npj | urban sustainability

Article

Published in partnership with RMIT University

https://doi.org/10.1038/s42949-026-00448-4

Decisive factors in sustainable stormwater management

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Sustainable stormwater management (SSWM) is widely promoted for urban sustainability, yet decisions often weigh modeled performance and measurable evidence more readily than the governance and relational conditions that shape delivery. Here, we examine how practitioners judged the prospective decisiveness of such conditions for future SSWM in Malmö and Östersund, Sweden. Using an exploratory sequential mixed-methods design, we combined retrospective interviews with a Best–Worst Method prioritization workshop. Interviews identified 40 factors that have shaped stormwater management since the 1960s, which were synthesized into 9 key factors for prioritization. Participants ranked External Collaboration as most decisive and Technological Innovation and Adaptation as least decisive. The results suggest that practitioners judged that future SSWM decision-making depends on expected system performance as well as delivery conditions, including coordination, policy authority, organizational capacity, land-use negotiation, funding continuity, and long-term maintenance. Our study offers a context-grounded approach for making delivery conditions explicit in future SSWM decision support.

Since the late nineteenth century, stormwater management in many regions has shifted from combined sewers to largely separate drainage networks, yet practice remains strongly shaped by pipe-centered engineering solutions[1,2]. Amid rapid urbanization, climate change and rising concern over contamination, sustainable stormwater management (SSWM) is now widely endorsed. SSWM seeks to mimic natural hydrological cycles by embedding decentralized infrastructure into urban landscapes alongside conventional pipe networks[3]. These infrastructures reduce flooding, enhance ecosystems, improve water quality, buffer drought, and promote urban well-being[4]. Worldwide, concepts such as Sponge City, Sustainable Urban Drainage Systems, Water-Sensitive Urban Design and Low-Impact Development, which employ blue-green infrastructure and other nature-based solutions (NbS), signal this shift toward sustainable practice[5]. By retaining and treating runoff, conserving biodiversity, cooling cities and providing recreation, SSWM enhances urban sustainability[6] and supports several Sustainable Development Goals[7]. Hereafter, we use SSWM as an umbrella term for these related concepts and strategies.

Although stormwater engineering has advanced substantially, SSWM is now tasked with delivering core stormwater functions and securing multifunctional co-benefits, while balancing diverse and often competing priorities among stakeholders (e.g., flood risk reduction, ecosystem services, and land use)[8,9]. These demands increase the need for interdisciplinary evidence from both natural and social sciences, as decision-making must often navigate trade-offs across flood risk reduction, ecosystem services, land use, and long-term management[10]. Yet translating these expectations into workable governance arrangements remains difficult, particularly in institutional settings where pipe-centered routines still shape what is prioritized, coordinated, and implemented[11–13]. The difficulty is often visible in forms of institutional lock-in, where sectoral silos, established routines, vested interests, and short-term delivery pressures make it harder to coordinate across organizations, land ownerships, and shared responsibilities[14–18]. This challenge is further compounded by hybrid SSWM systems that combine conventional pipes with landscape-integrated NbS (e.g., stormwater ponds), requiring coordinated institutional and governance frameworks for their long-term upkeep[19,20].

Prior research has shown that governance conditions, enabling arrangements, and broader social dimensions strongly shape how SSWM is interpreted, implemented, and maintained in practice. Within this body of work, stormwater governance research has shown that SSWM implementation is often constrained by institutional fragmentation and unclear responsibilities[12,21], coordination challenges[22], and local political dynamics[11]. Related work on water governance and sustainability transitions has also shown that stormwater change depends not only on technical development, but on how actors work within and across existing institutions[17,23,24]. Studies from Swedish municipal contexts and applied SSWM research further show that these governance conditions are experienced through municipal

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routines and actor perspectives[25,26], through barriers and drivers affecting implementation of SSWM[27,28], and through specific governance concerns such as public awareness, political priorities[29], mistrust in performance[30], and long-term maintenance[31,32].

This body of work provides a rich understanding of how SSWM implementation is conditioned by institutions, actor relations, and local context. Yet these governance-related and social conditions are less readily translated into decision-ready criteria than modeled performance and other measurable evidence. In broader sustainability assessment and decision-support settings, technical, environmental, and economic dimensions are therefore more readily converted into explicit criteria, metrics, or model inputs[33,34]. By contrast, governance-related and social conditions are more often addressed indirectly, qualitatively, or case by case[35]. Their context-dependency also makes them difficult to articulate as decision-relevant criteria and to judge consistently across settings[36–38]. As stakeholder engagement[39] and qualitative methods in environmental decision-making[40] receive increasing attention, this under-specification becomes more consequential for how governance-related and social conditions are carried into decision processes. This is particularly important in SSWM with NbS, where decisions often involve fragmented responsibilities, mixed land ownership, and long-term horizons, and where feasibility in models or plans may depend on institutional capacity, coordination, and legitimacy in practice[41,42]. The question, then, is how such governance-related and social conditions are understood, interpreted, and prioritized as decisive factors when future SSWM decisions are considered in practice.

Retrospective perspectives are relevant for understanding how present conditions take shape. Research has also shown that past governance contexts and organizational path dependencies are embedded in organizational behavior, including in climate adaptation[43] and stormwater management[44,45], and can obstruct cross-sectoral collaboration[46]. Learning from past governance and management can also help reveal conditions linked to path changes and more dynamic capabilities[47]. Against this background, we framed two research questions: 1) Which past and present factors have shaped stormwater management transitions? and 2) Which key factors are most likely to be decisive for future SSWM decision-making and implementation? Here, the term "decisive" refers to practitioners' judgments of how consequential each key factor is likely to be for future SSWM decision-making and implementation under real-world governance conditions.

