Urban stormwater: from risk to resource

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Executive summary

Whilst urban wastewater is recognised in policy and practice as a source of alternative water, nutrients and energy, the potential for urban stormwater to provide multiple benefits has yet to be systematically considered. Taking the first step in addressing this gap was the central aim of 'Urban stormwater: from risk to resource'; a co-creation collaboration project which provided space for practitioners and researchers from multiple disciplines and sectors to explore the appetite for and opportunities to access resources inherent within stormwater. The stormwater resources identified include the water itself (irrigation and technical water use), energy (power and heat) and the sediments (rare earth metals, nutrients and fill materials), with discussions focussed on how such resources could be accessed routinely. The project involved a combination of internal and external workshops and steering board meetings, where discussions revealed widespread support from municipalities, utilities and private companies for exploiting stormwater resources. However, there was also clear recognition that achieving a shift in how stormwater is currently perceived (e.g. as an unclean water) and managed (primarily through pipe systems) could not be achieved by individual actions or actors. Discussions revealed the need for changes in several parts of society at the same time, with range of multi-actor activities required to enable stormwater to successfully transition from risk to resource.

Actions identified include the need for adapted business and value models to support a shift in stormwater management, particularly the development of models that capture broader benefits and distribute investment across multiple actors. Such a development would effectively 'open a door' to new financial opportunities that would enable the long-term, multi-benefit approaches considered to underpin this paradigm shift. In tandem with these activities, a formal regulatory framework - where legislation moves from a perceived blocker to an enabler of stormwater exploitation – is also required. However, it was also recognised that these developments must be grounded in a strong evidence base of proven co-created concepts tested at field scale in real world environments. For example, whilst technical solutions and AI offer powerful potential to enable smarter and more adaptive systems for stormwater management, their use must be embedded within broader governance and value frameworks and a wider societal understanding if they to succeed. Likewise, a shift from managing stormwater via underground stormwater piped systems to above ground nature-based systems (as standalone- or in combination with - piped systems) in publicly- and privately-owned locations requires not only more data on system performance but also a receptive general public with skilled, resourced practitioners working within integrated institutional frameworks. Hence, crossing the gap between technical feasibility and real-world implementation is dependent on co-creation, aligned incentives and the ability to test, demonstrate and scale solutions across varied urban contexts. In conclusion, the findings of this project evidence appetite for a stakeholder-led initiative to explore the requirements for - and to then develop the in-depth knowledge and evidence base required to facilitate - stormwater resources to be fully exploited as a key contribution to achieving sustainable urban living objectives.

Table of contents

1. Introduction

‘Urban stormwater: from risk to resource’ is a co-creation collaboration project funded under the Impact Innovation: Collaboration for Sustainable Water for All call within the Water Wise Societies 2024 programme. Core project partners are the Swedish Centre for Sustainable Hydropower, DRIZZLE Centre of Excellence for Stormwater Management, and Dag&Nät, a national stormwater and wastewater research cluster (all hosted by Luleå University of Technology), Vattenmyndigheten i Bottenvikens vattendistrikt (catchment scale water management authority), Växjö Kommun (water supply, waste- and stormwater management department), Örebro Kommun (environmental inspection department), Vattenfall (Sweden’s largest producer of hydropower) and Tecomatic (industry partner whose activities include stormwater sediment management).

The central aim of this collaboration is to explore opportunities to fully and safely exploit the circular use of three different resources within stormwater: the water itself, energy and the sediments it transports. Whilst some research and policy attention has been given to the collection and reuse of stormwater (Piazza et al., 2025), the potential for energy and sediment recovery is novel. The traditional conceptualisation and management of stormwater as a risk to human and environmental health that needs to be removed from the local environment as quickly as possible (conventionally by using piped systems) contrasts sharply with internationally recognized best practice for the exploitation of wastewater resources. For example, the recast EU Urban Wastewater Treatment Directive (2024) establishes challenging requirements for the quaternary treatment of wastewater to facilitate its reuse as an alternative water source, as well as for energy and nutrient recovery, specifically to facilitate the contribution wastewater can make to circular economy and sustainable cities objectives. Whilst extracting the resources from stormwater is not anticipated to be an easy challenge (stormwater accumulates pollutants as it flows over urban surfaces, use of technologies to extract energy from stormwater is not proven and the benefits to be derived from urban sediments are yet to be fully characterized), the magnitude of challenges facing urban water managers is such that the systematic analysis of the contributions stormwater can make to a water wise society is long overdue.

The central objective of the ‘Urban stormwater: risk to resource’ collaboration is to bring together stakeholders working with and impacted by stormwater management, hydropower capture and sediment management to collaboratively identify and explore the potential for stormwater to derive multiple benefits, significantly contributing towards the Water Wise Societies’ central mission ‘Sustainable Water for all by 2050’. Involving a combination of internal and external workshops and steering board meetings, key activities include a systems analysis of opportunities and obstacles, conceptualization of future scenarios and relevant actors, and development of a follow-up project proposal including the identification of specific activities, solutions and actors.

