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Sitting in our own soup? Combined sewers, climate change and nature-based solutions for urban water management in Berlin

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ABSTRACT

Traditionally, the planning, investment, management, and evaluation of combined sewer networks has been the domain of hydraulic modelling using narrowly defined indicators associated with spill frequencies, flows and waterbody environmental quality standards. Due to concerns about the increasing frequency and impact of combined sewer overflow (CSO) 'spill' events, many cities and citizens are realising or reassessing the problems that accompany these systems, and considering alternatives including nature-based solutions (NBS). We report on an investigation of the impacts of urban stormwater management and CSOs, addressing key issues of framing, assessment and measures of success. With increasing interest being directed towards NBS for urban water management, we asked the questions: Which additional or alternative measures of success might be applied to judge the success or otherwise of different approaches? What outcomes are viewed as beneficial or problematic, what benefits should be optimised and what adverse impacts should be designed out? Reflecting on recent impact assessment guidance and drawing on research in a city with a globally leading reputation for innovation and ecological sustainability practices (Berlin), we explore how the conceptual, practical and methodological frameworks might evolve over time. Factors affecting investments in stormwater management, whether involving conventional hard infrastructure or using NBS, go well beyond simple measures of flow, storage, volume and frequency. Public notions of value and legitimacy in urban water management are changing fast. We conclude with recommendations as to how city stakeholders may together develop more comprehensive assessments of combined sewer impacts and stormwater management practices.

Introduction

Increasingly frequent intense precipitation mean that climate change impacts will exacerbate pressures on stormwater systems [1]. Combined sewer overflows (CSOs) remain a key source of pollution, downgrading the quality of water bodies [2] and these negative impacts can be expected to increase with more frequent flash flooding events in cities. Combined sewerage involves mixing surface and foul sewer water flows in urban drainage systems and passing untreated discharges directly into receiving waters during heavy flow conditions. Weir outlets act as pressure relief valves to prevent sewage from 'backing up' in the system [3], but cause pollution with bacteria, pathogens, industrial waste, oils and fats, nutrients, organic matter and solid waste [4]. CSO discharges - regulated as pollution '*point sources*' - in turn produce aesthetic degradation, erosion, deposition, eutrophication and depleted water oxygen levels with cascading effects on tourism, fishing, sports and recreation [5].

Whilst progress in addressing point-source pollution problems has generally been better than for diffuse sources, the former still accounts for 18 % of degraded inland waters in Europe [6]. The European Union (EU) Water Framework Directive (WFD) Assessment reported that "*the path towards full compliance with the WFD's objectives by 2027, after which exemption possibilities are limited, seems at this stage very challenging*" [7]. At the EU scale, Quaranta et al. [1] estimated that annual CSO spill volumes from 671 functional urban areas totalled 5739 Mm^3/yr. They noted that nearly 2 % of this total consisted of concentrated dry weather flows, which are highly polluting. These trends are not confined to the EU. The UK, which is not subject to WFD requirements since Brexit, recently saw significant declines in river water quality. CSO impacts have come into focus, linked with public health and nature risks emerging from river pollution in England [8]. According to Carver [9], in England there are around 14,500 storm overflows discharging

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frequently for hundreds of thousands of hours.

These factors, combined with insufficient investments from water service providers to keep up with the pressures, have led to increased frequency and durations of overflow events and associated risks [10]. The capacity of combined sewers can be considered as representing a technological lock-in, limited by older systems designed under very different socio-economic and environmental conditions. It is against this backdrop that research into alternative approaches to urban drainage has evolved quickly [11–15]. Numbers of publications addressing nature-based solutions have grown rapidly [16,17] including for hydrometeorological risk reduction [18].

Research into nature-based solutions (NBS) for urban water management highlights that many opportunities to improve the status of degraded aquatic ecosystems have been missed [19] in terms of citizen engagement, spatial planning [20], maintenance [21,22], and fragmented 'dis-integration' of water governance structures [23]. Therefore an important question is: *which measures of success should be used to understand the impacts, benefits and investment decisions around urban water management in the future?*

The ecological, social and economic impacts of combined systems for urban water management are manifold and complex, in part due to relationships between these human-made networks and aquatic ecosystems. This complexity on the one hand, and the importance to maximise potential 'co-benefits' of urban water management systems investment on the other, provides a potentially rewarding but problematic arena for research addressing the assessment of impacts of interventions. Rather than focusing purely on value, in strict cost-benefit terms, research into these systems must engage with broader, more fraught realm of values [24]. Put another way, why would societies and interests choose certain indicators for impacts and benefits? What are the risks and outcomes that are privileged or neglected within those assessments?

There is an increasing demand for evidence around the impact of NBS for stormwater management, to deliver multiple co-benefits and to complement or incrementally replace surface water flows in combined sewer systems [25]. These interventions seek to avoid storm-water runoff whilst avoiding flooding in urban areas, and may provide important natural habitats in themselves, whilst preserving ecosystem functioning and aquatic ecosystem biodiversity in receiving waters. Examples of relevant NBS include sustainable urban drainage systems (SUDS), constructed wetlands, soil unsealing and bioretention. NBS interventions in urban environments, such as green roofs, can be cost-effective in reducing stormwater flows and CSO spills, providing valuable co-benefits including environmental quality improvements [12,25–30]. Effective treatment of urban stormwater runoff can be achieved using specific SUDS-type NBS in combinations set out in a 'stormwater management train' [26,31].

Specific pollutant removal by SUDS can be predicted [32] along with associated improvements in receiving water quality (e.g. [33,34]). Key areas can be identified within urban catchments where opportunities exist to implement and manage flow routes through viable surface-water conveyance solutions [35]. River landscapes provide a particularly useful setting to make use of NBS [36]. Removing surface water from sewer networks using NBS can also have significant monetary benefits; Broadhead et al. [37] estimate that for a typical waste-water treatment works (WWTW), removing the 16 % of baseflow from surface water sources would deliver cost savings of £2–7 million.

Traditionally, many studies have not properly considered the wider co-benefits of SUDS or their integration within wider green infrastructure (GI) networks [38]. Attempts to improve upon the comprehensiveness of assessment include CIRIA's B£ST toolkit, and more widely for NBS, holistic frameworks for impact assessment [27,39,40]. The development of these impact assessment approaches offers an important backdrop against which to consider combined sewers and water quality (and vice versa), giving the focus for this research conducted within the Biodiversa+ NICHES project (https://niches-project.eu).

