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Review

The "Blue" Habitat of Urban & Suburban Areas and approaches for its biodiversity research: A scoping review

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ABSTRACT

This article explores recent research initially driven by interest in studying the "Blue" Habitat of Urban and Suburban Areas (BHUS), focusing on water-related ecosystems. BHUS, encompassing a wide range of aquatic habitats, is crucial to ecosystem health but is increasingly threatened by biodiversity loss resulting from climate change, land-use expansion, and unsustainable practices. Through a scoping review of 93 peer-reviewed studies, this article establishes a framework to classify BHUS types, identify target species, and analyze diverse and latest techniques in water system research. The main themes for studying biodiversity and environmental aspects of these blue habitats are highlighted, along with the urgent need to address BHUS in urban biodiversity conservation.

Findings reveal that water systems are biologically rich but present unique research challenges due to their variability and dynamic, interconnected nature. While there is growing recognition of the need to consider human influence, many studies overlook the complex, adaptive nature of BHUS as an integrated system. The article gives insight into establishing a comprehensive framework and integrating diverse methodologies and technologies for specialized research of the BHUS biodiversity, emphasizing the role of advancing technologies and interdisciplinary collaboration between urbanism and ecology. These approaches are essential to support sustainable development that addresses conservation needs and mitigates urbanization's impacts on BHUS. Further research should explore how spatial planning and strategies can more effectively integrate blue habitats to strengthen biodiversity conservation within the global urbanization context.

1. Introduction

Rapid urbanization is a major driver of environmental modification and ecosystem transformation (Vitousek et al., 1997), contributing to what is widely considered an ongoing sixth mass extinction (Ceballos et al., 2017). The diverse assemblages of species and ecosystems within human-altered environments are collectively termed "urban biodiversity" (Ossola and Niemelä, 2018). These urban ecosystems, characterized by complex ecological functions, are continually influenced by anthropogenic pressures. Urban expansion and densification increasingly threaten biodiversity and ecosystem stability (Kowarik et al., 2020). At the same time, urban and peri-urban areas retain a high capacity to support essential ecosystem services (ES) (Breuste et al., 2013), underscoring the importance of urban biodiversity measures in addressing the biodiversity crisis (Elmqvist et al., 2013). The recognition of biodiversity and ES issues in urban spaces as critical to sustainable development aligns with international priorities, such as those outlined in the Convention on Biological Diversity's COP-10 (Convention on Biological Diversity, COP-10 Decisions, n.d.).

Water-related ecosystems play a critical role in the overall ecosystem (Fitoka et al., 2020), while particularly suffering from biodiversity loss due to the altered climate, land use change and unsustainable management practices (Martín Muñoz et al., 2024; Tickner et al., 2017). Following the Aichi Biodiversity Targets of the Convention on Biological Diversity, the protection and restoration of water-related ecosystems have been included in the Sustainable Development Goals (Wetlands and the SDGs | The Convention on Wetlands, The Convention on Wetlands, n.d.). However, when discussing water systems, identifying the specific aquatic ecosystems contained inside urban & rural environments can be difficult.

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From an ecological standpoint, many concepts characterized by their water-related habitats have been delineated separately, emphasizing defining the natural ecosystem according to ecosystem-based approaches (Raymond et al., 2017). For example, "freshwater ecosystems", encompassing one-third of the world's vertebrates (Wang et al., 2021) are among the most extensively altered ecosystems on Earth; "river systems", as a vital part of freshwater ecosystems, including their floodplains and deltas, which are among the most threatened and deteriorated ecosystems on the planet (Yousry et al., 2022); or "coastal ecosystem" which includes wetlands, estuaries, and coral reefs, etc. (Klemas, 2011) as some of the most heavily used and threatened natural systems globally (Barbier et al., 2011).

