infrastructures

Article

Infrastructure Transitions Through Nature-Based Solutions: Aligning Perceptions

Hade Dorst [1,*], Suzan van Kempen [1] and Agnieszka Bigaj-van Vliet [2]

[1] TNO Vector, Centre for Societal Innovation and Strategy, 2595 DA The Hague, The Netherlands
[2] TNO, Mobility and the Built Environment, Molengraaffsingel 8, 2629 JD Delft, The Netherlands
* Correspondence: hade.dorst@tno.nl

Abstract

We argue that mainstreaming Nature-based Solutions (NbS) requires alignment of diverse value systems and integrated, cross-sectoral collaboration, and we present the necessary conditions for increasing practical implementation. NbS are increasingly recognised as effective strategies to protect critical infrastructures against climate change impacts while enhancing them by delivering ecological, social, and economic benefits. Despite growing policy support, the integration of NbS into mainstream infrastructure planning remains limited due to siloed responsibilities and decision making, entrenched institutional structures that favour grey infrastructure, and challenges in balancing short-term risks with long-term value. We examine if and how NbS mainstreaming in the infrastructure sector could be enabled. Building on insights into infrastructure governance and innovation mainstreaming, we explore perceptions and engagement with NbS and opportunities for strengthening co-governance and collaborative decision making in the Dutch infrastructure domain. A critical insight is that NbS must be understood as part of a broader socio-ecological–technical system rather than isolated interventions. This results in requirements for more integrated approaches to governance and planning as well as assessment. Asset managers in particular could play a pivotal role by adopting holistic performance assessments that consider co-benefits and trade-offs.

Keywords: asset management; climate resilience; cross-sectoral governance; mainstreaming; nature-inclusive infrastructure; socio-technical infrastructure regimes

1. Introduction

Nature-based solutions (NbS) are increasingly seen as viable strategies to protect critical infrastructure in the built environment against the impacts of climate change [1,2]. Developing climate-resilient and nature-inclusive infrastructures—e.g., enhancing the performance of energy, mobility, water, or building infrastructures—is a key element in building more sustainable and resilient societies [3]. In addition to climate-proofing critical infrastructure, NbS harness natural processes to address other societal challenges—from climate mitigation to biodiversity loss—while providing multiple co-benefits. Nature-based infrastructure solutions have gained increasing prominence in global and regional policy debates, with UNEP analysis showing that across eight infrastructure sectors, they can contribute to progress on up to 79% of SDG targets, rising to as much as 95% when deployed in combination with conventional (built) infrastructure [2]. The broader uptake of NbS exemplifies such a shift towards future-oriented infrastructure development.

Academic Editor: Boulent Imam

Received: 29 January 2026
Revised: 26 February 2026
Accepted: 11 March 2026
Published: 18 March 2026

NbS are defined as 'actions to protect, sustainably manage and restore natural and modified ecosystems in ways that address societal challenges effectively and adaptively, simultaneously benefiting people and nature' [4]. Examples in the built environment include green roofs, bioswales, or green urban corridors (see Table 1 for an overview of NbS categories in the built environment and their expected ecosystem services). However, this study does not focus on a single NbS typology but adopts a broad conceptualisation of NbS as systemic, multifunctional interventions in the built environment. The overview in Table 1 is therefore intended to illustrate the diversity of relevant NbS categories rather than delimiting the empirical scope of the analysis.

Table 1. NbS examples [5–7].

NbS Category	Expected Ecosystem Services
Open green spaces/urban forests	Cooling and microclimate regulation; stormwater infiltration; carbon sequestration; habitat provision; air quality improvement; recreation and wellbeing.
Green roofs	Stormwater retention; insulation and energy savings; biodiversity habitat; evapotranspirative cooling; improved air quality.
Bioswales and infiltration trenches	Stormwater slowdown; infiltration; sediment capture; pollutant removal; groundwater recharge; dispersed cooling effects.
Riparian buffer zones	Bank stabilisation; nutrient and sediment capture; flood peak dampening; shading and cooling of waterways; habitat connectivity; groundwater recharge; pollination benefits.
Floodplain restoration	Flood storage; peak flow reduction; sediment retention; biodiversity enhancement; carbon storage in wet soils; recreation; groundwater recharge; microclimate regulation.
Rain gardens/bioretention	Pollution filtration (nutrients, metals); peak flow attenuation; increased infiltration; urban cooling; local biodiversity habitat.
Constructed wetlands	Wastewater purification; nutrient removal; flood buffering; carbon sequestration in soils; biodiversity; recreational/nature value; cooling via evapotranspiration.
Soil and water bioengineering (e.g., riverbank stabilisation)	Bank stabilisation; erosion control; slope reinforcement via roots; habitat for amphibians/invertebrates; sediment moderation; landscape integration.
Urban green corridors and street trees	Shading and heat island mitigation; particulate deposition; carbon sequestration; stormwater interception; habitat; psychological wellbeing.
Vertical greening	Thermal insulation; building energy reduction; noise buffering; habitat for insects; air pollutant capture; microclimate regulation.
Blue–green hybrid systems (e.g., water squares)	Pluvial flood retention; cooling; recreation; social cohesion through multifunctional space; biodiversity niches; air quality benefits.
Permeable pavements	Runoff reduction; improved infiltration; groundwater recharge; reduced sewer load; reduction of local flood peaks; pollutant filtration through sub-soil.

As Table 1 shows, NbS are inherently multifunctional, addressing multiple challenges simultaneously—such as climate change adaptation, health and wellbeing, biodiversity enhancement, or water management. This multifunctionality makes their implementation, operation, and maintenance cross-sectoral, requiring input and cooperation from various stakeholders. Furthermore, NbS are generally context-sensitive and aim at delivering long-term resilience. Yet while NbS have been found to be more cost-effective than engineered alternatives in various contexts, current appraisals often underestimate the long-term economic benefits of NbS due to a lack of appropriate frameworks and consideration of multi-functional benefits, trade-offs, changes in ecosystem services over time, and embeddedness in local ecosystems [8,9].

Although the concept of NbS is increasingly included in (inter)national policy agendas—such as the Urban Agenda for the EU or the Dutch City Deal Climate Adaptation—they are not yet part of the mainstream practices of the infrastructure sector across planners, engineers, developers, architects, infrastructure managers, or investors. A major reason for this may be that NbS implementation often does not fit within entrenched sectoral norms and routines, whether it concerns policy frameworks, financing models, professional expertise, infrastructure design, construction and maintenance practices, or organisational structures [10,11]. In essence, NbS differ from 'grey' infrastructure, which evolved through a paradigm of fragmented governance, siloed decision making, and the challenge of balancing short-term risks with long-term value. As a result, actual integration of NbS into mainstream infrastructure development remains limited. Martin et al. [12] describe this as an 'implementation gap,' where NbS projects are often fragmented and context-specific, lacking the scale needed to achieve systemic impact. Fragmented responsibilities and rigid institutional structures constrain the integration of NbS into the built environment [13,14].

Because of their cross-sectoral character, NbS address challenges in various domains and thereby benefit multiple stakeholders. Yet this also means they tend to fall between policy, financial, and operational responsibilities and political mandates. A key barrier to implementation of NbS therefore is limited collaboration across sectors and disciplines, exacerbated by different ways of working, timelines, and siloed policy and financial frameworks [9,15,16].

Furthermore, it remains difficult to engage the private sector, which is necessary as the government cannot afford the necessary climate, health, and economic interventions for a sustainable societal transition all alone. Private actors, such as project developers, are sometimes sceptical about costs, performance, and profitable business models of NbS and are therefore less willing to engage or invest. NbS may also compete with other (urban) functions and sustainability innovations over land use in dense urban environments, which requires further collaboration and may impede implementation altogether [15,17].

Other reasons the uptake of NbS is hampered are current perceptions of risks and value of NbS in the built environment. For instance, if a green roof mostly benefits the local community, insurers (health, decreased climate risks), and the sewer company (delayed and diminished runoff water), is the project developer willing to pay for the added expenses? Different views on the costs, risks, and advantages across different stakeholders—e.g., planners, asset managers, policymakers—complicate collaboration and slow down adoption. While NbS have been found to be more cost-effective than engineered alternatives in various contexts, particularly for less extreme hazard scenarios, such as flood risk reduction along coasts and in river catchments, current appraisals often underestimate the long-term economic benefits of NbS due to a lack of appropriate frameworks and consideration of multi-functional benefits, trade-offs, and changes in ecosystem services over time. Despite challenges in predicting the efficacy of NbS, there is growing consensus that combining green and grey infrastructure may offer the best solution for addressing climate change risks and providing additional ecosystem services [9].

It is these barriers in the infrastructure domain that we centralise in this paper by addressing the following question: How can the uptake of NbS in mainstream infrastructure planning and operations be improved?

To answer this question, we focus on the 'system' of the Dutch infrastructure domain—which is detailed further in the next section—and address a few critical sub-questions:

- How is the concept of NbS understood; 'what' do NbS represent in the infrastructure domain?