The aim of this research was to provide new insights into the framing of CSO impacts, interventions, and indicators (or measures of success). Future water management in Berlin, Germany provided the lens through which these relationships were examined, with the city being selected due to its status as a frontrunner in integrating blue-green infrastructure within its broader urban policy and management frameworks [41]. The key research questions were:

(1) What are the infrastructures, perceptions and institutions involved in urban stormwater and combined sewer management in Berlin (i.e. *what are the systems*)?
(2) What methods, models and metrics are employed in managing stormwater in Berlin, and how are the characteristics, priorities and methods changing? (i.e. *what are the extant frameworks*)?
(3) What factors and indicators could be considered in assessing the impact of more nature-based approaches to stormwater management (i.e. *what might be the future measures of success*)?

Semi-structured interviews and literature reviews were undertaken to explore extant conditions, changes influencing key decision-making processes, and institutions including economic frameworks for investment and modelling approaches. The research explored the relevance of - and implications for - NBS impact assessment as well as wider discussions around urban stormwater management governance and impact assessment frameworks [19,27,30,39,40,42].

Materials and methods

Literature review

To understand stormwater management issues and associated themes in Berlin, peer-reviewed publications were identified in November 2022 through Scopus and Google Scholar (dated 2015 - present). Search terms used in paired combinations included: Berlin; urban; water; green; infrastructure; nature; ecosystem; runoff; sewer; combined; and overflow. Fig. 1 summarises methods based on the PRISMA systematic review approach [43,44] and restricted reviews [45].

Abstracts, keywords and titles were screened for themes pertaining to stormwater, CSOs, NBS, blue-green infrastructure and urban watercourses in Berlin. Blind reviews of abstracts were used to reduce bias in developing, refining, and applying the codification methodology. Datasets were screened using the following exclusion criteria: (a) does not address urban water management or GI issues; (b) pertains to rural ecosystems; (c) does not relate to Berlin; (d) not peer-reviewed. Literature review results were stored and processed in Microsoft Excel. Reasons for screening out abstracts were recorded, enabling cross-comparison between searches across the domains or by different researchers. Duplicates were removed prior to the analysis of full manuscripts to code relevant content. The initial literature review search yielded 313 references. After screening for the themes of stormwater, CSOs and urban watercourses in Berlin (Fig. 1), the resulting dataset included 121 references. Following a review of full texts, publications were grouped according to similarity of themes and challenges addressed. The research sought insights into the different framings of urban stormwater issues, opportunities and threats, and associated potential indicators.

The results of the review were used to formulate questions for the semi-structured interviews and in processing responses (under six themes, with another three themes being developed inductively from interview results). Findings were further analysed through comparison with the themes of the European Commission's NBS Impact Assessment Handbook, using its set of 'societal challenges areas' [27] to categorise issues addressed in the literature, mapping them onto specific indicator types. Specific assessment methods ([30] - '*recommended and additional indicators*') were analysed for relevant indicators to prepare interviewers with probing questions and for detailed discussions.

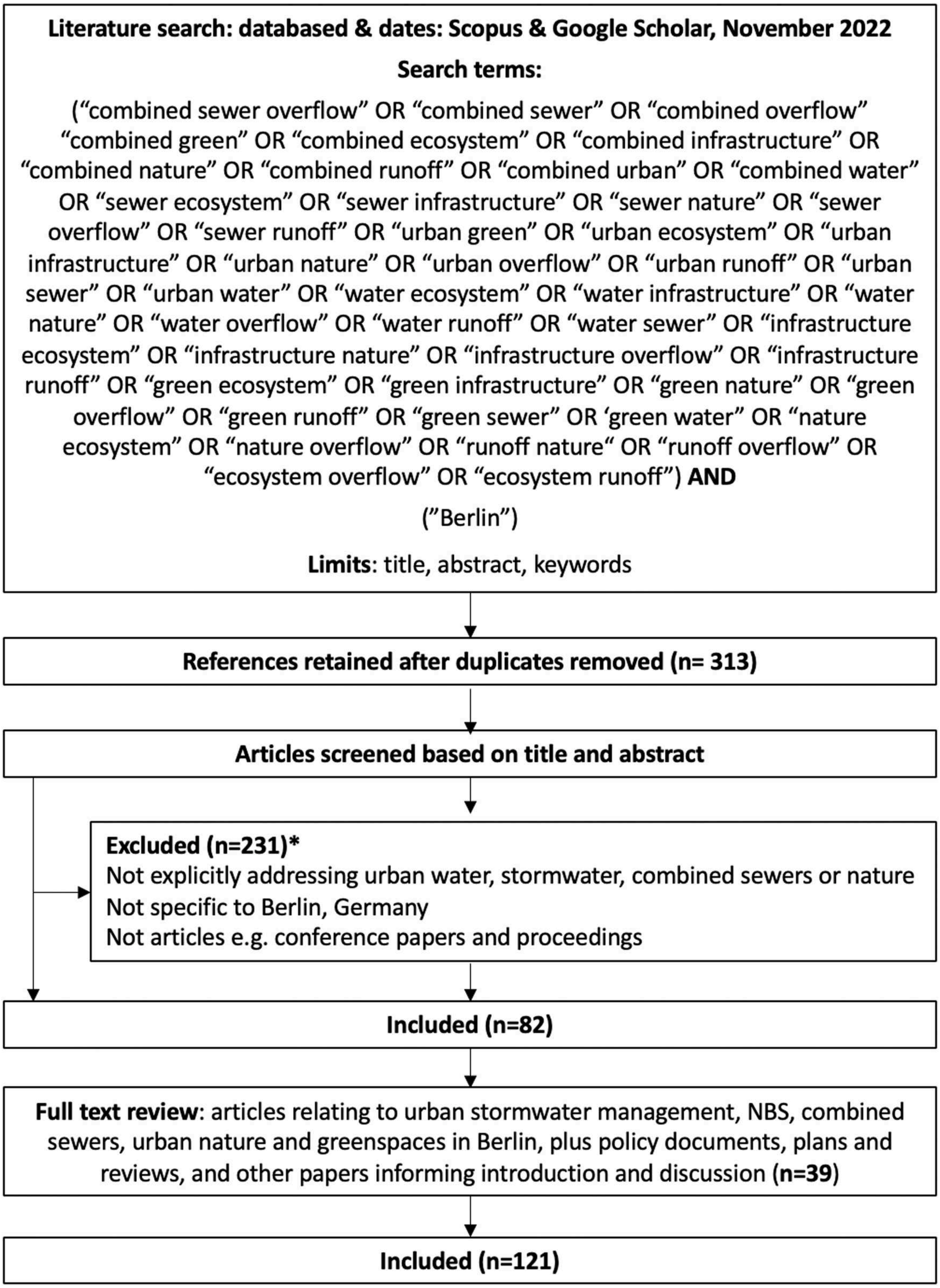

Fig. 1. Flow diagram of record selection (after [43,44]).