In urbanism, even if cities and the outskirts are designed and built to be human habitats, people find "urban nature" is a critical solution to many challenges (Childers et al., 2019). There are various terminologies (Table 1) and associated strategies following the trend of enhancing urban sustainability, which consists of crucial blue habitats for various species. For example, "Urban green space" and "Urban blue-green spaces" are important elements in cities for environmental conservation (Dunnett et al., 2002; Najihah and Abdullah, 2019) contains water bodies such as rivers and lakes (Abdul Aziz et al., 2011; Almanza et al., 2012; Song et al., 2022). "Green infrastructure" and "Blue-green infrastructure" integrates interconnected networks of waterways, coastal and marine areas, moist space such as wetland areas, providing ecological benefits to urban environments (Arcidiacono et al., 2016a; Benedict et al., 2012; Ghofrani et al., 2017). The concept of "Urban Ecological Infrastructure" is a more inclusive and newer alternative that emphasizes all ecologically supported city structures and functions containing comprehensive water-related systems (Childers et al., 2019). Apart from these concepts, some artificial and semiartificial water habitats or small waterbodies are easy to neglect, while they support a high level of biodiversity (Sundar and Kittur, 2013) and are among the threatened freshwater habitats because of heavy human use (Jia et al., 2011; Oertli and Parris, 2019; Pinilla, 2010; Wahlroos et al., 2015), such as ponds, dams, etc.

Among these concepts in the urbanism context, the purposes or utilizations are usually more closely related to dealing with development crises such as climate change, flooding, arid, health issues, etc. However, the significant impacts on human society with environmental crises, bring the trend of introducing ecosystem-based approaches into urban planning and policymaking (Raymond et al., 2017). Nature-based solutions (NBS) emerged as an encouraged approach to work interactively with ecosystems to adapt to the challenges and mitigate the impacts of biodiversity loss, etc. (Collentine and Futter, 2018). To support NBS, there is a demand to review these concepts and spaces or ecosystems they indicated in a complex system (Ying et al., 2022), to further decrease the gap between the ecology and urbanism professions in terms of biodiversity and related studies.

Table 1
The main relevant terminologies in the urbanism discipline contain variety of blue habitats.

Concept	"Blue" in the Scope/Description	Publication/Citation
Greenspace	Refer to any green patches; A range of vegetation; Includes forests, parks, **water bodies**	(Abdul Aziz et al., 2011; Almanza et al., 2012; Dunnett et al., 2002)
Urban blue-green spaces	Composite space made up of **blue space represented by rivers and lakes** and green space represented by grasslands	(Arcidiacono et al., 2016b; Song et al., 2022)
Green infrastructure	An interconnected **network of waterways, wetlands, wildlife habitats**, and other natural areas; greenways, parks, etc.	Mell (2008)
Blue-Green infrastructure	An interconnected network of natural and designed landscape components, including **water bodies** and green and open spaces.	Ghofrani et al. (2017)
Urban Ecological infrastructure	All parts of a city that support ecological structures and functions, contains **water-related systems** such as lakes, Urban streams and rivers, etc.	Childers et al. (2019)
Blue space	Urban **aquatic environment** as public spaces	Raymond et al. (2016)
Blue infrastructure	Biophysical, **aquatic elements** and related ES that play an important role in shaping urban justice and resilience, includes rivers, wetlands, seas, etc.	Hellman and Haeffner (2020)

When focusing on the "blue," it is important to understand the overall framework of water-related systems that establish the relationship between human society and biodiversity to safeguard ES's sustainable use for humans and all living things. Through a broad viewing of the relevant concepts above, these concepts frequently overlap, are unspecific, or have diverse meanings in different contexts. Furthermore, a comprehensive relationship between habitat types and species in these blue systems is lacking. When deliberating on urban and sub-urban "blue" habitats for biodiversity, achieving conceptual clarity and delineating the diverse habitats and species remains a formidable task.

At the same time, with an exponential increase in the application of new technologies, advanced methods such as Remote Sensing (RS) (García-Pardo et al., 2022), Machine Learning (ML) (Dang et al., 2020), etc. Have been implemented in interdisciplinary studies supported by cutting-edge tools and datasets. Many studies benefit from the convenience of these latest approaches compared to the traditional ones. For example, with the development of new sensors and cloud computing, big data analysis systems could support comprehensive or species-targeted assessments. The analytical approach that combined RS and ML allows high efficiency, less destructive, and more geographically expansive observation of the spatiotemporal changes in the study areas (Jafarzadeh et al., 2022). On the other hand, among many studies, traditional methods such as fieldwork, oral interviews, etc., still play a significant role. The importance of biodiversity and environmental issues has been fostering the use of diverse methods and tools ranging from state-of-the-art techniques to traditional methods, either separately or in combination. Currently, there is a scarcity of investigations that specifically examine of these methods.

