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REVIEW ARTICLE

Urban planning to support the conservation of freshwater biodiversity

Helen A.L. Currie[a,b]*, Andrea E. Kirkwood[c], Jack G. Imhof[d], Morgan L. Piczak[b]**, Irena F. Creed[e], Nicolas W.R. Lapointe[f], Nicholas E. Mandrak[g], Sarah E. Null[h], Jon S. Harding[i], Rebecca C. Rooney[j], John P. Smol[k], Elizabeth A. Nyboer[l], Irene Gregory-Eaves[m], Michael Stone[j], Charles H. Nilon[n], Joseph R. Bennett[b], Trina Rytwinski[b], Colin D. Meurk[o], John E. FitzGibbon[p†] and Steven J. Cooke[b]

[a]Centre for Blue Governance, Faculty of Business and Law, University of Portsmouth, Portsmouth, UK; [b]Department of Biology and Institute of Environmental and Interdisciplinary Science, Carleton University, Ottawa, ON, Canada; [c]Faculty of Science, Ontario Tech University, Oshawa, ON, Canada; [d]Freshwater Conservation Canada, Guelph, ON, Canada; [e]Department of Physical and Environmental Sciences, University of Toronto, Toronto, ON, Canada; [f]Canadian Wildlife Federation, Kanata, ON, Canada; [g]Department of Biological Sciences, University of Toronto Scarborough, Toronto, ON, Canada; [h]Department of Watershed Sciences, Utah State University, Logan, UT, USA; [i]School of Biological Sciences, University of Canterbury, Christchurch, New Zealand; [j]Biology Department, University of Waterloo, Waterloo, ON, Canada; [k]Paleoecological Environmental Assessment and Research Lab (PEARL), Department of Biology, Queen's University, Kingston, ON, Canada; [l]Department of Fish and Wildlife Conservation, Virginia Tech, Blacksburg, VA, USA; [m]Biology Department, McGill University, Montréal, Québec, Canada; [n]School of Natural Resources, University of Missouri, Columbia, MO, USA; [o]School of Earth and Environment, University of Canterbury, Christchurch, New Zealand; [p]School of Environmental Design and Rural Development, University of Guelph, Guelph, ON, Canada

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Freshwater biodiversity is in accelerating decline, yet it is disproportionately important to global biodiversity. Many international, national, and regional efforts exist to protect and restore freshwater biodiversity. These include local governments and their urban planning teams who are responsible for planning decisions related to land use and stormwater management. Although urban planners can be key players for achieving freshwater solutions, they are often not engaged in those initiatives, or lack adequate ecological literacy. Given the urgency of

*Corresponding author. Email: Helen.Currie@port.ac.uk
**Present address: Department of Forest and Conservation Sciences, The University of British Columbia, Vancouver, BC, Canada.

†We dedicate this paper to Dr John FitzGibbon who passed away during the final phases of preparing this paper. John had an impactful career at the interface of environmental conservation and urban planning through his creative scholarship, mentoring, and engagement with practitioners.

freshwater conservation, there is an immediate need to engage and upskill urban planners who often craft policy, make decisions, and are engaged in local governance relevant to freshwater systems. Urban planners should be equipped with the skills to include watershed planning principles that can achieve conservation gains for freshwater biodiversity in urban design, greenspace configurations, and stormwater management. We outline six actions for urban planners: 1) value freshwater biodiversity; 2) support community involvement and identity building; 3) transcend disciplinary silos in education and training; 4) facilitate knowledge exchange among practitioners; 5) develop actionable standards, tools and policies; and 6) address key knowledge gaps. We provide best-practice examples and case studies that meaningfully consider freshwater biodiversity and contribute to nature-based solutions. Mobilising urban planners as key allies would provide manifold benefits to freshwater systems and the communities they support.

Keywords: freshwater restoration; transdisciplinarity; ecological literacy; nature-based solutions; urban ecology

1. Introduction

Fresh waters, including rivers, lakes, and wetlands account for ~2.3% of the world's land surface area (Lehner and Döll 2004), yet support ~9.5% of all described animal species (Balian *et al*. 2008; A. J. Reid *et al*. 2019) and one-third of all vertebrates, including >50% of all fish species (Strayer and Dudgeon 2010; Tickner *et al*. 2020). Despite this disproportionately remarkable biodiversity, freshwater ecosystems are among the most threatened and anthropogenically modified on the planet (Grill *et al*. 2019), with climate-driven shifts in thermal regimes and hydrology further intensifying pressures. Global wetland loss is occurring at ~1.6% a year, over three times the rate of forest loss (Convention on Wetlands 2021; Darrah *et al*. 2019), and only 37% of the planet's longest rivers (>1000 km length) remain free flowing over their entire length (Grill *et al*. 2019). These trends mirror dramatic species declines, with freshwater vertebrate populations decreasing by an estimated 84% in recent decades (WWF 2020) and species declines outpacing those in marine or terrestrial realms (A. J. Reid *et al*. 2019). Primary threats, including habitat loss and degradation, pollution, hydrologic flow modification, fragmentation, hydroclimate change, overexploitation, and aquatic invasive species, have been well documented (Dudgeon *et al*. 2006; A. J. Reid *et al*. 2019; Sor *et al*. 2023). In urban environments, these persistent and emerging threats intensify due to concentrated land-use change, infrastructure expansion, and hydrological alteration (Francis and Hoggart 2008). It is therefore evident that we are in a freshwater biodiversity crisis (Harrison *et al*. 2018), and there is a dire need for action (Tickner *et al*. 2020).

Ambitious international goals have been established to safeguard biodiversity and promote sustainable development. This is a crucial component of the Nature 2030 IUCN Programme (IUCN 2021), a global call for action that promotes several interconnected Sustainable Development Goals (SDGs), (e.g. SDG6 clean water and sanitation; SDG9 industry, innovation and infrastructure; SDG11 sustainable cities and communities; and SDG15 life on land: UN 2015), and the post-2020 Global Biodiversity Framework (CBD 2020). However, freshwater ecosystems remain consistently undervalued in these global policy frameworks. The Emergency Recovery Plan (ERP) for Freshwater Biodiversity (Tickner *et al*. 2020; van Rees *et al*. 2021) highlighted the need to "bend the curve" of biodiversity loss, identifying six priority actions to catalyse change and emphasising that many SDG and CBD indicators inadequately represent freshwater systems and require substantial revision. A considerable body of work has since responded to the ERP through recommendations, strategic measures (Arthington 2021; Cooke *et al*. 2024; Piczak *et al*. 2024; van Rees *et al*.

2021) and identification of key research gaps (e.g. Harper *et al*. 2021; Maasri *et al*. 2022). Recent updates to the Kunming-Montreal Global Biodiversity Framework, such as targets 1 (30% of degraded ecosystems under restoration) and 3 (30% land and waters effectively conserved), now explicitly recognise inland waters as distinct from terrestrial regions, marking important progress (Cooke *et al*. 2023). Nonetheless, translating these commitments into practice remains a major challenge.

High-level policy changes should motivate actioning freshwater biodiversity recovery at the regional governance and river basin management scales (Twardek *et al*. 2021), where planning, investment, and regulation occur, yet significant implementation gaps remain. A prominent barrier is the enduring 'knowledge-action gap', whereby scientific understanding of freshwater threats and solutions remains disconnected from the decisions, policies, and practices needed to implement them (Clare and Creed 2022; V. M. Nguyen, Young, and Cooke 2017). Given the urgency of freshwater conservation, there is an immediate need for a mobilised and coordinated response to "bend the curve" within an urban context (Tickner *et al*. 2020; Twardek *et al*. 2021) and, therefore, strategic measures and up-to-date scientific advancements should be readily accessible and better summarised for knowledge users to ensure their adoption in practice (J. C. Walsh, Dicks, and Sutherland 2015). Accordingly, translating global freshwater ambitions into practice hinges on green, sustainable urban environments and the professionals who shape them.

Urban environments are where pressures on freshwater ecosystems, human needs, and infrastructure most strongly converge, positioning urban planning as a pivotal lever for change, and a critical opportunity to integrate freshwater biodiversity with the needs of city-dwelling societies and economies, and the ecosystem services (ES) upon which they rely (Piczak *et al*. 2024). Key ES include drinking water supply, food provision, transportation, industrial uses, and recreational or cultural values, and accordingly, more than 50% of the world's population lives within 3 km of a surface freshwater body (Kummu *et al*. 2011). Landscape fragmentation and major land-use changes, such as rapid infrastructure expansion to support urban population growth (urban sprawl), have had far reaching impacts on urban freshwater ecosystems, contributing to increased flooding, water scarcity, water quality deterioration, point source pollution, and habitat loss (see also 'urban stream syndrome': Booth *et al*. 2016; Teurlincx *et al*. 2019; C. J. Walsh *et al*. 2005). At the same time, there is renewed appreciation for the value of greenspace (Nilon *et al*. 2017; O'Neill *et al*. 2023), including investment in freshwater restoration for human health and wellbeing (Pedersen, Weisner, and Johansson 2019) and adoption of the sponge city concept to mitigate flooding (Liu, Jia, and Niu 2017). However, while governments and institutions often invest in well-meaning urban stream restoration projects, these are often disconnected from community or wider-stakeholder needs, leading to missed social and ecological outcomes (Scoggins *et al*. 2022). Urban freshwaters also encompass priority habitats requiring protection and restoration, and better appraisal and targeted intervention could reduce societal risks associated with anthropogenically driven environmental change (Piczak *et al*. 2024). In many towns and cities, however, the biodiversity value of urban waterbodies, including constructed or heavily engineered waterways, has conventionally been secondary to their utility as stormwater conduits, transportation networks, recreational spaces, or stock water sources. As a result, these ecosystems are now among the most altered and degraded globally (Table 1; Francis and Hoggart 2008), differing substantially from their rural counterparts, which face their own pressures under intensifying agricultural modification and industrial expansion.

In parallel, the quadruple bottom line for sustainable prosperity ('people,' 'planet,' 'profit,' 'progress': Ragazou *et al*. 2024; or, 'social', 'environmental/ecological',

Table 1. Approaches to urban planning and associated ecological impacts that should be updated to benefit freshwater biodiversity. Note: see Figure 1 for reference to symbology. Although alternative approaches do not contain 'plan attributes', their targets and goals are grouped into analogous conceptual categories to maintain consistency with the plan attribute framework.