1.1 Urban stormwater: from risk to resource – a complex challenge

One of the most challenging effects of a warming climate is its impact on where, when and how often it rains (Dharmarathne et al., 2024). Ongoing changes in rainfall patterns have increased the risks of extreme weather events, from floods and droughts to heatwaves and wild fires, with direct and indirect implications for industrial, agricultural and domestic water users. For example, increases in the frequency and intensity of extreme rainfall events have major implications for urban areas due to a combination of their largely impermeable nature (generates stormwater runoff), limited green spaces (reduced opportunities for infiltration and evapotranspiration) and ageing drainage infrastructure (piped systems are expensive and disruptive to excavate) (e.g. Shuster et al., 2007). A further challenge is that rapid urbanisation over the course of the last 150 years means that many piped systems are already beyond their design capacity, further exacerbating the frequency of urban flooding events with associated (and increasing) social, environmental and economic damages. Within a national context, temperatures are predicted to increase in Sweden by 3-5^{o}C by 2080 (SMHI, 2021), with more rainfall occurring in autumn, winter and spring. Likewise, warmer summers will increase rates of evaporation contributing to an increasing number of low flow days in rivers, falling groundwater levels and drought events. Hence, the same urban areas – nationally and internationally - could face an annual increase in both flooding and drought events, raising a challenging but potential paradigm-shifting question: can the urban stormwater generated in wetter months provide an alternative water resource to mitigate summer droughts? However, reusing stormwater as a locally derived alternative water source is only one of the benefits to potentially be derived from stormwater, with the types and levels of benefits associated with stormwater as a source of energy (hydropower and heat) and the benefits derived from urban sediments (for example as a source of critical and rare earth elements and fill material) yet be to be systematically assessed from a range of user perspectives.

Exploiting stormwater for its water, energy and sediment resources – henceforth referred to as circular stormwater management - is not a straightforward process. From a water reuse perspective, particular attention needs to focus on stormwater quality. Stormwater runoff can mobilise and transfer a wide range of organic and inorganic substances from a diversity of sources to receiving waters (Müller et al., 2020). Hence stormwater not only needs collection but treatment prior to use, one of the drivers behind the increased interest in the use of nature-based solutions (NBS). NBS refer to a range of systems types - from street-scale biofiltration units to larger storage systems such as retention ponds – which enable stormwater to be managed from water quantity and water quality perspectives as well as facilitate opportuniti4es for its reuse (DRIZZLE, 2023). As with all water treatment processes, stormwater treatment using NBS results in the generation of a sludge (referred to as stormwater sediments) that then requires disposal, with the issue of stormwater sediment management identified as a major challenge for municipalities. Unlike wastewater sludge (referred to in regulation as biosolids and utilised as a source of organic matter and nutrients), the potential for stormwater sediments which accumulate in NBS to provide resources - ranging from nutrients to rare earth metals - has yet to be systematically assessed. In addition, NBS can generate a range of other benefits including habitat provision, urban cooling, improved air quality and physical and mental health benefits. However, challenges remain in their implementation as a new approach which urban planners and municipalities require support to integrate into current institutional, operational and management strategies and approaches.

From a governance perspective, implementing circular stormwater management is not only a technical challenge but also an institutional one. Municipalities must navigate overlapping responsibilities, unclear mandates, and fragmented decision-making structures (Brown and Farrelly, 2009). Even when policies formally support NBS, their uptake in practice depends on how responsibilities are distributed, how maintenance is organized, and how different departments and actors coordinate (Lundy et al., 2025). These factors shape the extent to which stormwater resource exploitation becomes a feasible and integrated part of urban water management.

Implementing a system for circular stormwater management also involves dealing with social aspects. Many studies in the field of sociotechnical systems in general highlight how technically sound systems fail to achieve their intended effects due to lacking harmonization with the so-called ‘social system’ (e.g. needs, wishes, cultures, and norms of people) (Mumford 2006). With changes to stormwater management this can involving addressing issues ranging from usability and technology acceptance in the sense of making sure new technologies are used (e.g. for using/processing etc. stormwater), to changing perceptions regarding what is reasonable to expect of individuals/citizens and/or homeowner with regards to tasks and responsibilities related to stormwater management (e.g. collection, maintenance).

A further complexity relates to harvesting energy from stormwater, a concept which is technically challenging due to its irregular, low-pressure, and short-duration nature, often occurring in bursts during rain or snowmelt. Nevertheless, with creative approaches, this untapped resource can be utilized in urban environments – for example, to power sensors, lighting, or local control systems. Solutions such as microturbines in drainage systems, or small-scale heat recovery can contribute to smarter, more resilient infrastructure. Further research is needed to develop reliable and efficient technical systems that can adapt to the variable and site-specific conditions of stormwater flows. Integrating fluid dynamics and energy flow optimization is key to making these systems effective at the city scale.

Given the current predominantly underground piped infrastructure approach to stormwater management, traditionally siloed institutional, organisational and legislative structures delivering urban drainage, and the fact that stormwater management has yet to embrace the technological developments routinely used in other parts of the water sector e.g. online sensors and machine learning utilised in drinking water supply and wastewater management, a shift to circular stormwater management is a major challenge. However, the opportunity for stormwater to provide a locally derived but - as yet - untapped alternative water source, energy supply and materials resource offers an opportunity to make a considerable contribution in supporting the transition to a Water Wise Society, both nationally and internationally, with the default use of NBS as a delivery mechanism. Stormwater is the only component of the urban water cycle yet to be integrated into circular economy and sustainable city thinking, with ways in which circular stormwater management could contribute to the Water Wise Society mission and sub-goals described in the following section.