Despite growing interest, significant research gaps remain in the field of biodiversity studies within the context of "Blue" Habitats in Urban and Suburban Areas (BHUS). Key habitat types and species within BHUS have not been clearly identified, nor has there been a comprehensive review of the techniques and methods specifically addressing BHUS biodiversity. Consequently, a few pressing questions arise: Can existing research endeavors contribute to a coherent understanding of the BHUS? What are the advanced approaches in analyzing environmental and biodiversity issues and what are the essential species been studied? With the research questions, we broadly review the most relevant studies. This research aims:

1) To classify the types of habitats found in the BHUS;
2) To identify the target species in the BHUS that is highly associated with biodiversity and relevant researches;
3) To summarize and analysis the techniques that have employed to study the BHUS biodiversity.

2. Methods

2.1. Search method and criteria

This study employed a scoping review as its methodology. A comprehensive review of existing research literature was conducted to identify relevant studies, utilizing the Web of Science (WOS) and Scopus databases. Google Scholar is not used as the primary search engine due to the overwhelming volume of papers, which can make it challenging to focus on higher-quality sources. WOS is a globally leading scientific citation search and analytical information platform (K. Li et al., 2018), whereas Scopus is an advanced database working with 21 research institutions and more than 300 researchers and librarians (Burnham, 2006). Scopus and WOS complement each other, providing inclusive data from various research journals across disciplines, which is essential for this article. To focus on advanced approaches and technologies, the selection of articles within the 10 years between September 16, 2015 and March 09, 2024. The application of the scoping review methodology offers several advantages, including the ability to identify research gaps across disciplines through comprehensive metadata analysis. It also facilitates the clarification of key concepts (Munn et al., 2018), and provides a valuable foundation for guiding future systematic reviews and investigations into emerging research questions.

The search utilized a structured syntax comprising three groups of keywords (Fig. 1), which delivered a logical literature search query to discover highly pertinent references, resulting in the retrieval of 31,798 papers.

The review process adherence to the PRISMA 2020 Checklist (PRISMA 2020 Checklist — PRISMA Statement, n.d.-a) ensured the application of rigorous inclusion criteria:

1) Studies had to pertain to one of the designated spaces: urban, rural, metropolitan, infrastructural or ecological corridors;
2) Studies must include discussion of water-related systems;
3) Cross-disciplines researches were considered such as landscape and urban ecology, planning and landscape architecture, ecology, environmental science, etc.;
4) The paper should provide various approaches or technologies in terms of evaluate or improving biodiversity in general, or target at specific species;
5) Excluded a range of topics (Appendix 1) that have little significance to spatial study and planning.

The objective of this search is to extract water-related content contributing to the enhancement of biodiversity. Subsequently, a targeted examination is conducted during both abstract and full-text review phases to exclude non-water subjects. To provide specificity, the criterion for differentiating water-related or non-water topics is the presence of visible water.

Three sets of keywords that identify biodiversity themes, technologies, space type are chosen respectively (Fig. 1). In order to ensure that the search objects are concentrated in urban or peri-urban areas and to limit the total amount of literature, during the search process, when the search results are greater than 20,000, or for space types “Water”, “River”, “Habitat” that are not necessarily related to the urban environment, these three qualifiers: “urban”, “city”, “cities” will be added to the search.

The initial screening of the resulting papers was filtered by title and abstract. The analysis excluded documents categorized as review studies, book chapters, reports, and non-English papers. From the title review, 32,327 papers from WoS and 888,917 from Scopus were selected. After merging the data from WoS and Scopus and removing duplicates, 31,798 records remained. A comprehensive title review further reduced this number to 2396 records. Afterward, a subsequent abstract review narrowed the pool down to 611 candidates. To ensure the selection procedure aligned with the research objectives, a ‘pilot test’ (Van Teijlingen and Hundley, 2002) was conducted following the abstract review. This involved picking 10 articles from the literature pool that covered various topics and conducting a pre-testing phase for the main study. Ultimately, through a full-text review, the systematic search yielded 93 scientific publications. An overview of the paper selection methodology as per the PRISMA (Page et al., 2021) statement and review process is outlined in Fig. 1.

2.2. Data analysis and validation

The data analysis and validation process were conducted using a combination of tools and techniques to ensure robust and accurate results. Python, within the Anaconda toolbox, was used to identify and remove duplicate articles from the dataset and visualize the trend chart. Bibliometric to process several data analyses, including the co-occurrence of keywords and the presence of nations in the literature pool. Flourish studio app to create Sankey diagrams, which allowed for the visualization of data flows and the relationships between different categories. This visualization method was instrumental in understanding the distribution and connections within the dataset.