Conventional approach	Impact(s) on freshwater biodiversity and/or current approach flaws Δ	Alternative approach	Targets and goals for alternative approaches	References Δ
"Burial", or historical filling in of natural watercourses and/or wetland drainage	• Habitat degradation/ fragmentation • Decreased water quality • Biodiversity loss • Altered heat budget	• Integration of freshwater bodies into developments • Restoration and protection of existing wetlands • Daylight previously buried streams		Elmore and Kaushal 2008; Han *et al*. 2020; Imberger *et al*. 2023; Itsukushima and Ohtsuki 2021; Napieralski and Welsh 2016
Concrete channelisation of creeks/ streams and shoreline hardening	• Altered sediment balance (spatial and temporal patterns of erosion, transport and deposition of sediment) • Alteration of fluvial systems and excess water runoff • Altered hydrological regimes • Elevated contaminants and impaired water quality • Reduced vegetation • Altered heat budget	• Bioengineered and/or living shorelines • Incorporating natural meandering into channelisation		Booth and Jackson 1997; Cooke *et al*. 2020; Paul and Meyer 2001; Pilkey and Cooper 2012
Storm sewer outflow to creeks/streams	• Increased phosphorus, hydrocarbons, suspended solids, metals, and total ammonia • Higher bacterial densities, particularly after storms • Modifying fish migration or increased stranding events • Decreased invertebrate abundance • Increased flashiness and erosion	• Green roofs and rain gardens to flow and filter storm runoff • Permeable pavements • Bioretention cells • Separated sewage overflows • Integration of naturalised SMPs prior to outflows • Replace "end of pipe" solutions with low impact development (LID)		Eppehimer *et al*. 2021; Lawson and Jackson 2021; Paul and Meyer 2001; Porcella and Sorensen 1980; Thorne, Williams, and Gordon 2000

Lateral fragmentation of rivers and floodplains	• Altered magnitude, frequency and duration of flooding events • Increased flashiness and erosion • Decreased inundation • Decreased aquatic habitat, and increase in terrestrial ecosystems • Decreased abundance and biomass of invertebrates • Increased risk of fish kill events	• Protect and/or restore floodplain connectivity • Protect and/or restore riparian areas • Plan for dynamic floodplains in urban green areas and/or dedicated flood zones		Cooke *et al*. 2020; Cooke *et al*. 2022; Kingsford 2000; Thoms 2003
Stormwater management ponds (SMPs) designed for flood control; and replacement of natural wetlands	• Higher conductivity, contaminants, runoff, and nutrient load • Modified shorelines and banks • Altered community composition of invertebrates • Reduced biodiversity • Goals of SMP revolve around hydrology, not biology	• Enhance habitat complexity (mosaiced landscape effect) and structure to improve habitat quality • Naturalised stormwater ponds and engineered wetlands with gentler slopes and native plantings improve biodiversity and water quality over wet ponds • Conduct restoration based on the needs of the ecosystem (i.e. multi-species)		Birch *et al*. 2022; Hassall and Anderson 2015; Meland *et al*. 2020; McKercher *et al*. 2024; Rooney *et al*. 2015

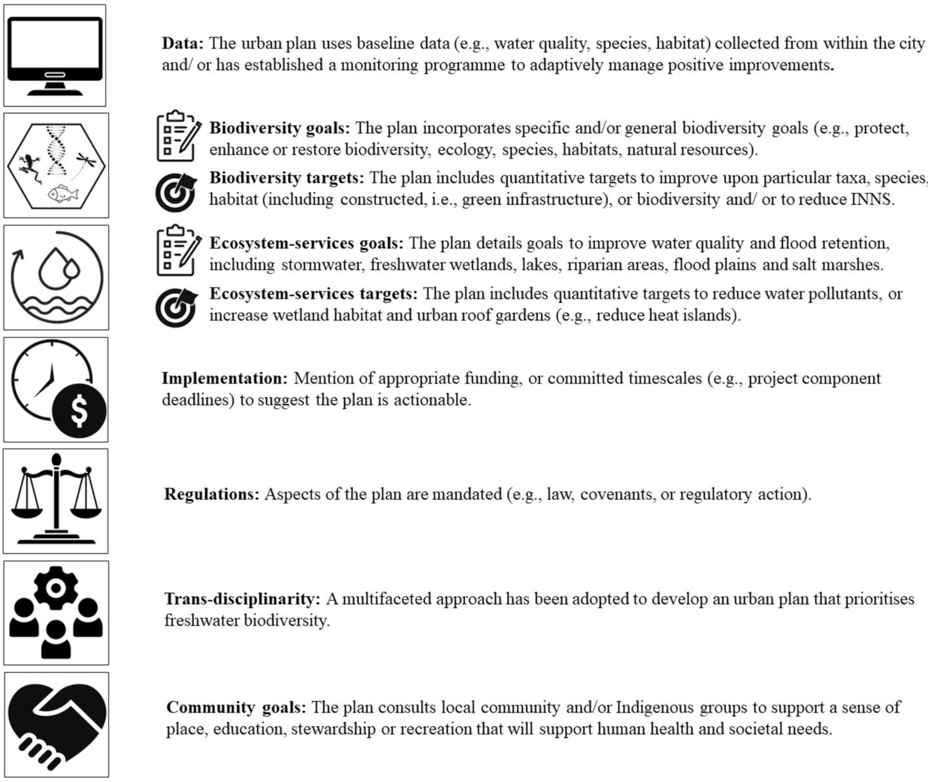

Figure 1. Plan attributes of importance to urban planning for freshwater biodiversity (adapted from Nilon *et al*. 2017).

'economic', and 'cultural stability': Scrimgeour and Iremonger 2011; see also "triple bottom line") provides an inclusive framing that has often been overlooked. Approaches such as nature-based solutions (NbS), including green roofs, rain gardens, wetland detention basins, and urban green spaces (Filazzola, Shrestha, and MacIvor 2019; Prudencio and Null 2018), are increasingly used to complement or replace grey infrastructure and restore natural processes within urban systems. Recent advances in addressing sustainability challenges highlight the need for inclusive models that strengthen partnerships and co-produce transdisciplinary knowledge among stakeholders to support societal change and bend the curve for freshwater biodiversity (Bixler *et al*. 2022; Murphy *et al*. 2022; Scoggins *et al*. 2022; Tickner *et al*. 2020). "Transdisciplinarity" is a practical, integrative approach that engages academic and non-academic stakeholders in participatory processes, uniting scientific rigor with societal relevance and allowing personal and professional experiences to co-evolve (Rigolot 2020). Importantly, there is an increasing role of Indigenous peoples (i.e. rightsholders), such as New Zealand Māori, who have strong cultural connections to water and sustained harvestable resources, to support conservation measures through long-standing stewardship practices (*kaitiakitanga*). Collectively, these diverse knowledge systems are essential foundations for sustainable urban planning that prioritises freshwater biodiversity.

Involvement of frontline practitioners at the local scale is, therefore, critical to implementing the ERP (Twardek *et al*. 2021), as it enables the development of (potentially repeatable) grass roots/bottom-up, community-driven, context-specific solutions (Ometto Bezerra *et al*. 2023; Vollmer *et al*. 2022). This includes urban planners, whose work shapes stormwater infrastructure, riparian zones, urban ponds, wetlands, parkland protection and development, and broader patterns of urban form. They are essential actors in delivering the sustainable environments needed to improve urban waterbody health and restore freshwater biodiversity. For the purposes of this paper, the term “urban planner” encompasses developers and their planning team (including civil and water-resource engineers), as well as those working for regulatory bodies and in decision-making roles (e.g. standards development) whose work is focused on urban areas. Urban planners are influenced by policy, and they work directly with developers, local governments and communities to reinvigorate ageing infrastructure, support growing human populations, and address global sustainability challenges. In practice, however, urban planning is also influenced by individual (Murtagh, Odeleye, and Maidment 2019) and cultural knowledge systems, including understandings of infrastructure systems design and land use (e.g. green or blue space design, zoning regulations) relative to economic goals, societal needs, and environmental considerations. Their decisions are shaped by governance frameworks and local knowledge systems, making their engagement vital to bridging the gap between global freshwater ambitions and on-the-ground implementation.

Historically, conventional urban planning practices that are often grounded in natural capital thinking and heavily engineered design, have contributed to the degradation of freshwater ecosystems, with ecological processes frequently overlooked or poorly understood (van Rees, Hernández-Abrams, *et al*. 2023). Although biodiversity is now more commonly acknowledged in planning documents, it is frequently framed around broad biodiversity goals without accompanying plans, metrics, or implementation pathways for achieving them (Nilon *et al*. 2017; O’Neill *et al*. 2023). Collaboration between urban planners and freshwater ecologists during project planning and design phases has too often been limited (Apfelbeck *et al*. 2020; Felson 2013), reinforcing siloed practices and an oversimplified understanding of ecological communities within urban planning design (Hersperger *et al*. 2021). Taken together, these legacies and current shortcomings help explain why freshwater biodiversity objectives remain difficult to realise in practice.

A more harmonious shift that positions biodiversity as a core objective, alongside environmental justice and human-wellbeing, is essential for achieving equitable, sustainable, and nature-positive infrastructure development (Kay *et al*. 2022; McKay *et al*. 2023; van Rees, Hernández-Abrams, *et al*. 2023). When approached in this way, urban planning can become a key solution pathway for restoring and sustaining freshwater ecosystems rather than contributing to their decline. In this paper, we first outline the consequences of historical approaches to urban planning on freshwater biodiversity and then identify six major actions to guide urban planners in improving and preserving freshwater ecosystems. These actions were developed collaboratively through an author brainstorming exercise, with the scope of understanding the challenges and opportunities faced by urban planners, drawing on expertise spanning freshwater biodiversity, environmental policy, watershed management, and urban and regional planning. Our aim is to highlight opportunities for urban planners to benefit and restore freshwater biodiversity, including improvements to conventional urban-planning approaches, standards, and policy instruments (Figure 1).

To illustrate how freshwater biodiversity can be incorporated into planning practice, we draw on a series of case studies spanning cities in Asia, Europe, Oceania, and North and South America, where nature-based solutions and socio-ecological design approaches are increasingly being used to replace or adapt outdated assets. These examples are presented as success stories but are also intended to be interpreted in light of the challenges and opportunities that emerged following the acute global crisis phase of the COVID-19 pandemic, including shifting population dynamics and socio-economic pressures (Zhu and Xu 2023). While these examples are drawn primarily from industrialised contexts which have been comprehensively documented, the actions and principles we describe must ultimately be realised globally and adapted to diverse local contexts, including varying resource availability, cultural partnership structures and governance arrangements, particularly in the global South (Nagendra *et al*. 2018; van Rees, Hernández-Abrams, *et al*. 2023). In many regions, political instability, corruption and poorly developed governance structures continue to constrain conservation gains for freshwater biodiversity (Tickner *et al*. 2025), underscoring the importance of context-appropriate, practitioner-led approaches. Finally, we highlight existing tools and online resources to assist urban planners in embedding freshwater biodiversity objectives. Together these materials provide practical, accessible recommendations across educational and professional pathways and help advance components of the ERP that intersect with urban development.