We use the multi-level perspective (MLP)[48] as a heuristic lens for organizing the retrospective analysis of stormwater management transitions. Transition theory examines how societal functions are reorganized over time through incremental and more substantial forms of change[15]. Within this field, MLP distinguishes between landscape pressures, regime conditions, and niche-level developments that interact in processes of change toward sustainability[16]. At the landscape level, broader external pressures such as climate change, urbanization, and weather extremes challenge existing stormwater systems. The regime level encompasses the dominant engineering approaches, governance structures, policy arrangements, financial resources, technical knowledge, and institutional frameworks that sustain prevailing stormwater management practices. Niches refer to spaces where innovations can develop and mature with some protection from dominant regime pressures[48]. In this study, these MLP distinctions helped us examine how established stormwater practices were challenged by external pressures, how NbS initiatives and pilot projects emerged, and how such developments interacted with prevailing governance and management arrangements.

MLP also informed the semi-structured interview guide, which was designed to examine how participants described changes in stormwater management within their organizations over time. The 1960s provided the point of departure for the retrospective inquiry, marking a period in Sweden when wastewater treatment plants were established, and separate sewer systems for stormwater became increasingly common in new developments[49]. The interviews comprised 16 open-ended questions and included both retired and currently active stormwater professionals, hereafter referred to as participants, allowing reflections on earlier and more recent periods to be considered together ("Methods"). The framework thereby helped connect retrospective reflection with present-oriented descriptions of governance, management, and technical change. The interview approach used temporal and thematic prompts to support retrospective recall, while treating participants' recollections as situated interpretations of professional experience rather than complete historical records[50].

Our study forms part of a broader Formas-funded research initiative conducted with Luleå University of Technology and the Swedish cities of Malmö and Östersund. While the wider project examines SSWM alternatives in selected urban catchments, the present study focuses on city-scale governance-related conditions that shape transitions toward SSWM. Malmö and Östersund share ambitions for NbS and SSWM, yet differ in climatic, spatial, and institutional conditions. In Malmö, stormwater management responsibilities are divided between municipal planning and the regional water and wastewater organization VA Syd, whereas in Östersund, governance is more centralized within the municipal organization. This contrast provides an analytical basis for examining how a shared factor-development and prioritization process operates across two different municipal settings, while avoiding claims of systematic city-by-city comparison or statistical representativeness.

The research was conducted in two empirical phases, comprising eight steps (Fig. 1a; "Methods"). In Phase 1, we interviewed 17 participants from Malmö and Östersund whose professional roles and experience together covered stormwater management from the 1960s to 2024 (Fig. 1b). The interviews were followed by an inductive analysis that identified recurring themes. This process generated 40 decisive factors (hereafter, factors), which were then synthesized into nine key decisive factors (hereafter, key factors), in response to the first research question ("Methods"). In Phase 2, the nine key factors were examined through a prioritization assessment and facilitated workshop discussion with 10 of the interviewees, addressing the second research question ("Methods"). The workshop used the open-ended term 'SSWM systems' to keep the assessment boundary broad, allowing participants to consider diverse infrastructures, technologies, configurations, and strategies rather than a single type of solution. The workshop concluded with a dedicated discussion in which participants reflected on the prioritization results and contributed additional qualitative insights.

Results

Interview findings and factor identification

The interviews traced how stormwater management and its governance conditions evolved from the 1960s to the present through participants' professional recollections. Participants whose professional experience reached back to the 1960s described stormwater as a largely secondary concern. As one recalled, "in the beginning, no one really thought about it," with stormwater and wastewater still handled through combined systems and stormwater treated largely as a matter of rapid conveyance. Organizational culture was likewise described as more hierarchical, with restricted collaboration even within departments. In more recent decades, participants described stronger collaboration within organizations, yet continued difficulty in working across departmental and sectoral boundaries. Across the material, collaboration remained a recurrent concern, although its meaning shifted over time. For contemporary practitioners, cross-sector collaboration was described as necessary not only in planning and design, but also in implementation and maintenance. Several participants described a recurring planning-to-implementation gap: stormwater could be discussed early in planning, yet become diluted later when space or funding were no longer secured. Differing understandings of responsibility could also compromise holistic approaches to SSWM and the long-term performance of surface-based NbS, such as rain gardens. As one participant noted, "unclear responsibilities and inadequate resources" had at times resulted in maintenance being "skipped."

Regime-level concerns dominated the interview material. Participants whose professional experience extended from the 1960s to the 1990s spoke