1.2 Mapping to the Water Wise Society mission and sub-goals

Shifting to a circular stormwater management approach has the potential to make a direct, significant contribution to the central Water Wise Society mission ‘Sustainable water for all by 2050’ by providing an alternative locally derived water source for use in multiple contexts in industrial, agricultural and domestic contexts. In providing a source of water in applications that do not require drinking water quality water e.g. irrigation, cooling water, car washing and garden watering, it is a strategy which aligns with the use of water on a ’fit for purpose’ basis in response to changing climate where drought and floods occur more frequently. In relation to sub-goal 1 ’Resilient water supply and management in society’, circular stormwater management can contribute to all four sub-missions, with a particular focus on sub-mission 3 ‘adapt society to floods and droughts’ through providing buffer for water demand in times of drought. The use of default use of stormwater NBS will also reduce the diffuse pollutant load entering surface waters and groundwater (contributing to ensuring good drinking water) and providing green-space benefits in urban areas (build and manage society in harmony with water).

In terms of sub-goal 2 ’Wise water use’, the use of treated stormwater to recharge surface water and groundwater contributes to achieving water availability targets for future abstraction operations (sustainable water withdrawals) with the systematic collection and treatment of stormwater providing new opportunities for reducing drinking water in applications where water of this quality is not required e.g. firefighting. Circular stormwater use – in the broader context conceptualised here to include energy supply and sediment materials recovery – makes a particular contribution to the third sub-mission ’recycle and reuse water and its resources’. Circular stormwater management also has the potential to contribute to all three sub-mission of sub-goal 3 'healthy lakes, streams and groundwater' with the use of NBS to treat stormwater having a direct impact on health of aquatic systems, by reducing the discharge of hazardous substances and nutrients to surface waters and groundwaters.

2. Methodology

As a novel and inherently multidisciplinary and cross-sectoral issue, conceptualising circular stormwater management and identifying activities required to enable its implementation necessitates a co-creation approach. Hence, two complementary methods underpinned project activities:

- multidisciplinary project work
- stakeholder-driven innovation

Both approaches were guided by co-creation principles to support inclusiveness, systems thinking, and cross-sectoral learning between research disciplines and between research and practice. These methods were also chosen to strengthen stakeholder ownership and to increase the project's potential for long-term impact. More specifically, a co-creation approach facilitates participants to work collaboratively across roles and sectors to enhance understanding of complex problems and to develop innovative solutions and more grounded outcomes together.

For co-creation to work as intended, a number of central principles must be in place: early and active participation by relevant actors, a shared understanding of the purpose, and collective ownership of both processes and outcomes (Brandsen et al., 2018; Voorberg et al., 2015). The requirement for early and active participation of relevant actors was achieved through identification of project partners who had previously expressed interest in the topic during earlier projects and within network meetings of the two competence centres, and hence core partners could be involved at all stages; from proposal development through to reviewing the final report. On commencement an initial project activity was the establishment of a steering board, comprising representatives from all project partners, whose role was to continuously review and validate the group's proposals. Internal project work was carried out within two complimentary fora:

- interdisciplinary: a research group drawn from six disciplines at LTU (stormwater management, fluid mechanics, entrepreneurship and innovation, environmental law, political science and human work science) who were responsible for conducting a system analyses, identifying key stakeholders and for coordinating project activities led by the project manager.
- intra-organisational: core partners Växjö and Örebro municipalities held internal meetings to e.g. enable colleagues from various municipal departments to contribute to discussions and assess the appetite of senior management to support the use of municipal resources to explore new concepts proposed

Hence, development of a shared understanding of the purpose of the project was fostered through a series of online and face-to-face meetings held at organizational, cross-organisational (steering board meetings) and open event (e.g. open work shop in which the steering board participated with a wider range of participants from their own networks) levels. This approach was well received, fostering a collective ownership of both processes and outcomes.

A central milestone in the stakeholder-driven process was a full-day co-creation workshop titled *Urban Stormwater - From Risk to Resource* which was designed and facilitated by the project manager in accordance with key co-creation principles. Its aim was to explore future scenarios, identify potential system shifts, and outline pathways forward. The workshop brought together forty participants from municipalities (including municipal water and sewage companies), County Administrative Boards, universities and other authorities, consultancies and companies, including the Swedish power company Vattenfall. To build a shared foundation, the day began with an introduction to the *Impact Water Wise Society* programme and this project. Expert input from researchers in urban stormwater engineering and fluid mechanics followed, framing the broader challenges and opportunities surrounding urban stormwater from both technical and systemic perspectives.

The core of the workshop focused on structured co-creation activities in small, consistent groups. Participants engaged in futures-oriented exercises using the Janus Cones method (Voros 2003). This is a tool designed to encourage backward and forward reflection, helping participants develop a shared situational understanding by examining past and present system dynamics (the "backward-looking" perspective) and then imagining desirable futures (the "forward-looking" perspective). Guided by the question *What is possible in the future?* groups developed visions for stormwater, energy, and sediment solutions in relation to their own perspective of the future, with groups proposing timelines for 'the future' which ranged from 2035 to 2100. These visions were then traced back to the present to identify the system transformations (e.g. frameworks and tools) necessary to enable envisaged changes to be delivered in practice. This included discussing whether current structures and responsibilities would still be relevant in the future. Using a simplified version of Context Mapping (Visser et al., 2005), the groups identified important relationships, conditions, and institutional factors that could either support or hinder implementation. These reflections helped clarify which shifts might be necessary and provided input for the final step – to develop ideas on how to move the work forward. The day concluded with the co-development of conceptual ideas, reflections on which additional actors should be involved and what concrete activities would be needed to move forward. Hence, the co-creative approach fostered meaningful knowledge exchange and engagement across disciplinary and sectoral boundaries.