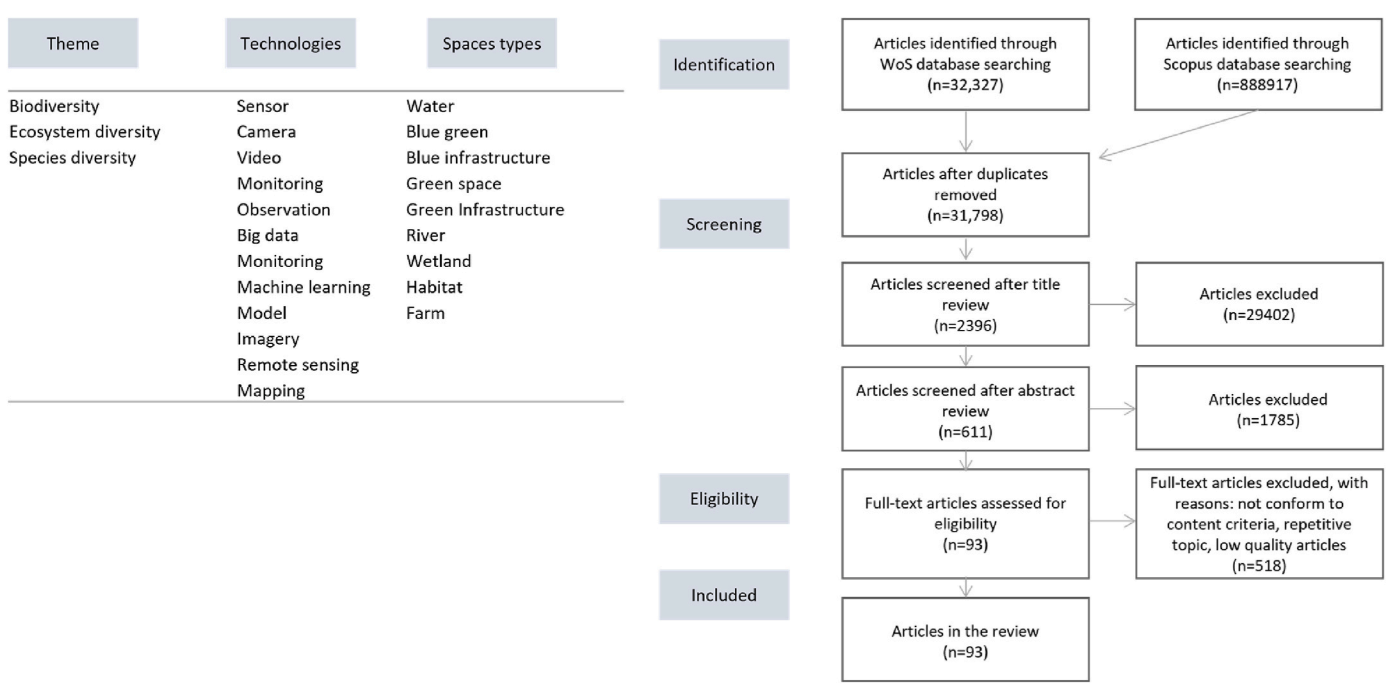

Fig. 1. The list of searching keywords and Prisma protocol figure.

3. Results

3.1. Overview

The survey retrieved a final set of articles as international standards from 8 continents covering 31 countries. The studies span eight continents and 31 countries, with the largest share from Asia (34%), a comparatively high proportion from Europe (24%), North America (15%), and Australia (10%). Among all countries, China leads with 19 articles published, accounting for 20% of the total. The USA follows with 11 articles (12%), then Australia with 10 articles (11%), Spain and India each with 5% (5 articles), Canada, Japan, and Brazil each with 4% (4 articles) (Appendix 2). When examining the corresponding authors' sampling locations across all nations, China, Australia, and the USA were the largest contributors, accounting for 19.4%, 11.8%, and 10.8% of the total, respectively. Following these, Canada, India, Italy, and the UK each contributed 5.4% (Appendix 3). Over the past decade, the global number of relevant research articles has risen, with the USA, China, and Australia standing out as the leading contributors. Appendix 4 provides detailed information on each country's contributions during this period.