Stakeholders' perspectives of combined sewers & stormwater management (interviews)

Interviews were held with key local contacts between December 2022 and February 2023 to establish and review key principles, definitions, topics, components, conditions and outcomes relating to Berlin's urban water management. This method enables comprehensive analysis of stakeholders' knowledge, values, beliefs or decision-making [46], providing a flexible approach focusing on participants' experiences. CSO challenges and nature-based responses were discussed to develop understanding of the conditions, processes and networks at play. Information was sought on key baselines, trends and local opportunities to address urgent city priorities (environmental, social, economic, political etc.).

Key participant types were established for Berlin, including stakeholders in water companies, political bodies, academia, lobby groups and knowledge centres. Initial contacts were identified in NICHES project workshops discussions (September 2022; January 2023), during which project partners mapped out key issues, concepts, regulatory frameworks and impact assessment regimes. Further contacts were identified using the snowballing method. Table 1 provides a summary of participants' roles and key interests. The sample of stakeholders provided a broad range of insights and opinions to yield understanding of the historical evolution, current status, and future directions of stormwater management in Berlin. After having conducted six in-depth interviews, thematic saturation point was reached whereby no new themes emerged.

Part one of the interviews targeted participants' roles, professional backgrounds and experiences, including current work, tasks and knowledge. Part two focussed on what is changing and driving those changes. Part three related to systems planning and management. Part four addressed political and organisational frameworks. Part five covered opinions and knowledge about measures, impact assessments and indicators, including discussing ideas for alternatives (notably elements of the NBS Impact Assessment Framework, [27,30]). Interviews established participants' involvement in processes related to CSO and stormwater management, including responsibilities for interventions, under which circumstances, and understandings of the methods involved, as well as views about the development of alternative measures. Review findings were used in shaping questions and follow-up probing points, e.g. regarding existing indicators and potential future measures of success. Interviews were piloted in a separate city, to test and refine sequencing. Open and closed questions were included to understand key trends, contexts, assessments and data needs. Table 2 summarises semi-structured interviews format (topics).

Interviews were transcribed in German and translated into English using Deepl Pro (https://www.deepl.com/en/pro), highlighting relevant themes and important contextual details. Text analysis was carried out in Microsoft Word and Excel. Following a hybrid approach, deductive analysis of the literature was used to identify broad interview themes, followed by inductive analysis of interview data, using literature review themes to interrogate theoretical perspectives for the observed evidence.

Results and discussion

Deductive analysis of the literature resulted in six clustered themes around key urban challenges linked with stormwater in Berlin, namely: (a) governance, management and planning; (b) pollution, water quality and waterbody conditions; (c) CSO spills and spill reduction using SUDS; (d) access to greenspace and blue-green infrastructure; (e) un/sealing of urbanised land, permeability, infiltration and water resources; and (f) biodiversity and urban ecology.

Governance, management & planning

Much debate has been reported over water resource issues in Berlin, from the perspective of water use, storage and reuse on the one hand, and stormwater discharges, pollution and flooding on the other. Moss [47,48] notes that the desirability of water conservation and embeddedness of socio-technical systems has been contested and framed in relation to the city's turbulent history and key historical events. Papasozomenou et al. [49] highlight how particular imaginaries of urban rainwater harvesting relate to institutional and infrastructural contexts in Berlin's post-reunification development. Suleiman et al. [50] demonstrate how these complex themes can be categorised, framing urban rainwater harvesting as socio-technical systems.

Collaboration and co-creation between researchers and policy officers in Berlin has led to mutual learning, trust and new relationships [51], with policy-science dialogues and knowledge co-production about strategic urban environmental governance supporting concerted urban water management action. According to Beveridge & Naumann [52,53], political contestation has created an ambitious, vibrant and progressive political approach to re-municipalisation of water services, based on advanced citizen dialogues about the Berlin water company's role (Berlin Wasserbertriebe or BWB; water services are provided by this company in the city, established in 1994 as a public-private partnership).

Addressing urban commons, Scharf et al. [54] indicate how better governance can strengthen identification, participation, self-organisation, and social resilience, providing powerful tools for urban sustainability transformation, if the political integration is structurally viable. Berlin partially reflects this progressive approach in its transition towards sustainable urban water management, addressing key challenges for GI implementation such as space and cost constraints, and barriers to inter-sectorial and stakeholder collaboration [41].

Yet several challenges remain in Berlin's urban green governance, including (a) increasing pressure and financial constraints on the municipal budget; (b) loss of expertise; and (c) low awareness of green benefits among different actors through insufficient communication [55]. These themes are not unique to Berlin but highlight the need for integrated approaches to infrastructure planning, operation and management, not least in enhancing multifunctionality at different spatial scales and in targeting improvements [56]. Hansen et al.'s [57] analysis of Berlin's strategic plans found little evidence of enhanced multifunctionality being a key criterion for success. Furthermore, existing assessment protocols aiming to be integrative – such as the Berlin Biotope Area Factor (BAF, an ecological parameter used in development planning to mitigate against biodiversity loss) – largely overlook social aspects provided by ecosystem services [58].

Pollution, water quality & waterbody conditions

Despite efforts to address these water governance challenges, Berlin faces significant problems with water quality and water body conditions, with urban stormwater runoff being both a significant pollution source and valuable water resource [59]. Lowitzsch [60] reports how the River Spree experiences regular massive fish deaths during heavy rainfall as sewers become overburdened and CSOs discharge to prevent backups. Implemented measures, including underground concrete basins and advanced canal control systems, remain insufficient to capture the 3-4 Mm^3 of untreated wastewater discharged each year. Other city-specific issues include the prevalence of urban drainage issues associated with lake ecosystems, fed by nutrient-rich river discharges and effluents containing priority hazardous substances and manufactured chemical pollutants (e.g. [61,62]). Contamination of rivers by trace organic compounds poses risks for aquatic ecosystems and drinking water quality, although river sections that are more densely populated by macrophytes (aquatic vegetation) generally provide more favourable conditions for photo- and biodegradation of these substances [63].