- Who are the main stakeholders operating in the infrastructure domain, and how do they currently understand and engage with NbS?
- Why are stakeholders motivated to adopt NbS—or not?
- Which institutional conditions promote more systemic, integrated adoption of NbS?

The next section introduces the perspective of socio-technical infrastructure regimes as a heuristic to help understand the structural factors moving against the wider uptake of NbS in infrastructure and built environment development and operation.

2. Socio-Technical Infrastructure Regimes

For a better understanding of the uptake of innovation in society, we build on a conceptualisation of socio-technical regimes. The regime concept is central to socio-technical transition studies, referring to the dominant and stabilising configuration of practices, rules, and technologies within a societal system [18,19]. The socio-technical regimes concept was developed as part of the heuristic of the multilevel perspective to explain path dependency and lock-in in socio-technical development. The perspective understands the regime to be in continuous interaction with external forces and pressures at the 'landscape' level, such as demographic shifts or climate change, as well as with emerging innovations and alternatives to this dominant regime—the 'niche' level, protected 'spaces' where radical innovations can develop without the selection pressures of the dominant regime [20,21]. Successful innovations at the niche level can eventually influence and transform the regime [22]. This perspective helps explain how societal transitions occur through interactions between these levels, and particularly how niche innovations can disrupt and eventually transform or replace established regimes.

For transitions in the infrastructure sector, the conceptualisation of urban infrastructure regimes can be of use in examining if and how the more widespread adoption of innovation—such as the integration of NbS—can occur in this particular sector [10,11]. Urban infrastructure regimes are defined as 'the stable configurations of institutions, techniques and artefacts which determine "normal" sociotechnical developments in a city and thus shape general urban processes and the urban metabolism' [11] (p. 1937). The notion of regimes signals that development of the built environment and key infrastructures like water, waste, energy, or mobility is shaped by institutionalised practices, governance structures, and path-dependent development patterns. These regimes embed power relations, privileging certain technological trajectories in urban infrastructure while marginalising alternative, innovative approaches [11,23]. Urban infrastructure regimes thereby represent a material and institutional selection environment for innovations in the development of infrastructures and the built environment [10]. Because our study also concerns built infrastructures outside of cities, we draw inspiration from the concept of urban infrastructure regimes but broaden it to socio-technical infrastructure regimes, encompassing all built infrastructures. This broader perspective is necessary because infrastructure and the built environment are not limited to urban areas; the term 'urban' can therefore be misleading when analysing wider spatial and infrastructural systems.

Socio-technical infrastructure regimes are characterised by several aspects of relevance to NbS development. Due to their high societal importance and high initial investment, infrastructure systems usually necessitate a long life cycle [24]. Conventional infrastructure development therefore tends to emphasise incremental upgrades to existing systems rather than transformative redesign, as well as risk aversion through standardised solutions with proven performance records and techno-economic optimisation prioritising cost efficiency over ecological or social co-benefits. Infrastructures are characterised by obduracy [25]. Furthermore, the sector is characterised by fragmentation where, for instance, water, energy, and transport systems are mostly separately planned, developed, owned, operated, and maintained by a range of larger and smaller organisations in a varied value chain [10].

NbS as Regime Disruptors

Within this setting of obdurate built infrastructures and the institutional systems supporting their functioning, NBS can be viewed as a prime example of a spatial and infrastructural innovation. While 'nature' itself is not new, its application as a solution in the physical and urban planning space is. It answers a range of challenges from climate change adaptation and climate risk reduction (such as flood protection or heat stress mitigation) to health and wellbeing, ecological connectivity, and biodiversity loss.

Yet their uptake challenges the norms of the socio-technical regime outlined above. First, a reconceptualisation of the physical–functional character of spatial interventions is required; whereas traditional engineered 'grey' infrastructure tends to be designed as monofunctional interventions, NBS are characterised by multifunctionality. For instance, green roofs simultaneously manage stormwater, reduce urban heat, and enhance biodiversity. Green and grey interventions can also be implemented together as hybrid systems, such as combining wetlands with conventional drainage to handle peak flows. This means that a more holistic appraisal of benefits is needed, and often also other financial and physical risk perceptions (and associated regulations) need to come into play [26].

Second, governance transformations are needed. Due to their multifunctionality, NbS fall between the cracks of how responsibilities for urban and infrastructure development are organised and financed. Their benefits are those of a 'commons,' which implies that the party planning for and investing in their development is often not the (only) party reaping its benefits. Not only does the implementation of NbS therefore require cross-sectoral governance and coordination and coherence between different policy and implementation domains but also a more participatory planning approach, where communities are involved in co-designing green spaces [26], as well as novel (co-)financing models blending, for instance, green bonds with traditional infrastructure funds [27].

Third, a shift in the dominant knowledge and data paradigms is required. Usual performance metrics do not apply, as NbS deliver co-benefits. For instance, if carbon sequestration and mental health benefits are valued alongside the drainage capacity of infrastructure, NbS become a relevant and cost-effective option (albeit perhaps to a different selection of stakeholders) for which different kinds of monitoring need to be in place. In addition, their lifecycle will look different—less linear—than that of grey infrastructure, which also requires different kinds of monitoring. Furthermore, their living nature requires ecological, local, and collaborative governance knowledge for adequate design, implementation, and maintenance.

3. Research Design and Methodology

We adopted a qualitative research design to explore perspectives on if and how NbS can be mainstreamed and contribute to systemic transitions in infrastructure development and operation considering NbS as a broad and diverse set of nature-based interventions in the built environment, with a particular focus on stakeholder roles, motivations, and governance conditions shaping their uptake. This design was chosen to enable an in-depth, systematic exploration of institutional perceptions, motivations, and governance dynamics that cannot be captured through purely quantitative approaches.

The methodology consisted of two core components: (1) preparatory stakeholder mapping and (2) the main empirical component, a set of semi-structured interviews with strategically selected actors across the Dutch NbS ecosystem. A unifying analytical framework guided both data collection and subsequent analysis.

3.1. Analytical Framework

To structure both data collection and interpretation, the study adopted an analytical framework grounded in earlier NbS governance and the socio-technical transition literature, as presented in Section 2. This framework conceptualises NbS mainstreaming across three interrelated analytical dimensions—the NbS concept, the stakeholder landscape, and the conditions for engagement shaping the implementation and institutionalisation of NbS (see Figure 1). These dimensions correspond analytically to how NbS are perceived and conceptualised (Level 1), how roles and responsibilities are distributed across actors (Level 2), and how governance and institutional conditions enable or constrain engagement and implementation (Level 3).

Level 1—The NbS concept (what): Perceptions, conceptualisation, and operationalisation of NbS

Our analysis starts by uncovering how NbS are understood, conceptualised, and subsequently operationalised in the infrastructure domain.

Level 2—The stakeholder landscape (who): Roles, responsibilities, and interactions

NbS require multi-actor involvement across government, markets, civil society, and knowledge institutions, each operating under different mandates, incentives, and temporalities. Stakeholder mapping (Appendix B) served as empirical grounding for this level. It investigated how each party plays a different role with different responsibilities and perceptions of, e.g., risk or value.

Level 3—Underlying conditions for engagement (why and how): Motivations and structural enabling conditions

At the third, underlying level, the framework accounts for how actor-specific motivations (e.g., sustainability commitments, regulatory compliance, financial incentives) and structural conditions (e.g., policy frameworks, funding mechanisms, market logics, knowledge) mediate the potential for collaboration and NbS uptake.

The analytical framework served a dual purpose: it structured the interview guide, ensuring consistent coverage of the systemic, institutional, and behavioural dimensions of NbS uptake, and it provided a lens for synthesising findings into thematic insights (Section 4).

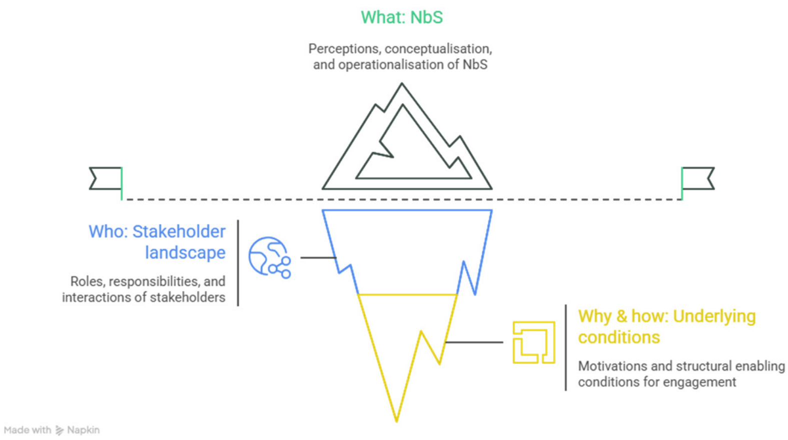

Figure 1. Analytical framework visualisation illustrating three interrelated analytical dimensions of NbS mainstreaming—NbS conceptualisation and operationalisation, the stakeholder landscape, and the underlying conditions for engagement—and their interconnections within a socio-technical governance context.