2. Contextual background: conventional approaches to urban planning

Urban planning has traditionally adopted a Western, anthropocentric approach to the design and regulation of city spaces (Freestone 2000), with economic growth commonly prioritised over the integration of potentially less profitable (in the short-term) or time-demanding blue-green design. In Section 2, we summarise problems with conventional urban planning and infrastructure design as they relate to freshwater biodiversity (Table 1). Then, in Section 3, we outline six actions to help conserve and restore freshwater biodiversity in urban environments. We argue that these actions are needed to incorporate more holistic socio-ecological approaches into urban and regional planning.

Conventional urban planning and infrastructure design has been complicit in the freshwater biodiversity crisis (Birch *et al*. 2022; Cooke *et al*. 2020; Hintz *et al*. 2022; Imberger *et al*. 2023). From an engineering perspective, the quick and efficient removal of urban "stormwater" runoff (i.e. water from rainfall collected from impervious surfaces) away from urban infrastructure and sometimes to storage ponds, is a top priority to prevent localised flooding and property damage. Yet this reliance on impervious materials reduces groundwater recharge, facilitates flooding (Nelson, Bledsoe, and Shepherd 2020), and contributes to thermal pollution (Somers *et al*. 2013) and elevated nutrient and metal concentrations from surface runoff (Sekabira *et al*. 2010). Structural measures (e.g. channelisation), or the installation of grey infrastructure (e.g. levees, pipes, and conduits) to facilitate flood control and further land development, significantly modifies the natural planform of waterways and basin landscapes (see "active river channel" concept: Chambers *et al*. 2023; Wolman and Leopold 1957) to the detriment of freshwater biodiversity (Table 1).

A related challenge arises in the management of urban ponds and wetlands. Stormwater ponds are primarily managed for flood mitigation and to prevent overwhelming sewage treatment plants, despite supporting valuable freshwater biodiversity (Marques *et al*. 2024; Oertli and Parris 2019). In many cities, wetlands are often infilled in an effort to claim more land for development. Marques *et al*. (2024) argue that advancements in the ecological management of urban stormwater ponds can only be addressed if it evolves from managing urban ponds primarily for flood control to a more integrated approach that recognises their socio-ecological roles. Florida (USA) alone has over 76,000 stormwater urban ponds that contribute to a mosaic landscape effect. If managed appropriately, these networks could benefit freshwater biodiversity, but without informed oversight they risk fostering ecosystem disservices, including creating hotspots for invasive plant species (Sinclair *et al*. 2020).

Urban development practices that accelerate water removal or eliminate waterbodies entirely have severe consequences for freshwater ecosystems. Concrete channelisation (Cooke *et al*. 2020) and flashy hydrographs from urban stormwater runoff (Anim *et al*. 2018) trigger adverse geomorphological responses (e.g. increased erosion, channel downcutting, bank slumping, and sedimentation) that engineers continue to artificially "fix" on a localised scale (e.g. installation of concrete or riprap armouring), (Booth and Jackson 1997; Cooke *et al*. 2020). This perpetuates a negative feedback loop, transferring stream energy farther downstream and displacing rather than resolving erosion issues, while also generating a high carbon and ecological footprint (Cooke *et al*. 2020). Piped or buried streams (commonly headwater) are hydraulically efficient and enable more land to be developed, but cause structural homogenisation, absence of light, habitat fragmentation, and increased diffuse and point-source pollution that degrades the ecological health of urban watercourses (Levi and McIntyre 2020). Stream burial reduces sediment and nutrient retention, primary productivity, and habitat diversity (Elmore and Kaushal 2008; Pennino *et al*. 2014), and is a key driver of biodiversity loss (e.g. reductions in periphyton biomass and macroinvertebrate density and taxa richness: Hintz *et al*. 2022). Because freshwater ecosystems form a longitudinal continuum, headwater burial has cascading impacts, including the degradation of downstream rivers, lakes, and coastal waters (C. J. Walsh *et al*. 2005).

A further, often overlooked, driver of freshwater biodiversity loss is development in floodplains and riparian zones. Flood protections (such as levees) and encroachment into these areas disrupt the dynamic interactions between freshwater and adjacent terrestrial systems. Decades of research emphasise the need to "back off" (Cooke *et al*. 2022) and give freshwater systems the space required for both hydrological and ecological functioning (Chambers *et al*. 2023; Skidmore and Wheaton 2022). Freshwater and terrestrial ecosystems are intrinsically interconnected: enhancing freshwater biodiversity supports terrestrial biodiversity, and vice versa (Soininen *et al*. 2015). Urban planning that respects these connections yields substantial ecological benefits across both aquatic and terrestrial systems.

Despite the impacts of conventional approaches (i.e. urban sprawl, channelising waterways, etc.) on freshwater biodiversity, recent advancements in urban planning (e.g. Nelson, Bledsoe, and Shepherd 2020; van Rees, Hernández-Abrams, *et al*. 2023) offer encouraging signs of progress. Global commitments such as the New Urban Agenda (UN 2017) and widespread adoption of NbS approaches, including the sponge city concept (Liu, Jia, and Niu 2017), signal a shift toward more integrated planning. Many urban planners are motivated to improve freshwater outcomes but face a gap between their ambitions and the knowledge, skills, tools, and frameworks needed for effective implementation. Considering the critical juncture for freshwater biodiversity and the imminent need for operational measures to reverse decline, we outline six actions below to promote freshwater biodiversity in urban planning. Each action is structured around four core components: i) action definition, context and importance to freshwater biodiversity; ii) overview of existing knowledge and exemplar tools; iii) barriers, challenges, and opportunities in practice (examples and case studies); and iv) implications for urban planning policy and practice.

3. Six urban planning actions to support freshwater ecosystems

3.1. Action 1: value freshwater biodiversity for more holistic urban planning

Prioritising the protection and restoration of healthy, biodiverse urban ponds, wetlands, and rivers (including their riparian habitats, floodplains and corridors) is fundamental to sustaining freshwater biodiversity, human life, and well-being (Higgins *et al*. 2019). While urban lands face many competing uses (e.g. real estate or commodity value versus local community needs), this prioritisation necessitates recognising the multifaceted values of biodiversity and implementing closely aligned actions to promote these values (Lee *et al*. 2022).

Building on this framing, the following transformative shifts in freshwater biodiversity conservation efforts are central to strengthening how these values are embedded in urban planning - the shift towards more inclusive strategies founded on both nature- and human-centred perspectives in biodiversity conservation (Chan *et al*. 2016); the shift towards holistic strategies that integrate freshwater biodiversity and the habitats upon which species depend (Lynch *et al*. 2023; 2024); and the shift in mindsets from compliance of laws, policies, and plans to the effective achievement of cherished biodiversity objectives. Taken together, these shifts expand the conceptual and practical space available to planners seeking to integrate biodiversity into urban design.

3.1.1. Shift towards more inclusive strategies

Nature-centred perspectives emphasise intrinsic values – the inherent worth of biodiversity, independent of its utility to humans, as well as its relational values including ethical, spiritual, and cultural dimensions (Arias-Arévalo, Martin-López, and Gómez-Baggethun 2017). These perspectives, broadly referred to as ecological literacy, connectivity, identity and guardianship, underscore the reciprocal relationships people develop with nature, and are well articulated in Indigenous (e.g. *Kaitiakitanga* in New Zealand Māori culture: https://teara.govt.nz/en/kaitiakitanga-guardianship-and-conservation) and non-Western worldviews (Chan *et al*. 2016). Although these values are subjective and challenging to quantify, they remain indispensable to biodiversity conservation strategies. Complementing these perspectives, human-centred perspectives include the tangible and intangible benefits that biodiversity provides to people. These are often captured through "ecosystem services", categorised into cultural (e.g. aesthetic, spiritual, and relational), regulative, supportive, and provisioning roles (Costanza *et al*. 1997; Coutts and Hahn 2015). While ES frameworks consider all four categories of human utility, they often prioritise provisioning roles – such as food or water – due to their direct and measurable economic benefits. However, this emphasis risks undervaluing utilitarian aspects that cannot be economically appraised. For instance, salmon holds both provisioning (food) and cultural value to Canadian Indigenous peoples, just as eels do for New Zealand Māori, alongside their reliance on high-quality supportive habitats (Klain, Satterfield, and Chan 2014; Knowler *et al*. 2003).

3.1.2. Shift toward holistic strategies

Holistic strategies integrate freshwater biodiversity and the habitats upon which species depend, yielding broader ES benefits for humans, including clean water provision (filtration) and flood risk reduction (attenuation). Biodiverse freshwater ecosystems with intact protected, restored or constructed habitat should be regarded by urban planners as assets that add value to urban landscapes, reflecting both nature- and human-centred values (e.g. Lynch *et al*. 2023; 2024, Oertli *et al*. 2023; Oertli and Parris 2019). For instance, constructed channels may act as a critical refuge for local freshwater biodiversity, including endangered species that originated from no longer existing source habitats (van Rees, Jumani, *et al*. 2023). Eliminating or piping these areas for financial reasons – as occurred with New Zealand's Canterbury Plains stock water races – contradicts progressive trends such as "daylighting" buried waterways. Realising this holistic shift in planning will require transdisciplinary alliances (Actions 3 and 4), involving urban planners, natural and social scientists, economists, and health professionals. These alliances can develop urban planning policies (Action 5), inform research (Action 6), and promote biodiversity-friendly urban spaces (Action 2) that also safeguard human health and wellbeing.

3.1.3. Shift in mindset

While laws and policies exist to mitigate the effects of urban development on freshwater biodiversity, they often set a baseline minimum. Urban planners should aim higher by supporting innovative design that elevates freshwater biodiversity and its associated habitats. To achieve this, urban planners may require a change in their approaches - first, urban planners should minimise disturbance to habitat structure and function; second, if habitat is already disturbed, actively restore habitat through the design and implementation processes; and third, if restoration is not possible, habitat can be artificially created. Protection of natural habitats typically yields greater biodiversity and ES than restored or artificial alternatives. An illustration of shifting mindsets is the Cheonggyecheon Stream restoration project in Seoul (Figure 2; supplementary Table S1). Once paved over (mid-twentieth century) as part of the city's sewer system, this 10.9 km stream was restored between 2003 and 2005 following a dismantling of the overlying freeway. Restoration not only elevated freshwater biodiversity but also fostered community pride (Jeon and Kang 2019). This example of shifting mindsets enables construction of habitat, reimagining of stormwater management in urban landscapes (Hassall and Anderson 2015), and creative urban waterfront developments such as riverwalks and lakeside parks (Golet *et al*. 2008; Jeon and Kang 2019).

Together, these three shifts underscore the pivotal role of urban planners in shaping policies and practices that safeguard freshwater ecosystems. Planners can design urban spaces that integrate freshwater biodiversity, protect and restore natural habitats, and raise public awareness. Of course, conservation actions should be carefully prioritised by appropriate experts using well-defined metrics and models that are aligned with intended outcomes (Ettinger *et al*. 2021).