3. System analysis of Urban stormwater – from risk to resource

3.1 Transitioning to circular stormwater management

Throughout human history, excess surface runoff (generated during rainfall events when permeable grounds have become saturated) has been a challenging concept to manage. This is particularly the case in cities, where impermeable urban surfaces (roads, pavements and buildings etc) prevent rain infiltrating into the ground, which can result in the rapid generation of large volumes of surface runoff (Shuster et al., 2007). The traditional approach to managing runoff is to directly drain it via a series of pipes to the closest water course. However, this approach neglects water quality impacts (as it moves over surfaces runoff mobilises pollutants from a range of sources e.g. traffic and building materials), with deleterious impacts on receiving waters that have implications for its subsequent use as a drinking water source and in achieving environmental objectives. Further, as a result of rapid urbanisation, many piped systems are at (or beyond capacity) leading to pluvial flooding (i.e. blinded drains surcharge causing inland flooding). This has led to a shift in best practice from piped systems that move – rather than manage – stormwater to use the use of nature-based solutions (NBS), a series of blue-green infrastructure measures that capture and treat stormwater. The increasing use of these aboveground decentralised systems additionally offers new opportunities to extract further resources from stormwater e.g. water, energy and sediments.

Whilst this paradigm shift is underway in relation to the reclamation of water, energy and nutrients from treated wastewater from research, policy, regulation and practice perspectives (e.g. EU Water reuse regulations 2020), similar attention has yet to apply to stormwater. In reusing treated wastewater, a barrier in its default adoption is a lack of wide spread public support for the approach, as treated wastewater is typically viewed negatively. Whilst this is starting to change – particularly in countries routinely experiencing drought - similar concerns about reusing stormwater could be anticipated, and efforts to work collaboratively with stakeholders (including the public) are urgently required to understand practitioner and user perspectives on using stormwater, the types of information that would give confidence in use and who would be trusted to provide that information (e.g. creation of social license Cooper et al., 2022).

Hence, reconceptualising urban stormwater from a risk to a resource requires holistic thinking which would require actions across multiple systems levels, with interactions between these systems required to enable this transition to occur. As a baseline to inform discussions, five central system components were identified on discussion with steering board members as being pertinent to delivering systemic change at a catchment level:

- infrastructure
- technical solutions
- business models
- governance
- cultural values

These components were scoped by the LTU multi-disciplinary team and discussed with stakeholders during the one-day co-creation workshop. The below sections summarise key discussion points.

3.1.1 Supporting infrastructure and production systems

To be able to extract resources from stormwater, physical infrastructure is required with preference given to systems that are flexible, robust and adaptable to meet both current and future needs. Workshop participants highlighted the importance of green and blue infrastructure (i.e. stormwater NBS such as wetlands, ponds and swales) becoming an integrated part of urban planning approaches. More specifically, there is a need to shift from the use of NBS as a ‘desirable add-on’ to its inclusion as a core urban water management supporting structure that can address stormwater management from quantity and quality perspectives as well as deliver a range of other ecosystem services. This means that stormwater management systems such as detention ponds, biofiltration units and green roofs are designed to both manage stormwater from quantity and quality perspectives, as well as generate other services such as biodiversity, mitigation of air, noise and urban heat island effects as well as social spaces for physical and mental health wellbeing.

However, participants were clear that existing stormwater piped systems should not be removed and replaced wholesale (viewed as a waste of resources), rather that stormwater NBS should be deployed in a parallel manner to complement, extend and work with existing systems as best suits local circumstances i.e. use of NBS both as a standalone system (where appropriate) and in combination with local stormwater management systems that are already in place. Future stormwater systems must also be resilient to change in climatic (e.g. increase in extreme events such floods, droughts and heat waves driven by a warming climate) and societal (e.g. greater participation in local decision-making and access to real-time data) demands through, for example, integration of stormwater within strategies used within the drinking water supply and wastewater management sectors. Specific suggestions include avoidance of the duplication of pipeline systems, greater use of pipe leak detection and remediation technologies and digital control systems for efficient operation and maintenance of urban water systems. Several groups suggested increased use of artificial intelligence (AI) and smart monitoring as important components of a future, resilient infrastructure, noting that, for example, whilst the use of e.g. sensors and machine learning is routinely utilised in drinking water and wastewater contexts, such technologies have yet to be fully utilised in stormwater management arenas.

3.1.2 New technical solutions

To enable more sustainable and resource-oriented stormwater management, innovation is required in several technical areas. Among topics discussed, workshop participants highlighted the need for new solutions to extract energy from stormwater – for example, by utilizing potential and kinetic energy in flows and recovering heat from water masses. There was also a strong interest in nature-based treatment solutions, where, for example, biofilter beds or wetlands are integrated into the urban environment to enhance water quality through facilitating a range of processes – e.g. sedimentation of suspended particles and associated pollutants to microbial degradation and photolysis – to occur, and at the same time contribute to biodiversity objectives. Furthermore, there was a demand for development in measurement technology and digital systems, where AI and simulations can play a central role in monitoring flows, identifying pollution sources and dynamically controlling stormwater systems. The future scenarios also visualized 'urban mines', where sediment from stormwater systems are analysed and substances extracted for reuse such as rare earth metals, nutrients and fill materials. The technology to recover a range of materials from a variety of matrices is largely available, their applicability to urban stormwater sediments has yet to be systematically interrogated and it is unclear if existing technologies will require further development and how they can be integrated into existing systems.