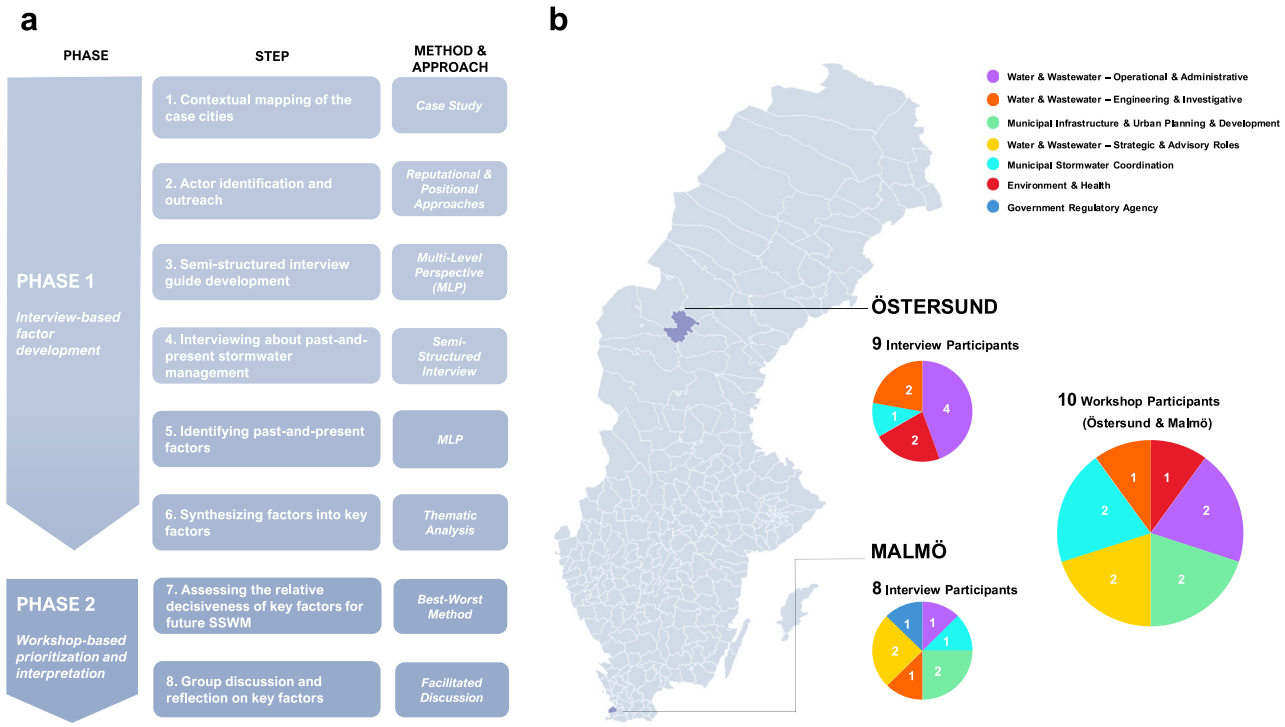

Fig. 1 | Research approach for decisive factor development, refinement, and prioritization. a Overview of the research phases conducted between 2023 and 2024, showing the primary methods and approaches used in each step. **b** Map of Sweden showing the two case cities, Malmö and Östersund. Pie charts indicate participant composition by professional role, including urban planners, engineers, and strategists, with collective professional experience spanning the 1960s to 2024. The two smaller charts on the left correspond to the interview phase, while the larger chart on the right represents the workshop phase. Map outline: Statistics Sweden, CC0.

primarily about conventional system expansion, technical routines, municipal responsibilities, and early detention measures. Among participants working from the 1990s onward, references to governance and organizational conditions broadened to include coordination, support structures, policy guidance, and maintenance, although regime-level concerns remained dominant. Currently active participants referred more evenly to landscape, regime, and niche developments, although the regime level remained the most prominent. In practice, these regime-level reflections centered especially on coordination, responsibilities, governance structures, policy interpretation, long-term maintenance, and the organizational routines through which stormwater decisions were carried forward.

Landscape-level findings appeared less as stand-alone implementation tasks than as wider agendas and public expectations that altered what stormwater management was expected to justify and deliver. Across the interviews, these pressures clustered around long-term wellbeing, biodiversity and ecosystem conservation, public trust and acceptance, and changing social practices. Although flooding and drought events are not new, participants described climate change, urban densification, droughts, and sea-level rise as making stormwater pressures more visible in current practice. Participants linked these pressures to different local concerns in the two cities. In Östersund, participants more often connected them to receiving-water protection, treatment performance, and the functioning of systems under local climatic conditions, since the receiving water body is the city's drinking water resource. In Malmö, they were more often translated into concerns about pluvial flooding, densification, retrofitting, and the difficulty of coordinating land-use decisions across fragmented responsibilities. Landscape pressures, therefore, entered the analysis through regime-level questions of responsibility, planning routines, land-use authority, and long-term maintenance.

At the niche level, innovation appeared in the interviews as a trajectory of experimentation, reference projects, and selective uptake. Participants repeatedly referred to Augustenborg, Malmö, where the late-1980s and 1990s work associated with Peter Stahre became a formative reference point for open, surface-oriented stormwater systems in Swedish practice[49], and for approaches that would later be closely aligned with NbS. Later innovations extended this trajectory through digital tools, modeling, and AI, which participants described as useful for improving evidence, communication, and shared understanding. Yet these tools did not dissolve the institutional and spatial conflicts through which SSWM decisions are made. As one participant put it, AI may provide "much better facts," but it cannot remove the conflicts themselves, including a lack of space.

Across the full interview material, the analysis generated 40 factors spanning all three MLP levels ("Methods"), with 30 located at the regime level, six at the niche level, and four at the landscape level (Fig. 2). Recurring concerns such as cross-departmental coordination, fragmented responsibilities, land-use rights, long-term maintenance, and public support appeared as distinct, though related, aspects of stormwater management transition. This distribution reinforced the centrality of regime-level conditions in participants' descriptions of how stormwater management had changed over time.

Key factors for SSWM decision-making

Figure 3 shows how the 40 interview-derived factors were synthesized into nine broader key factors ("Methods"; hereafter referred to in italics): *Multifunctionality*; *External Collaboration; Financial Resources*; *Land Use*; *Long-Term Integration*; *Organizational Capacity*; *Policy, Rules, and Legislation*; *Societal Dynamics*; and *Technological Innovation and Adaptation*. The synthesis brought conceptually related concerns into a more manageable analytical structure for the prioritization stage, while retaining their connection to the underlying factors. For example, issues of cross-sector coordination, external partnerships, and organizational silos converged within the broader key factor of *External Collaboration*. The nine key factors then provided the basis for the next stage of the study, in which participants considered their prospective decisiveness for future SSWM.