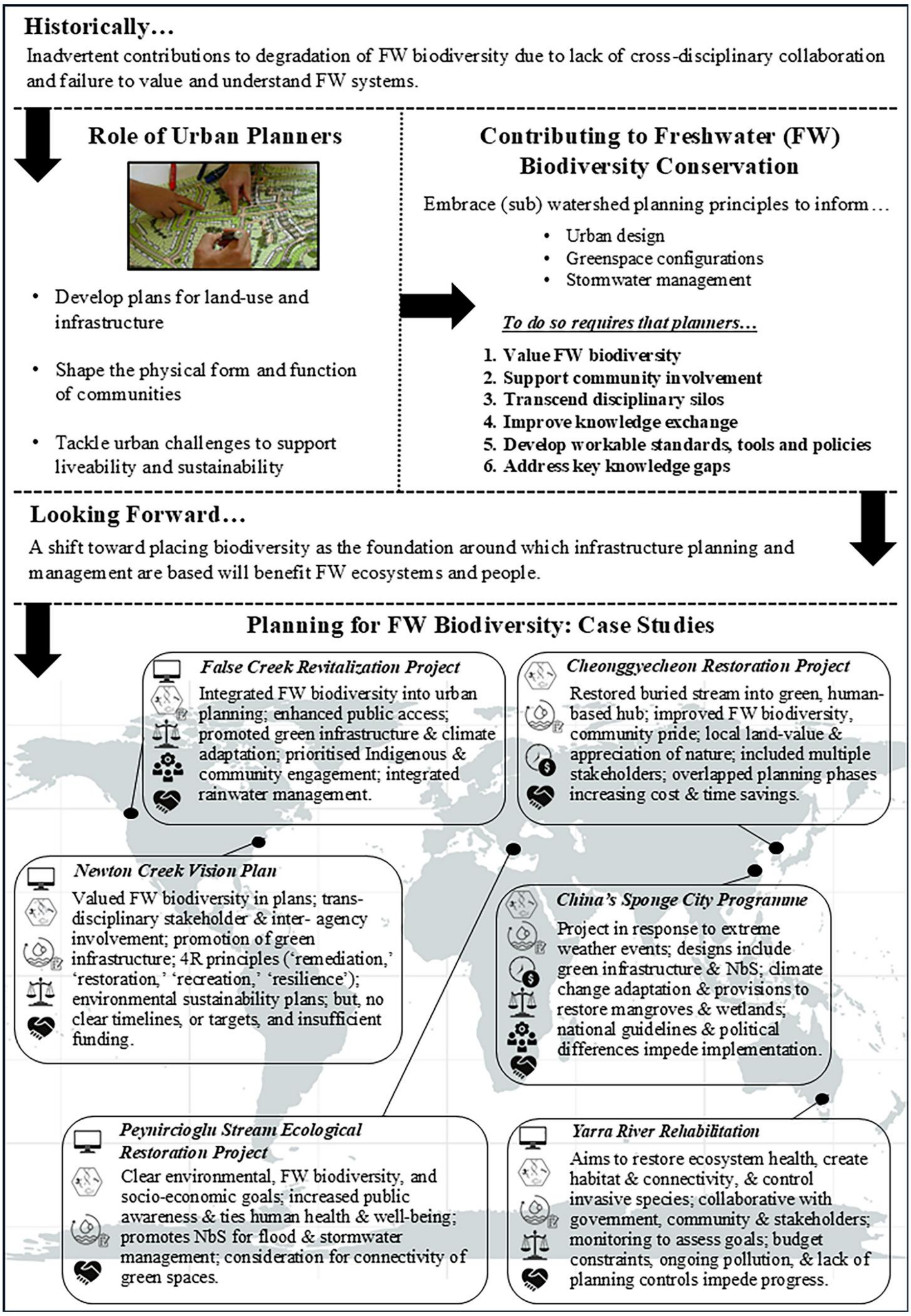

Figure 2. Urban planning for freshwater biodiversity. Notes: see supplementary Table S1 for in-depth analysis of international case studies highlighting urban planning best practice and challenges/lessons learned in conserving and restoring freshwater biodiversity. See Figure 1 for reference to project component symbology.

3.2. Action 2: support community involvement – building knowledge and identity

Communities are essential partners in freshwater conservation, bringing place-based knowledge, cultural values, and lived experience that can meaningfully shape planning processes (e.g. Norström *et al*. 2020; Vollmer *et al*. 2022). Supporting community involvement requires recognising both the willingness of residents to engage and the diverse social, cultural and institutional contexts in which engagement occurs (Cross and Chappell 2022; Sarvilinna, Lehtoranta, and Hjerppe 2018). When communities are informed, empowered and meaningfully included, they can advocate for freshwater biodiversity, contribute to restoration efforts, and build long-term stewardship capacity (Merenlender *et al*. 2016; Scoggins *et al*. 2022). Within this context, the following components outline key pathways to foster community involvement across urban planning practice.

3.2.1. Leverage existing organisations

From neighbourhood associations to local nature clubs, towns and cities host a variety of community groups with diverse missions and goals. These organisations are well-positioned to advocate for freshwater biodiversity within local land-use planning and decision-making. Nature clubs, such as the RSPB or National Audubon Society, are especially attuned to biodiversity issues, and can serve as leading voices in larger centres, opposing developments that impinge on important habitats. Their sizable member bases and cumulative engagement in outreach activities (e.g. Toronto Field Naturalists) and active habitat restoration, create substantial opportunities for municipalities to engage residents in planning conversations via these organisations. Many municipalities are mandated to maintain community advisory committees (e.g. Ontario, Canada; Biosecurity and Biodiversity Advisory Groups for District and Regional Councils in New Zealand – including emerging co-governance between Māori and other elected representatives), representing a fuller range of values. Although environmental planning may seem distant from pressing community priorities (e.g. housing, transportation), public buy-in increases when residents recognise synergies between environmental and social goals; indeed, most do not support urban development at the expense of the environment (Arman *et al*. 2009). Accordingly, urban planners and institutions can play a crucial role in enabling community involvement, though doing so requires nuanced understanding of residents' willingness to engage (Sarvilinna, Lehtoranta, and Hjerppe 2018).

3.2.2. Promote community science initiatives

A growing body of work supports the potential of community-led action in advancing freshwater biodiversity conservation. Urban and regional planners can strengthen public support for sustainable planning proposals by promoting "community science" initiatives focused on freshwater protection and restoration (e.g. Metcalfe *et al*. 2022). Community science, also known as "participatory science" or "citizen science", involves public participation in the collection of ecological data - from crowd-sourced biodiversity inventories ("BioBlitz"), to continuous environmental monitoring (e.g. lake monitoring programs), (Conrad and Hilchey 2011), or nature protection (e.g. Travis Wetland Nature Heritage Park, Christchurch, New Zealand: https://traviswetland.org.nz/). Community science is especially valuable for early detection and distribution mapping of aquatic invasive species (e.g. Price-Jones *et al*. 2022), supporting Target 6 of the Kunming-Montreal Global Biodiversity Framework (CBD 2023). Pocock *et al*. (2024) also suggest that initiatives such as the "iNaturalist" City Nature Challenge (UK) could be further activated to assess aquatic invasive species impacts and management effectiveness.

Participation in community science additionally facilitates learning and fosters stewardship. It enhances understanding of conservation issues (Somerwill and Wehn 2022), strengthens environmental stewardship and advocacy (Merenlender *et al*. 2016), and has matured into a scientifically validated data-collection methodology over the last decade (Ramirez, van Meerveld, and Seibert 2023). This makes community science a viable approach for engaging both urban and Indigenous communities in the monitoring of their local environments, while also reinforcing pro-environmental attitudes (Toomey and Domroese 2013).

3.2.3. Clearly communicate benefits and trade-offs

Opportunities for community engagement must be paired with clear communication, education, and contextual understanding. While specific community actions can directly benefit freshwater biodiversity, the public require leadership and effective communication from urban and regional planners to ensure actions are done in a coherent manner. For example, subsidised programmes such as the "Rain Ready Ottawa" programme (Canada), encourage homeowners to reduce impervious surfaces and runoff from their properties in dysfunctional watersheds (or subwatersheds, i.e. smaller sub-basins nested within a larger watershed; hereafter collectively referred to as "watersheds"), (https://ottawa.ca/en/living-ottawa/environment-conservation-and-climate/protecting-ottawas-waterways/rain-ready-ottawa). In addition to subsidies, residents also need to understand how their property decisions affect the watershed. As planning shifts towards less concrete-intensive approaches, community engagement is fundamental to success.

Public hesitancy also needs to be understood and addressed. Resistance can arise from perceived (rather than real) links between forested (or otherwise natural) riparian zones and crime or reduced aesthetics (N. Zhang, Zheng, and Wang 2022), or from concerns that natural stormwater channel design and bio-engineering solutions increase flood or erosion risk (Gao *et al*. 2018) – despite sponge city principles offering more absorptive, resilient systems that are less prone to disaster (T. T. Nguyen *et al*. 2020). Recognising these hesitations, planners should work collaboratively with community members to build trust, address concerns, and strengthen community capacity for stewardship, which can, over time, support bottom-up initiatives (Scoggins *et al*. 2022). Local contextual factors, including socio-economic complexities, strongly influence willingness to engage as well as the goals that communities prioritise (Cross and Chappell 2022).

3.2.4. Co-produce and co-develop strategies with diverse engagement

Building from a community-science model of community engagement and buy-in, is the participatory research co-production/co-design model (Norström *et al*. 2020) involving community members from project inception through to research design and decision-making. These approaches emphasise social equity, and the inclusion of diverse perspectives. Working collaboratively with communities in transdisciplinary co-production, including the use of decision support tools, or trade-off analysis (e.g. Ometto

Bezerra *et al*. 2023; Vollmer *et al*. 2022), can explicitly highlight the social significance of conserving freshwater biodiversity through urban planning choices. Existing tools and mechanisms supporting co-production include the Intergovernmental Science–Policy Platform on Biodiversity and Ecosystem Services (national and regional platforms and networks and Nexus assessment tools), (Kuiper 2023). Effective co-production requires transparency and communication, with diverse stakeholders participating to ensure meaningful dialogue and equitable power sharing dynamics (Gerlak *et al*. 2023).

The importance of these approaches is especially clear for Indigenous and marginalised communities, who have historically been excluded from urban planning, yet disproportionately face environmental burdens of urbanisation such as pollution and poor sanitation (Agyeman *et al*. 2016; Marques *et al*. 2024; McMillan, Spronk, and Caswell 2014). In multicultural settings, representatives from different cultures (including Indigenous peoples) should be present, and have special or defined roles during the planning process (e.g. Māori and *tangata whenua* as part of the planning team under the New Zealand Resource Management Act 1991 and Local Government Act 2002, given they are rightsholders) to ensure multiple knowledge systems guide decisions. These approaches support community cohesion, particularly in post-colonial contexts, and acknowledge the value of freshwater purity, food and fibre provision. Beyond legal and moral imperatives, there is growing evidence that Indigenous stewardship practices and resource management – rooted in long histories of sustainable engagement with nature – can outperform Western scientific approaches in achieving outcomes beneficial to both people and biodiversity (Y. Zhang *et al*. 2023).