More specifically – and from a fluid mechanics perspective - many of these innovations require a deeper understanding of unsteady, multiphase, and turbulent flows in complex geometries involving free surfaces and sediment transport. Advanced simulation tools, combined with empirical data, are essential for predicting key factors such as pollutant dispersion and velocity profiles in both engineered and nature-based conveyance systems. Optimization of hydraulic structures is necessary to control flow separation and energy dissipation, particularly to reduce peak loads on the drainage network. At the microscale, flow through porous media such as biofilters needs to be analysed to optimize retention time and filtration efficiency. Harnessing interactions between flow regimes and thermal gradients for heat recovery requires detailed quantification of convective heat transfer, which correlates with boundary layer development under variable flow rates. In these contexts, AI can enhance simulation workflows by identifying patterns in complex flow data. Machine learning algorithms can be trained on high-fidelity numerical results and sensor data to create fast, surrogate models for flow prediction, enabling dynamic system optimization without the need for computationally intensive simulations. Integrating fluid mechanics and AI into stormwater system innovation enhances technical performance, operational efficiency, and supports more resilient and sustainable urban water management. However, moving innovations from simulation to real-world applications, testbeds and pilot installations are essential. They provide opportunities to validate simulation results under real conditions, adapt solutions to site-specific constraints, and accelerate the transition from concept to scalable practice. Such experimental platforms are critical for refining technical designs, building confidence among stakeholders, and supporting the broader uptake of innovative stormwater technologies.

3.1.3 Working business and value models

To reposition stormwater as a societal asset rather than a management burden, its diverse functions and benefits must be explicitly recognised and integrated into economic systems. Participants in the workshop underlined that a fundamental shift is required—from treating stormwater management as a municipal cost centre to recognising it as a generator of value. This value extends beyond conventional water infrastructure performance and includes ecosystem services such as biodiversity enhancement, climate adaptation, recreational opportunities, and urban cooling. Realising this shift entails the development of business and value models that not only allow but encourage multifunctionality and long-term returns on investment. Valuation methods—such as those used for assessing ecosystem services—can help translate intangible benefits into economic terms, which is essential to attract financing, build political support, and guide policy development (Johnsson and Geisendorf, 2022). Participants emphasised the need for a “common language” where benefits and costs are equally weighted and where systemic co-benefits are acknowledged across sectors.

A key mechanism identified in both the workshop and scenario development was the polluter pays principle, which links environmental responsibility directly to economic accountability. This principle is gaining traction within EU policy, notably in the revised EU Urban Wastewater Treatment Directive (2024), and could serve as a financial driver for stormwater innovation. It also opens the door to new market logics where improved upstream management and pollution prevention—whether by industries, landowners, or consumers—can be incentivised or regulated through economic instruments. Furthermore, participants envisioned future stormwater systems as platforms for value creation, capable of generating revenue through sediment recovery (e.g. urban mining of metals and minerals), small-scale energy production (e.g. from hydraulic pressure or thermal recovery), or through cost offsets in heating, cooling, or green infrastructure maintenance. These propositions are not yet fully explored in mainstream urban water management but offer potential for novel financial mechanisms.

However, unlocking this potential will require new collaborative financing and investment models. These must span sectors and institutional silos, enabling cooperation between public authorities, utilities, real estate developers, infrastructure providers, and civil society. Participants noted that such models would need to accommodate both short-term accountability and long-term system resilience. Clear distribution of both responsibilities and benefits is vital to avoid fragmentation or inertia. Co-investment schemes, outcome-based financing, green bonds, and payment for ecosystem services were all mentioned as promising avenues for exploration. Ultimately, business models for stormwater as a resource will need to be adaptable, transparent, and capable of managing complexity. They must not only support existing policy frameworks but also help shape more integrated planning environments where water, energy, material flows, and land use are considered together. The development and testing of such models could be a fruitful area for future research and pilot projects, in collaboration with municipalities, utilities, and the private sector.

3.1.4 Enabling policy and regulations

A crucial dimension of implementing any change is governance. In this case, this relates to the regulations, norms and responsibilities that surround stormwater management systems. The workshop clearly pointed to the need for a more proactive and enabling regulatory framework, where stormwater is recognised as a resource in planning and legislation rather than solely as an environmental problem. This included calls for clearer limit values for stormwater use on a per application basis, functioning self-monitoring systems and instruments that not only encourage circular solutions but make them easy to use (Johansson et al. 2024). Overall, this means, among other things, that the legal framework for stormwater management needs to be reviewed. The legal conditions for using stormwater as a resource and thereby promoting both sustainable development and a circular economy, must be investigated with the goal of finding more appropriate solutions (Johansson, 2024; Pettersson and Johansson 2023).

The need for clearly identified boundaries of responsibility between different actors is another key issue, where today's often unclear division of responsibilities can lead to conflicts or delays in action. Challenges have been identified in terms of vertical integration, primarily linked to the spatial planning system, and in terms of horizontal integration between actors at the same level. By clarifying roles, and by integrating stormwater management into comprehensive planning, climate adaptation strategies and community development processes, more coordinated development can be enabled (Brown and Farrelly, 2009). Workshop participants also highlighted the time dimension. Circular use of water, energy and sediments requires long-term perspectives in policy and planning, but also that stormwater issues and relevant stakeholders (such as private property owners) should be included early in the planning process.

