model as an analytical framework (Ordóñez et al., 2019; Qiao et al., 2018)

For clarity, we used the following definitions for the review:

Discourse: represents the "pre-defined" problems and the intentions behind the SWM approach. In this review, *discourse* may resonate with the research questions and terminology used in the articles to communicate ideas and concepts related to sustainable SWM.

Rule(s) of the game: refers to both legally and non-legally binding documents, reports, guidelines, standards, *etc.*, which may require the use of specific DSTs, or have an influence on the decision-making process in the context of sustainability assessment for SWM.

Actors: stand for both stakeholders who have a direct interest and are actively involved in the decision-making process, as well as those who are indirectly affected and may be distantly addressed. It includes proponents, decision agencies and end users from both public (governmental) to private (consultants and community) domains.

Resources: denote knowledge, finance, data, time input, *etc.,* influencing the selection and utilization of DSTs.

3. Results

3.1. Geographical and research context

The reviewed studies encompass a variety of 19 countries (Fig. 2a) with a dominant number of studies in North America, Europe, China, and Australia (Fig. 2b). Most of the articles included in the review are based on studies in Europe (n = 16), North America (n = 14), China (n = 10) and Australia (n = 6). This global distribution corresponds to the widespread acceptance and application of sustainable SWM concepts, regions with a high study representation, in particular, are frequently at the forefront of introducing novel concepts to stormwater management. While early studies from Europe and the North America were based on the concepts such as Sustainable Urban Drainage Systems, Best Management Practices (a term less commonly used today and being replaced by *e.g.,* NbS), and Low Impact Development (with stormwater control measures). In recent years, there has been a notable global rise in the adoption of these systems and concepts, specifically, Australia has shown a specific interest in Water-Sensitive Urban Design, while China has emphasized Sponge Cities, as discussed in detail by Fletcher et al. (2015). The specific focal points and driving factors vary due to the diversity of local, regional, and national challenges, including but not limited to climate change adaptation, reduction of combined sewer overflows, improvement of bathing and receiving water quality, and the necessity of rainwater harvesting due to drought. Nonetheless, amidst these variations, there exists an overlap in these concepts and technologies.

Overall results also indicate how the research area of DST in SWM as finally included in this review has increased between 2010 and 2022 (Fig. 2c), and how most research papers have economical (n = 45) and environmental (n = 42) sustainability criteria being included, compared to social (n = 26) and technological criteria (n = 28) (Fig. 2d). The emphasis on technical-environmental criteria revealed the predominant consideration in these countries/regions. Technical-environmental needs (retention and water quality treatment) have long been the main drivers for the implementation of stormwater control measures (Butler et al., 2018). When including ecosystem services, SWM moves from being a technical water management issue to a multidisciplinary issue involving a broader spectrum of actors and requiring other economic considerations (Darnthamrongkul and Mozingo, 2021). Issues to be regarded besides the technical function are *e.g.* public and societal perception and multiple economic beneficiaries of sustainable SWM. Still, the relatively lower representation of social and technological criteria in current DSTs shows potential for further investigation and development, particularly in terms of combined social and technological advancements in SWM.

We also found a steady increase in the number of publications over the last 10 years, with a peak of 12 publications in 2020. The years 2016 and 2022 were also notable with 8 and 10 publications respectively. These findings suggest that the research topic of using DSTs as part of sustainability assessment in SWM has gained increasing interest in recent years. With regards to sustainability criteria, economic and environmental concerns scored the highest interest (n = 45 and 42 respectively) compared to the technological and social domains (n = 28 and 26). These findings suggest that social and technological sustainability may not be given as much emphasis in the DST's assessment of SWM strategies compared to economic and environmental sustainability.

3.2. Application of DSTs in SWM

In response to objective 1, in total 11 DSTs were identified in the

Fig. 2. a) Location by country of the reviewed studies; b) the number of the published studies by country; c) timeline of studies in review based on year of publication; d) identified sustainability assessment pillars in the published studies.