3.3. Action 3: transcend disciplinary silos in urban planning education and training

Historically, urban planning roles have been dominated by skilled civil and water-resource engineers and planning professionals who have operated in disciplinary silos during their educational and professional development (Anacker 2024). Consequently, with limited social-ecological training or collaboration, urban environments have frequently been formulated through conventional engineering solutions that overlook the wider complexity of these social-ecological-technical systems (Bixler *et al*. 2019), including urban freshwater biodiversity and natural ecosystem function. To address freshwater challenges effectively, a shift in how urban planners are educated, trained, and supported across their careers is required. In view of this, the following components outline key approaches for transcending disciplinary silos in urban planning practice.

3.3.1. Encourage transdisciplinary collaboration and working groups

Transdisciplinary collaboration is increasingly important as human-induced ecological problems intensify (Reyers, Roux, and O'Farrell 2010; Zhou, Pickett, and McPhearson 2021). Although the availability of specialised interdisciplinary postgraduate programmes is growing, the foundations of urban planning curricula still require a shift away from traditional models, toward interdisciplinary, and ultimately, transdisciplinary education (Anacker 2024). Interdisciplinarity integrates knowledge and methods from multiple academic disciplines to develop unified insights into complex problems. Accordingly, interdisciplinary education combines two or more academic disciplines within its teaching to equip students with these integrative perspectives (Tobi and Kampen 2018). Transdisciplinary education extends this further by incorporating participatory, real-world learning and input from academics, practitioners and other relevant stakeholders or partners, to address locally relevant problems (Kubisch *et al*. 2022).

Frameworks supporting such integration include "One Health", socio-ecological systems approaches, and integrated water resource management. These are reflected in exemplar formal education programmes and networks, such as the "Collaborative Water Program" (University of Waterloo, Canada), "One Health Program" (University of Guelph, Canada), and "OneHealth - WaSH network" (Stockholm Environment Institute, Sweden).

Cultivating a transdisciplinary mindset among early-career urban planners (and more broadly among environmental policy makers and practitioners) – including critical or systems thinking, collaboration and integrated problem-solving, and co-production of environmental decision making – is crucial for addressing global freshwater challenges, including urban aquatic ecosystems (e.g. Frank *et al*. 2021; Marques *et al*. 2024). For educators, this will involve compulsory course components on the conservation and enhancement of freshwater biodiversity, or demonstrable micro-credentials for undergraduate and postgraduate students (Morse *et al*. 2007). Although many planning graduates receive training in sustainable development, as stipulated by many accrediting planning bodies (e.g. Royal Town Planning Institute; Planning Accreditation Board), we propose the need for "blue-green planning" courses (Mell *et al*. 2023) that integrate the principles of aquatic ecology, biodiversity, and ecosystem dynamics into the urban planning syllabus. This could include virtual guest lectures by freshwater ecologists, field courses led by freshwater resource managers, mock stakeholder meetings where students role-play diverse interests, and the inclusion of freshwater scientists on curriculum advisory boards to embed ecological perspectives in course design.

3.3.2. Adopt blue-green planning strategies

Promotion and adoption of "blue-green planning" (i.e. the integration of water- and vegetation-based ecological components into sustainable urban development: see also "Blue-Green Infrastructure", Mell *et al*. 2023) requires a concerted effort from academics and institutions to develop transdisciplinary coursework and degrees. Pedagogical strategies should align with both scholarly expectations (e.g. outlets for publication) and practitioner needs, ensuring that programmes preparing students for urban planning careers reflect the realities of cross-sectoral work. Developing novel programmes that address well-defined transdisciplinary learning objectives and content will require the dismantling of discipline-bound barriers and interdepartmental cooperation among key actors (Morse *et al*. 2007). Programmes should also offer students opportunities to integrate academic and professional insights (i.e. outreach and extension with practitioners), deepening their critical thinking skills, as the ideas and concepts they acquire in one discipline can be effectively transferred and applied to others.

The development of new transdisciplinary programmes will require working across existing institutional structures while remaining connected to existing resources and programmes. For example, creating the "Sustainable Urban Development" bachelors' level degree at Tampere University (Finland), necessitated extensive planning between urban development practitioners and scholars (over two and a half years), followed by ongoing iterative curriculum enhancements (see J. Taylor *et al*. 2021). Although resource-intensive, such investment pays dividends: transdisciplinary blue-green planning credentials prepare students with the flexibility, active learning skills, and resilience needed to address global urban challenges, and compete in the modern job market (Fung and Hosseini 2023). Experiential opportunities such as internships or service-learning projects with local freshwater organisations (e.g. designing urban NbS) further extend training beyond the classroom while leveraging existing partnerships and community resources.

Working on shared environmental challenges can fuel intrinsic motivation (Carr and Walton 2014), but differences in motivation and capacity exist across professional roles. Faculty may be overstretched or adapting to unexpected challenges (e.g. shift from face-to-face to online teaching during COVID-19), affecting teaching quality, professional learning, and staff well-being (Daumiller *et al*. 2021). Urban planning professionals face evolving expectations for continuing professional development (CPD), standards, and chartership or industry certification programme requirements (Twardek *et al*. 2021). In both sectors, institutions have, and must, continue to invest in support systems and contingency strategies that enable proactive responses to unexpected challenges (Rapanta *et al*. 2020), ensuring that blue-green planning and freshwater biodiversity objectives remain achievable in practice.

3.3.3. Create clear pathways for professional development

To ensure meaningful engagement in cross-sectoral initiatives like the ERP, clear and accessible professional development pathways are essential. Rather than placing new course design burdens on already constrained faculty, institutions can recruit staff motivated to explore transdisciplinary collaborations (J. Taylor *et al*. 2021). Access to readily available professional certificates or training programmes (e.g. WYFLIP Blue Green Infrastructure Training Programme, UK), or subject specific academic texts (see Bell *et al*. 2021: “Urban Blue Spaces”) may serve as important intermediate steps. Nonetheless, staff require appropriate institutional support mechanisms (at the university and administrative levels) to incentivise participation and maintain healthy work-life balance (Daumiller, Stupnisky, and Janke 2020).

Urban planners also benefit from existing CPD frameworks, such as the Canadian Institute of Planners CPD Hub (https://www.cip-icu.ca/cpl-learning-hub/), which houses free resources for ongoing learning. Environmental and sustainability competencies are tested internationally in accreditation assessments (e.g. Professional Standards Board for the Planning Profession in Canada; Royal Town Planning Institute [RTPI], UK). To effectively protect freshwater biodiversity, however, urban planners require dedicated training units that build holistic understanding of waterways within catchment contexts. Current short-term, low-intensity environmental CPD opportunities (e.g. RTPI: “BNG for Planners” and “Environmental Impact Assessments”: https://www.rtpi.org.uk/events-training-and-awards/rtpi-training/) should evolve into longer-term, experiential, and context-specific learning programmes. While such programs are being developed, urban planners should seek blue-green planning training opportunities that strengthen learning and inform practice adaptation. Ideally, transdisciplinary blue-green thinking would stem from educators and persist throughout an urban planner’s career, supported collectively by professional institutes, regulators, and consulting organisations.

3.4. Action 4: improve knowledge exchange between urban planners and other practitioners

As mandates to conserve, sustain, or restore urban freshwater biodiversity expand, cities require clear and systematic conservation frameworks that can guide planning across multiple stakeholders. Urban planners, ecologists and local communities must work in coordination to embed freshwater priorities into decision-making. However, despite the volume of fundamental and applied research produced by universities, think tanks, and professional sectors, much of this knowledge remains disconnected from urban planning practice. Evidence-based planning is underutilised due to institutional, cultural, and logistical barriers (Hurley *et al*. 2016; Krizek, Forsyth, and Slotterback 2009). Practitioners frequently lack the time, resources, or institutional support to access and apply current research findings (E. J. Taylor and Hurley 2016). Discrepancies in methodological approaches between disciplines create further barriers, making it difficult to align research outputs with practice-specific drivers and contexts (e.g. conservation: J. L. Reid *et al*. 2022; J. C. Walsh *et al*. 2019; urban planning: Hurley *et al*. 2016; Krizek, Forsyth, and Slotterback 2009). For example, only 14% of citations in marine protected area management plans draw from primary scientific literature (Cvitanovic *et al*. 2014; Hunter *et al*. 2021). Strengthening knowledge exchange is therefore essential for embedding freshwater biodiversity considerations into urban planning practice, and the following components outline key pathways for achieving this.

3.4.1. Leverage existing frameworks

Several interdisciplinary and adaptive frameworks already demonstrate how freshwater biodiversity can be prioritised in planning. A compelling example of such a framework is the eight-step urban amphibian conservation model, which establishes procedures for monitoring, analysis, and community engagement to support amphibian conservation in large urban environments (Lee *et al*. 2022). This adaptable approach demonstrates how biodiversity preservation can be advanced through interconnected modelling techniques that assess species presence, identify priority habitats, and evaluate functional connectivity. Similarly, the Nine-Step Iterative Planning process for stream corridors in Ontario - developed by engineers, geomorphologists, and ecologists through the Natural Channels Initiative (Ontario Ministry of Natural Resources [OMNR] 2002) - outlines a structured three-stage, nine-question method for planning and implementation (see Action 5). These frameworks underscore the importance of tools that can be flexibly applied across contexts, provided they are continually updated with new scientific evidence and practical case studies (Figure 2; Supplementary Table S1).

3.4.2. Advance open-access tools and databases

The continued growth of open-access databases and interactive planning tools is essential to bridge knowledge exchange gaps (see Supplementary Table S2 for a list of tools). Systematic watershed frameworks – such as the IUCN global species assessments (Lacher, Boitani, and da Fonseca 2012) and the HydroBasins spatial datasets of hydro-ecological systems (Lehner and Grill 2013) – enable planners to identify biodiversity threats and inform design decisions. Urban planners should contribute actively to these platforms by documenting case studies, workshop minutes, and monitoring data

(Figure 2; Supplementary Table S1). Beyond expanding databases, knowledge creators and urban planners must ensure these tools remain usable and accessible. Advances in spatial planning platforms (e.g. ArcGIS Online; Nel *et al*. 2016) and predictive modelling tools (e.g. R/Shiny; Jagadeesan, Barden, and Kasprzyk-Hordern 2023) provide timely, applied insights that can be integrated into planning decisions. Such tools enhance foresight and facilitate resource-sharing, supporting the broader shift toward transdisciplinary education and training described in Action 3.