The research was conducted in three main phases. First, an exploratory desk study was undertaken to map the Dutch NbS stakeholder landscape and to situate the study within ongoing policy programmes, innovation networks, and infrastructure practices. This included a review of the academic literature, policy documents, and programme materials related to NbS, climate adaptation, and infrastructure governance, as well as systematic mapping of relevant actor groups. This phase resulted in a structured overview of stakeholder categories, their roles, and their positions within NbS development and implementation, which informed both the interview sampling strategy and the analytical framework.

3.2. Step 2: Interview Design

Building on the stakeholder mapping, the research team identified and prioritised actors whose work, mandates, or expertise positioned them centrally in Dutch NbS development and implementation. This led to the selection of 13 participants across 9 organisations, representing national and regional-level government, private engineering and consultancy firms, NGOs, and academia. Given the exploratory and qualitative nature of this study, the aim was not statistical representativeness but the inclusion of diverse, information-rich perspectives across the NbS ecosystem, consistent with purposive sampling approaches in qualitative research. Interviews were conducted until thematic saturation was reached, meaning that additional interviews yielded no substantially new themes relevant to the analytical framework. Sector representation allowed us to explore divergences in institutional logics, professional cultures, and knowledge needs.

Semi-structured interviews—structured in line with the analytical framework (see Appendix A)—were chosen to balance consistency across thematic domains with flexibility to explore context-specific insights. Interview questions were open-ended to enable participants to articulate their own narratives, while targeted probes were used to clarify mechanisms of collaboration, risk perception, and decision making practices. All interviews were recorded, anonymised, and transcribed for analysis.

Data Analysis

Interview transcripts were analysed using a thematic analysis approach supported by qualitative coding software. The coding scheme was developed deductively from the analytical framework (Appendix A). Coding occurred through an iterative process in which emerging subthemes (e.g., asset management bottlenecks, quantification challenges, cross-sector coordination problems) were cross-checked among researchers. A validation session with the research team strengthened interpretative reliability. Rather than presenting interview excerpts descriptively, the coded data were systematically synthesised into cross-cutting themes aligned with the analytical framework, which were subsequently used to structure the results and interpret stakeholder perspectives.

3.3. The Dutch Infrastructure Ecosystem

Our analysis centred on the Dutch infrastructure domain; as Zuniga-Teran et al. [27] (p. 717) note, as the Netherlands is ‘a [green infrastructure] trailblazer in so many ways,’ findings may inspire and benefit other countries and communities in their efforts at integrating NbS in infrastructure development, too.

Dutch infrastructure is internationally regarded as dense and high-quality, yet the system is under pressure [28]. A large share of bridges, tunnels, and waterways built in the 1950s–1970s is ageing simultaneously, leading to mounting maintenance backlogs and more frequent defects. Rijkswaterstaat’s *State of the Infrastructure 2024* shows that networks still perform at ‘average to good’ levels, but a growing portion has exceeded its intended lifespan and requires increasingly intensive management to remain safe [29,30]. The sector itself is fragmented across public and semi-public authorities (e.g., the Ministry of Infrastructure and Water Management, Rijkswaterstaat, ProRail, provinces, municipalities, and water boards), operating under tighter budgets, labour and resource shortages, and complex, climate-driven performance demands complicating renewal efforts [28]. This contextualisation is essential, as the Dutch case offers a particularly relevant setting for examining NbS mainstreaming given the coexistence of strong institutional and spatial planning capacities within complex multi-level governance arrangements that shape cross-sectoral coordination and the direction of systemic transitions in the infrastructure sector.

4. Results

To analyse how the uptake of NbS can be further supported in the context of resilient urban infrastructure, the coded interview data were synthesised according to the three analytical dimensions of the framework: (1) the NbS concept, (2) the stakeholder landscape, and (3) the structural conditions for engagement. Table 2 presents a structured synthesis of the key findings derived from the thematic analysis, which are elaborated in the following subsections. To systematically analyse how the uptake of NbS can be further supported as an innovative way of improving the resilience of urban infrastructures, we focused on the coded interview data, which were synthesised according to the three elements of the analytical framework: (1) the NbS concept, referring to perception, conceptualisation, and operationalisation of NbS in infrastructure development; (2) the stakeholder landscape, including roles, responsibilities, and strategies for innovating with nature in infrastructure development; and (3) the structural conditions for engagement, encompassing stakeholder preferences and enabling governance and institutional factors related to NbS implementation. Table 2 provides a structured synthesis of the key findings derived from the thematic analysis, which are further elaborated in the following subsections.

Table 2. Overview of results.

Analytical Framework Elements	Key Results
Level 1—'What': NbS as tangible systemic interventions (part of broader socio-ecological–technical systems)	• Perceived as needing a 'systems' framing rather than a catalogue of individual measures • Practitioners critique 'NbS' label; it can push discussion too quickly toward discrete projects ('solutions'), whereas terms like *nature-inclusive*, *nature-positive/net gain*, and *natural capital* better signal a whole-cycle perspective (planning, financing, design, implementation, operation) in which natural assets are intrinsically valued • Multi-scale interconnectedness (from building to landscape) and cross-system integration (ecology with mobility/energy/water) are stressed, implying that assessment and governance must move beyond site-bounded project logics to capture cumulative and long-term functioning
Level 2—'Who': Stakeholder landscape (multi-actor involvement across government, markets, civil society, knowledge institutions; differing mandates, incentives, time horizons; roles/responsibilities and collaboration patterns)	• Mainstreaming is constrained by fragmentation and misaligned responsibilities across the stakeholder ecosystem • Absence of an 'integral' decision locus: tasks are cut up across organisations and departments, with divergent horizons and objectives, producing coordination gaps and slow, watered-down compromises • Tensions between national guidance and local implementation capacity; NbS connectivity often exceeds municipal boundaries, demanding collaboration structures that match ecological scale • Need for shared language and an 'integrality' logic to enable cross-sector cooperation and clearer role allocation

Table 2. *Cont.*

Analytical Framework Elements	Key Results
Level 3a—'Why': Actor motivations (e.g., intrinsic sustainability commitments, societal pressure, compliance; perceived risks/values; willingness to engage and invest)	• Support for NbS seen as requiring alignment between bottom–up societal motivation and top–down regulatory/strategic signals • Societal awareness and community attachment described as protective forces (making it harder to degrade green assets) • Scaling argued to require clearer legal anchoring and stronger incorporation into formal decision processes (e.g., national programmes), while fears of over-regulation also exist • Divergent perceptions of risk, responsibility, and 'who benefits'—this constrains willingness to invest, especially where benefits accrue broadly but costs sit with specific actors
Level 3b—'How': Structural conditions for engagement (policy/finance frameworks, market logics, knowledge and data; governance arrangements enabling collaboration and uptake)	• Three enabling conditions dominate: (1) reorienting asset management; (2) standardisation and operationalisation; (3) actionable evidence and a business case • Asset managers repeatedly identified as a leverage point but also a bottleneck: NbS can be 'designed in' during projects yet later undone in operations due to budget constraints, risk aversion, model-based management routines, and short time horizons • Standardised criteria/parameters for 'nature-inclusive' design would create clarity and a level playing field, yet subjectivity and plural values complicate universal metrics and remain barriers • Needed: (1) concrete, context-specific performance examples; (2) metrics usable for decision making, including simple communicable indicators (e.g., rules of thumb) and risk-framed appraisal methods; (3) better data interpretation capacity • Clearer incentives and financing arrangements needed to make the long-term value visible and investable while remaining attentive to distributional questions about who profits and who pays

4.1. NBS in the Built Environment: Beyond Singular Solutions

Section 4.1 synthesises how practitioners across public authorities, NGOs, consultancies, and knowledge institutions currently conceptualise the role of NbS in the built environment and the types of challenges these approaches are expected to address. Interpreted through the analytical framework, this primarily relates to the NbS concept dimension while also reflecting differences in stakeholder roles and responsibilities that shape engagement with NbS implementation.

Across interviews, a shared recognition emerges that a nature-inclusive built environment is about considering nature-based systems, not singular solutions. While the concept of NbS served as a useful starting point for our inquiry, this term invites scrutiny from the practitioners we interviewed, perceiving this as a label that can unintentionally narrow the discussion towards the implementation of particular projects ('solutions'), while, for some, more generic concepts (such as nature-inclusive, nature-positive/net gain for nature, natural capital) are preferred that denote a different perspective on the infrastructural cycle of planning, financing, design, implementation, and operation, in which natural assets are intrinsically valued and taken into account.