sustainability assessment of SWM (Table 1), of which 16 % (n = 9) out of the 50 papers used integrated DSTs. Instead of simply counting the number of instances, we counted the occurrences of different DSTs used in the research papers. The most used DST applied both as a separate approach and in combination with other tools, was Multi-Criteria Analysis (MCA), which appeared in 26 of all reviewed papers. Cost-Benefit Analysis (CBA) was the second most frequently used tool (n = 11), followed by Life Cycle Costing (LCC) (n = 7), Life Cycle Assessment (LCA), and System Dynamics (SD) (n = 3 each), Cost-Effectiveness Analysis (CEA) (n = 2), and finally the remaining DSTs were only used once each (n = 1). Table 1 presented a general description of these tools and their applications in the reviewed studies. The disparity in the usage of DSTs reflects the complex nature of sustainability assessments. Notably, the prevalent use of MCA suggests its suitability for multifaceted assessment demands. This predominance is attributed to its flexibility with various techniques (Luan et al., 2019), its capacity to integrate complex quantitative and qualitative data (Axelsson et al., 2021), and its applicability to handle multiple, often conflicting, criteria in a consistent manner (Liquete et al., 2016). Conversely, tools with fewer occurrences may be associated with their highly novel, specialized, and complex application. For instance, Rapid Decision Support Tool use unique Ecosystem Services variables for the SWM retrofitting purpose (Scholz and Uzomah, 2013), Agent-based Model excels in simulating the actions and interactions of agents to assess their collective impact on the system (Castonguay et al., 2018), and Long-Term Hydrologic Impact Assessment can leverage detailed land and climate data to estimate long-term effectives and payback time (Wright et al., 2016). However, in contrast to MCA's broad applicability, these tools often target highly specialized domains and require significant computational resources, or they might be seen as innovative and novel, lacking in accessible datasets. These may confine their application to a smaller community of SWM sustainability assessment specialists. Nonetheless, accelerating advancements in computational power and artificial intelligence technologies could broaden the accessibility and applicability of some of these tools in the future (Dwivedi et al., 2021).

Despite the diversity of DSTs available for specialized applications in SWM sustainability assessment, these tools were utilized to assess various design variations within the same stormwater control measure, such as different types of rain barrels. Additionally, 49 % were used to compare different stand-alone stormwater control measures to each other, *e.g.*, assessing the performance of green roofs versus rain gardens. Furthermore, 51% of the tools were utilized to assess the combined performance of multiple stormwater control measures, such as integrated constructed wetlands, sedimentation ponds, and rain gardens as a combined system to another alternative within the same catchment scale. By linking the records of the DST and its usage, the result indicates the capacity of each DST towards the modes of the stormwater control measures.

3.3. Application of DST in stormwater governance and management

3.3.1. Discourses

The primary discourse related to the use of DST was towards water quantity control (*i.e.*, managing the volume and velocity of stormwater runoff) and represented in 34 % (n = 17) of the papers, 24 % (n = 12) were related to water quality interests (*i.e.,* the reduction of pollutants and contaminants), and 42 % (n = 21) were addressing both, as mutual concerns. This latter approach indicates that some DSTs (*e.g.,* MCA, SD, CBA) can assist in developing effective solutions for interrelated issues, which is needed in practice when *e.g.,* multifunctionality is desired (Castro, 2022; Ebrahimian and Wadzuk, 2022; Koc et al., 2021; Liang et al., 2020; Luan et al., 2019; Oladunjoye et al., 2022; Xiong et al., 2020). The combined approach to sustainable SWM also resonates with how the DSTs are used to assess individual measures (*i.e.,* separate installations of swales, bio-retention ponds, *etc.*) or combined measures (*i.e.*, a system approach with several combined installations), and how the comparison between alternatives are possible, either between individual measures, combined measures, or both. Additionally, some studies have explored the optimal scenarios for SWM by comparing individual stormwater control measure with combined measures (Kaykhosravi et al., 2022), and some studies have explored implementing scenarios across multiple scales (Dong et al., 2020), and even the feasibility of multi-site implementations (Locatelli et al., 2020).

Furthermore, as presented in Table 2, the objectives of the reviewed articles indicated that 47% (n = 29) focused on the performance of stormwater control measures, 34% (n = 21) discussed the benefits and values of SWM, and 18% (n = 11) evaluated overall strategies and policies.

3.3.2. Actors

Understanding who the actors are, and their roles, is crucial for examining the governance and management aspects in the application of DSTs, especially with concern to potential conflicts of interest (Barton et al., 2020). By categorizing actors based on their roles and responsibilities, we can better understand their likely contributions (interests) to the SWM decision-making process (McIntosh et al., 2011). Some actors may fit into more than one category depending on their roles and mentioned responsibilities. Governmental or municipality officials represent the most occurring category of actors by 43% (n = 23), followed by the utility sector, 20 % (n = 10), and experts, 12 % (n = 6). The least representative actors were local community stakeholders, 8 % (n = 4), property owners, 4 % (n = 2), and actors from industry banks and insurance companies, 2 % (n = 1).

3.3.3. Resources

Resources play a significant role in the decision-making process, for instance, via access to knowledge and data, *etc*. This was recognized as the paramount resource in the decision-making process when utilizing the DSTs with 48 % (n = 24) including 5 papers specifically addressing local knowledge and expertise as valuable and 4 studies relating to expertise and scientific judgment. Time was addressed in 4 papers, and financial resources, as in the budget allocated to the project, were only mentioned in 2 papers. Also, the DSTs themselves can be regarded as a resource, based on their ability to support and define other resources needed in the decision context.