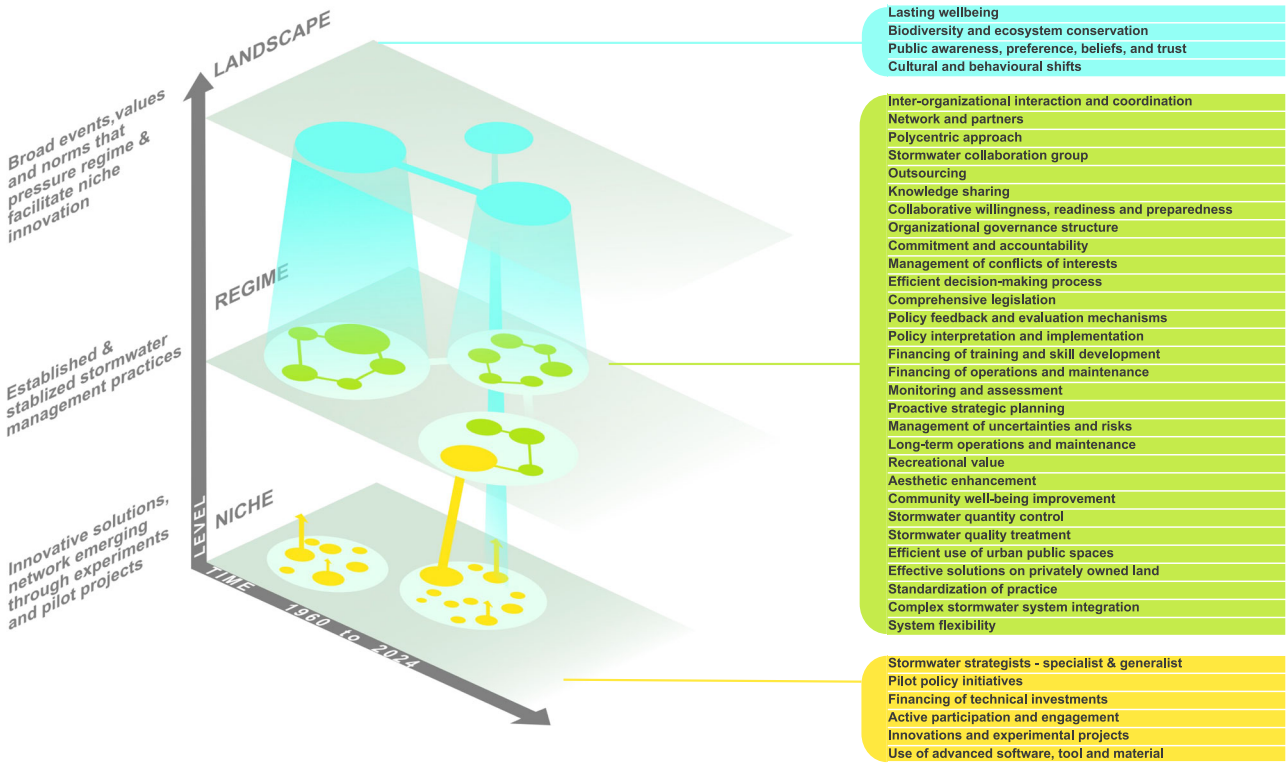

Fig. 2 | 40 factors influencing stormwater management transitions. The diagram illustrates the MLP framework (inspired by Garcia et al.[72]), with its three levels, landscape, regime, and niche, briefly described on the left. On the right, the 40 factors developed through semi-structured interviews are shown and color-coded by MLP level. Full details and descriptions of the factors are provided in Supplementary Note 1.

Leading key factors for prospective decisiveness

The prioritization assessment, together with the follow-up workshop discussion, revealed a coherent pattern in how participants judged the decisiveness of the nine key factors for future SSWM (Fig. 4). *External Collaboration* stood apart as the highest-scoring factor. *Policy, Rules, and Legislation*, *Land Use*, and *Organizational Capacity* formed a closely spaced second group, suggesting similar levels of decisiveness among governance and spatial conditions rather than a strict sequence of priorities. *Financial Resources*, *Long-Term Integration*, and *Multifunctionality* occupied an intermediate range, with the small difference between *Financial Resources* and *Long-Term Integration* best read as proximity in judgment rather than categorical separation. *Societal Dynamics* and T*echnological Innovation and Adaptation* received the lowest scores. Overall, participants located the decisive challenges for future SSWM less in choosing technical solutions than in securing the institutional, legal, spatial, and organizational conditions through which such systems can be coordinated, implemented, and sustained in practice.

External Collaboration received the highest mean decisiveness score, indicating that participants viewed cross-organizational coordination as the most decisive condition shaping whether future SSWM could move beyond sectoral silos and be carried into practical decisions. The follow-up workshop discussion repeatedly returned to fragmentation of responsibilities, land-use authority, inter-organizational misalignment, and overlapping mandates across sectors, including environment, parks, transport, streets, planning, engineering, water utilities, housing, and municipal sustainability offices. In this light, *External Collaboration* was not framed as a general virtue, but as a practical governance condition for aligning land-use decisions, responsibilities, and long-term implementation. At the same time, participants noted that collaboration is demanding in its own right, as it can generate coordination costs, mandate ambiguity, and dependence on actors who do not share the same timelines or decision logics.

Policy, Rules, and Legislation were also regarded as highly decisive for future SSWM. Here, the emphasis fell not only on formal legislation, but also on the role of guidelines, local policy instruments, and the practical authority to act across sectors. Across the underlying factors, this key factor encompasses not only legislative frameworks but also policy interpretation, implementation, and feedback mechanisms that shape how strategic ambitions are carried into everyday practice. The prominence of this key factor points to the vulnerability of stormwater ambitions where policy frameworks remain fragmented or weakly aligned, particularly when established water-service obligations continue to carry greater institutional weight. In other words, policy coherence mattered not only for setting direction, but for giving stormwater ambitions sufficient institutional force to last in practice.

Land Use was likewise regarded as highly decisive, highlighting the extent to which future SSWM is conditioned by access to space, land-use authority, and the negotiation of competing urban functions and sectoral priorities. This is especially pertinent for surface-oriented and nature-based systems, whose implementation depends not only on physical availability but also on who can allocate, adapt, or share space across public and private domains. *Land Use,* therefore, appeared not as a purely spatial issue, but as a practical condition shaping what can realistically be implemented in dense, contested, or multifunctional urban settings.