> *'[When it comes to] nature-based solutions, it's actually very quickly all about measures, wanting to move to implementation [of concrete projects]. And nature-inclusive is a more overarching concept, that can also be about natural capital. And about arranging funding in a different way, and behaviour, and education.'* (Interview #3, National government)

While NbS often focus on specific measures using natural elements and processes at various scales to address (multiple) societal issues, nature-inclusive approaches encompass wider considerations like natural capital, financing, behaviour change, and education. Nature-positive development implies a net-positive impact for nature through the improvement of the natural quality of a site by way of the development, even if it was not the primary goal of the infrastructure or building development.

Although multiple terms are used interchangeably at times, the labels 'nature-based' or 'nature-inclusive' highlight the need to consider 'systems' at multiple scales, from individual buildings to entire urban ecosystems. NbS aim to enhance overall ecosystem functions rather than provide isolated interventions. This means that to improve and assess the quality of nature-based or nature-inclusive interventions and development and achieve multiple benefits simultaneously, considering scale and interconnectedness in designing and implementing them is key. This requires an integrated approach of taking the geography beyond the development site into account as well as the diverse values and knowledge backgrounds of the stakeholders to be impacted by the development. Effective implementation therefore requires a better understanding of both natural and human-made systems, including the built environment, mobility, and energy infrastructures. At the level of geographical scale, this also implies considering infrastructural systems beyond the project site and even beyond the neighbourhood, city district, or city level. At the level of infrastructural systems, this implies considering the ecological system but also the mobility, waste, or energy systems. And, at the institutional level, a systems perspective implies considering how to anchor nature-based development into coherent policy strategies or (co-)financing structures. As one respondent noted, the most visible NbS interventions (such as urban greening campaigns or rooftop vegetation) may help shift public perceptions, yet the 'big hitters' for climate resilience lie in addressing system-level dynamics, including water table management, landscape fragmentation, and the cumulative effects of spatial development choices.

> *'Not the green roofs, but the large areas of the Netherlands [are needed for impactful greening]. Look, when we are implementing green roofs, but everyone keeps popping these logistical blocks into the landscape like that—what are we talking about? Or if we keep lowering the groundwater level but keep CO_2 levels rising. And that's really where the big hitters are. Housing construction should certainly not be neglected. [. . .] A lot of people have eyes on that housing development. So if something happens there, it does a lot for perception. It might prompt people to do something. But the real impact lies elsewhere.'* (Interview #6, Engineering consultancy and design)

The interviews also revealed that moving beyond singular solutions requires a more explicit recognition of the multifunctionality of NbS. Practitioners increasingly understand that NbS cannot be evaluated solely through traditional engineering logic based on monofunctional performance. Instead, they generate co-benefits—cooling, ecosystem restoration, biodiversity, mental health, stormwater buffering—that unfold over varying spatial and temporal scales. This implies a need for assessment frameworks capable of capturing cumulative and long-term effects rather than focusing narrowly on immediate project outputs. Several interviewees pointed out that this wider value proposition is not yet embedded in prevailing planning and appraisal routines, which are often tied to sectoral mandates, rigid regulations, and short decision cycles.

Overall, practitioners increasingly conceptualise NbS not as technical fixes but as interventions embedded within and dependent on broader socio-ecological–technical dynamics. This reframing highlights the importance of multiscale design, interconnected governance, and lifecycle thinking in supporting climate-resilient and nature-inclusive infrastructure development. It also underscores why mainstreaming NbS will require moving from project-based solutions to more systemic planning, assessment, and decision making practices attuned to long-term ecological functioning and cross-sectoral interdependencies.

4.2. Stakeholder Roles, Responsibilities, and Strategies: Reorienting Asset Management

The interviews highlight that mainstreaming NbS within the infrastructure domain is strongly shaped by the stakeholder landscape, particularly the distribution of roles, responsibilities, and governance strategies across actors, which is the focus of Section 4.2. While societal ambitions and policy agendas increasingly address the need for greener, more resilient built environments, practitioners consistently identify that the real bottlenecks lie in the fragmented, multi-actor governance landscape in which NbS must operate. The interviews reveal that effective implementation depends not only on technical capacity but on the alignment of mandates, incentives, and time horizons.

A key reflection emerging from the interviews is that to generate more support for nature-inclusive building practices, top–down regulation and bottom–up civil society motivation need to align. There is a growing recognition that societal pressure and awareness are crucial for the successful implementation of NbS. Experts believe that if people understand the value of natural areas and NbS, it becomes more difficult to ignore or damage them. Initiatives such as 'tile flipping' (a national movement of replacing concrete tiles with greenery) are seen as effective ways to engage citizens and create awareness. So, on the one hand, it is recognised that change must come from below, with acceptance and involvement from citizens.

> *'If everyone very much cherishes the areas and has embraced the NbS... then it does become more difficult to do crazy things with it. I believe this is actually the best way. That there is so much more backlash socially if you put the flail mower over it [...] then no one gets it in their head... Or that the municipal council gets reprimanded right away. That really happens.'* (Interview #5, NGO)

On the other hand, there is a need for guidance and support from above, especially in scaling up successful experiments. Because while there is a preference for intrinsic motivation, the systemic aspect—NbS only functioning as a part of a broader ecology—also requires a broader vision and approach to infrastructure and urban development. In addition, respondents recognise the need for legal anchoring of NbS; this would provide clarity and a level playing field for all involved. For instance, there are calls for better integration of NbS in decision making processes, such as in national programmes like the Dutch Multi-Year Programme for Infrastructure, Spatial Planning and Transport (MIRT). This would make NbS considerations mandatory for major infrastructure projects. However, there is still debate about the extent to which this should happen, as some fear overregulation.

> *'You would actually like to make agreements with several parties at the same time [about sharing both in the contributions to and benefits of NbS in the public domain], which just apply to everyone. But to do that, you actually have to start on a small scale [to show the business case], and people don't think that distributes the risks fairly.'* (Interview #3, National government)

Furthermore, an often-noted challenge is the coordination of actions between various levels of government and stakeholders—politicians and government agencies, knowledge institutes and universities (including students), companies (especially in the real estate sector), and citizens (including children) and civil society organisations.

While most innovations need some degree of coordination between (sectoral and policy) domains to embed them into societal structures, NbS being inherently cross-sectoral and multifunctional interventions exacerbates this issue. NbS provide a case that really highlights the issues arising in mainstreaming sustainable innovation, such as a lack of governmental coordination and integrated approaches. There is no overarching responsibility or decision making authority, leading to fragmentation of tasks and objectives. The current system lacks a central point of contact that can make quick and efficient decisions. Even within organisations, this remains difficult; for instance, different departments within one governmental agency may be carrying out projects in the same area without mutual coordination. There is a call for a stronger coordinating role from the national government in spatial planning and land use. The current situation, where provinces and municipalities play a large role, leads to inconsistency and inefficiency. Yet there are tensions here: the national government sees its role primarily as supportive, focusing on formulating policy and providing guidance. Actual implementation of green spaces is seen as the responsibility of municipalities and provinces, but these have little capacity to do so. Municipalities and regional authorities do tend to have better knowledge of the local issues and area, which is key to fruitful implementation of context-specific interventions like NbS. They also have the formal responsibility of implementing and maintaining green spaces at the local level, but the wider connectivity of green areas beyond municipal boundaries requires the involvement of a wider range of responsible parties.

> *'In the end, there is no one who has some kind of integral responsibility and can also make decisions at this level. Everything is cut up. Everyone is concerned with a small piece with a different horizon. And other goals. [. . .] I think with a lot of nature-based solutions, I think this is really the big bottleneck.'* (Interview #5, NGO)

There is ongoing debate about which institutions should bear the responsibility and costs for implementing and maintaining NbS. For instance, the responsible government agents express hesitation to take on additional costs for biodiversity measures in infrastructure management, viewing it as outside of their core responsibilities. Thus, compromises are made at the expense of ambition. Consultation processes and area-based processes cost a lot of time, money, and energy but often lead to suboptimal solutions and watered-down plans where everyone gets something but no one is fully satisfied. This means there is an inherent tendency towards incremental results instead of ambitious, transformative solutions. To more effectively address the lack of coordination, one interviewee pleads to bring together frontrunners and leaders from different sectors to effect change. A key condition emerging from the interviews is to create a shared language and impress a logic of integrality in relation to developing the built environment.

One link in the chain of infrastructure development stood out: asset managers were identified as being in a key position to enable the accelerated adoption of NbS, as critical issues arise when moving from project implementation to long-term management. While projects may initially incorporate NbS, maintenance teams often revert to traditional methods due to budget constraints, risk aversion, and short-term goals. Asset management is perceived to be somewhat conservative in its approach, prioritising proven solutions and quantifiable risks, with good reason, as the safety and durability of infrastructures are prioritised. Yet this also sometimes results in the degradation or abandonment of NbS within a brief period after implementation.