3.3.4. Rules of the game

A number of papers (n = 46) were found to employ the rules of the game in their research on applying the DSTs. These rules primarily consisted of non-legally binding documents (n = 44), including agendas, reports, guidelines, and standards from international to local levels. Only 3 articles specifically referred to the legally binding regulation, and a small subset of articles (n = 5) drew upon additional rules from projects as the primary setting. These legally or non-legally binding rules played a pivotal role in various aspects of the decision-making process for sustainability assessment, as they provided a basis for defining SWM problems, and setting motivations, rationales, and objectives for the SWM assessment. Additionally, they guided the establishment of sustainable SWM requirements, alternatives, functions, and benefits, as well as the determination of criteria for sustainability assessment. Furthermore, these rules were instrumental in identifying DSTs, as well as in conducting scenario analysis, which allowed for the assessment of various sustainable SWM strategies through modelling and simulation processes.

4. Discussion

Policy arrangement model as the analytical framework in our review, is not an ontological description of reality, but an analytical and heuristic framework to articulate governance and management. In the following discussion, we deliberate on our findings from the objectives that have framed this review.

Table 1
Identified DSTs with summarized descriptions and techniques in sustainable assessment of SWM case studies, illustrating the application modes - Individual (I) stormwater control measure or Combined (C) stormwater control measures.

DST	Description	Techniques		Individual (I) or Combined (C)	Occurrences
Multi-Criteria Analysis (MCA)	MCA is a family of methods that enables the evaluation of alternatives based on multiple criteria. It utilizes various approaches and techniques to assess different SWM practices and stormwater control measures within the various frameworks, while also being able to engage stakeholders and decision-makers.	- Analytic hierarchy process - Fuzzy-based approach - Technique for order of preference by similarity to ideal solution - Preference ranking organization method for enrichment evaluations - Optimization approaches	- Shapley choquet aggregation - Delphi method - Scoring (Likert scale) - Parameter ESTimation - Multi-attribute value - Bayesian belief networks	I or C	26
Cost-Benefit Analysis (CBA)	CBA is a tool used to evaluate the costs and benefits associated with different SWM strategies. It is a valuable tool for decision-makers to determine the most cost-effective solution while considering multiple objectives, such as monetized environmental and social benefits. It can help to identify the best management practices that deliver the greatest benefits and maximize the return on investment.	- Benefits Estimation Tool (B £ST) - I-DST - Net present value - Average service life span - The economics of ecosystems and biodiversity - Benefit cost ratio	- System for urban stormwater treatment and analysis integration - Willingness to pay - Investment framework for economics of water sensitive cities	I or C	11
Life Cycle Cost (LCC)	LCC can evaluate the cost of stormwater control measures over its entire life cycle, including initial capital costs, maintenance costs, and end-of-life disposal costs. It can help decision-makers compare the cost-effectiveness of different SWM strategies and identify the most cost-effective option.	- Net present value - Benefit cost ratio - Internal rate of return		I or C	7
Life Cycle Analysis (LCA)	LCA can be used to assess the environmental impacts of a stormwater control measure over its entire life cycle. It can provide value to compare different design options and identify areas for improvement in terms of reducing the measure's environmental impact.	- International Organization for Standardization (ISO) protocols. - Cumulative energy demand - Carbon footprint - ReCiPe midpoint hierarchist		I	3
System Dynamic (SD)	SD is a modelling tool used to understand the behavior of complex systems over time, such as combined stormwater control measures. It supports evaluating long-term performance, predicting future impacts, and developing adaptive strategies that are resilient to changes.	- Casual loop diagram - Fuzzy cognitive mapping - Participatory modeling		C	3
Cost-Effectiveness Analysis (CEA)	CEA is a tool or sometimes a technique for LCC that is used to compare the costs of different strategies in SWM that achieve similar outcomes. It assists decision-makers to identify the most efficient and cost-effective solution, such as reducing stormwater runoff or improving water quality.	- Monte Carlo simulation - System for urban stormwater treatment and analysis integration - Benefit cost ratio - Cost effectiveness ratio		I or C	2
Rapid decision support method (RDSM)	RDSM is a structured and participatory decision-making approach that helps to identify and evaluate alternative solutions to complex problems promptly. It is based on the Ecosystem Services' variables.	- Ecosystem Services' variables		I	1
Agent-Based Model (ABM)	ABM is a tool that models the behavior of individual agents and their interactions in a complex system. It is commonly used to study complex social, economic, and ecological systems and to explore the impacts of different policies and interventions.	- UrbanBEATS & DynaMind		C	1
Green pass Toolbox	Greenpass Toolbox is a web-based platform that supports decision-making in the management of green infrastructure, such as urban parks, green roofs, and wetlands. It provides tools and data for planning, designing, and assessing the performance of green infrastructure projects.	- GIS with Simulation & Evaluation System		C	1
Long-Term Hydrologic Impact Assessment (L-THIA)	L-THIA is a model that estimates the long-term hydrologic impacts of land use changes on a watershed. It can be used to assess the impacts of urbanization, agricultural practices, and other land use changes on water quality and quantity.	- Modeling with curve number method		I	1
Strengths, Weaknesses, Opportunities, and Threats (SWOT)	SWOT is a framework for assessing the internal and external factors that affect the performance of an organization or project in strategic planning and management to identify potential risks and opportunities	- Analytic hierarchy process		I	1

Table 2
Summarized main objectives of reviewed articles related to SWM.