These studies encompass a range of scales, from small ponds to worldwide analyses, with research units varying greatly. Beyond common administrative boundaries such as cities and metropolitan regions, many studies focus on cross-administrative or geographical regions like nature reserves, watersheds, estuaries, and river valley. We categorized the scales of analysis into five groups, ranging from large to small, based on the reviewed research and general definitions of scale: continental scale (Burrough and McDonnell, 1998) (more than 50,000,0 km^2), regional scale (5000 km^2 - 50,000,0 km^2), city scale (100 km^2–5000 km^2), local scale (Smith et al., 2009) (10 km^2–100 km^2) and community scale (less than 10 km^2). In the studies reviewed, the city scale was the most frequently used, accounting for 30% of the total. Regional and local scales each represented 24% and 23%, respectively, followed by the community scale at 15%, and the continental scale at 9%.

Keywordco-occurrence analysis revealed several prominent clusters. Biodiversity and ecosystem services emerged as the two most significant keywords. Biodiversity is strongly associated with terms such as connectivity, conservation planning, freshwater, citizen science, and machine learning. Meanwhile, ecosystem services were more closely linked to water quality, agriculture, species richness, and biodiversity conservation. Additionally, keywords like urbanization, urban ecology, and green infrastructure served as bridges between the biodiversity and ecosystem services clusters. These bridging terms were also closely connected to remote sensing, ecological engineering, wetland, the blue economy, and ecological corridors (Fig. 2).

The 93 articles were published across 52 different journals. To categorize the disciplines of these articles, the paper classifies the journals into three categories: ecological, urbanism, and hybrid. First, ecological discipline: encompasses fields such as ecology, biology, environmental science, and oceanography. Second, Urbanism discipline: includes areas like urban studies, regional and urban planning, environmental studies, and urban forestry and greening. Third, Hybrid discipline: covers topics such as environmental management, ecosystem services, landscape ecology, remote sensing, sustainability, geography, and agronomy. Based on this classification, about half of the journals specialize in ecological and environmental disciplines, with notable examples including "Biological Conservation" (7 articles) and "Science of the Total Environment" (6 articles). 29% of the articles appeared in hybrid journals, such as "Remote Sensing" (5 articles) and "Sustainability" (4 articles). 13% of the articles were published in journals related to urbanism, such as "Landscape and Urban Planning" (5 articles) and "Land" (3 articles).

3.2. Ecosystems and their habitats

The main habitats identified through research can be categorized into five groups: freshwater ecosystems, which account for more than half of the studies; marine ecosystems, comprising 22% of the research; agroecosystems, making up 9%; and estuarine ecosystems, representing 4%.

Agroecosystems and estuarine ecosystems are complex, often overlapping with freshwater and marine systems. Agricultural irrigation generally uses freshwater, though some regions rely on salt or brackish water for aquaculture. Estuarine ecosystems span various wet environments, including rivers, lakes, wetlands, and saltwater lagoons, and can contain freshwater, saltwater, and brackish water. To clarify distinctions, the research categorizes these ecosystems independently, and includes a "general water ecosystems" category (13%), for mixed systems where blue areas are visible but unclassified. Marine ecosystems are further divided into the intertidal, benthic, and near-shore (neritic) zones, while other aquatic ecosystems are categorized as lentic, lotic, or wetland types.

Certain ecosystems in BHUS papers defy easy classification as natural or artificial. For instance, mangrove research may examine natural or artificially planted areas, and coastal studies may focus on natural floodplains or man-made structures like seawalls. To address this, the paper classifies all research into three groups by defining the main water systems of the study subjects.