A common denominator in several groups' visions was that stormwater should become a politically prioritized area with clear leadership and guidance provided from the national level. A circular approach to stormwater use could drive such a development. In addition to creating added value in urban environments (e.g., recreational values and increased biological diversity), innovative stormwater management can reduce vulnerabilities, for example, by using stormwater for irrigation during droughts or providing emergency water supplies in times of crisis. Increased public awareness was also highlighted as a driver for a more ambitious stormwater policy. When stormwater is made visible in the urban environment, through multifunctional and nature-based stormwater solutions, public understanding of it as a resource can increase (Frantzeskaki, 2019).

3.1.5 Permissive culture and values

Cultural norms and attitudes are also crucial in creating acceptance for new solutions and investments. Here, a human-focused approach, which emphasises that technological transitions must be grounded in human-centric values and social purpose, may play an important role (European Commission, 2021). Such an approach is not only more just, but often more effective, particularly in systems where public trust and local engagement are essential, and where democratic participation and the joint optimisation of social and technical systems can enhance both performance and quality of life (Mumford, 2006).

The workshop showed that today's view of stormwater – as something unattractive or dangerous – needs to change to create the conditions for innovation. For example, it was discussed how the view of water barrels – as open systems or dirty water - is negative, which adds to the difficulty of implementing visible solutions. Participants called for increased water awareness, both among citizens, decision-makers and professionals, with this referred to as "water literacy". Through education, communication and co-creation, understanding and commitment can be built. A changed risk perception – where risks are managed through participation and small-scale testing – can pave the way for more imaginative decisions and a more open conversation about how stormwater can be used more actively in the city. Importantly, acceptance is not just about individual attitudes but about collective values and individual interests. New systems must reflect the needs and concerns of those affected, offering benefits such as affordability, ease of use or alignment with personal views. Active involvement of stakeholders in the design process – not merely informing them – arose as a theme in the workshop. A component of this is a permissive culture, where experimentation is encouraged and diverse perspectives are valued.

3.1.6 Closing reflections

From the above discussions, it is clear that transforming urban stormwater from a risk to a resource requires more than individual actions – it requires change in several parts of society at the same time. The scenarios and insights developed in this project show that a systems analysis that includes technology, economics, infrastructure, governance and culture is necessary. In particular, the need to adopt a co-creation approach through widening participation at all stages (i.e. problem identification, consultation, design, implementation and knowledge exchange) and the use of small-scale testing sites to demonstrate proof of concept are highlighted as a mechanism to developing collaborative understanding and commitment to implementing changed practice.

The above discussions have revealed a range of key actions and activities required to facilitate the paradigm shift of stormwater transitioning from risk to resource. These include the need for functioning business and value models to support the shift, particularly models that capture broader societal benefits and distribute investment and responsibility transparently across actors. Addressing this need opens the door to developing new financial mechanisms and institutional arrangements that enable long-term, multi-benefit approaches. In parallel with these activities, a formal regulatory framework - where legislation shifts from a perceived obstacle to an enabler of stormwater utilisation – is required. However, the development of new legislation and business models must be based on a strong evidence base of proven co-created concepts tested at field scale in real world environments. For example, technical solutions which integrate fluid mechanics, energy recovery strategies and AI offer powerful potential to enable smarter and more adaptive systems for making use of stormwater as a resource, but their use must be embedded within a broader governance and value frameworks and societal understanding to succeed. Likewise, a shift from underground stormwater piped systems to above ground NBS in publicly- and privately-owned locations requires not only more data on system performance but also a receptive, water literate general public with skilled, resourced practitioners working within integrated institutional frameworks. Hence, bridging the gap between technical feasibility and real-world implementation will depend on co-creation, aligned incentives and the ability to test, demonstrate and scale solutions across varied urban contexts. This analysis hence forms the basis for further work – in the form of continued collaboration, practical pilots or future research initiatives.

3.2 Future visions for circular stormwater management

During the co-creation workshop, cross-sector and disciplinary teams co-created a series of scenarios, each of which focused on considering how resources extracted from stormwater (such as energy, heat, sediment, and nutrients) could contribute to sustainable circular urban living. While the scenarios highlight different aspects of stormwater use, they share a common focus on collaboration, long-term planning, and the need to rethink current systems. Key findings are summarised below together with key words and identification of relevant actors. Group work also involved the development of 'newspaper front page' story boards as a way to share main messages, with two examples inspired by this activity presented in Figure 1.