> *'What we are up against now is that [when] it goes from the project organisation to the management organization, [they] say, well, the project was executed, but now I just have a management task with a budget and certain goals. [. . .]. So you actually see those NbS just being killed within a year. Because the manager only looks at: what is my budget and my task this year or in the coming years. They don't look at the long term at all. We are dealing with [. . .] the management department, which says, well, this is a situation we can't control. Because we can't predict NbS in our models.'* (Interview #5 (NGO))

Furthermore, the long-term, scenario-based nature of climate adaptation makes it challenging to conduct traditional risk assessments, which can hinder investment in NbS. Traditional asset management relies heavily on predictive models. The relatively unpredictable 'living' nature of NbS makes it difficult to integrate them into existing management and maintenance frameworks, leading to resistance from departments that rely on such models for decision making.

> *'In infrastructure it is definitely asset managers [who can accelerate the implementation of alternative (i.e., nature-based) solutions. They are] more conservative, they know what works, and they have the best insights into the risks. Once you know the actual risks, you can try to find fitting alternatives. With climate adaptation, it is about potential future impacts. But it is so far ahead, and we work with scenarios, we cannot specifically identify risks into models.'* (Interview #7, Engineering consultancy and design)

So, despite positive policy and societal movements, challenges remain, such as finding the right balance between regulation and voluntary action and sharing mandates at multiple political levels (and, perhaps, more often also with civil society). Furthermore, the expert interviews revealed a complex landscape of institutional, financial, and operational challenges in implementing NbS within Dutch infrastructure and asset management systems. The analysis highlighted the need for more integrated approaches, clearer allocation of responsibilities, and adapted management practices to fully realise the potential of NbS.

4.3. Sector Preferences and Enabling Conditions: Standardisation, Concretisation, and a Business Case

A third set of insights relates to the sector's expressed preferences and enabling conditions for adopting NbS in practice. Across both public and private stakeholders, there is a clear call for greater standardisation, operational clarity, and tangible evidence to support decision making—particularly regarding performance expectations, risk assessment, and economic viability. At the same time, interviewees emphasise that such operationalisation must balance the inherently context-dependent and value-laden nature of NbS, revealing ongoing tensions between the desire for uniform metrics and the need for flexible, place-sensitive approaches.

Respondents, particularly those with roles in the private sector, expressed the need for standardising criteria for adequate nature-inclusive building development. They indicated that this would boost practical implementation due to the clarity it provides to all partners involved regarding technical specifications and economic viability.

> *'[The insights we need are] very practical; [. . .] What parameters [do you use] to say: this is nature-based design?'* (Interview #6, Engineering consultancy and design)

However, such standardisation is complicated by the inherently subjective nature of evaluating nature inclusivity and its associated values. Establishing a universally accepted definition and operationalisation of NbS and their associated benefits is difficult due to the multifaceted values attributed to nature-inclusive development; opinions diverge on the relevant criteria to determine the quality of the living environment. Furthermore, and as previously stated, interest in the functions that physical infrastructures should provide is divergent, as well.

> *'Start designing with a different focus, to help people get out of normal ways of thinking. Organise design sessions with all stakeholders, focusing on sustainability, and ask them: which alternatives are there, and which is the most sustainable. Broaden the problem scope. [. . .] We get the question: we have no capacity for traffic in [the city of] Eindhoven so we want to go underground. But if you rephrase it to: we want a better*

living environment—that is a very different assignment.' (Interview #7, Engineering consultancy and design)

The absence of a standardised definition and consensus regarding nature-based infrastructure development poses challenges for policy formulation and decision making processes about, for instance, expected industry efforts. The building sector's obligations, particularly in terms of the requisite degree of nature integration in developments, remain ambiguous without clear parameters. The fields of urban development, engineering, policymaking, and spatial planning are inherently prone to be metric-driven. Consequently, the lack of operationalisation methods for nature-inclusive approaches presents a substantial barrier to the adoption and integration of natural solutions in building construction and infrastructure projects. While quantification methods do exist, translating ecological benefits into monetary terms remains challenging, especially in communicating value to both the infrastructure sector and the public. Current tools often fail to provide a comprehensive picture of benefits. The extent to which certain values associated with our (natural) environments can be summarised into more standardised parameters for urban development needs to be determined.

'Benefits are difficult to measure and monetize, such as a decrease of biodiversity. Monetization, quantification is important for decision-makers. [. . .] Using measurement and performance tools is not business as usual yet; often they also only cover one share of benefits, but do not give a comprehensive picture.' (Interview #2, Engineering consultancy and design)

In addition to standardised assessment frameworks, respondents from the infrastructure sector indicate that they require concrete, context-specific, practical examples of NbS performance—real-world evidence that a nature-based alternative works for the problems they aim to solve or the infrastructural functions they aim to deliver. This implies that policy incentives alone are not sufficient to engage the private sector but that trust in these solutions needs to be engendered by real-world evidence. Moreover, it highlights the tension between local experimentation and wider scaling of 'tried and tested' solutions, as most NbS are very much embedded into, intertwined with, and impacted by their physical (climate, soil, etc.) and socio-economic (land use, regulatory, etc.) environments. This makes it difficult to predict their viability in different contexts.

'I think, above all, there is a great need for practical examples. Where was an idea conceived? Where was the idea tested? And did it lead to positive results? If you can demonstrate that in quick wins, you have the first key to the solution.' (Interview #6, Engineering consultancy and design)

'Some people live on arguments, some work on intrinsic feeling. It already helps to show pictures. But for asset managers, it needs to be tested, tested, tested.' (Interview #7, Engineering consultancy and design)

However, collecting more data is not the answer; it is the type of data and knowledge and their interpretation and practical use that are decisive. Improving data collection and interpretation (data literacy) is crucial for making informed decisions. There is a relative abundance of data on NbS in the built environment (and outside of it), but not always of the 'right' kind. For instance, asset managers often lack basic data about issues like flooding frequency. In addition, there is a lack of capacity to effectively analyse and utilise data for policymaking. One expert calls for more data officers who can interpret complex information and translate it into actionable policy insights. Furthermore, many practitioners are still unaware of technological solutions for collecting the necessary data for decision making (for instance, using drones for surveying the status of large natural areas). In terms of knowledge more generally, smaller municipalities often face more difficulties in implementing innovative and cross-sectoral solutions due to limited knowledge and capacity. They lack in-house expertise (like urban ecologists), therefore relying on external consultants, which is costly and can lead to a loss of accumulated knowledge over time.

Lastly, there are questions around how to turn complex information on NbS impact and performance into plain and easy-to-understand metrics, which would be much more effective in stimulating broader societal involvement. A successful example of such a metric is the 3-30-300 guideline, a rule of thumb for urban planners that aims to provide equitable access to green spaces and their benefits by setting the thresholds of having at least three trees in view from every home, school, and place of work, 30% of tree canopy cover in each neighbourhood, and a maximum of 300 m distance to the nearest public green space from each residence [31]. One respondent suggested developing assessment methods for the unpredictability of NbS, framed in terms of risk, to make these solutions more palatable to policymakers and the public. Overall, there is a need for simple, easily interpretable, and monitorable data to facilitate wider adoption and change narratives around NbS. These could contribute to clearer public narratives about the benefits of NbS. The power of visual storytelling is emphasised as an additional way to bridge the gap between scientific research and practical application.

One goal that could ultimately be achieved through clearer insight into the performance, risks, and cost–benefit ratios of integrating NbS into infrastructures is a 'path of clear incentives' for NbS—playing into but also, potentially, transforming market preferences.

> *'We are competing with [energy transition] and they are winning because they have clear numbers. They have clear benefits for individuals. They are getting like energy discounts or things like that, [such as] mortgage discounts.'* (Interview #1, Academia)

More generally, private sector actors are looking for a business case for nature. Interviewees propose to create more economic incentives for sustainable practices, such as discounts on mortgages or insurance premiums for green initiatives. Making nature-based infrastructure a 'growth market' could accelerate adoption. Opportunities lie in the creation of new jobs and businesses around NbS, potential for increased competitiveness and the possibility of significant cost savings through NbS. Economic arguments from influential stakeholders can also be powerful in shifting policy. Vice versa, laws and regulations play a role in reshaping certain market logics (for instance, by incentivising different behaviour).

> *'We experienced that a municipality wanted to intensify livestock farming, while there was no space. We really tried to get that changed, but it didn't work. Then we used a forum that includes, for example, ASML and Philips, the hi-tech campus. You only have to tell them once: listen, we all made this vision of how we can increase a business climate. And those high potentials that we very much need, that we are going to look for all over the world, they really won't come and live here if they have to sit in a pigsty. Well, then it was done. It was just off the table. But then, that is quite a heavy economic argument.'* (Interview #5, NGO)

However, there is debate about who profits from these transitions and how to ensure equitable distribution of benefits. Several interviewees therefore emphasised the importance of considering long-term benefits and true costs. As noted, the benefits of urban green spaces often outweigh the costs, but not all benefits are easily quantifiable or immediate. There is a need to make visible the potential damage or loss of not including natural solutions. And, a more general reframing of how spatial development and infrastructure challenges are defined and scoped—i.e., including (a broader variety of) sustainability considerations—could help to find more holistic innovative solutions.