Organizational Capacity was similarly prominent, shifting attention inward toward the internal arrangements that allow stormwater ambitions to become embedded in organizational routines rather than remain dependent on individual initiative or short-term momentum. Across the underlying factors, this key factor brought together knowledge sharing, collaborative readiness, governance structure, accountability, conflict handling, and decision-making capacity. Its position indicates that participants saw future SSWM as dependent not only on collaboration between organizations, but also on whether each

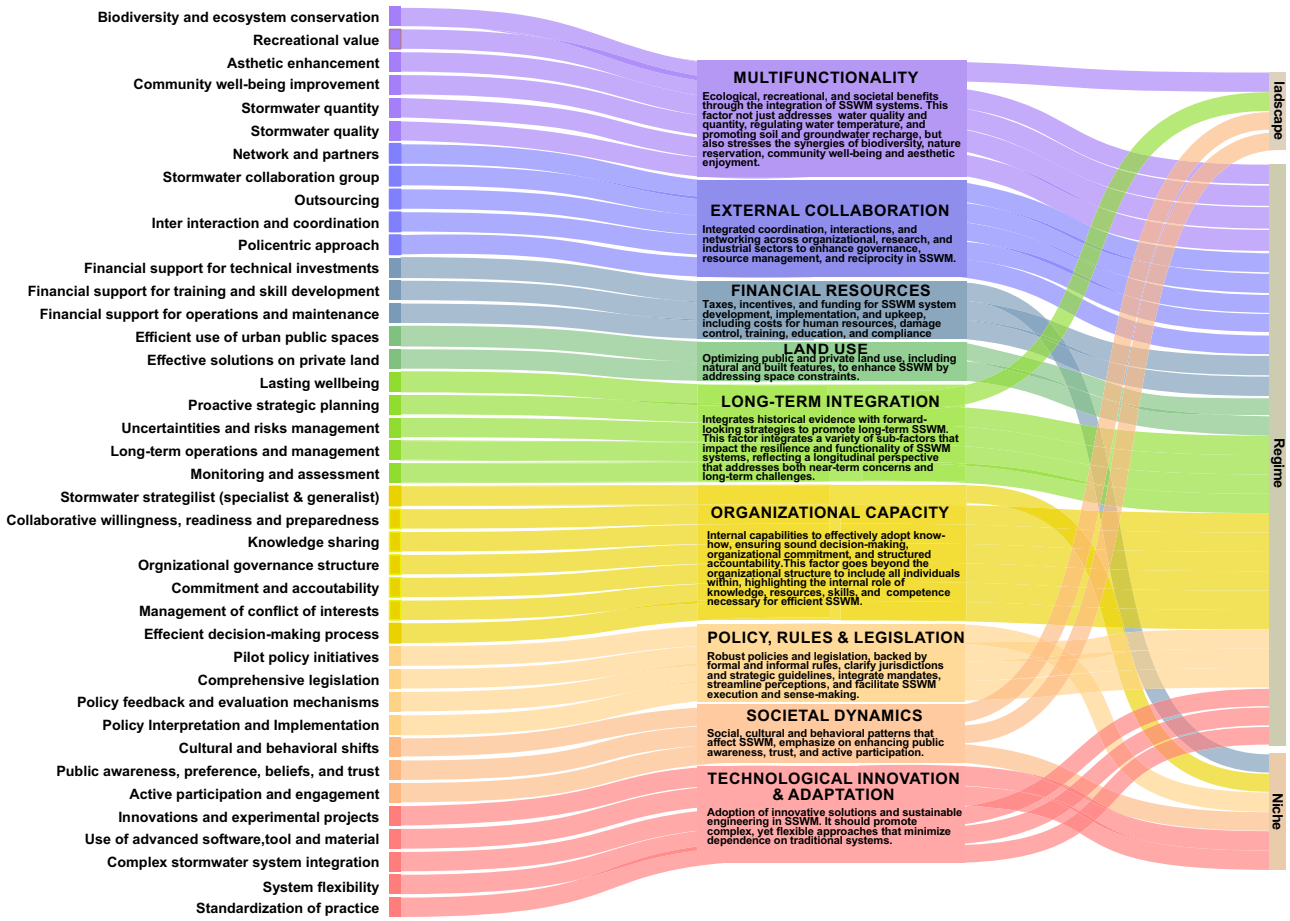

Fig. 3 | Thematic synthesis of identified factors into key factors. The figure shows how the 40 factors identified from interviews, organized across the three MLP levels, were assembled into nine broader key factors. The order of the key factors does not indicate priority. The connecting lines indicate how individual factors relate to more than one broader key factor.

Fig. 4 | Relative decisiveness of key factors influencing future SSWM. Bars represent mean decisiveness scores determined by participants during the assessment workshop using the Best–Worst Method. Error bars indicate standard deviation; the average consistency ratio was $\xi = 0.16$ ("Methods"). Source data are provided as the Workshop Source Data file.

organization had the internal coherence and continuity needed to act on shared ambitions.

Financial Resources showed moderate decisiveness, placing it below this governance and spatial cluster but still within the main set of implementation conditions. It was not treated as a stand-alone budget issue. Across the underlying factor set, financing entered through questions of technical investment, training and skill development, and long-term operations and maintenance. Projects were seen to lose momentum after pilot stages when funding was short-term, inconsistent, or weakly anchored in follow-up and maintenance. What mattered, then, was not funding in the abstract, but the continuity it made possible, allowing broader SSWM ambitions to outlast initial commitment.

Lower-ranked key factors for prospective decisiveness

For these factors, lower placement indicated a different form of prospective decisiveness rather than limited relevance. *Long-Term Integration* made this especially clear. Its placement pointed to a different timescale of decisiveness. Where the more highly placed key factors concerned whether SSWM could be initiated and coordinated under present conditions, *Long-Term Integration* concerned whether it could endure: whether stormwater considerations entered planning early enough, whether operation and maintenance were sustained, whether monitoring and assessment supported learning over time, and whether systems remained responsive as conditions changed. What this ranking captures is a form of decisiveness that comes into view as SSWM decisions move beyond implementation and into longer-term care.

Multifunctionality showed a similar pattern. This placement did not suggest that participants discounted the wider ecological, social, and stormwater-management value of SSWM. Across the underlying factors, *Multifunctionality* referred to the combined delivery of stormwater quantity control, water-quality treatment, biodiversity support, recreational use, esthetic value, and community well-being. Its ranking suggests a distinction between what SSWM is expected to deliver and what participants saw as

most immediately decisive for future decisions. The result points to a practical tension in which multifunctionality remains central to what SSWM is expected to deliver, yet appears in the prioritization as less immediate than the conditions through which that promise can be carried into practice.