	Themes	Objective	Occurrences
Discourse	performance of stormwater control measures	Functions & configuration; combination mode; spatial layout; spatial scale; and spatial distribution	29
	Benefits and Values	Direct or indirect benefits trade-off & synergies	21
	SWM Strategies	Policies; regulations; and schemes/scenarios	11

4.1. What SWM themes are DSTs applied for?

To address objective 2 of this study, we identified three major themes relating to the discourses throughout the reviewed papers: (i) performance of stormwater control measures, (ii) benefits and values, and (iii) SWM strategies (Table 2).

4.1.1. Performance of stormwater control measures

The performance of stormwater control measures, including retention, purification, infiltration, storage and reuse, evapotranspiration and heat absorption, provision, and improvement of habitat and green spaces, *etc.* was the most mentioned objective, ranging from grey infrastructure to green infrastructure based on their technical function and configurations to control and management of stormwater, including measures of *e.g.*, bio-retention, rain gardens, permeable pavement, and green roofs. The efficiency of the measures is reflected in the optimal performance of the proposed measure. Moreover, the objective of some studies was to use DSTs to find the combination of spatial location, scale, and distribution for implementation. Instead of focusing on the functions, these studies also used DSTs to investigate the baseline alternatives of the measures based on either centralized or decentralized approaches, the spatial layout (*e.g.,* source control, process control, end control), and the size of the catchment area. Two studies included both aspects and used DSTs to assess the optimization of different measures based on the functions and configuration, combination mode, and spatial distribution (spatial scale and size).

4.1.2. Benefits & values

Benefits and values were the second most addressed SWM theme of the reviewed articles, and could, in turn, be identified as either direct benefits (*e.g.*, reduced runoff, improved water quality, water restoration, groundwater recharge, improved water supply, protection of green space, reduced temperature, and reduced greenhouse gas emissions) or indirect benefits (*e.g.*, enhanced aesthetics, improved public health, flood mitigation, biodiversity conservation, human well-being, education, and urban heat island reduction).

4.1.3. SWM strategies

Several studies also sought to evaluate the effectiveness of the overall management approach or top-down stormwater policy, rather than specifically examining the implementation of stormwater control measures or their associated benefits. These studies typically focused on evaluating schemes, scenarios, and policies derived from the functions of stormwater control measures, and comparing different strategy alternatives to identify the long-term pathway that best aligns with their contextualized sustainability in SWM (*e.g.*, addressing the impacts of climate change or urbanization).

4.2. How do DSTs support stormwater governance and management aspects

4.2.1. Rules

In this review, most studies demonstrate a reliance on non-legally binding rules that are specific to the context, which allows for flexibility and adaptation to geographic contexts and evolving knowledge. In addition, it enables proponents to incorporate local pertinent indicators into SWM assessment (Halla et al., 2022). As emphasized by Hartmuth et al. (2008), sustainability assessment must be customized to the specific characteristics of the local context. Despite the instrumental role of these rules in establishing the local pertinence for DSTs in SWM assessment, the limited utilization of legally binding rules can pose a potential barrier to achieving consistent and standardized sustainability assessment approaches to sustainable SWM across different contexts. Further, the absence of legislation in sustainability assessment may impede the acceptance and support of sustainable SWM strategies by stakeholders (Castro, 2022).

4.2.2. Resources

As aforementioned, under the resources dimension of policy arrangement model, the DST could consider or be affected by a range of identified resource factors, such as the financial resources available for implementing SWM strategies, the availability of human resources to support, design, and implement the strategies, the accessibility of appropriate data and time needed to evaluate the stormwater control measures, and the availability of land for stormwater control measures (Qiao et al., 2018). However, financial resources and budget allocation were only mentioned in 2 studies (Castonguay et al., 2018; Ebrahimian and Wadzuk, 2022). Therefore, and in line with Mullins et al. (2023), we view DSTs themselves as a resource that supports the execution of the decision objectives, *e.g.,* as supporting data acquisition, insights, knowledge, expertise, financial resources, time, *etc*. CBA, CEA, and LCC can be attributed to the availability of accessible monetized resources and policy incentives, and this influence of financial considerations is reflected in the choice of DSTs. However, some researchers have argued that proponents tend to use these tools to simplify SWM decision strategies, rather than taking a holistic approach. Holz et al. (2004) and Furlong et al. (2017) have highlighted the potential drawbacks of over-reliance on monetization-based DSTs, as this dependency may oversimplify the decision-making process by structuring complex issues to a single criterion. Similar arguments were raised by Scerri and James (2010) who claimed that sacrifices made, *e.g.*, environmental or social aspects to achieve improvements in economic aspects, will lead to prioritization of economic development at the expense of the other aspects of sustainability.