Johnson & Geisendorf [64] note that Berlin residents view these matters as being important, weighing fish deaths and the need to improve surface water quality in the urban area as an unfulfilled utility of ecosystem services. Such concerns have resulted in a shift in management goals towards source control, and decentralised rainwater harvesting (e.g. substituting stormwater for potable water whilst reducing pollution loads). Regarding the treatment of high stormwater pollution loads for key urban water contaminants, Simperler et al. [65] report success in the use of NBS, delivering co-benefits including urban heat island mitigation. Other measures include phosphorus elimination plant usage to buffer high nutrient supply in Lake Tegel [61,62] and in the Lower Havel, near Berlin, to reduce phytoplankton blooms [66].

CSO spills & reductions using SUDS

CSOs are increasingly under scrutiny in Berlin as a major source of microbiological contamination affecting bathing water quality [67] and

Table 1
Participants in semi-structured interviews on urban stormwater and CSOs in Berlin.

Participant no.	P1	P2	P3	P4	P5	P6
Summary of role, interests & responsibilities	Member of Parliament for a Berlin central district with a water focus	Scientist based in a Berlin knowledge centre on urban water	Manager and expert in the Berlin rainwater agency	Scientist with a publicly funded association promoting river bathing	Manager for stormwater services in Berliner Wasser-betriebe	Campaigner for NGO focussing on environment and nature in Berlin

Table 2
Format used for semi-structured interviews.

1. About you
About the participant, their role and their work. Ways of understanding and obtaining knowledge.
2. About your organisation
Organisational interests in urban stormwater and combined sewers. Questions on responsibilities and roles.
3. System planning, design, funding & management
Tools, frameworks and indicators used (e.g. where participants were involved in modelling & assessment).
4. Change, politics and citizen representation
Drivers of change and challenges in the city. How this is considered to affect stormwater systems.
5. Assessment frameworks and alternatives
Perspectives on assessment frameworks, indicators and measures of success, and potential alternatives.

pollutant levels [68]. Pollutant levels discharged from these systems are strongly linked with weather conditions (especially heavy precipitation events), and high pollution loads straining WWTW. Planning and managing combined sewers has involved linking together urban drainage models, water quality models and tools to quantify in-river conditions e.g. dissolved oxygen levels (e.g. [69]). Micropollutants in Berlin's stormwater runoff have been examined and compared with environmental quality standards (EQS) for surface waters, with Wicke et al. [70] showing that 13 micropollutants in storm-water runoff and 8 micropollutants in receiving rivers exceeded German water quality standards during storm events. The increasing prevalence of hazardous substances in urban drainage is a concern; Wicke et al. [71] found that concentrations in stormwater exceed limit values for surface waters for biocides diuron and terbutryn, the root protection agents mecoprop and MCPA (from bituminous sheeting), and zinc from roofs and façades. In urban areas, limit values were exceeded for smaller surface waters during wet weather.

However, the relationship between CSO discharge volumes and water quality is far from straightforward. Riechel et al. [67] demonstrate how in Berlin, outlets with the largest CSO volumes are not automatically the greatest wastewater emitters and assumed hotspots for pathogen contamination do not coincide with hydraulic hotspots; just 5 % of wastewater from CSOs contributed 99 % of river pathogen loadings. This indicates that CSO discharges and impacts vary greatly between rivers and drainage catchments. On a global level such knowledge has led to a greater focus on live monitoring and management ('smart', 'real-time') of sewer flows, but again, the results can be less encouraging. Caradot et al. [72] question the reliability of online measurement and online monitoring of CSO spills in Berlin and river impacts where no local calibration (manual sampling and regulation) occurs; overreliance on in-sewer monitoring technology alone is unlikely to solve CSO impact problems - other, complementary responses are needed.

An adapted urban sewage infrastructure, moving from stormwater disposal to more sustainable management, can help to overcome urban challenges in the city of Berlin [73]; SUDS can help address complex urban challenges including heat stress, biodiversity, floods and environmental impacts due to CSOs. Wang et al. [74] and Rost et al. [75] identify the impact of green roofs and urban GI in mitigating urban heat island effects and improving thermal comfort, as well as providing stormwater benefits in Berlin. The costs and financing implications of scenarios integrating large-scale implementation of NBS measures such as swales and infiltration have also been investigated in Berlin. Cost-benefit analyses at the neighbourhood-level have demonstrated the economic feasibility of SUDS for a range of urban ecosystem services [76].

Access to greenspace and blue-green infrastructure

Distance to urban green space has been found to affect Berlin residents' wellbeing, based on self-reported health outcomes [77] and physical health outcomes [74]. Honold et al. [78] report that Berliners whose homes had views of substantial, diverse vegetation showed significantly lower cortisol levels; participants who regularly used vegetated trails within blue-green infrastructure networks had significantly lower cortisol levels and reported significantly higher life satisfaction than less frequent users. Additional cultural ecosystem services and disservices have also been explored (e.g. [79]), with key qualities varying greatly across the city including enjoyment of nature, social relations, cultural diversity, cultural heritage, education, natural awareness, recreation, and aesthetics [80–82].

Berlin has been progressive in integrating GI to supplement conventional water infrastructure [41]. Retrofitting NBS for urban water management (e.g. creating new green and blue spaces through SUDS) can further help address disparities in neighbourhoods where disadvantaged status coincides with poor access to urban greenspace [83]. Use of the BAF factor can be an important tool in monitoring local blue-green infrastructure development in Berlin [84,85]. Evidence that citizens value green interventions [86] underline the need to consider multifunctionality in urban infrastructure planning [57], not least in tackling high sealing rates in dense urban centres. Yet challenges for implementation, including space and cost constraints, and barriers to intersectoral and stakeholder collaboration, leave clear deficit patterns along city highways and in the densest urban districts [87]. Consequently, most Berlin residents (75 %) have insufficient access to green space [88] and face persistent environmental and health inequities. Furthermore, blue-green infrastructure and NBS interventions can only subsist with adequate water resources and - despite the abundant green surfaces present in Berlin - only 50 % of natural landscape patches have direct access to freshwater surfaces or sources [89].

Un/sealing, permeability, infiltration and water resources

Local aquifers have been central to Berlin's water supply and - being close to the surface - have made for intricate interactions between urban development and groundwater levels [90]. While conventional urban drainage systems quickly discharge water, the city's urbanisation and associated soil sealing has led to an increase of annual river runoff by >9 % in Berlin's Spree River basin [91], thereby reducing water resources. An important effect is that the city-region's streamflows have become dominated by effluent from WWTW, especially in warm dry years and in lower reaches of river catchments [92,93]. In the heavily urbanised Panke catchment, sealed surfaces have significantly reduced the relative contribution of groundwater to streamflow, and WWTW effluents dominate stream flow in the lower catchment up to levels ~90 % of annual runoff [94]. Catchment imperviousness and connection to drainage infrastructure have resulted in green spaces being bereft of water ([95] & b), causing low soil moisture storage, low groundwater recharge, and intermittent streamflows [96]. The result of the lack of urban soil water recharge in winter is that high water demands for green assets - especially urban trees - may be hard to sustain during dry periods.