Societal Dynamics was among the lower-scoring factors. Participants did not treat public attitudes, trust, and participation as immediate implementation levers in the same way as policy, land, or organizational capacity. Their significance appeared more gradually, through the formation of acceptance, shared responsibility, and everyday support for SSWM in neighborhoods, public spaces, and private land settings. The workshop discussion also highlighted a scale mismatch: SSWM is often planned and managed at the catchment scale, while its visibility, use, and contestation are experienced much closer to daily life.

Technological Innovation and *Adaptation* received the lowest decisiveness score. This may appear counterintuitive at a time when smart technologies, models, and treatment innovations are widely explored in stormwater research and practice. In the workshop discussion, participants did not dismiss technical advances, but treated them as insufficient on their own. They repeatedly returned to the institutional, spatial, financial, and organizational conditions required for innovations to gain traction in practice. What ranked lowest, then, was not the value of innovation, but the assumption that technical solutions alone could carry the transition toward SSWM.

Discussion

The highest ranking of *External Collaboration* places coordination capacity at the center of prospective SSWM decision-making in Malmö and Östersund. This result is in line with Pahl-Wostl and Gorris[51], who highlight coordination, collaboration, and networks as key governance conditions in multifunctional water landscapes, and with Qiao et al.[30], whose comparative work showed that governance factors such as public awareness, political priorities, trust in performance, and long-term maintenance funding influence whether SSWM can be carried forward in practice. It also resonates with recent Swedish work by Glaas et al.[25], which shows that climate-robust stormwater management often depends on collaboration between municipalities and property owners. In Malmö and Östersund, this meant the practical ability to coordinate across fragmented organizational settings, sustain working relationships across sectors, and mobilize partnerships that can move stormwater ambitions into implementation. Yet this finding does not imply that collaboration is simple. In contrast, participants described collaboration as demanding work, hindered by formal responsibilities, issue-based problem-solving, coordination costs, and the uneven timelines and decision logics of different actors[51]. Rather than presenting governance as a newly identified concern, our analysis clarifies how participants weighed governance conditions against other legal, spatial, financial, social, and technological conditions for future SSWM. In Malmö and Östersund, this comparison brought *External Collaboration*, *Policy, Rules, and Legislation*, and *Organizational Capacity* into view as the governance conditions most closely tied to coordinated decision-making for future SSWM.

The ranking is therefore best read not as a ladder of prioritization, but as an indication of where decisiveness enters the SSWM decision process. The higher-ranked factors pointed to the conditions that make action possible under current governance arrangements: coordination across actors, authority to interpret and apply policy, organizational capacity, access to land, and continuity of resources. The lower-ranked factors pointed to what these arrangements are expected to support. *Multifunctionality* captured the combined delivery of stormwater quantity and quality functions, biodiversity, recreation, esthetic value, and community well-being. *Societal Dynamics* captured the public awareness, trust, acceptance, and everyday practices through which SSWM gains support or becomes contested. *Long-Term Integration* and *Technological Innovation and Adaptation*, in turn, drew attention to whether SSWM can be maintained, learned from, and adjusted as conditions change.

This interpretation helps explain why governance, spatial, and resource conditions ranked above multifunctionality, societal dynamics, and technological innovation. Participants did not appear to treat the latter as less important. Rather, they treated them as less directly actionable unless the delivery conditions of authority, coordination, space, capacity, and funding were already in place. This distinction is consistent with recent work on multifunctional green infrastructure, which shows that multifunctionality does not follow automatically from adding more potential benefits, but depends on intentional choices about which functions are prioritized, coordinated, and maintained[9]. It also sits alongside urban NbS research showing that implementation barriers are often structural rather than isolated[29], and are shaped by infrastructure regimes, institutional routines, actor networks, governance processes[42], and assessment practices[52].

The low ranking of *Technological Innovation and Adaptation* gives this delivery-condition interpretation particular force. In a field increasingly shaped by demanding questions of hydrological performance as well as public health and ecological integrity, including PFAS[53] and other runoff-borne toxicants[54], the ranking should not be read as suggesting that technical knowledge is complete or that innovation is secondary in an absolute sense. An early Swedish sector guideline provides a useful historical parallel. In 1983, local stormwater management was described as technically clarified in many respects, while administrative and legal questions were still presented as unresolved[55]. Later developments have shown the limits of such closure, with emerging pollutants, new monitoring needs, and changing performance expectations reopening technical questions that once appeared settled.

Thus, the participants' ranking does not diminish innovation; it places its practical force in the institutional conditions needed to embed, coordinate, fund, legitimize, and sustain it over time. Recent work on stormwater maintenance reinforces this interpretation by showing that long-term performance often turns less on technical novelty than on clear responsibilities, funding arrangements, and the governance capacity to maintain systems across their life cycle[32]. This is especially relevant in SSWM, where NbS are increasingly embedded in Swedish municipal stormwater policy and practice, yet their long-term performance is still jeopardized by unclear responsibilities, insufficient funding, and a lack of long-term maintenance arrangements[31,56]. This shifts attention from technology-led decision-making toward the conditions under which technical possibilities gain traction in practice, aligning with earlier stormwater work on socio-institutional change and implementation politics[11,41], and with wider urban sustainability arguments that meaningful transition depends on connecting social, ecological, and technological change through governance rather than leaving them to unfold in parallel[57].

Beyond the case of technological innovation, this interpretation also clarifies how conditions for change in SSWM governance can be described without reducing them to fixed barriers or drivers. Recent studies in stormwater and NbS implementation have identified what obstructs or supports transition[28,58,59], while adaptation scholarship has long stressed the need to understand why such barriers arise and persist[60]. Our results add a comparative and prospective layer to this discussion. The same condition was not necessarily a barrier or a driver in itself; its decisiveness depended on the actor, decision setting, and phase of work through which it entered the process. In this study, decisiveness therefore refers not only to whether a key factor may hinder or enable SSWM, but to how consequential participants judged it to be for future action in Malmö and Östersund.