3.4.3. Develop pathways for urban planners in freshwater spaces

Understanding how different actors perceive their societal roles and responsibilities is key to addressing freshwater issues and restoring aquatic habitats. Freshwater scientists may need to instigate broader conversations to surface stakeholder perspectives (e.g. *via* interviews, focus groups, or surveys), while urban planners can begin operationalising freshwater-supportive insights within planning processes (see Section 4). Engagement with policymakers, practitioners, Indigenous groups, and scientists can occur through freshwater-focused professional associations, scientific conferences, or local environmental charities. Volunteering, co-authoring research, or participating in community events can also foster relationships and mutual learning. Although informal practitioner networks exist – such as InFish and the Alliance for Freshwater Life – few initiatives directly target urban planners or create shared spaces for their expertise, underscoring the need for dedicated dialogue channels to support more meaningful exchanges.

3.4.4. Participate in broader public and policy platforms

To ensure engagement extends beyond technical or specialist circles, urban planners – particularly those trained in blue-green planning – should participate in public-facing platforms that reach policymakers and communities. Sharing urban planning insights with non-specialist audiences helps integrate freshwater biodiversity priorities into everyday decision-making. These platforms should promote the involvement of freshwater ecologists and conservation scientists at each stage of the planning cycle (see co-production model: Action 2). When ecological sustainability is embedded in project design from the outset, it avoids the tendency to retrofit biodiversity considerations late in the process. This is fundamental to reverse the decline in freshwater biodiversity, as despite the adaptability of nature, it is less likely to bend to accommodate design strategies than the inverse.

Examples include the New Zealand Planning Institute's workshop "Freshwater Science: Basics for Planners and Others Implementing the National Policy Statement for Freshwater Management [NPS FM]" (November 2023), bridging technical expertise and planning practice. Other initiatives, like CityStudio Vancouver, foster collaboration between students, municipal staff, university faculty, and residents to co-create solutions to urban challenges (https://citystudiovancouver.com/), while Urban Living Labs across Europe offer similar spaces for public agencies, businesses, academic institutions, and citizens to work together (Rizzo, Habibipour, and Ståhlbröst 2021). Paired with curricular changes described in Action 3, such platforms can catalyse two-way knowledge flows and spur demand for transdisciplinary events that prioritise actionable knowledge for freshwater biodiversity.

3.4.5. Encourage participatory planning

To complement tools and platforms, knowledge exchange must be embedded in decision processes through inclusive and participatory governance. Deliberative democratic tools, such as citizen assemblies, participatory forums, and community panels, offer structured ways to elevate diverse values and knowledge systems (Gerlak *et al*. 2023). These forums can reveal how lived experiences, cultural perspectives, and Traditional Ecological Knowledge shape public attitudes toward freshwater ecosystems (Chapman and Schott 2020). When applied to conservation areas or species-at-risk decisions, participatory planning encourages mutual learning between scientists and communities and ensures that marginalised voices are central to policymaking (Raymond *et al*. 2022). Institutionalising these processes within formal planning frameworks helps urban planners move beyond tokenistic consultation toward genuine co-production and co-management of freshwater systems – an especially important shift in complex urban environments where competing land uses often marginalise aquatic habitats. By championing inclusive engagement and plural knowledge systems, urban planning can advance ecological integrity and social equity while translating freshwater biodiversity priorities into day-to-day practice.

3.5. Action 5: develop actionable standards, tools, and policies

Global commitments to halt freshwater biodiversity decline are a promising step toward stronger international and domestic protections (e.g. CBD 2023; IUCN 2021; UN 2015). While global biodiversity governance offers common-language and ethical frameworks that transcend national boundaries to reach a common goal, achieving meaningful outcomes for freshwater biodiversity requires effective policy development, multi-level governance, and stakeholder buy-in within national, regional, and local planning systems (Hostetler, Allen, and Meurk 2011; MacKinnon *et al*. 2019). Countries employ diverse strategies to conserve freshwater biodiversity, including national monitoring programmes, setting conservation goals (e.g. Canada's 2030 Nature Strategy 2024) or targets, and differing offsetting schemes (e.g. Ambrose 2000). However, international ambitions cannot be realised if local governance systems and planning capacity remain weak. The following components outline key pathways for developing actionable standards, tools, and policies to enable urban planners to deliver freshwater biodiversity outcomes.

3.5.1. Explicitly include freshwater biodiversity in urban planning policies

Mandatory 'Biodiversity Net Gain' (BNG) requirements introduced in England (UK) provide a relevant example of efforts to better integrate biodiversity considerations into planning policy. As of 2024, most developments must deliver $a \geq 10\%$ uplift in biodiversity value (noting some exceptions: Schedule 7 A of the Town and Country Planning Act; as per Schedule 14 of the Environment Act 2021). This includes a dedicated statutory 'water metric' applied to development within 10 m of a freshwater body (or riparian zone), requiring targeted surveys and a separate 10% net gain uplift in addition to terrestrial (and hedgerow) BNG accounting. While BNG offers a structured mechanism for incorporating freshwater biodiversity into planning, empirical reviews highlight several shortcomings (Rampling *et al*. 2024; zu Ermgassen *et al*. 2021). The metric may undervalue ecologically significant, "low value" freshwater habitats or fail to account for the loss of rare or irreplaceable ecosystems and their associated functions, such as chalk streams, 85% of which occur in England. Recent statutory clarification specifies that losses to unique chalk stream ecosystems cannot simply be offset elsewhere (DEFRA 2023: Amended July 2025), reinforcing the need for habitat-like-for-like compensation (see Maron *et al*. 2012). Practical constraints further complicate implementation, including limited opportunities for on-site habitat creation, constrained or complex off-site options, or additional permitting requirements (e.g. FRAP). This example underscores the importance of continual scrutiny, local expertise, and iterative improvements of biodiversity metrics to ensure that freshwater biodiversity is not underestimated in planning decisions.

3.5.2. Co-develop objectives across sectors

Implementing new biodiversity policies can strain local planning authorities (LPAs), many of whom may lack ecological expertise or adequate resourcing. These pressures have intensified under concurrent reforms, such as accelerated housing targets in the UK's National Planning Policy Framework, most of which trigger BNG compliance (MHCLG 2024). Yet such legislation also creates opportunities for urban planners to achieve freshwater biodiversity gains and enhance communities through holistic infrastructure design (Action 1). Proposals to streamline planning approvals *via* delegated powers (e.g. Planning and Infrastructure Act 2025) further highlight the need for clear, up-to-date local development plans with robust, co-developed objectives prioritising freshwater protections. Effective implementation of biodiversity policies requires multi-level governance, ecological expertise, adequate resources, and mechanisms for public participation (Actions 2, 3, and 4: Knight-Lenihan 2020). Without these, freshwater offsetting schemes risk repeating local compliance and public-acceptance failures observed in other national contexts (e.g. Wetland Mitigation and Banking Policy: USA: Rampling *et al*. 2024). Urban planners therefore play a crucial role not only in applying policy frameworks, but also in shaping their local operationalisation to ensure freshwater biodiversity outcomes are realised.

3.5.3. Prioritise watershed-based planning

A contextual understanding of the local watershed is crucial for urban planners and decision makers to improve the protection, restoration, and management of aquatic biodiversity. Because watersheds often cross political boundaries, planning must consider ecological processes at the appropriate scale. Where watershed studies are lacking, municipalities can use tools such as FERM (Framework for Ecosystem Restoration Monitoring: FAO 2023) to identify ongoing pressures on freshwater biodiversity within their jurisdiction and predict the potential negative consequences of new planning or development proposals (Genskow and Born 2006). Watershed-based planning and analysis, widely adopted across North America, offers this perspective. For example, Ontario's watershed planning tools introduced in the early 1990s (MOE 2003) help planners understand hydrological functioning, identify suitable development locations, and develop design standards to protect water resources and aquatic biodiversity. These tools assess nutrient and sediment transport, water quality and quantity, fish migration corridors, wetland form and function, and stream character to construct local aquatic biodiversity baselines.

Despite their utility, municipalities face barriers implementing watershed-based policies due to conflicting objectives, inconsistent regulations, and fragmented governance structures (Romein, Trip, and de Vries 2003; Sorensen 2018). This can hinder urban planners' abilities to protect aquatic biodiversity or provide reasonable societal benefits (Daniell and Barreteau 2014). Determining which policies best apply, or should be prioritised, requires a consideration of natural watershed or landscape characteristics, municipal goals, and the ecological function of waterbodies. Local conservation or planning authorities require mandates or policies that consider biodiversity, and, as illustrated from the Greater Toronto Area (Canada), that provide clarity on the application of provincial (e.g. Ontario Conservation Authorities Act) and federal legislation (e.g. Canada Fisheries Act), in this instance, as applied to constructed urban ponds with ecological value (Marques *et al*. 2024). Watershed-based planning thus provides the ecological context needed to reconcile regulatory frameworks and avoid piecemeal, ad hoc decision making.

3.5.4. Conduct comprehensive watershed analysis

Watershed-based planning and analysis (Schmidt and Morrison 2012; Summers, Plummer, and FitzGibbon 2003), assessment of cultural ecological services (see Cultural Health Indicators: Harmsworth 2002) or urban-water metabolism approaches (Serrao-Neumann *et al*. 2017) further strengthen this contextual foundation by illuminating land-water interactions at the catchment scale. When combined with local societal priorities, these approaches help planners navigate competing regulatory frameworks while maintaining or restoring natural function and biodiversity. They may also discourage development in sensitive or high-risk areas and guide investment toward more suitable (less destructive) locations, reducing policy conflict and minimising impacts on important natural features and processes (Nault *et al*. 2020). Healthy urban aquatic ecosystems additionally offer economic benefits, with properties adjacent to ponds, or ravines, trading at a premium (Nicholls 2019). Although initial design costs to achieve these outcomes may exceed those of standard approaches, long-term savings in maintenance and environmental mitigation underscore the value of proactive watershed planning and guidance over *ad hoc* decision making.

A concise illustration is the Canadian Stream Corridor Guidance document (OMNR 2002), (mentioned in Action 4), which integrates expertise from government, NGOs, consultants, engineers, biologists and geomorphologists to improve long-term functional stability and aquatic biodiversity within streams, floodplains, wetlands, riparian areas and channels. Science-based planning tools such as these offer clear pathways for achieving better outcomes for both society and freshwater biodiversity.

3.6. Action 6: address key knowledge gaps in urban planning practice

Despite progress being made, pervasive knowledge gaps remain around scale, ecological thresholds, ecosystem-service valuation, and social and policy dimensions of freshwater management. To be clear, these are not merely academic knowledge gaps but rather practitioner knowledge gaps that impede the ability of urban planners and environmental managers to make decisions that benefit freshwater biodiversity, while also enabling responsible and sustainable development of urban infrastructure. Urban planners themselves could also have a role in helping close these gaps by deliberately designing plans that facilitate monitoring and learning through observation of ecological response. The following components outline key areas where clearer knowledge, better guidance, and improved integration across disciplines are required.