Different vegetation types of urban green spaces have been found to enhance groundwater recharge in Berlin [97] and significantly contribute to evapotranspiration [98], not least to mitigate heat island effects. Harnessing these benefits in the city is critical in managing future resilience to climate change [99]. Furthermore, in dry months, valuable water resources are lost in the treatment process; reusing greywater in NBS close to its source can assist in closing water cycles in Berlin [100]. As such, the city has supported the disconnection and reduction of impermeable areas ('unsealing') e.g. in the recent 'Regenwasser' laws[1]. Accordingly (a) all new building projects should have a decentralised approach with no stormwater outflow; (b) there should be a yearly reduction of 1 % (0.7 km^2) of the surface area previously connected to the combined sewage system to reduce the stormwater entering the system by circa 1 %; and (c) discharge rates of stormwater should be limited to a 'natural rate' of maximum 10 l/ha/s, depending on the water body. In the future, a more integrated land and water management strategy will also be essential.

Biodiversity & urban ecology

Urban biodiversity and ecological integrity represent important qualities that can be enhanced through NBS for stormwater management. Berlin has been a centre of excellence in urban biodiversity. Herbert Sukopp's contributions, based on many studies in Berlin and beyond were groundbreaking for the establishment of urban ecology [101]. In the city, novel ecosystems harbour the highest numbers of protected species' total populations, total species, and species exclusively confined to one type of novel ecosystem [102]. This serves to highlight the importance of urban biodiversity conservation and opportunity of NBS for stormwater management. Doing so not only benefits rare flora and fauna - urban wetlands and peatlands also provide vital carbon sequestration and climate regulation services [103]. Biodiversity-friendly design and maintenance interactions for a broad range of users would help counteract the loss of experience in human-nature interactions [104].

Stakeholders' perspectives on combined sewers & stormwater management (interviews)

Interviews were held with six Berlin stakeholders, covering representatives from the local municipal government, water companies and knowledge centres, NGOs and networks (Table 1). The results provide insights into how stormwater management has evolved over the last decades as well as prospects for different kinds of impact assessment, CSOs and NBS interventions (Table 3). Responses to questions for the semi-structured interviews derived from the literature review are reported under themes 4–9 inclusive, also providing labels for analysis under these broader subject areas. Three further labelling themes were derived through inductive analysis of the transcribed discussions (themes 1–3). The latter related to topics clustered around: (1) impact assessment, indicators and measures; (2) change, trends, future developments and new initiatives; (3) citizens, participation, people and engagement.

Table 4 summarises dominant discussion themes and participants' observations within each subtheme (see also Tables 1 & 3). The quotes that follow provide contextual information about Berlin's stormwater management and CSO issues, and insights into the challenges, opportunities, responses, and important developments. Participants' comments illuminate key considerations in relation to impact assessment, including information about techniques, benefits and indicators, and

Table 3
Sub-themes for interview participants' observations with core discussion topics.

Stormwater management & combined sewer themes (core discussion themes - participant P1–6, in brackets)	**Subthemes discussed by participants** (core discussion topics - participant P1–6, in brackets)
1. Impact assessment, scenarios & indicators *(P2, P4, P5, P6)*	• Scenarios, impacts, trends (P2, P5, P6) • Measurement, evaluation, assessment (P2, P4, P6) • Benefits and values (P2, P5) • Indicators, parameters, data (P4, P5, P6)
2. Change, trends, transformation, futures *(P1, P2, P5)*	• Change, future, long-term (P2, P5) • Risks, trends, vulnerabilities (P2, P5) • Transformation, pathways, innovations (P1)
3. Citizens, engagement, activism & education *(P1, P4, P6)*	• People, public, Berliners, citizens (P1, P6) • Dialogue, engagement, exchange (P6) • Participation, support, activism (P6) • Learning, education, campaigns, awareness (P4, P6)
4. Governance, management & planning *(P1, P2, P3, P4, P5)*	• Funding, costs, agreements (P2, P3, P4, P5) • Laws, rules, directives, regulations (P1, P3) • Politics, government, decisions, multi-level (P1) • Priorities, goals, objectives (P4, P5) • Frameworks, plans, programmes (P1, P2, P3, P4, P5) • Openness, justice & inclusivity (P2, P5)
5. Pollution, water quality & waterbodies *(P3, P4, P6)*	• Water quality, pollutants & pollution (P4, P6) • Bathing waters (P4, P6) • Environmental & ecological quality (P3, P4, P6) • Discharges, standards, compliance (P3, P4, P6) • Rivers, canals, waterbodies (P3, P4, P6)
6. Combined sewer system, overflows, reductions *(P3, P4, P5, P6)*	• Sewers, overflows, discharges (P3, P4, P5, P6) • Construction, services, network (P3, P4, P5, P6) • Flooding, capacity, flows (P4, P5) • Streets, roofs, housing, property drainage (P3, P5, P6) • Technology & monitoring (P4, P6) • Costs & expenditure (P3, P4, P5, P6)
7. Greenspace & blue-green infrastructure *(P1, P2, P5, P6)*	• Green & blue space, blue-green infrastructure (P1, P2) • Neighbourhoods, districts, squares, traffic (P1, P5, P6) • Co-benefits, heat, energy, irrigation, place (P1, P2, P5)
8. Un/sealing, permeability, infiltration & water resources *(P1, P2, P3, P5, P6)*	• Rainfall, rainwater, runoff (P1, P2, P5, P6) • Water resources, harvesting (P1, P2, P5, P6) • Un/Sealing, permeability, infiltration (P1, P2, P3) • Disconnection, decentralisation (P1, P2, P3, P5, P6) • Climate, hydrology, models (P2, P5, P6)
9. Biodiversity, ecosystems, urban ecology & NBS *(P2, P4)*	• Nature, biodiversity, habitats, species (P4) • Nature-based solutions (P2, P4) • Ecosystems, ecological networks (P4) • Ecological processes (P4)

[1] https://www.berlin.de/sen/uvk/umwelt/wasser-und-geologie/regenwasser/rechtliche-regelungen/https://www.berlin.de/sen/uvk/umwelt/wasser-und-geologie/regenwasser/rechtliche-regelungen/https://www.berlin.de/umwelt/themen/wasser/artikel.156440.php

Table 4
Summary of participants' observations and dominant stormwater discussion themes in interviews in Berlin.