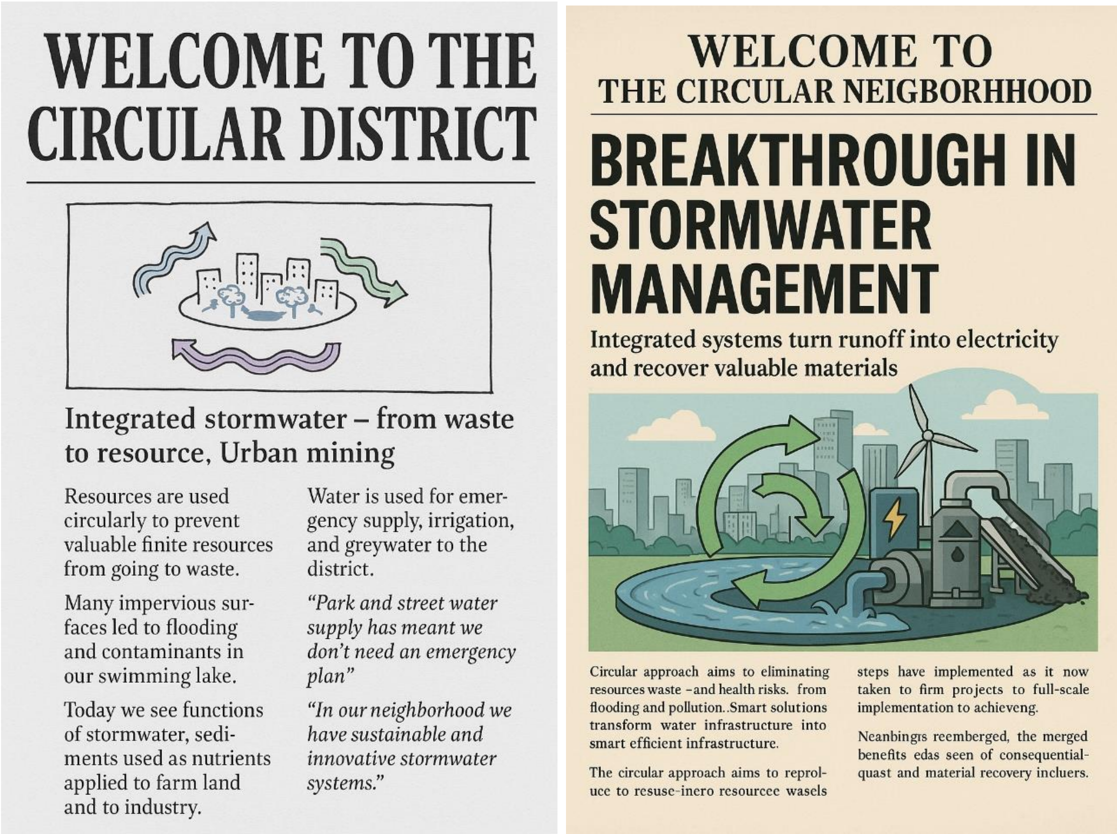

Figure 1. Newspaper front page story boards inspired by those developed during co-creation activities

3.2.1 Scenario 1: Circular Water Communities - stormwater at the centre of resource management and climate resilience

In the future, stormwater has become an integral part of circular urban development (see Figure 2). The systems are designed to reuse water and sediment locally – for irrigation, drinking water production, and extraction of metals, nutrients and fill materials. Co-ordinated and timely planning, clear threshold values for water quality, active participation of end-users and citizens and strong political prioritization have created long-term conditions for sustainable stormwater management. Green and blue infrastructures are standard, and biodiversity is benefited in all parts of the city.

Figure 2. Image inspired by the vision 'Circular water communities – stormwater at the centre of resource management and climate resilience' (Image credit: Vinter)

Keywords: Circular use, sediment extraction, green/blue infrastructure, urban mining, timely planning, cross-sector collaboration,

Relevant actors: local and regional actors (municipal water utilities, municipal departments for urban planning and environment, County Administrative Boards, local citizens), private companies to build and maintain NBS, technology to enable on-line monitoring of NBS, policy makers, researchers, Vinnova, RISE and IVL

3.2.2 Scenario 2: Energy from Water – Power in Every Drop: rainwater systems as energy producers in the cities of the future

The cities of the future use the potential and kinetic energy of runoff to produce electricity – in pipes, NBS and smart energy hubs (see Figure 3). At the same time, heat is recovered from runoff to heat buildings. Technology and AI are used to optimize and simulate energy flows based on the expressed needs of citizens and end-users established through their involvement in the development process, and investments enable large-scale expansion. This has made urban stormwater runoff an obvious part of the energy system and increased citizens' awareness of its value.

Figure 3. Image inspired by the vision 'Energy from water' (Image credit: Vinter)

Keywords: Energy recovery, potential energy, new technology, AI-based optimization, small-scale hydropower

Relevant actors: energy companies, the Swedish Energy Agency, municipalities (urban planners and municipal water utilities), researchers with expertise in fluid mechanics, AI and energy systems, hydropower technologists and citizens, Vinnova, RISE and IVL, property owners and developers.

3.2.3 Scenario 3: From Risk to Raw Material: sediment as a key resource in the city

Stormwater systems have developed into urban mines where sediment is controlled, analysed and refined (see Figure 4). Through effective separation and purification, rare earth metals, fill materials and nutrients are extracted and returned to the city's cycle. This is done in collaboration between municipalities, business (as producers and end-users) and research actors, with active participation of citizens. The system is based on the polluter-pays principle, clear division of responsibility and strong legislation on pollution.