> *'Many people follow the path of least resistance. This can be a clue. You never pay for extra [environmental] costs of a [technical] solution. If those costs are also included,*

choices may be different. If you pay the actual costs, you choose differently.' (Interview #7, Engineering consultancy and design)

In sum, practitioners in the infrastructure domain express an urgent need for standardised criteria as well as practical examples. These are crucial for the effective implementation of nature-inclusive building practices but also for clarity on the value and benefits and, more specifically, the business case for nature in the built environment. However, challenges such as subjective evaluation, data interpretation, and the complexity of quantifying ecological benefits must be addressed to facilitate broader adoption and policy formulation.

5. Discussion and Conclusions: An Action Perspective for the Infrastructure Domain

We set out to assess how the adoption of NbS for climate resilience in infrastructure development and operation can be improved by examining stakeholder perceptions, institutional conditions, and governance dynamics within the Dutch infrastructure domain. To do so, we used a perspective of socio-technical infrastructure regimes to shine light on the tensions between 'business as usual' in the infrastructure sector and the relative novelty that NbS represents for how infrastructure practices take place. We analysed the perspectives of infrastructure sector representatives on the status of development of NbS for climate resilience in the Dutch built environment as well as their motivations and considerations for further engagement in this field.

A key takeaway is that to arrive at a nature-inclusive built environment, NbS should not be viewed as isolated interventions but as functioning as and within broader socio-ecological–technical systems (SETS); it is these systems and the interplay between them that need to be considered in all phases of design and implementation. While much of the analysis highlights governance and implementation challenges, the findings also show that NbS are valued by practitioners for their potential to generate integrated economic, social, and ecological benefits. Interviewees frequently referred to co-benefits, such as enhanced climate resilience, ecosystem services, improved spatial quality, and long-term lifecycle value, even when these were not yet systematically incorporated into formal appraisal and decision making frameworks. This indicates that the added value of NbS is widely recognised in practice yet remains insufficiently operationalised in infrastructure planning, cost–benefit assessments, and asset management processes, thereby constraining their mainstream uptake. The SETS approach offers potential for ensuring a balanced consideration of the various dimensions and feedback loops of urban NbS from initiation through to evaluation [32,33]. The socio-technical infrastructure regime's reconfiguration through NbS demands concurrent changes across technical, governance, and cultural dimensions—a 'socio-ecological–technical' transition requiring decades-long commitment.

Second, reorienting governance roles and decision making structures may provide a path to mainstreaming NbS. Cross-sectoral interventions require coordination between cross-sectoral divisions of responsibility, and different perceptions of trade-offs and benefits currently complicate decision making and stakeholder alignment. This challenge is rooted in large part in the siloed approach to policymaking, budgeting, infrastructure development, and management [34,35]. Current infrastructure management practices often demarcate responsibilities and budgets by sector, including, for example, roads, green spaces, water systems, and sewers, leading to inefficiencies and missed opportunities. Improved governance alignment enables social and environmental benefits, such as improved quality of living environments, public health gains, community resilience, and civic engagement in green spaces [36].

In the existing stakeholder ecosystem, one crucial key to change towards more nature-inclusive infrastructure might lie in reorienting the role of asset managers. Asset management stood out as a link in the infrastructure development chain with much potential for improvement in terms of its more integral performance or function orientation; if asset managers were to consider more holistically the potential benefits brought by nature-based options and carry responsibility for the broader performance of infrastructure (rather than being mostly assessed on budget spent), NbS would not so often be neglected, ignored, or considered difficult. A shift in their perspective—of NBS as systemic solutions, with broader values than those directly calculable—may be a key leverage point in NBS adoption. Reorienting asset management could unlock long-term cost savings, reduced maintenance risk, avoided damages, or improved infrastructure lifespan.

Third, sectoral stakeholders indicate that they require the standardisation of demands and performance indicators for nature inclusiveness to better integrate NBS into their practices. A key barrier to further uptake is the lack of systemic monitoring and evaluation of the performance of NbS—especially where economic and non-economic benefits are combined—hindering evidence for a business case [32]. A systems approach would support such holistic assessment of infrastructure systems, increasing our understanding of impacts beyond a single domain [24]. Co-benefits should be positioned as part of the value case that, e.g., asset managers and decision makers, overlook. Standardising criteria for adequate nature-based infrastructure development would boost practical implementation, as it provides clarity about technical specifications and economic viability. Regulation can also be improved by more standardised parameters for design. Zuniga-Teran et al. [26] give the example of the United States, where constructed wetlands are classified in such a way that they are subjected to stringent water quality regulations originally designed for grey infrastructure, resulting in rigorous compliance evaluations that can increase costs and uncertainty. In contrast, several European countries have a longer history of implementing constructed wetlands, with well-established design parameters and proven treatment efficiency. As a result, these systems are subject to less intensive regulatory oversight, reducing administrative burdens and facilitating more cost-effective deployment.

However, such standardisation is often complicated by the inherently subjective nature of evaluating nature inclusivity and its associated values. As market logic shapes the building sector, incentives for NbS can be created by either playing into market preferences (e.g., providing 'thumbnail' assessment formats) or aiming to transform them (e.g., through education or awareness raising on risks and co-benefits). For instance, a more integrated fiscal approach and more elaborate co-benefit assessment would allow for the dynamic allocation and pooling of resources across infrastructure and policy domains [37]. Instead of restricting funds to specific departments, resources could, for instance, be managed collectively, allowing funds to flow toward projects that produce the highest overall value, even if they lie outside of the original domain of expenditure. This model would enable managers to redirect savings or surplus funds—such as from reduced road maintenance—to projects that generate broader systemic benefits. For example, by harvesting rainwater, a municipality can reduce the volume of water entering the sewage system, thereby lowering treatment and infrastructure costs. These savings can then be reinvested into green infrastructure—such as permeable pavements, bioswales, and urban greenery. This, in turn, enhances stormwater absorption, reduces flood risk, and supports groundwater recharge. Over time, this integrated approach not only strengthens climate resilience and water security but also reduces long-term public expenditure on water management and infrastructure maintenance. By prioritising projects based on their overall (co)benefits rather than narrow departmental outcomes, public managers can maximise overall value, foster cross-domain synergies, and make infrastructure spending more strategic and impactful.

Yet to complement standardised assessment approaches, the infrastructure sector requires concrete, context-specific, practical best practice examples of suitable NbS, with the important caveat that the answer does not lie in generating more evidence and data; it is about the type of data and knowledge and their interpretation and practical use. This echoes findings by McPhearson et al. [32] stating that improved ecological and technical knowledge is needed for planning and designing NbS, a challenge related to limited ways in which scientific findings are available and operationalizable to planners and engineers. Also, there is a shortage of local design guidelines, as NbS are often not included in engineering and planning curricula or professional education [15,32].

Finally, there are two underrunning currents across our findings regarding the Dutch infrastructure sector:

- There is a lack of insight into co-benefits and trade-offs and especially how these play out along the value chain of infrastructure development.
- This undercuts the effective division of roles and responsibilities and diminishes impactful collaborative decision making in and beyond the sector.

These findings also reveal clear knowledge gaps in the systematic assessment of NbS co-benefits, governance coordination mechanisms, and long-term performance evaluation within infrastructure and asset management contexts.

Based on perceptions of NbS and associated challenges around their wider implementation outlined in this paper, we propose that the infrastructure sector—including asset managers but also the wider ecosystem, including policymakers and knowledge partners—would be much aided by an evidence-based, accessible, and holistic practical action framework for more systematic assessment of NbS co-benefits and trade-offs. Such a framework could foster inclusive decision making, strengthen governance for co-development and cross-sector collaboration, bridge knowledge gaps, and align stakeholder priorities, thereby offering a standardised yet locally sensitive approach that supports the integration of NbS into infrastructure planning and operations. These findings highlight that mainstreaming NbS requires a systemic shift from project-based, mono-functional infrastructure logics toward integrated socio-ecological–technical governance approaches that recognise co-benefits, long-term value, and cross-sectoral collaboration.

A second promising direction for future research concerns the governance and financing arrangements needed to address the persistent fragmentation of responsibilities surrounding NbS implementation. Across both studies, it becomes clear that while NbS generate cross-sectoral benefits, costs and mandates remain rigidly siloed. This misalignment not only constrains investment decisions—particularly among asset managers—but also leads to situations where nature-inclusive measures implemented in projects are later undone in day-to-day management. Understanding how new governance models could enable shared fiscal responsibility and joint stewardship therefore represents an important next step. Future work could examine how multi-actor financing mechanisms, integrated budget structures, or co-benefit-based cost-sharing arrangements might help redistribute risks and rewards more equitably along the infrastructure value chain [27,37]. Such research would support addressing one of the most structurally entrenched barriers identified: the absence of institutional configurations capable of recognising and acting on the systemic value that NbS provide.