Interview transcript analysis themes	P1	P2	P3	P4	P5	P6
(1) Impact assessment, scenarios & indicators						
(2) Change, trends, transformation, futures						
(3) Citizens, engagement, activism & education						
(4) Governance, management & planning						
(5) Pollution, water quality & waterbodies						
(6) Combined sewer system, overflows, reductions						
(7) Greenspace & blue-green infrastructure						
(8) Unsealing, permeability, infiltration & water resources						
(9) Biodiversity, ecosystems, urban ecology & NBS						

Notes: darker shaded boxes indicate more dominant interview discussion themes.

their relevant purposes, application, contexts and gaps. Most of the time spent in discussions related to just four themes of nine, i.e. themes 4, 5, 6 and 8. Relatively little time was spent in discussions relating to themes 3 and 9. Substantively, most of the participants' observations pertained to technical, political and environmental themes; little discussion centred around ecological or socio-cultural factors.

Dominant themes related to (8) impermeable surfaces unsealing and disconnection, (6) reductions in CSO spill events and durations, (4) governance frameworks and decisions, and (5) pollution control, river water quality and bathing. Under theme 8, most participants discussed key processes, targets, actions and impacts around disconnection and decentralisation (linking with theme 4). One of two core subthemes concerned practicalities and challenges around unsealing policy:

- "*What is missing are the small quick places to unseal … car parks with permeable pavement, removing paving stones between trees… there is still a lack of … concrete policy guidance on how to unseal the small spaces more quickly. A path has to be described on how to get to net-zero sealing*" (P1).
- *"The greatest potential is on private properties, in the existing stock. BWB can't get to it, it's not in its area of responsibility. This is why public streets and squares are the field of activity… not an easy business… streets have to be shared with other users, cycling, walking… areas are hard-fought"* (P5).

The second main disconnection subtheme gives insights into contrasting indicators for stormwater discharges as compared with sources in different urban and suburban areas:

- *"The decoupling target of one per cent land per year is not working so far and is being implemented mainly in the outer districts. It is difficult to implement this in the inner city - the discussion is often steered towards the outer districts"* (P6; see [87]).
- *"All new building projects should have a decentralized approach - no outflow. Yearly reduction of 1 % of the surface area connected to the combined sewage system is a huge goal.. the discharge rule of 10l/ha/s… [is] the standard approach in Berlin, but is problematic because also policy wants to see that something is happening"* (P3).

For some respondents, pollution control and river water quality (theme 5) was their main focus:

- *"BWB [only] reduced the amount of discharges by about 50 % between 1998 and 2024… So much sewage is discharged into this [Landwehr] canal every year that the canal is completely filled with sewage twice over the total length of 11 km - absolutely appalling"* (P6).
- *"We have set ourselves the goal of improving the bathing water quality in the Spree to provide Berliners with a safe and clean bathing water"* (P4).
- *"CSOs go into the Landwehr Canal and Spree on the entire length in the city. Landwehr is most affected [as] a smaller water body that hardly moves. CSOs have a huge impact on water quality"* (P3).

Furthermore, some interviewees held detailed understandings of the relationships between water quality metrics associated with the WFD – e.g. good ecological potential, biological quality etc. - compared with Bathing Waters indicators relating to pathogens such as faecal coliforms (P2, P4). Whereas P5 tended not to cover topics around pollution (theme 5), the exception below highlights that environmental outcomes are still critical issues in Berlin, meaning that quality standards remain important:

- *"BWB would be lucky not to get a worse situation during the dry spells in summer. CSOs will not be solved so quickly. It is important that [it] does not increase - the massive negative effects on bathing waters, fish mortality, oxygen deficiency"* (P5).

Notably, the BWB interviewee contended that the number of CSO spills and their volume alone was *"no longer the right metric"* (P5).

On this point (theme 6), diverging messages and emphases emerged as to how best to proceed, with an NGO sector participant arguing that the economics of different urban water management strategies have been insufficiently clear, open or understood: "*How much would it cost to significantly reduce combined sewer discharges? You can't reduce them to zero, of course…, but how much would it cost to reduce them significantly? To date [they have] not produced a single projection showing the cost of various schemes to reduce these discharges*" (P6).

Politically, there has been a shift such that CSOs are firmly on the agenda: "*In 2013, politicians were still saying that stormwater management is none of our business, the potential of NBS was not seen. Berlin's urban development department also said that stormwater does not concern them"* (P2). This can also be seen to feed through to management practices: *"However, old employees have since been replaced by new ones… the scepticism towards the new approaches and necessary changes is disappearing bit by bit"* (P2). But two very different positions also emerge on the relative effectiveness of storage vs unsealing strategies:

- "*300,000 m^3 of [sewage storage] reservoir space is not as much of an achievement as it sounds… 240,000 m^3 were already there from the existing Berlin sewer network. The remaining 60,000 m^3 have been tinkered with for decades… when they [BWB] have finished something, like the stormwater basin at Mauerpark they act as if they had reinvented the world. Compared to the Gotthard Tunnel, which is over* 50 km *long, that's not much of an achievement"* (P6).
- "*BWB does not know everything about where the districts build [or] unseal… Berlin is growing, being redensified, sealing is increasing, climate change is advancing… In summer, there's no fresh water inflow – 'sitting in our own soup' increasingly and for longer and longer… can we control this*?" (P5).

The last point highlights a shift in thinking around measures of success (themes 1 and 4): "*Progress in existing buildings is even slower. Decentralisation is being implemented, especially for new quarters, to reduce heat stress, flood prevention and water protection*" (P2).

Presentation of elements of an NBS Impact Assessment Framework [27,30] at the end of each interview prompted some discussion by participants of alternative approaches to measuring success. Few were familiar with the framework; none had considered applying the wider assessment methods and indicators to CSO issues. However, there were signs that adaptations in measures of success are required: "*climate change issues are increasing: urban heat, drought, heavy rain - the value structure is shifting due to climate change*" (P5). Participants referred to the need for projects with multiple planning objectives and intended co-benefits (P2, P4) even if those outcomes were not assessed using formal impact assessment frameworks.