3.6.1. Align scale for action

Although critical research needs remain for protecting and restoring freshwater biodiversity (reviewed in Harper *et al*. 2021; Maasri *et al*. 2022), most of that effort and scientific thinking occurs at the watershed or bioregional scale, whereas urban planners (and urban development) typically operate at a more localised scale. Perhaps there is a need to rethink the scale at which urban planning operates (e.g. see theoretical and practical guidance to incorporating biodiversity into the urban environment in New Zealand: Ignatieva *et al*. 2008). Indeed, models on how to move water off landscape and manage contaminants while providing for biodiversity remain small-scale (e.g. parcel, city block). Larger-scale modelling and research are needed to weigh design alternatives, guide green infrastructure placement, and support functional integration across broader landscapes to enhance freshwater biodiversity (cf. Watts *et al*. 2000).

3.6.2. Provide clear recommendations and transparency of limitations

Planners and policymakers need clearer information on how development typically affects biodiversity across gradients rather than hard thresholds. Generalisable rules based on ecology, such as, “maintain 30 m riparian setbacks,” or, “avoid more than 10% impervious surface,” are rare, given uncertainty associated with tipping points (Hernández Martínez de la Riva *et al*. 2023). Instead, ecosystem responses are more likely to reflect continuous gradients such as 95% biodiversity is retained at 10% impervious surface, 90% at 15%. Moreover, generalisable projections, such as “more connected is better” may not hold when connectivity increases risks associated with disease or invasive species spread from waterways. Likewise, “larger will support greater biodiversity” overlooks the importance of small ponds, wetlands and headwaters that act as biogeochemical reactors, or provide specific habitat needs (e.g. nesting or pairing ponds for birds; fish-free ponds for some frogs). Identifying and communicating these gradients and their associated uncertainty would help urban planners weigh socioeconomic and environmental trade-offs (Linke, Turak, and Nel 2011). Selection of limits is a social decision that needs to be informed by science, but science cannot identify the ‘right’ limit – only the probable consequences of alternate decisions (with estimates of uncertainty: Cressie 2023). Holistic ecological science should be incorporated early in development or land use-change processes to ensure there is good projection of outcomes and unintended consequences of actions. Too often this expertise is brought in at the end of the concept design phase, when redesigning the project becomes difficult and costly.

3.6.3. Improve estimates of ecosystem services - values and trade-offs

Quantifying ES as well as potential synergies or associated trade-offs is essential for decision making (Tratalos *et al*. 2007). This includes quantitative assessments of resilience associated with different policy decisions that protect against floods (and drought), while at the same time benefiting freshwater biodiversity (Béné *et al*. 2018).

So-called "nature-based solutions" need to become institutionalised in urban planning (Albert *et al*. 2019). Many research needs relate to planning for long-term freshwater biodiversity protection (Lynch *et al*. 2024), with questions remaining about how we can adapt or upgrade existing stormwater infrastructure to cope with climate change. Thinking about stormwater infrastructure in terms of providing connectivity to natural aquatic systems and other built infrastructure, improvements in habitat quality, contaminant removal (*in situ* and at source) and remediation, and invasive species and disease control will require empirical research to guide such efforts, and big-picture design to enable the integration of all parts.

3.6.4. Integrate social science and policy perspectives

Beyond natural science and engineering research gaps, there is also a dire need for policy scholarship to understand how to bring key aspects of freshwater protections (e.g. as part of NbS) into urban and regional planning policies (Hostetler, Allen, and Meurk 2011). Finally, social-science work is essential for understanding how urban and regional planners, municipal leaders, and the broader public perceive freshwater biodiversity and their willingness to support or embrace initiatives that benefit it. Underpinning all of the aforementioned efforts will be the need for better processes that integrate the disciplines into better and more meaningful design teams. That will not come naturally but rather will require careful consideration (and experimentation) to identify the "best recipe" for success.

4. Urban planning for freshwater biodiversity: best-practice case studies and approaches

There are of course many instances where the consideration of freshwater biodiversity has been well integrated into urban planning. Here, we outline exemplar case studies and key project components relevant to addressing impacts on freshwater biodiversity (Figure 2; expanded details within Supplementary Table S1; see Figure 1 for reference to project component symbology). These case studies cover a wide scope of interventions, from large-scale watershed strategies to targeted stream, river, and wetland restorations embedded in local planning. They reflect broad geographical and contextual diversity, spanning cities across Asia, Europe, Oceania, and North and South America, each facing distinct freshwater challenges. The detail and complexity of these examples are demonstrated through their diverse planning tools, co-design processes, cultural considerations, ecological monitoring, and adaptive management approaches. Together, these international examples also highlight a set of recurring challenges and lessons learned that may be common across similar urban planning projects.

Across the case studies, several common barriers limited the integration of freshwater biodiversity into urban planning. Competing land uses and development pressures constrained opportunities for ecological restoration in densely developed urban areas (e.g. Los Angeles River, USA; Cheonggyecheon Restoration Project: Seoul, South Korea). Fragmented governance structures and misaligned institutional responsibilities frequently slowed or complicated implementation (e.g. Newtown Creek: New York, USA; Ecological Infrastructure Strategy: Lima, Peru), often exacerbated by outdated or siloed planning tools. Social and cultural barriers, such as early public scepticism that projects were overly ambitious or unlikely to succeed (e.g. Cheonggyecheon:

South Korea) and community resistance to relocation or land-use change, added further complexity (e.g. Pluit Reservoir Revitalization Project: Jakarta, Indonesia). Finally, climate change posed a pervasive challenge across all projects. For instance, flooding, storm intensity, and heatwaves required urban planners to integrate extensive climate-focused interventions (e.g. rain gardens, infiltration swales, detention tanks, and upgraded storm and sanitary sewers) into their plans (e.g. North East False Creek: Vancouver, Canada). These themes reflect systemic constraints that regularly affect the implementation of Actions 1 through 6 across diverse urban contexts. Systemic failures are also reflected in an illustrative worst-case urban freshwater environment (Figure 3), highlighting where chronic under-investment, governance failure, and poorly designed grey infrastructure have accelerated biodiversity loss. Together, these worst-case examples underline how, without cross-sector coordination, adequate resourcing, and long-term maintenance, freshwater biodiversity rapidly deteriorates under the cumulative pressures typical of urban environments globally.

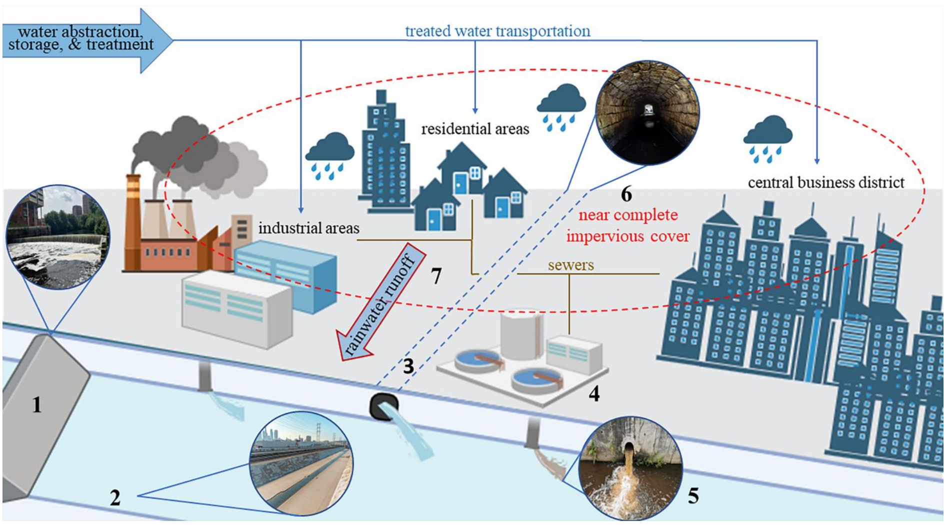

Figure 3. Worst-case example of a conventional urban environment.
Figure numbers key: 1) In-river impoundments, often present within urban rivers on a cumulative-scale, modify natural flow regimes and disconnect floodplains. This both facilitates the establishment of invasive aquatic species, and reduces habitat connectivity for resident and migratory species with life-history strategies dependent on characteristic patterns of flow variability (see Comte, Grantham, and Ruhi 2021); **2)** concrete channelisation/ levees contribute to lateral fragmentation of rivers and floodplains and homogenise the environment, therefore limiting freshwater habitat availability, and biodiversity; **3)** historically buried or piped streams are a key driver of biodiversity loss owing to absence of light, habitat fragmentation, and increased diffuse and point-source pollution that may significantly impact the urban watercourse ecological health; **4)** traditional wastewater treatment facilities do not incorporate constructed wetlands into the water purification process to remove contaminants from discharge and improve water security and access; **5)** straight-piped stormwater and sewage outfalls impact upon water quality and contribute to increased flashiness or erosion; **6)** near complete impervious cover leading to extensive run-off and freshwater biodiversity degradation; **7)** minimal access or connectivity to fresh water bodies for aquatic dependent flora and fauna, and local communities who benefit from the ecosystem services that freshwater biodiversity provides. For further detail, see Section 2 (Table 1): “contextual background: conventional approaches to urban planning.”

Despite these challenges, the case studies also illustrate how freshwater biodiversity can be effectively embedded into urban planning when key enabling conditions are present. First, multifunctional design approaches (Action 1) delivered both ecological and social co-benefits, including habitat creation, flood resilience, and improved public recreational spaces, all contributing to strengthened public support (e.g. Cheonggyecheon: South Korea; Peynircioglu Stream Ecological Restoration Project: Izmir, Turkey; Ōtākaro/Avon River Catchment Project: Christchurch, New Zealand: T. T. Nguyen *et al.* 2021). Early and consistent community engagement, alongside the integration of cultural values and traditional ecological knowledge (e.g. *Te Ao Māori*: the Māori worldview) into urban design (Action 2), helped build legitimacy and strengthen place-based relevance (e.g. Christchurch, New Zealand; GreenQuays project: Breda, The Netherlands). Adaptive and phased implementation (Action 3) enabled real-time learning and iterative refinement before wider rollout, as demonstrated by piloting of nature-based interventions (e.g. rain gardens and infiltration swales) in Vancouver (Canada). Developing actionable standards, tools, and policies (Action 5) also played a critical role when such frameworks were explicitly embedded into planning processes using GIS-based tools, design principles, and water-sensitive planning manuals (e.g. Lima, Peru). Many projects also emphasised the importance of robust biodiversity monitoring frameworks (Action 6), to support long-term learning, accountability, and adaptive management (e.g. Yarra River Rehabilitation: Melbourne, Australia – ongoing monitoring to assess restoration activity effectiveness). Finally, knowledge co-production among diverse stakeholders, including governments, NGOs, community groups, and academia (Actions 2 and 4), facilitated locally context-specific solutions (e.g. Christchurch, New Zealand – earthquake prone regions), as exemplified by collaborative approaches in Lima, Peru.