Overall, the findings contribute to the literature on NbS in the context of infrastructure governance by showing that the mainstreaming of NbS is less constrained by technological feasibility than by fragmented institutional arrangements, misaligned incentives, and the limited incorporation of multifunctional value into infrastructure planning and asset management. By adopting a socio-ecological–technical systems (SETS) perspective and thoroughly analysing stakeholder perceptions, roles, and underlying conditions for engagement, this study points towards a more systemic understanding of NbS uptake as a transition challenge rather than a purely technical implementation issue. Consequently, the paper offers an empirically grounded analytical framework and an action-oriented perspective to support more integrated, lifecycle-based, and cross-sectoral decision making for the context-sensitive embedding of NbS in infrastructure development and operation. In conclusion, the mainstreaming of NbS in the infrastructure sector requires more than technological innovation alone; it calls for a systemic shift in how infrastructure is governed over its lifecycle. The findings highlight that better alignment of stakeholder roles, governance arrangements, and valuation practices is crucial for recognising and operationalising the economic, social, and ecological benefits of NbS. Rather than treating NbS as isolated project-based interventions, they should be understood as integral components of socio-ecological–technical infrastructure systems. This perspective underscores the need for integrated, cross-sectoral, and lifecycle-oriented approaches that enable the durable and context-sensitive adoption of NbS in infrastructure planning, renewal, and long-term management.

Author Contributions: Conceptualisation, H.D. and A.B.-v.V.; methodology, H.D.; validation, H.D.; formal analysis, H.D.; investigation, H.D.; writing—original draft preparation, H.D. and S.v.K.; writing—review and editing, H.D., S.v.K., and A.B.-v.V.; project administration, H.D.; funding acquisition, A.B.-v.V. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Balanced Spatial Choices research programme of TNO, which promotes integrated and evidence-based approaches to spatial development. In addition, this research was funded by the European Union's Horizon Europe research and innovation programme under grant agreement No. 101157448 for the Nature-DEMO project.

Data Availability Statement: The data presented in this study are available on request from the corresponding author due to privacy restrictions.

Acknowledgments: The authors gratefully acknowledge the contributions of all project partners and stakeholders involved in shaping the insights presented in this work. We thank Rudolf Muis and Francesco Cinquini for their support with data collection, and our interviewees for their openness to participate and their candid responses. In some places, our phrasing was refined with the assistance of M365 Copilot (Premium) version 19.2603.43051.0 to support clarity. The authors have reviewed and edited the output and take full responsibility for the content of this publication.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Appendix A. Interview Protocol and Coding Scheme

Table A1. Interview structure and coding scheme.

Category	Code (Long)	Explanation
NBS	NBS types, examples	Examples given, types interviewee is mostly involved in
	Definitions	How the interviewee defines NBS or nature-inclusive practices
	NBS status	Current state of NBS/nature-inclusive practices (in NL)
Stakeholder landscape	Actor types and roles	Who is involved, who is not, who should be Which role does interviewee play, which roles do they see in the landscape, which roles are missing/not taken
	Collaboration	Collaboration (or lack thereof), dependencies, relations of influence +Barriers or opportunities related to this theme +Reasons to collaborate (or not) +Strategies for collaboration, partnerships

Table A1. *Cont.*

Category	Code (Long)	Explanation
Stakeholder motivations	Motivations	Which personal or professional motivations does the interviewee have to be involved in NBS? Which advantages do they see?
	Resistance	Which motivations are there to not be involved? Drawbacks, hesitations, challenges
	Conditions for getting involved	What would it take (institutionally, infrastructural, knowledge, . . .?) for actors to get more involved?
Future	Trends	Visions for the future, which trend will be influential +Sources of potential disruption in the field
	Mainstreaming	Opportunities, strategies, examples of NBS mainstreaming into built environment planning and practice +Changes needed to achieve mainstreaming/scaling

Appendix B. Stakeholder Mapping—Dutch NbS Implementation Landscape

Before conducting the interviews reported here, general stakeholder identification was carried out. Recent or ongoing activities related to NbS in the Netherlands have been identified and analysed in the context of stakeholder identification, which include but are not limited to the following initiatives and projects:

- Numerous national and international programmes, research collaborations, pilot projects, and urban/regional experiments focusing on climate adaptation, coastal resilience, river system restoration, and nature-inclusive spatial development.
- Activities span coastal zones, rivers, urban contexts, and infrastructure environments, illustrating a diversified landscape of NbS experimentation and implementation.
- Overall, these initiatives show a maturing ecosystem of actors, from research consortia and public authorities to engineering firms and community-oriented pilots.

A more detailed breakdown of research, policy, and implementation activities and the main responsible actors and beneficiaries is presented below, alongside an overview of general observations for each stakeholder category in the context of their role in NbS development and implementation, as well as their specific concerns regarding NbS mainstreaming and scaling. Although this analysis was exploratory and generalised and conclusions do not apply to every party within each category, it provided valuable insights for a tentative understanding of the dynamics influencing NbS adoption and collaboration potential as preparation for the in-depth interviews that followed this stakeholder mapping.

Appendix B.1. Public Sector

- Encompasses national ministries, regional authorities, municipalities, public agencies, regulators, and water-related authorities involved in spatial planning, infrastructure, nature, and environmental management.
- Hold high influence, though their level of interest varies depending on mandate.

Typical concerns:

- Aligning NbS strategies with overarching policy frameworks.
- Conducting robust environmental and social impact assessments.
- Efficiently allocating public resources while maintaining transparency.
- Managing complex spatial trade-offs across sectors.
- Engaging communities effectively in planning and decision making.

Appendix B.2. Private Sector

- Includes advisory firms, engineering and design consultancies, construction companies, and financial institutions operating at national and international levels.
- Generally high interest in NbS due to emerging markets, professional positioning, and sustainability ambitions but limited direct influence on public policy.

Typical concerns:

- Advisors: effectiveness, demonstrability, scalability, monitoring, and alignment with best practices.
- Implementers: cost efficiency, timelines, safety regulations, environmental standards, community impacts.
- Financial actors: investment certainty, long-term value creation, risk management, alignment with sustainability criteria.

Appendix B.3. Private and Public Landowners

- Includes both public landowners (government and semi-government) and individual or collective private owners of land impacted by NbS interventions.
- Hold high interest and high influence, as NbS directly affects their land management activities and long-term stewardship strategies.

Typical concerns:

- Property value impacts—whether NbS enhances or threatens long-term land value.
- Land use implications—access, landscape change, operational constraints.
- Environmental trade-offs—short-term disturbance vs. long-term benefits.
- Compensation mechanisms for restrictions or functional changes.

Appendix B.4. Non-Governmental Organisations (NGOs)

- Typically operate as advocacy, monitoring, and advisory entities, providing recommendations on environmental and community interests.
- Low direct influence on project-specific decisions but high societal relevance.

Typical concerns:

- Monitoring NbS outcomes and pushing for accountability and transparency.
- Mobilising societal engagement and strengthening public awareness.

Appendix B.5. Academia and Research Institutes

- Includes universities, applied research institutes, and specialised knowledge centres engaged in NbS knowledge creation, experimentation, and long-term environmental monitoring.
- Generally high interest and low formal influence, though strong agenda-setting power is achieved through evidence, models, and analytical frameworks.

Typical concerns:

- Improving mechanisms for knowledge transfer and practical application.
- Strengthening long-term monitoring and data collection.
- Building interdisciplinary collaborations for holistic NbS design and evaluation.
- Securing long-term funding for research and experimentation.
- Supporting practitioner capacity and community understanding.