In considering the results, it is helpful to consider why several matters appeared to be centrally important in the Berlin literature, but perhaps less so in interviews. This provides insights into dominant narratives and the potential for interests to be side-lined, plus future avenues in developing assessment frameworks (research question 2). This section thus first emphasises the less discussed themes.

Citizens, engagement, activism & education

A striking difference between literature review and interview findings was that in the latter, discussions about citizen engagement and public participation were limited, especially considering the whole conception-planning-construction-management spectrum. This is a significant gap, given the ethos for public participation underpinning key WFD principles [105], reflexive adaptation for resilient water services [106] and co-design as emphasised in NBS frameworks [107]. Primary discussion points around the role of Berliners were not about openness and dialogue, but more narrowly defined in terms of specific users and uses (mainly bathing) or challenges such as surface sealing and property drainage. Language used mainly involved campaigns, awareness and education, rather than perspectives, exchange or dialogue. The Berlin literature highlights key findings of relevance around the opportunities of participation and engagement [54,56], which were not dominant interview themes.

Biodiversity & urban ecology

Relatively little attention was given to the topics of biodiversity, nature and ecosystem restoration, beyond a primary focus on water quality. Limited debate emerged around possibilities for urban ecology linked with terrestrial, marginal or riparian ecosystems, including biodiversity benefits of NBS for water management integrated within the urban fabric (sometimes far away from waterbodies).

This was evident for most participants and is surprising, given Berlin's globally leading scientific capacity and heritage in urban ecology research [101]. Integrating wild habitats into urban settings provides "fourth nature" spaces where urban ecology can thrive [83,108,109] and NBS also support biodiversity benefits indirectly, by ameliorating urbanisation impacts such as heat island and air quality impacts. For instance, urban wetlands and green roofs provide vital climate regulation services such as heat regulation [103,110]. In Berlin, GI provides a wide range of urban ecosystem services [111] such as air pollution removal [112]. Assessment of biodiversity benefits in diverse urban spaces provides opportunities for community-led action and citizen science [113].

Urban ecology research undertaken in Berlin confirms that biodiversity can be just as high in urban settings as in rural areas [114,115], highlighting the importance of urban nature conservation and NBS opportunities. Since NBS definitions and frameworks agree on the need to enhance biodiversity and ecosystem integrity [107], such policy priorities should have a bearing on decision-making frameworks. Neglecting this factor is likely to be problematic as regards monitoring and evaluation of the dis/benefits of different interventions options (e.g. see CIRIA B£ST toolkit). This might represent a blindspot in developing compelling narratives and impact assessments for NBS, yet Berlin stakeholders have significant experience in using ecosystem service indicators including through the BAF system [55,85,116].

Access to greenspace and blue-green infrastructure

A further reflection on topics largely absent from the interview discussions relates to environmental justice, including distributive aspects, in contrast with the Berlin literature [77,78,83,88,117]. It is perhaps surprising that in/equity in access to quality greenspace was not raised during interviews. With the advent of the EU Nature Restoration Law and proposed urban greening plans, one might anticipate this topic to be raised in Berlin, which is relatively well-known for its discussions around access to greenspace (e.g. [117]). The results indicate the existence/persistence of systemic silos between sectors, which may hamper efforts to integrate NBS for urban water management in the city. This brings us to governance.

Governance, and measures of success

The need for improved evidence around the governance, planning, management and impacts of stormwater management systems remains urgent. Climate change and increasing heavy rain events have resulted in greater emphasis being placed on the frameworks through which access to, or protection from, urban water is managed [105,118,119]. These priorities and other societal challenges including social justice, biodiversity loss, and unequal health and wellbeing mean that urban drainage issues are receiving increasing attention. Responses go beyond environmental-technical interventions and include action to stimulate interest in urban water management through capacity-building measures, e.g. to develop "*networks composed of key stakeholders in order to increase public awareness of water issues and thus lead to better implementation on the ground*" [120].

Close attention to multifunctionality and connectedness is critical to effective advocacy for the uptake of urban NBS within broader blue-green infrastructure networks [57]. Articulation of these multiple benefits by NBS advocates may be centrally important and has underpinned calls for more holistic conceptions of assessment (e.g. [27,30,40]). However, does this necessitate frameworks of indicators that address broader benefits beyond CSO flows, pollution, costs and infiltration? Overall the Berlin literature indicates an interest in broader sets of co-benefits that go beyond strictly water- and drainage- related themes. What then could the evolution of impact assessment for urban stormwater NBS look like in a place like Berlin?

To help visualise relationships between various impacts of stormwater and its management using NBS, research findings were mapped on to the societal challenges, indicators and evaluation methods presented in Dumitru & Wendling's [27,30] NBS Impact Assessment Handbook. Doing so highlighted 22 categories of indicators with associated assessment methodologies, within 11 broad areas of impact. Of these, 10 are already closely aligned with policy imperatives in Berlin around stormwater management (biological quality of water, eutrophication, dissolved oxygen, total faecal coliform bacteria, total pollutant discharge to local water bodies, flooding, volume of water treatment avoided and associated energy savings, water storage capacity, and soil sealing), supported by statutory monitoring programmes and models.

Synopsis and critical discussion

Addressing research questions 1 and 2 (extant systems and frameworks) currently, spatial-technical issues relating to unsealing, disconnection, CSO spills and water quality (themes 5, 6, 8) were dominant. Thus, the *first* conclusion is that the choice of impact assessments, scenarios and indicators (theme 1) primarily focus on these three issues of drainage, CSO flows and receiving water quality. This leads to a *second* conclusion: an open process to broaden the debate and choice of measures of success could prove helpful in engaging Berliners in change processes to transform urban stormwater systems (themes 2 and 3; [51, 54]).

Third, citizen engagement may itself be formulated as a measure. The co-productive framing of NBS lends itself towards social capacity as an important indicator (theme 3). Dumitru & Wendling [30] and the IUCN NBS framework [39] provide useful descriptions of methods that go beyond education towards social cohesion outcomes (although as Bulkeley [121] highlights, co-design processes should not automatically be considered as a means via which to achieve social inclusion). As one participant noted, "*climate change issues are increasing - urban heat, drought, heavy rain, - the value structure is shifting due to climate change*" (P6). A central concern may be to develop and maintain a close sense of citizens' values. Public Participatory Geographical Information Systems (PPGIS) offers a useful tool to support this process [56].

Related to this is the *fourth* conclusion, on the need to develop governance indicators that can be used to monitor participation in shaping the assessment frameworks themselves (theme 4). Such governance indicators show promise in relation to NBS [122]. Evaluating participation in the process of 'defining what success looks like' has the potential to improve the conditions for gathering valuable datasets, and to go beyond static governance assessments. *Fifth* is the challenge to reduce environmental inequity, with an emphasis on districts with poor access to urban greenspace and ecosystem services (theme 7, [80,82,83, 87]).