This reframing also sets the boundary of transferability. The prioritization is situated in the institutional, spatial, and professional conditions of Malmö and Östersund, and should not be read as a hierarchy for SSWM elsewhere. What is more transferable is the analytical sequence we used: reconstructing how conditions have shaped stormwater management over time, translating them into decision-relevant key factors, and examining their prospective decisiveness in context. We therefore identify empirically grounded decisive factors for the two case cities, while treating their relative ranking as context-bound. The broader contribution is a way of making

contextual judgment explicit before future SSWM decisions become stabilized in plans, assessments, and implementation pathways.

Within this analytical sequence, MLP gave our retrospective analysis a temporal and multi-level grammar (Fig. 2). It helped us trace how landscape pressures, regime arrangements, and niche developments entered participants' descriptions of stormwater management over time, while keeping the resulting factors connected to the conditions from which they emerged. Our study does not test transition theory or offer a new account of transition pathways, path dependency, or windows of opportunity. The value of MLP here was to carry a historically grounded reconstruction into the governance and decision-support question of which historically shaped conditions practitioners judged most consequential for future SSWM decisions. This allowed us to connect past transition experience with prospective prioritization, while keeping the ranking situated in the cases where those judgments were made.

For decision support, our findings sharpen the practical question facing future SSWM decision-making by shifting attention from selecting promising SSWM systems to identifying the conditions that allow them to be delivered. SSWM systems may appear attractive in plans, models, or design visions, but their implementation depends on whether key delivery conditions are assembled before choices become fixed. The key factors make these conditions explicit, including cross-sector coordination, authority to act across organizational and land-use boundaries, continuity in maintenance, financing, legitimacy, and shared responsibility. This is especially important in mixed-ownership urban settings, where implementation and long-term functionality depend on workable arrangements with private landowners as much as coordination within municipal organizations[42].

The key factors can therefore be read as decision-support prompts. They make delivery conditions visible before SSWM systems are fixed in planning and assessment, and bring governance-related judgment into clearer dialog with hydrological, environmental, and economic evidence[35]. This matters for a wider urban sustainability challenge, where water is increasingly understood as a governance-intensive question connecting stormwater, other urban water flows, and wider catchment relations across scales[61]. Future work should explore this retrospective-informed approach to prospective prioritization across other geographic and institutional contexts, including how the key factors can be translated into measurable or assessable indicators. Such work would benefit from involving larger and more varied stakeholder groups, including end-users, through iterative and deliberative approaches[62,63], in which judgments about decisiveness can be revisited as conditions change.

In conclusion, as SSWM agendas expand from water quantity and quality toward broader urban sustainability goals, future decision-making needs to look beyond whether SSWM systems appear promising and consider how they can be delivered, maintained, and adapted over time. In our study, this delivery challenge was most clearly expressed through *External Collaboration*, which emerged as the most decisive key factor for future SSWM. Its prominence points to the governance work required to coordinate actors, clarify authority, align organizational capacity, and sustain responsibility across planning, implementation, and maintenance. The lower-scoring key factors remained consequential, capturing complementary forms of prospective decisiveness related to what SSWM is expected to deliver, how it gains public support, and how systems endure and adapt as conditions change. By combining retrospective reconstruction with prospective prioritization, we identify empirically grounded decisive factors while treating their relative ranking as context-bound. The value of the approach lies in making contextual judgment explicit and bringing governance-related evidence into closer dialog with hydrological, environmental, and economic assessment before future SSWM decisions are formalized in plans and implementation pathways.

Methods

We used an exploratory sequential mixed-methods design[64], conducted in two empirical phases (Fig. 1a). Phase 1 comprised semi-structured interviews with professionals whose stormwater management experience covered the period from the late 1960s to the present, followed by thematic analysis and factor identification. Phase 2 comprised a workshop prioritization and discussion of the synthesized key factors using the Best–Worst Method[65]. This design allowed qualitative findings from the retrospective interviews to inform the subsequent prioritization exercise, linking factor development with prospective judgment about future SSWM decision-making.

Malmö and Östersund as case studies

Malmö and Östersund (Fig. 1b) were included as two Swedish case cities within a wider collaborative project with Luleå University of Technology. In Östersund, water quality has traditionally been the primary concern, as Lake Storsjön is the main recipient of surface runoff. By contrast, Malmö has placed stronger emphasis on water quantity, flood protection, and climate adaptation, particularly following extensive flooding in 2014. For this study, the two cities were treated as case studies, following Yin's definition of case study research as inquiry into a contemporary phenomenon within its real-world context[66]. The interview and workshop material were analyzed across the combined participant group rather than through a systematic city-by-city comparison. The two cities, therefore, provided contrasting municipal settings for factor development and prioritization, not a basis for statistical comparison or regional representativeness.

Participating professionals in stormwater management

Sweden's shift from conventional, pipe-based stormwater management toward more decentralized and sustainable solutions began in the 1960s[2], providing the point of departure for the retrospective interviews in Phase 1. We included both retired and currently active professionals in stormwater management. The interview sample combined participants whose professional experience reached back to the 1960s, as well as participants whose careers began later. This allowed us to trace change across periods while keeping recollections anchored in first-hand professional experience. Participants were identified through a combined positional and reputational logic[67]. Positional selection focused on professionals with formal responsibility for planning, regulating, designing, operating, managing, or maintaining stormwater-related work. Reputational selection was used to identify participants with long-term historical knowledge of stormwater management in Malmö and Östersund, including retired professionals, through recommendations from project partners and interviewees. A total of 17 participants from Malmö and Östersund took part in the semi-structured interviews, spanning sectors such as engineering and technical services, roads and planning, agriculture, environmental health, and wastewater and sewage management. Their roles ranged from technical investigators to senior organizational leaders. In the subsequent workshop, 7 of the 17 interview participants did not attend due to availability constraints.