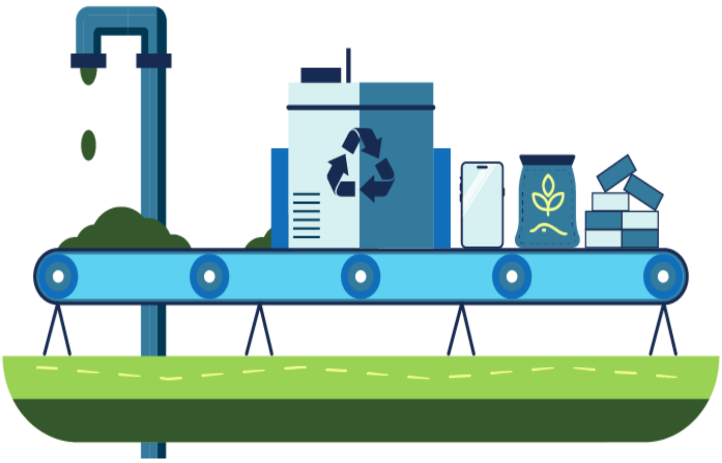

Figure 4. Image inspired by the vision 'From risk to resource: sediment as a raw material' (Image credit: Vinter)

Keywords: Sediment management, recycling, urban mining, division of responsibility, polluter-pays

Relevant actors: researchers, Vinnova, RISE, IVL, municipalities, technologists, NBS operation and maintenance companies, potential end-users and citizens

3.2.4 Scenario 4: Co-creation and System Shift: the city as a learning system with the citizens at the centre

In this scenario, stormwater management has become a common concern at regional and local political, organisational and citizen levels (see Figure 5). Through co-creation, education and increased water awareness, residents, decision-makers and experts have found new forms of collaboration. Risk perception has changed, as have attitudes towards pollution. NBS and local management are the norm. Decisions are based on AI support and scenario planning that integrates both benefit and risk in governance.

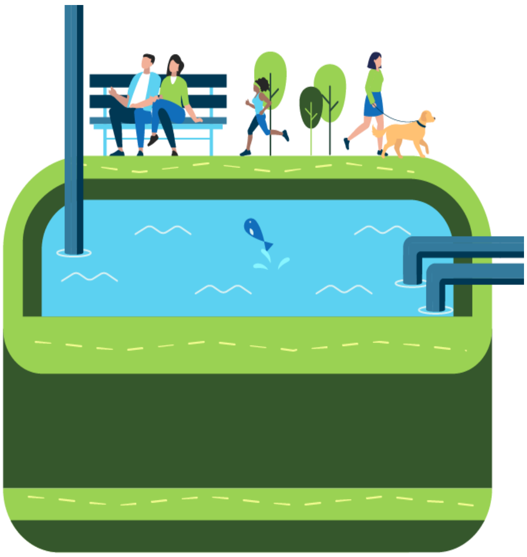

Figure 5. Image inspired by the vision 'Co-creation and System Shift' (Image credit: Vinter)

Keywords: Co-creation, water literacy, nature-based solutions, AI, changed risk perception

Relevant actors: general public, NGOs, Swedish Civil Contingencies Agency, educationalists, researchers, urban planners and municipalities, Vinnova, RISE, IVL

4. Next steps - what type of follow-up project is needed?

Based on the steering board discussions and co-creation workshop activities, the below recommendations for next steps are put forward.

Explore stormwater as a multi-faceted resource
How can stormwater be seen as an asset rather than a burden in the city? We see a need for further investigation to characterise and benchmark (quantitatively or qualitatively) how specifically stormwater can contribute to:

- ecosystem services delivery: what types of benefits are delivered, understanding of who benefits and under what conditions are benefits generated?
- water supply: can stormwater of the required quality and quantity be available as needed? How should use/users be prioritised if supplies are limited? Where and how should it be treated and stored?
- energy production: what types of energy can be extracted? What can it be used for? Do we have the required technology to extract energy? At what scale is energy recovery viable? Can it be used by homeowners and in industrial applications? Who has the competence to do so?
- sediment recycling – detailed characterisation of stormwater sediments is needed to evaluate their resource potential. Key questions include: Are current maintenance routines, emptying methods and sampling strategies adequate to support efficient recycling? what materials can be recovered? under what technical, economic and regulatory conditions is recovery viable? Who are the key actors with the responsibility, mandate, or competence to enable recovery at scale?
- what barriers and opportunities exist to scale up of above approaches to a city-scale?

Identify system changes that enable circular and resilient solutions
To take the next step, we need to:

- undertake urban stormwater stakeholder mapping to identify those with responsibilities for stormwater management, who are impacted by decisions made and who holds the finances for implementing stormwater management strategies
- map out what changes in views/perceptions, governance modes, responsibilities, financing and technology may be needed
- identify how can current structures be (re-)developed to support long-term sustainable stormwater management

Deepen understanding of the interaction between technology, governance and societal actors
Stormwater issues concern many different actors with different roles and perspectives. A next step is to study the interaction between technology, policy, people (including norms and culture) and practice – and how we can create better conditions for collaboration across sector boundaries. What lessons can we learn from the interplay between technology, policy, people (including norms and culture) and practice from other parts of the water sector where for example, sensor technologies are routinely used for ensuring water quality and quantity requirements are delivered.

Analyse possible paths forward – tools, methods and forms of collaboration
By building on the scenarios from the workshop, there is an opportunity to concretize different development paths. For example, what types of tools (e.g. AI, simulations, risk assessment) and processes (e.g. co-creation, testbeds) can support the stormwater system of the future? Are new tools needed or can existing technologies be deployed in new ways?

Creating a basis for continued development and collaboration – in practice and in research
Based on the work that has already been done, we see an exciting opportunity for a stakeholder-led initiative to enable a joint exploration between practice and research to

establish the requirements for and to then populate an in-depth knowledge and evidence base required to co-create the basis for future projects, applications and partnerships.

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