A *sixth* key point involves the need for monitoring and evaluation of biodiversity impacts in terms of habitat provision, species diversity and species richness, across a range of scales (theme 9). Strengthening relationships between the use of the BAF tool and stormwater management processes offers significant prospects. Ecologically speaking, it is important to consider stormwater management NBS not just as contributors of cleaner water for the benefit of rivers, but also as novel habitats optimised for biodiversity, including for terrestrial species; further evidence is required on the biodiversity benefits of NBS [123–126].

Returning to the question of future measures of success (research question 3*),* taken together the nine themes discussed here provide an invaluable picture of stormwater management issues in Berlin. Arguably a *meaningful* yet *manageable* step towards more comprehensive impact assessment could entail focusing on six key outcomes as co-benefits of urban water management NBS (themes 1,2, 3, 4, 7 and 9), alongside the existing stormwater metrics for pollution control, CSO spills and unsealing (5, 6 and 8 respectively).

On the other hand, neglecting or disregarding spill frequency and volumes at CSOs would be a risky strategy ("*the massive negative effects on bathing waters, fish mortality, oxygen deficiency"*, P5*;* see also [64,67, 68,127]). Difficulties in monitoring rainwater inputs and disconnections in Berlin – and forthcoming stricter WFD requirements – highlight this point. The basis of good ecological status including water quality remains important, including the comparison of known volumes of discharges against EQS in receiving waters (see [72]). The assessment of pollution levels and environmental water quality remains an important tool in the toolkit to prioritise investments in stormwater management interventions.

Although EU water policy has delivered significant water quality improvements in recent decades almost 60 % of EU waters have failed to achieve good ecological status [2]. Key hindrances include governance and uncertainty over effectiveness of measures, particularly in relation to urban water and diffuse pollution [105]. Grizzetti et al. [128] highlight the need for intersectoral integration, synergism, multi-functionality, biodiversity conservation, and more comprehensive evaluations to improve water catchment planning (see also [129]). Our research findings echo these conclusions.

EU Member States have until now been permitted exemptions to WFD where reasons for 'derogations' are given [130]. Many of these derogations, where less stringent objectives can be applied, involve 'heavily modified water bodies' [131–133] deemed affected by human activity [134]. In Germany 82 % of all surface water bodies were previously exempted [135] from needing to reach good status. With less demanding targets for water quality improvements, communities living nearby these waters could potentially benefit less from access to clean and ecologically rich rivers, but also from fewer co-benefits of associated NBS.

Limitations and future research priorities

Shortcomings in the research approach were evident. Firstly, despite considerable efforts, interviews with stakeholders were fairly limited in scope and span, and focussed primarily on those with professional backgrounds and socio-political interests in stormwater management in Berlin. Deeper reflections on citizens' and city priorities would be helpful here, and could be achieved using well-publicised online surveys and additional qualitative research. Similarly, whilst the conditions and dynamics may resonate with most large cities particularly in Europe, in many urban areas stormwater systems are managed separately (segregating storm and foul water drainage). This limits the applicability of the results and possible conclusions relating to NBS uptake and associated impact indicators to urban areas with combined sewer networks. Finally, although relevant literature available for Berlin is unusually extensive, there is a limit to how many conclusions can be drawn from just one city.

Certain directions for future research are apparent. Firstly, the scope for greater application of public volunteered information, and notably PPGIS, was beyond what was possible in this project (see [56]). The potential exists to gauge wider citizens' perspectives (theme 3) as regards urban water management challenges, in Berlin and beyond. Complementary research could entail media discourse analysis (at various scales), to provide wider reflections on the societal relevance, impact and critically, framing of urban water management systems. Secondly, future research into notions of added value of NBS for stormwater management could prove valuable, especially if these were compared with other interventions such as incentives for rainwater harvesting vs. sealing. Social perspectives of SUDS have been researched previously but in very different contexts, and less often linked directly with valuation (notable exceptions include [136–139]). A separate line of enquiry would be to reconsider the various categories and impacts within emerging concepts related to NBS, such as the social-ecological-technological system (SETS) framework. Such an approach would provide the opportunity for comparative research spanning multiple cities and to revisit impact assessment frameworks. Finally, addressing the current gap around created NBS habitat value, long-term monitoring programmes to understand biodiversity benefits in cities would be invaluable.

Conclusions

Stormwater management issues in general - and particularly CSO impacts - are receiving increasing media attention and given the impacts of climate change, this is unlikely to be a topic that will go away any time soon. After all, citizens can usually 'sniff out' a bad deal. Factors affecting investments in stormwater management, whether involving conventional hard infrastructure or using NBS, go well beyond simple measures of flow, storage, volume and frequency. Public notions of value and legitimacy in urban water management are changing rapidly. Planning for future urban water management requires engagement with multiple values, well beyond what can be modelled, monitored, or calculated – as well as targeted consideration of local conditions, barriers and opportunities in decision-making. In this context, the scope of impact assessment is also shifting, and requires deeper reflection of synergies and trade-offs between potential co-benefits to achieve diverse sectoral and stakeholder-specific objectives. Thus understanding local contexts is increasingly vital in setting key indicators to assess the impact of NBS for urban water management, and this provides opportunities to both utilise and refine emerging assessment frameworks.

Cities, as key stakeholders in water management decisions, face choices in how to frame and communicate their decision-making processes, and whether to involve people more directly in the shaping those processes. Based on the results of systematic reviewing of the literature, and interviews with key stakeholders, we report on the examination of 9 key themes around urban water management. These themes provide clues as to future bases for participative impact assessment, addressing change, citizen participation, governance, pollution and water quality, CSO spill reductions, greenspace access, water resources and biodiversity. The investigative process and findings reported here can be of interest to cities, to researchers and water industry stakeholders considering their next moves as regards stormwater and GI decision-making processes.

CRediT authorship contribution statement

Tom Wild: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Supervision, Writing – original draft, Writing – review & editing. **Gregory Fuchs:** Data curation, Investigation, Writing – original draft, Writing – review & editing. **McKenna Davis:** Funding acquisition, Project administration, Writing – review & editing.

Declaration of competing interest

We assert that there is no conflict of interest regarding the content of this manuscript and that the work has not been published elsewhere and is not under consideration by another journal.

Data availability

Data will be made available on request.

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