References

1. Silva Zuniga, M.C.; Watson, G.; Watkins, G.G.; Rycerz, A.; Firth, J. *Increasing Infrastructure Resilience with Nature-Based Solutions (NbS)*; Inter-American Development Bank: Washington, DC, USA, 2020.
2. UNEP. *Nature-Based Infrastructure: How Natural Infrastructure Solutions Can Address Sustainable Development Challenges and the Triple Planetary Crisis*; United Nations Environment Programme: Nairobi, Kenya, 2023; ISBN 978-92-807-4099-8.
3. Moser, J. Here's Why Infrastructure Will Make or Break Our Response to Climate Change. Available online: https://www.weforum.org/stories/2019/09/here-s-why-infrastructure-will-make-or-break-our-response-to-climate-change/ (accessed on 18 April 2025).
4. IUCN. *IUCN Issues Brief: Ensuring Effective Nature-Based Solutions*; International Union for the Conservation of Nature: Gland, Switzerland, 2020.
5. Urban Nature Atlas. Available online: https://una.city/ (accessed on 17 February 2026).
6. Dorst, H.; van der Jagt, A.; Raven, R.; Runhaar, H. Urban Greening through Nature-Based Solutions–Key Characteristics of an Emerging Concept. *Sustain. Cities Soc.* **2019**, *49*, 101620. [CrossRef]
7. Wirth, M.; Canga, E.; Machi Castañer, C.; Findlay, S.; Slade, R.; Seifert, L.F.; Heffer Flaata, E.; Conevski, S.; Obriejetan, M.; Kuschel, E.; et al. Nature-Based Solutions for Demonstrating Climate-Resilient Critical Infrastructure. Deliverable 1.1: Catalogue of Suitable NbS for Climate-Resilient Infrastructure. [Project Deliverable] Nature-DEMO, 2025. Available online: https://zenodo.org/records/18812283 (accessed on 28 January 2026).
8. European Commission. *Towards an EU Research and Innovation Policy Agenda for Nature-Based Solutions & Re-Naturing Cities: Final Report of the Horizon 2020 Expert Group on "Nature-Based Solutions and Re-Naturing Cities"*; European Commission: Bruxelles/Brussel, Belgium, 2015; ISBN 978-92-79-46051-7.
9. Seddon, N.; Chausson, A.; Berry, P.; Girardin, C.A.J.; Smith, A.; Turner, B. Understanding the Value and Limits of Nature-Based Solutions to Climate Change and Other Global Challenges. *Philos. Trans. R. Soc. B Biol. Sci.* **2020**, *375*, 20190120. [CrossRef]
10. Dorst, H.; van der Jagt, A.; Runhaar, H.; Raven, R. Structural Conditions for the Wider Uptake of Urban Nature-Based Solutions–A Conceptual Framework. *Cities* **2021**, *116*, 103283. [CrossRef]
11. Monstadt, J. Conceptualizing the Political Ecology of Urban Infrastructures: Insights from Technology and Urban Studies. *Environ. Plan. A* **2009**, *41*, 1924–1942. [CrossRef]
12. Martin, J.G.C.; Scolobig, A.; Linnerooth-Bayer, J.A.; Irshaid, J.; Aguilera Rodriguez, J.J.; Fresolone-Caparrós, A.; Oen, A. The Nature-Based Solution Implementation Gap: A Review of Nature-Based Solution Governance Barriers and Enablers. *J. Environ. Manag.* **2025**, *388*, 126007. [CrossRef]
13. Frantzeskaki, N.; Vandergert, P.; Connop, S.; Schipper, K.; Zwierzchowska, I.; Collier, M.; Lodder, M. Examining the Policy Needs for Implementing Nature-Based Solutions in Cities: Findings from City-Wide Transdisciplinary Experiences in Glasgow (UK), Genk (Belgium) and Poznań (Poland). *Land Use Policy* **2020**, *96*, 104688. [CrossRef]
14. Viljanen, A.; Harju, C.; Harmanen, J.; Lähtinen, K.; Toppinen, A. Toward Resilient Urban Environments: Transition Pathways in Nature-Based Solutions. *Futures* **2025**, *169*, 103595. [CrossRef]
15. Dorst, H.; van der Jagt, A.; Toxopeus, H.; Tozer, L.; Raven, R.; Runhaar, H. What's behind the Barriers? Uncovering Structural Conditions Working against Urban Nature-Based Solutions. *Landsc. Urban Plan.* **2022**, *220*, 104335. [CrossRef]
16. Sarabi, S.E.; Han, Q.; Romme, A.G.L.; de Vries, B.; Wendling, L. Key Enablers of and Barriers to the Uptake and Implementation of Nature-Based Solutions in Urban Settings: A Review. *Resources* **2019**, *8*, 121. [CrossRef]
17. Sarabi, S.E.; Han, Q.; Romme, A.G.L.; de Vries, B.; Valkenburg, R.; den Ouden, E. Uptake and Implementation of Nature-Based Solutions: An Analysis of Barriers Using Interpretive Structural Modeling. *J. Environ. Manag.* **2020**, *270*, 110749. [CrossRef]
18. Fuenfschilling, L.; Truffer, B. The Structuration of Socio-Technical Regimes-Conceptual Foundations from Institutional Theory. *Res. Policy* **2014**, *43*, 772–791. [CrossRef]
19. Loorbach, D.; Frantzeskaki, N.; Avelino, F. Sustainability Transitions Research: Transforming Science and Practice for Societal Change. *Annu. Rev. Environ. Resour.* **2017**, *42*, 599–626. [CrossRef]
20. Geels, F.W. The Multi-Level Perspective on Sustainability Transitions: Responses to Seven Criticisms. *Environ. Innov. Soc. Transit.* **2011**, *1*, 24–40. [CrossRef]
21. Geels, F.W. Technological Transitions as Evolutionary Reconfiguration Processes: A Multi-Level Perspective and a Case-Study. *Res. Policy* **2002**, *31*, 1257–1274. [CrossRef]
22. Smith, A.; Raven, R. What is Protective Space? Reconsidering Niches in Transitions to Sustainability. *Res. Policy* **2012**, *41*, 1025–1036. [CrossRef]
23. Broto, V.C.; Bulkeley, H. Maintaining Climate Change Experiments: Urban Political Ecology and the Everyday Reconfiguration of Urban Infrastructure. *Int. J. Urban Reg. Res.* **2013**, *37*, 1934–1948. [CrossRef]
24. Whyte, J.; Mijic, A.; Myers, R.J.; Angeloudis, P.; Cardin, M.A.; Stettler, M.E.J.; Ochieng, W. A Research Agenda on Systems Approaches to Infrastructure. *Civ. Eng. Environ. Syst.* **2020**, *37*, 214–233. [CrossRef]
25. Hommels, A. *Unbuilding Cities: Obduracy in Urban Sociotechnical Change*; Mit Press: Cambridge, MA, USA, 2008.

26. Zuniga-Teran, A.A.; Staddon, C.; de Vito, L.; Gerlak, A.K.; Ward, S.; Schoeman, Y.; Hart, A.; Booth, G. Challenges of Mainstreaming Green Infrastructure in Built Environment Professions. *J. Environ. Plan. Manag.* **2020**, *63*, 710–732. [CrossRef]
27. Biasin, A.; Toxopeus, H.; Pettenella, D.; Polzin, F.; Masiero, M. Financing Urban Nature-Based Solutions (NBS): A Literature Review from the Perspective of Funders. *Nat. Based Solut.* **2024**, *6*, 100195. [CrossRef]
28. Rijkswaterstaat. *Meerjarenoverzicht Vernieuwingsopgave Bruggen, Tunnels en Sluizen 2026–2030*; Rijkswaterstaat: Utrecht, The Netherlands, 2025.
29. Rijkswaterstaat. *De Staat van de Infrastructuur*; Rijkswaterstaat: Utrecht, The Netherlands, 2025.
30. Rasker, P.C. *Vernieuwingsopgave Infrastructuur*; TNO: Den Haag, The Netherlands, 2023.
31. Konijnendijk, C.C. Evidence-Based Guidelines for Greener, Healthier, More Resilient Neighbourhoods: Introducing the 3–30–300 Rule. *J. For. Res.* **2023**, *34*, 821–830. [CrossRef]
32. McPhearson, T.; Frantzeskaki, N.; Ossola, A.; Diep, L.; Anderson, P.M.L.; Blatch, T.; Collier, M.J.; Cook, E.M.; Culwick Fatti, C.; Grabowski, Z.J.; et al. Global Synthesis and Regional Insights for Mainstreaming Urban Nature-Based Solutions. *Proc. Natl. Acad. Sci. USA* **2025**, *122*, 2315910121. [CrossRef]
33. McPhearson, T.; Cook, E.M.; Berbés-Blázquez, M.; Cheng, C.; Grimm, N.B.; Andersson, E.; Barbosa, O.; Chandler, D.G.; Chang, H.; Chester, M.V.; et al. A Social-Ecological-Technological Systems Framework for Urban Ecosystem Services. *One Earth* **2022**, *5*, 505–518. [CrossRef]
34. Egusquiza, A.; Cortese, M.; Perfido, D. Mapping of Innovative Governance Models to Overcome Barriers for Nature Based Urban Regeneration. In *Proceedings of the IOP Conference Series: Earth and Environmental Science, Shanghai, China, 16–18 August 2009*; IOP: London, UK, 2009; Volume 323.
35. Frantzeskaki, N.; Wijsman, K.; Adams, C.; Kabisch, N.; Malekpour, S.; Pinto, M.P.; Vandergert, P. Governance of and with Nature-Based Solutions in Cities. In *Nature-Based Solutions for Cities*; McPhearson, T., Kabisch, N., Frantzeskaki, N., Eds.; Edward Elgar Publishing: Cheltenham, UK, 2023.
36. Fakirova, E.; van Lierop, M.; Dorst, H.; Pauleit, S. City-Civil Society Dynamics in Urban Green Infrastructure Development in Munich: Governance Features and Their Impacts. *Nat. Based Solut.* **2025**, *8*, 100272. [CrossRef]
37. Besters, M.; Chereji, M.; Griffin, H.; Sluimer, N.; Beunderman, J. *Financiering van Integratie*; City Deal Openbare Ruimte: Amsterdam, The Netherlands, 2022.