Data collection and analysis

During Phase 1, we conducted 17 online semi-structured interviews between February and April 2024, each lasting approximately 1 h. The interviews followed the methodological approach described by Brinkmann[68] and were designed to allow narrative recall of professional experience[50]. To keep the retrospective material grounded in first-hand experience, participants were asked to reflect only on periods and roles they had personally worked through. Of the 17 interviewees (Fig. 1b), one participant from Malmö was retired at the time of the interview and had been professionally active from the 1960s to the late 1990s. The remaining 16 were professionally active when interviewed. Among these, one participant had professional experience reaching back to the 1960s, three had started their careers in the late 1980s, eleven in the early 2000s, and one had two years of professional experience.

The interview process continued until the material became increasingly repetitive, and no substantially new factor domains were emerging. The study followed the ethical principles of the Declaration of Helsinki for research involving human participants. The interviews, processing only non-sensitive personal data about participants' professional roles, were

audio-recorded and transcribed verbatim with informed consent, in accordance with the Swedish University of Agricultural Sciences (SLU) Data-Protection Manual. Interview quotations included in the manuscript were translated from Swedish to English by the authors. The SLU Legal Affairs and Data Protection Office confirmed that no external ethical review was required for this study; no reference number was issued. The complete semi-structured interview guide is provided in Supplementary Note 2. This guide was structured around the three MLP levels introduced earlier, with questions addressing landscape pressures, regime conditions, and niche-level developments.

We conducted a two-stage thematic analysis informed by Braun and Clarke[69]. In the first stage, we used open coding to identify recurring themes in the interview material (Fig. 1a, Step 5). These themes were consolidated into 40 factors capturing conditions that had shaped stormwater management transitions, and were then mapped onto the three MLP levels shown in Fig. 2. In the second stage, the 40 factors were refined and synthesized into nine key factors for prioritization (Fig. 1a, Step 6; Fig. 3). Across both stages, we repeatedly compared the emerging categories with the interview material and with relevant literature on stormwater governance, management, and sustainability assessment. This process was used to clarify category boundaries, refine factor names, and reduce overlap while retaining evident interdependencies. Analytical decisions were discussed within the research team throughout the process, with the aim of keeping the synthesis grounded in participant descriptions while making the factors interpretable in relation to existing research.

Workshop and prioritization assessment

Phase 2 of our study comprised a 3-h online workshop conducted in November 2024 with 10 of the interview participants. The workshop consisted of four sections: (1) a re-introduction to the study, (2) a brief review of the 40 interview-derived factors and the nine synthesized key factors, (3) a quantitative prioritization of the nine key factors using the Best-Worst Method (BWM)[65], and (4) a facilitated group discussion to elaborate on additional insights and contextual interpretations of the prioritization results.

The BWM was chosen for its ability to derive relative weights from a limited number of structured pairwise comparisons[65]. This was suitable for the workshop setting, where participants were asked to evaluate conceptually broad key factors within a limited time. Compared with full pairwise comparison methods, BWM reduces the number of comparisons required while retaining a consistency check for the prioritization results[65,70].

First, participants identified the best and worst key factors, framed in this study as the "most decisive" and "least decisive" key factors for future SSWM decision-making. Participants then completed two sets of pairwise comparisons using a scale from 1 to 9: the most decisive key factor over each of the other key factors, and each key factor over the least decisive key factor. These judgments were entered into the Excel-based linear BWM Solver v2.0 workbook, which was used to calculate individual optimal weights following the BWM procedure[65,70]. Individual weights were then aggregated across participants using mean values, with standard deviations reported in Fig. 4.

The workbook also returned an input-based consistency ratio and associated threshold for each completed assessment[71]. During the workshop, the workbook visually flagged entries outside the acceptable range, allowing potentially inconsistent assessments to be identified and, where needed, clarified before final calculation. The completed assessments fell within the acceptable range, with an average consistency ratio of 0.16. This supports interpreting the prioritization as reasonably internally consistent within the workshop group, while not implying statistical generalizability beyond it. The workshop should therefore be read as a small-N, expert-based prioritization exercise that supports analytical interpretation rather than statistical inference.

The workshop concluded with a facilitated qualitative discussion that allowed participants to expand on additional insights and contextual interpretations of the prioritization results (Fig. 1a: Step 8). Five researchers from Luleå University of Technology joined as academic contributors and offered additional perspectives during the discussion. To preserve the practitioner-centered basis of the prioritization, these researchers did not participate in the BWM assessment (Fig. 1a: Step 7).

Data availability

The aggregated workshop prioritization data supporting Fig. 4, including BWM weights, mean values, standard deviations, consistency ratios, and related calculations, are provided in the Workshop Source Data file. Interview transcripts are not publicly available due to participant confidentiality and data-protection restrictions. Anonymized excerpts supporting the findings were translated from Swedish to English by the authors and are included in the manuscript where applicable.

Code availability

No custom code was used. BWM calculations were performed using an Excel-based linear BWM Solver workbook, publicly available from the Best Worst Method software page and based on Rezaei[70].

Received: 21 August 2025; Accepted: 13 July 2026;
Published online: 18 July 2026

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Acknowledgements

This work was supported by the Swedish Research Council Formas (grant numbers 2021-00116 and 2021-02393). The funder had no role in study design, data collection, analysis, and interpretation, or in the writing of the manuscript. We thank Mikael Brocki and Jack Richold from the Swedish University of Agricultural Sciences for their assistance with the assessment workshop. We are also grateful to Maria Viklander, Ico Broekhuizen, and Utsav Adhikari from Luleå University of Technology for their contributions to the facilitated workshop discussion.

Author contributions

Z.S., T.B.R. and J.D.S. conceived and designed the study. Z.S. and J.D.S. conducted the semi-structured interviews, and Z.S., J.D.S. and T.B.R. facilitated the prioritization workshop. Z.S. collected and analyzed the data and prepared the visualizations. Z.S., J.D.S. and T.B.R. drafted the manuscript. G.T.B. and K.U. provided substantive revisions. G.T.B. and T.B.R. secured funding.

Funding

Open access funding provided by Swedish University of Agricultural Sciences.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s42949-026-00448-4.

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