With respect to addressing this drawback, the integration of more than one technique in the decision-making process is observed, such as combining Analytic Hierarchy Process technique to develop weights of criteria and Technique for Order of Preference by Similarity to Ideal Solution technique to test stormwater policy alternatives in MCA (Axelsson et al., 2021; Koc et al., 2021). Similarly, as presented in Table 3., some studies applied one DST as an auxiliary to another, such as using CBA as supplementary to MCA to provide a more comprehensive assessment by incorporating both monetary and intangible criteria (Rizzo et al., 2021; Teotónio et al., 2022), likewise, utilizing MCA as auxiliary to SD to enhance the understanding of complex and dynamic systems, allowing for a more accurate representation of the real-world scenarios (Xi and Poh, 2015).

4.2.3. Actors

Sustainability assessment of SWM is a complex process that includes multiple actors, *e.g.*, state government, water utility, developers, civil society actors, and households, although different DST of sustainability assessment studies conceptualize the roles of actors in different ways, from the reviewed studies, we have discerned the following distinctive roles:

Proponents are typically the researchers who undertake the sustainability assessment (Pope and Grace, 2006) and develop, apply, or demonstrate the DSTs, which are designed to investigate various issues of sustainable SWM and to propose resolutions either with (engaged) or without (distance) other actors. They play a critical role in advancing

Table 3
Integrated DSTs and framework.

Integrated DSTs	Details and rationales	Reference
LCA & SD	Integrated LCA & SD in assessing and evaluating different nutrient treatment efficiencies under various spatial and temporal settings, this dynamic framework can be generalized to different environmental and system conditions to inform the future design and optimization of green infrastructures applications	Bixler et al. (2019)
MCA & LCC	LCC as auxiliary to many-objective optimization approaches[a], allowed stormwater best management practices to be evaluated by stakeholders before the portfolio selection process. MCA for assessing alternative solutions on hydro benefits was incorporated with LCC, with regard to enhancing planning-level analyses by expanding information for decision-makers.	Di Matteo et al. (2019) Gallo et al. (2022)
LCC & CBA	LCC and CBA as the integrated DST were utilized due to the quantitative and comparative purpose for the assessment of green infrastructure performance. Monetized climate impacts by LCC and community rainwater harvesting benefits with CBA to propose a community rainwater harvesting system as an alternative water supply solution for supporting policy decision-making.	Heidari et al. (2022) Islam et al. (2021)
LCA & LCC	Integrated LCA and LCC models were used to evaluate the cost and environmental impacts of permeable highway pavements.	Hung et al. (2021)
MCA & CBA	MCA to compare grey and green infrastructure alternatives for the management of a combined sewer overflow, in which the criteria related to ESS were monetized with an adjusted value transfer (VT) method (B£ST software)[b]. Developed Modelling of the attractiveness of Green Infrastructure through a combined approach (MAGIGA) with MCA and CBA for assessing the value of green roofs and walls, so as to overcome the limitation of CBA.	Rizzo et al. (2021) Teotónio et al. (2022)
MCA & SD	Synergized SD with MCA to compare different alternatives based on performance as revealed by the SD simulation and the judgment of decision makers.	Xi and Poh (2015)

[a] multi-objective assessment is a type of multi-criteria analysis (MCA).
[b] Value transfer (VT) method such as Benefits Estimation and Screening Tool (B£ST) is considered part of the CBA family.

knowledge in the field of SWM that can support decision-makers to make more informed and sustainable choices (Gibson et al., 2005).

Decision agency comprises the actors who have the power or are empowered by the proponents to make decisions and are directly involved in the decision-making process (Gorddard et al., 2016). They are responsible for developing strategies related to SWM, as well as implementing stormwater control measures and weighing the benefits in a decision-making process (leBrasseur, 2022). Decision agencies play a key role in determining the trade-offs in the sustainability of SWM practices and solutions. In this review, these actors include government agencies, authorities, utilities, property owners, and decision-makers.