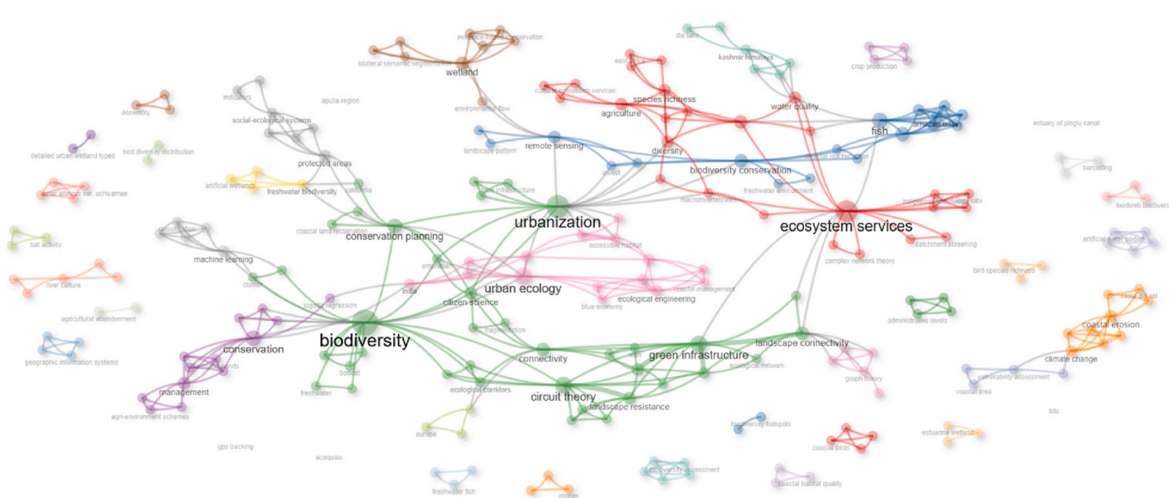

Fig. 2. The keyword co-occurrence clusters.

A natural ecosystem here doesn't imply a purely untouched environment. Instead, it refers to a community of living and non-living components that interact through biological, physical, and chemical processes. While human activities influence most natural systems to some extent in our increasingly urbanized world, the initial formation of natural ecosystems occurs naturally, without human intervention (GeeksforGeeks, 2024). The ecosystems such as rivers, streams, wetlands etc. Is self-sufficient, are included in the N (natural) group. Artificial ecosystems are obviously deliberately constructed for human purposes, often where no waterbody existed before, and thus undisputedly artificial (Clifford and Heffernan, 2018). The irrigation systems, dams, fishponds, reservoirs, wetlands conceived and built for water treatment, etc. are included in the A (artificial) group. H (hybrid) group contains hybrid systems that combine characteristics of both natural and artificial ecosystems. These systems typically describe complex landscapes or large geographical areas within an urbanization context, such as urban blue - green infrastructure, urban ecological networks, urbanized coastal zone, mountainous valleys, island and water basins. Hybrid ecosystems integrate natural elements like rivers, lakes, floodplains, seas etc. with artificial structures such as canals, dams, ditches, paddy fields etc.

The Table 2 shows that most current research on BHUS focuses on hybrid environments that combine natural and artificial systems. Notable exceptions are the intertidal and benthic zones of the sea, where environments are either natural (sea) or artificial (seawalls, dikes, etc.). In all other cases, hybrid environments represent the largest share of the research.

Figs. 3 and 4 illustrate the diverse ecosystems and habitat types (the detailed habitat names in Appendix 5). In the agroecosystem catalog, the research highlights seasonally flooded plains, rice fields with standing water, dams, and small water bodies like ponds and drinking tanks as key components of the lentic ecosystem. Watercourses and irrigation networks within agricultural basins form the lotic systems. In the estuarine ecosystem, the studies focus on complex estuarine wetlands, including intertidal wetlands, marshes, sand shores, tributaries/tidal creeks, lagoons, and mangroves. These water bodies create a landscape where lentic, lotic, and wetland systems overlap. The marine ecosystem, particularly near-shore (neritic) zones, is a research hotspot. Key features studied include seashores (beaches, dunes, coastal lagoons), coastal wetlands (tidal marshes, tidal rivers, mangroves), and intertidal and benthic zones (overall bay systems, dune-beach interfaces, seagrass beds, seawalls). While there is some overlap with estuarine ecosystems, coastal research sometimes highlights man-made landscapes such as urban-industrial seascapes, touristic coasts, reclaimed lands, and artificial islands. Freshwater ecosystems, including lentic systems like ponds, lakes, and reservoirs, and lotic systems such as rivers, streams, channels, drainage ditches, etc., are among the most extensively studied ecological systems. Research also covers various wetlands, such as riverine and constructed wetlands. The research cataloged the general ecosystem study of the water area in general, sometimes including concepts within the urban planning domain like blue infrastructure and blue-green infrastructure.