These enabling conditions also characterise exemplar environments for freshwater biodiversity (illustrated in Figure 4), where emerging best-practices, including ES-based approaches and NbS (e.g. green stormwater management), are increasingly being applied (van Rees, Jumani, *et al.* 2023; Vollmer *et al.* 2022). However, recent evidence highlights the need for stronger biodiversity monitoring to evaluate NbS performance, especially in naturalised wetlands and stormwater basins (Li *et al.* 2025). Ensuring that NbS genuinely support aquatic ecosystems requires careful consideration of ecological dynamics, potential unintended impacts across interconnected systems, and long-term investment in maintenance, maturation, and monitoring (van Rees *et al.* 2022). These conditions closely align with, and reinforce, the six actions outlined in Section 3. Collectively, these successes demonstrate that effective freshwater biodiversity focused planning depends on both sound ecological design and sensitivity to local cultural, social, and governance contexts.

5. Conclusions and a vision for the future

We submit that urban planners (embedded within local governments and integrating multiple expert lenses during concept, design, construction and post-construction maintenance phases) will be vital to reversing the freshwater biodiversity crisis. Mobilising this community will bring manifold benefits to freshwater systems and all that depend upon them, but operationalisation remains a key challenge. While many urban planners already engage in decisions that benefit freshwater biodiversity, given the urgency of the freshwater biodiversity crisis, and the need to engage diverse actors, greater efforts

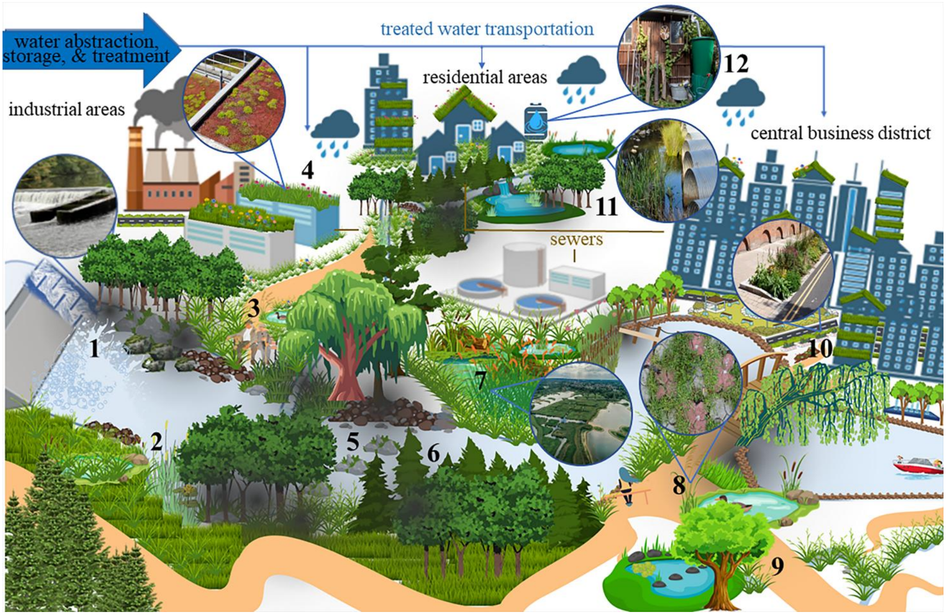

Figure 4. Example of an idealised urban environment for freshwater biodiversity.
Figure numbers key: 1) Lowering/removal of impoundments or addition of well-designed fish pass, ensuring appropriate attraction flow and downstream shaded refuge areas for fish (note, spatially prioritising target barriers to maximise biodiversity outcomes is key: see Kemp and O'Hanley 2010; and, the trade-off between assisting native aquatic species assemblages versus facilitating invasive species spread and establishment, must be considered: see Walter, Dettmers, and Tyson 2021); **2)** in-river/stream riparian planting, spawning habitat and in-stream habitat feature creation (e.g., riffles, pools) to support biodiverse communities; **3)** stream daylighting and accessibility to nature by water for local communities; **4)** green roofing designed for water conservation and filtration; **5)** floodplain reconnection/ restoration (note, where re-meandering unattainable owing to flood risk or space requirements, then partial restoration or in-channel enhancements, including sinuosity creation, should be implemented e.g., gravel/ woody debris introduction, two-stage channel creation, or use of flow deflectors); **6)** constructed riparian forests (note, stream temperature and energy flux is dependent on tree planting strategy: see Dugdale et al. 2018); **7)** landscape function approach to constructed or restored wetlands: see Biswal and Balasubramanian 2022, (note, this should include consideration for geographically isolated wetlands, i.e., those surrounded by uplands: see Cohen et al. 2016); **8)** water permeable surfaces to reduce runoff; **9)** off- and online urban ponds (including ornamental ponds optimised for biodiversity: see Oertli et al. 2023); **10)** sustainable drainage systems ("SuDS") or "bioswales" can slow, store, and better filter rainwater, and support groundwater recharge/ base flow (see Hamel, Daly, and Fletcher 2013); **11)** offline stormwater ponds (note, these should not replace natural wetlands); and **12)** rainwater gardens, storage, or harvesting systems.

are needed to build this awareness of values, threats and opportunities among planners. Freshwater initiatives are too often viewed as the remit of provincial/state and federal (or central) governments or the NGO sector; and while that may be appropriate for high-level regulatory guidance (Lynch *et al*. 2025), many decisions with direct biodiversity impacts occur at regional, district, and municipal scales. These local level governments may employ fewer freshwater scientists or restoration ecologists, but they do employ urban planners. Planners (and landscape architects) often serve as the interface between human development and the environment, including freshwater ecosystems and biodiversity. We therefore argue for revisiting the decades' old ethos of the quadruple bottom line to ensure all lenses shape early urban conceptual and planning phases.

There have already been calls to leverage the capacity of urban planners to address climate change (van Rees, Hernández-Abrams, *et al*. 2023; Wamsler, Brink, and Rivera 2013) and recent work emphasises the role of municipal and regional governments in bending the curve for freshwater biodiversity (Twardek *et al*. 2021). The question is, therefore, not whether the involvement of planners is necessary, or 'nice to have', but how to enable and support their contributions to the ERP. Relatedly, one could question why urban planners might take on such roles given that their jobs are already quite complex. To that end, and beyond the actions outlined here, this includes revisiting formal training and professional development so that urban planners in training, and those already practicing, are equipped with the freshwater ecological principles and skills required to integrate watershed planning principles and contexts into urban design, greenspace configurations, and stormwater management. Given that many planning jurisdictions require professional accreditation (Alexander 2005), there may be merit in revisiting accreditation criteria to ensure freshwater ecological literacy is recognised as an essential competency.

However, urban planners cannot achieve this alone. Stronger partnerships are needed with freshwater scientists, water resource engineers, economists, and restoration ecologists – many of whom work at provincial/state or national scales but may rarely engage deeply with urban planning processes. Multi-scalar and multi-level governance will hamper progress on the ERP if there is not a collective willingness to collaborate in new, respectful, and multi-stakeholder ways. Creating space for such collaboration may introduce complexity but, if done effectively, it could enrich professional practice and accelerate shared progress toward freshwater biodiversity recovery. Urban planners also need robust toolboxes to support these activities (Groves 2008; Twardek *et al*. 2021). For example, what are the best ways to design stormwater systems that also support freshwater biodiversity? And how do you best develop planning policies and instruments that recognise the value of freshwater biodiversity? These questions are the domain of the research community and must be addressed if planners are to fulfil their potential roles. There is also a need for social-science research to understand planners' perceptions of the challenges they face in delivering on the ERP – akin to work on smart city planning (see Meenar and Afzalan 2023) and understanding the role of artificial intelligence in urban planning (see Sanchez *et al*. 2023). Our author team includes scholars and practitioners who have begun articulating a vision for planning and freshwater biodiversity, but future efforts would benefit from complimentary surveying across a wide range of planning practitioners to identify the barriers and enabling conditions needed to support their effective mobilisation in addressing the ERP for freshwater biodiversity.

We have highlighted opportunities for urban planners to conserve and restore freshwater biodiversity. To do so, we presented six actions to better support urban planners including the need to: value freshwater biodiversity (ecological literacy and identify with local nature); support community involvement; transcend disciplinary (and cultural) silos in education and training; improve knowledge exchange among practitioners; develop actionable standards, tools and policies; and address key knowledge gaps. While the ERP and other global sustainability frameworks (e.g. SDGs and Kunming-Montreal Global Biodiversity Framework) outline the high-level actions required to protect and restore biodiversity (e.g. improve water quality, protect and restore habitat, enhance or maintain connectivity; see Tickner *et al.* 2020), the six actions presented here focus specifically on implementation, and align closely with the actions highlighted by Birnie-Gauvin *et al.* (2023) and Tickner *et al.* (2025). While those papers offer a candid overview of some of the general implementation challenges faced with the ERP, our analysis is more specifically concerned with the role of urban planners given their key (but often forgotten) potential to contribute meaningfully to the ERP's success. The diverse case studies and illustrative examples demonstrate how these actions are already being realised in different contexts, albeit with a focus on developed countries.

If we can work collectively, across professions, sectors, and governance scales, we envision a future in which freshwater biodiversity thrives within urban areas, providing benefits for people and nature. Moreover, because water flows downstream through connected catchments, we anticipate that biodiversity gains achieved in urban areas will carry forward into other waters, enhancing their ecological condition and the communities they sustain.

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Supplemental data

Supplemental data for this article can be accessed here.

ORCID

Helen A.L. Currie http://orcid.org/0000-0001-5792-3488
Andrea E. Kirkwood http://orcid.org/0000-0003-2947-574X
Morgan L. Piczak http://orcid.org/0000-0002-0816-3221
Irena F. Creed http://orcid.org/0000-0001-8199-1472
Nicolas W.R. Lapointe http://orcid.org/0000-0002-1055-9997
Nicholas E. Mandrak http://orcid.org/0000-0001-8335-9681
Sarah E. Null http://orcid.org/0000-0001-7451-7908
Jon S. Harding http://orcid.org/0000-0002-1070-1594
Rebecca C. Rooney http://orcid.org/0000-0002-3956-7210
John P. Smol http://orcid.org/0000-0002-2499-6696
Elizabeth A. Nyboer http://orcid.org/0000-0003-3004-009X
Irene Gregory-Eaves http://orcid.org/0000-0002-0380-5061
Michael Stone http://orcid.org/0000-0001-8085-8231
Charles H. Nilon http://orcid.org/0000-0002-6857-0259
Joseph R. Bennett http://orcid.org/0000-0002-3901-9513
Trina Rytwinski http://orcid.org/0000-0001-6764-7309
Steven J. Cooke http://orcid.org/0000-0002-5407-0659

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