End users include actors who may not have a direct role or stake in the decision-making process but are impacted by SWM outcomes (McIntosh et al., 2011). These actors were observed in this review as commerce, contractors, bank and insurance industry, public/citizens, and residences/community. End users can provide feedback and input on SWM decisions, as well as influence outcomes through their actions. For example, the bank and insurance industry can influence implementation of stormwater control measures through their lending and insurance practices (Kordana-Obuch and Starzec, 2020), while residents and community groups can promote sustainable stormwater practices through advocacy and education campaigns in developing and implementing SWM plans and strategies (Kaykhosravi et al., 2022).

All in all, the nature of sustainability assessment in SWM is not only a technical appraisal approach providing direct input for decision-making, but also a possible approach for supporting governance, which involves communication and knowledge dissemination among the actors with different roles that are deployed in sustainability assessment decision contexts (Bond and Pope, 2012; van Zeijl-Rozema et al., 2008). The density and openness of the decision context in sustainability assessment of SWM consider the actors (proponents and decision agency) that establish the decision process, including the interconnected systems of values, rules, and knowledge that determine how the decision process is framed (Gorddard et al., 2016). In this regard, the plurality of actors addressed in the decision-making process from the review studies can serve as a basis to resonate what van Zeijl-Rozema et al. (2008) called *'deliberative governance'*.

However, despite the recognized importance of actor engagement in decision-making processes, most studies have only superficially addressed actors by simply stating that the decision outcome would benefit them. Only a handful of studies had comprehensively presented the process of engagement, and just one study had the recorded uptake of the decision result by the water utility (Rizzo et al., 2021). As stated by Giordano et al. (2021), stakeholders' engagement has a crucial role to support understanding and valuing the differences among individual co-benefits. Nonetheless, this also presents a dilemma regarding *when* and *where,* and *how* actor engagement will ensure the uptake of the decision-making, not to mention the quality, quantity, and appropriateness of their involvement in the actual decision-making processes (McIntosh et al., 2011). Furthermore, actors involved in Sustainable SWM have diverse interests and competing agendas, which have a significant impact on policy goals and influence trade-offs between short and long-term objectives, as well as the hydrological processes integral to SWM practices (Dhakal and Chevalier, 2016; Henstra et al., 2020). This complex interaction of diverse interests and conflicts among stakeholders shapes decision-making processes and outcomes. In this review, only one study was found to specifically address conflict per se, with a focus on the assessment of the stormwater control measures response to different policy conflicts (Castro, 2022). Therefore, future research should highlight the research gap of actor engagement and their multifaceted interests and conflicts in the application of DSTs, in order to ensure optimal decision-making outcomes and facilitate effective deliberative governance.

4.3. *How can future DST best include governance and management aspects?*

Understanding governance dimensions such as discourses, rules of the game, actors, and resources (Arts et al., 2006), and integrating them into the sustainability assessment of SWM would significantly enhance the decision-making context. This, in turn, facilitates the selection of suitable DSTs and the effective alignment of their distinct strengths. For instance, the capacities of MCA in considering intangible criteria and trade-offs among actors emphasize its potential in including governance-oriented elements inherently. Conversely, tools such as CBA and LCC, with their specific focuses on assessing economic feasibility and temporal impacts, respectively, offer valuable insights into management-oriented concerns such as landscape design, maintenance, and planning.

However, solely focusing on the capacity of the DST or how to apply DST is not sufficient. After all, the fundamental input criteria remain crucial, regardless of the DST applied, it is necessary to utilize sustainability criteria to determine whether the stormwater control measures or strategy is likely to contribute to the set objectives (Foxon et al., 2002). Of the 50 reviewed papers, 49 papers utilized DST to assess at least two pillars of sustainability, with economy and environment being the most frequently assessed. Relatively fewer articles assessed the social aspect, with only 17 articles covering all pillars of sustainability, this demonstrates that there is still a gap in DST in assessing all pillars of sustainability. To ensure a comprehensive and robust assessment of sustainability objectives in sustainable SWM, it is essential to incorporate all pillars of sustainability, as emphasized by several studies (Foxon et al., 2002; Hugé et al., 2013; Pope et al., 2017).

It was observed that social criteria were not adequately addressed in most of the articles. Specifically, only 26 articles included social criteria, as presented in Table 4. Health and recreation are the most predominant indicator of the social criteria, followed by aesthetics, accessibility, and green economy. However, most of the papers only mentioned the concepts by name and did not elaborate on how and in which context in the decision-making process these intangible criteria were applied. We also observed inconsistency in some of the papers regarding how social criteria was addressed, *e.g.*, air pollution removal as the social criterion in Yao et al. (2022) and as the environmental criterion in leBrasseur (2022). Similar inconsistency was noticed in the categorization of water quality improvement, where Johnson and Johnson and Geisendorf (2019) addressed this as a social criterion and Liquete et al. (2016) as environmental. Nevertheless, the legitimacy, credibility, salience, and feasibility of the indicators are the keys to open and informed deliberations (van Oudenhoven et al., 2018). By incorporating social criteria in the sustainable assessment of SWM, open and informed deliberations can be encouraged to enhance the capacity, motivation, and habitual inclination of private actors and end-users toward sustainable decision-making. Moreover, the fostering of reciprocal awareness and collective responsibility can further promote long-term sustainability (Gibson, 2001, 2006).

Table 4
Of all 50 papers, a total of 26 specifically addressed aspects of social sustainability as a part of the DST. Identified benefits and values either as indicators or criteria under the social pillar of different sustainability assessment frameworks are outlined in this table.

Social value & benefits	Numbers of instances	Reference
Environmental justice and green space accessibility	10	Axelsson et al. (2021); Coletta et al. (2021); Ebrahimian and Wadzuk (2022); Johnson and Geisendorf (2019); Kaykhosravi et al. (2022); leBrasseur (2022); Scharf et al. (2021); Teotónio et al. (2022); Xiong et al. (2020)
Civic engagement (the public/local community)	9	Axelsson et al. (2021); Brudermann and Sangkakool (2017); Coletta et al. (2021); Di Matteo et al. (2019); Iftekhar and Pannell (2022); Koc et al. (2021); Liquete et al. (2016); Oladunjoye et al. (2022); Shojaeizadeh et al. (2019)
Education	6	Ebrahimian and Wadzuk (2022); Kaykhosravi et al. (2022); Langemeyer et al. (2020); leBrasseur (2022); Oladunjoye et al. (2022); Rizzo et al. (2021)
Green economy (new enterprising)	4	Koc et al. (2021); Liquete et al. (2016); Teotónio et al. (2022); Xiong et al. (2020)
Health & recreation	16	Axelsson et al. (2021); Brudermann and Sangkakool (2017); Castro (2022); Di Matteo et al. (2019); Ebrahimian and Wadzuk (2022); Iftekhar and Pannell (2022); Johnson and Geisendorf (2019); Kaykhosravi et al. (2022); Langemeyer et al. (2020); leBrasseur (2022); Liquete et al. (2016); Oladunjoye et al. (2022); Rizzo et al. (2021); Scharf et al. (2021); Xiong et al. (2020); Yang and Zhang (2021)
Aesthetics	11	Brudermann and Sangkakool (2017); Ebrahimian and Wadzuk (2022); Iftekhar and Pannell (2022); Johnson and Geisendorf (2019); Kaykhosravi et al. (2022); Koc et al. (2021); Kordana-Obuch and Starzec (2020); Langemeyer et al. (2020); leBrasseur (2022); Oladunjoye et al. (2022); Shojaeizadeh et al. (2019); Teotónio et al. (2022)
Tourism	2	Scholz and Uzomah (2013); Oladunjoye et al. (2022)

Future studies in sustainability assessment of SWM should therefore establish principles for standardizing frameworks to ensure adequate and contextually correct inclusion of all sustainability criteria, especially the social criteria. This will allow the best practices to be replicated on multisite, enabling greater consistency in the deliberative governance of sustainable SWM.

4.3.1. Long term management

Long-term approaches in sustainable SWM are recognized as crucial to really gain sustainability over the live length of the facility (Gibson et al., 2005; Qiao et al., 2018). Failed facilities due to lacking maintenance are a common challenge, meaning wasted investments and involve a risk for negative public perception towards sustainable SWM (Blecken et al., 2017). In this respect, DSTs, as well as hydrological models in SWM planning, are well-equipped to allow for long-term perspectives. Several DSTs, such as LCA, SD, LCC, and CBA, are developed to make longitudinal assessments ranging from 10 years to 50 years (Bixler et al., 2020; Hengen et al., 2016; Krieger and Grubert, 2021) This, in turn, allows decision-makers to understand how a system will behave over time and to identify potential long-term consequences of different decisions, or to evaluate management strategies that relate to operations and maintenance costs, as well as the stormwater control measure technical functionality per se. In addition, hydrological models that are used as auxiliaries to the DST are also used to generate long-term simulations. Storm Water Management Models, for example, can be used to simulate the quantity and quality of stormwater runoff under long-term hydrological scenarios (Jayasooriya and Ng, 2014). Still, long-term viability and function of NbS require empirical evidence of trial and errors, where experience of ongoing maintenance work of *e. g.,* raingardens and bio-swales contribute to valuable knowledge. This means embedding such expertise into DSTs to aid landscape planning and management and help link design of storm water measures to the long-term maintenance.

Moreover, several studies have investigated the long-term effectiveness of SWM policies and strategies, particularly in response to the challenges posed by climate change and urbanization. In these studies, different strategy alternatives and scenarios were compared from a long-term perspective (Brudermann and Sangkakool, 2017; Iftekhar and Pannell, 2022; Melville-Shreeve et al., 2016; Song and Chung, 2017). However, it is noteworthy that these strategy-related studies in sustainable SWM primarily focus on evaluating schemes, scenarios, and policies based solely on the assessment of stormwater control measures' functions or benefits. In addition, they tend to compare different strategy alternatives to identify the long-term pathway that best aligns with their objectives or discourses. As a result, the effectiveness of these strategies, which are based solely on the functions of stormwater control measures or solely on assessing the economic benefits of specific them as part of a larger plan, is questionable.

When it comes to the use of nature, or natural features of stormwater control measures, *e.g.*, expressed as NbS, our review has not generated enough evidence to suggest how long-term perspectives can be incorporated into DSTs. It is a fact that nature takes time to develop and that the transition of applying NbS in sustainable SWM will take a long time to develop from establishment (small scale) to extensive distribution (Köhler et al., 2019). But although nature-based, many stormwater control measures need maintenance to ensure long-term functionality (Blecken et al., 2017). Therefore, long-term monitoring of sustainable SWM when using NbS is needed, but often underdeveloped (Al-Rubaei et al., 2016). Future studies should include ex-post assessment, which will provide more tangible examples of the accurate long-term practice, local communities assessment, and experience, to identify NbS data as well as conditions that have led to sufficient maintenance to secure the technological requirements of NbS (Blecken et al., 2017). Given that lack of studies including the long-term functionality, incorporating it into DSTs remains a challenge and justifies further research.

5. Conclusion and limitations

This review aims to bridge the gap between sustainability assessment, sustainable SWM, and governance and management by investigating the roles of DSTs in sustainability assessment. We have applied the policy arrangement model as a heuristic framework to identify how DST may include governance dimensions. Further, we have explored DST's potential in supporting future real-world governance and management of urban SWM. In doing so, our findings indicate that, while there is a consensus on the significance of involving actors in the sustainability assessment of SWM, most efforts are still directed toward the technical development of DSTs. Therefore, there is a need to develop and combine the technical development of the DST with social aspects to ensure optimal decision-making outcomes and uptake. Furthermore, tangible examples and data on the long-term functionality of stormwater control measures through ex-post assessments were underexplored, this encompasses understanding how to effectively incorporate them into DSTs. Overall, despite the reviewed DSTs being primarily ex-ante, we identified significant potential for these tools to serve as a facilitative medium in supporting stormwater governance and management practices. Moreover, our results highlight three key aspects crucial to improving the effectiveness of decision support tools within stormwater governance and management, namely:

(i) Exploring practical challenges in integrating all sustainability assessment pillars with consistent criteria into DSTs. This is crucial to determine the optimal use of all criteria in fostering open and informed stormwater governance and management.
(ii) Understanding how to engage diverse stormwater actors with future DST, to secure ownership and relevance.
(iii) Use of retrospective (ex-post) sustainability assessments *e.g.* as evaluations, are needed to provide more tangible knowledge and to support long-term management. This is particularly related to nature or natural aspects in sustainable SWM.

To our knowledge, this is the first study of a substantially interdisciplinary nature that systematically examines how governance aspects relate to prospective DSTs of sustainable SWM. We have utilized the policy arrangement model to examine associations among decision science, sustainability science, and natural science, and our results add to the rapidly expanding field of governance research in SWM, especially in sustainability assessment studies.

Regarding the limitation in this current review, the strength of the model as an analytical framework is at the same time its weakness. It contextualized the governance dimensions in the decision-making context and facilitated our understanding of the utilization of DST in the sustainability assessment. However, the model simplifies the complex understanding of the intricate policy-making processes that have dynamic actors' involvement. This makes it challenging to provide a comprehensive understanding of the broader governance structure surrounding SWM just by projecting from the ex-ante DSTs applied in academic research projects. Notwithstanding this limitation, continued efforts with grey literatures should be undertaken to explore how DST is applied in urban SWM practice. By bridging the gap between sustainability assessment, governance, and management in addressing real-world SWM challenges, we can acknowledge more potential of DSTs in future decision-making processes.

CRediT authorship contribution statement

Zhengdong Sun: Writing – original draft, Methodology, Formal analysis, Conceptualization. **Johanna Deak Sjöman:** Writing – original draft, Methodology, Conceptualization. **Godecke-Tobias Blecken:** Writing – review & editing, Funding acquisition. **Thomas B. Randrup:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Cities are shifting toward holistic, multifunctional and sustainable stormwater management using nature-based solutions. Yet in existing urban areas, long-term outcomes depend as much on governance and place-specific delivery conditions as on technical performance. This thesis shows a recurring mismatch in early decision stages: technical evidence is often ready to use, while key delivery conditions remain under-specified even when they shape what is feasible to implement and sustain. It surfaces the resulting trade-offs and keeps uncertainty explicit in early-stage decision-making.

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