3.3. Species and their habitats

The research identified seven primary categories of species: vegetation, birds, mammals, insects, reptiles, amphibians, invertebrates, and fish. In addition to species-specific studies, some research has addressed biodiversity and ecosystem dynamics more broadly, without targeting any types of species. These broader studies are compiled into a separate catalog dedicated to general ecosystem analyses. Research focusing on rare or endangered species is categorized distinctly, underscoring the conservation emphasis of these investigations.

Across all species, the majority of research focuses on their habitats within freshwater ecosystems. Marine ecosystems also receive significant attention, particularly concerning fish, vegetation, birds, and

Table 2
The habitat classification.

Main ecosystem	Ecosystem habitat type	A/N/H	Publication
General water ecosystem	Complex system	H	(Wang et al., 2022; Shi et al., 2021; Aznarez et al., 2022; Donati et al., 2022; Magle et al., 2019; Lopes et al., 2023; Sordello et al., 2022; Müller et al., 2015) (Y. Zhang et al., 2023; Fitoka et al., 2020)
	Wetlands		(Kim et al., 2023; Zheng et al., 2024)
Agroecosystem	Lentic ecosystem	A	(Malerba et al., 2021, 2023; Zamora-Marín et al., 2024; Świtek et al., 2019)
	Lotic ecosystem		(Sánchez Martín et al., 2018; Shipley et al., 2020; Świtek et al., 2019)
	Wetlands		Kidera et al. (2018)
		H	Hatamkhani and Moridi (2023)
Estuarine ecosystem	Wetlands	H	(Pham et al., 2022; Tian et al., 2023)
		N	(Dou et al., 2020; Brown et al., 2018)
	Lotic ecosystem	H	(Pham et al., 2022; Tian et al., 2023)
		N	Dou et al. (2020)
	Lentic ecosystem		Dou et al. (2020)
Marine ecosystem	Near-shore (neritic) zones	H	(Molina et al., 2023; Yu et al., 2018; De Santis et al., 2023; Li et al., 2022; Casazza et al., 2021; Roy et al., 2023; Perschke et al., 2023; Graells et al., 2022; Graells et al., 2022; Wikramanayake et al., 2020; Schulz et al., 2020; Damastuti et al., 2023; Bradley et al., 2023; Liao et al., 2023)
		N	(Myers et al., 2019; Parisi et al., 2022; Bento et al., 2023)
		A	Chee et al. (2017)
	The intertidal zone	N	(Guilherme et al., 2018; Bento et al., 2023; Damastuti et al., 2023; Bradley et al., 2023; Liao et al., 2023)
		A	Strain et al. (2020)
	The benthic zone	N	Liao et al. (2023)
Freshwater ecosystem	Lentic ecosystem	H	(Yang et al., 2019; Penfound and Vaz, 2024; Hou et al., 2018; Rawal et al., 2021; Hyseni et al., 2021; Pinel-Alloul et al., 2021; Hamer, 2022; Sheergojri et al., 2023; Liang et al., 2022; O'Brien et al., 2021; Lee et al., 2021; Howard et al., 2018; Beaujean et al., 2021; Higashikawa et al., 2023; Chen et al., 2023; Theis et al., 2022; Yousry et al., 2022; Xu et al., 2022; Bylak et al., 2024)
		A	(Romano et al., 2023; Fiorella et al., 2019; Bennett and Agpalo, 2022; Zamora-Marín et al., 2022; Greenway, 2017)
		N	(Keppeler et al., 2018; Xi et al., 2023)
	Lotic ecosystem	H	(Xiu et al., 2017; Zingraff-Hamed et al., 2018; Andrade et al., 2018; Salviano et al., 2021; Liu et al., 2023) (C. Zhang et al., 2020; Howard et al., 2018; Beaujean et al., 2021; Higashikawa et al., 2023; Chen et al., 2023; Theis et al., 2022; Yousry et al., 2022; Xu et al., 2022; Bylak et al., 2024)
		N	(Datry et al., 2016; Bohus et al., 2023; Keys et al., 2016; Matsuzawa et al., 2023; Hack et al., 2020; Xi et al., 2023)

(*continued on next page*)

Table 2 (*continued*)

Main ecosystem	Ecosystem habitat type	A/N/H	Publication
		A	(Bhagyanathan and Dhayanithy, 2023; Greenway, 2017)
	Wetlands	H	(Law et al., 2017; Hamer, 2018; Kasada et al., 2022; Javaid et al., 2023; Lee et al., 2021; Bhagyanathan and Dhayanithy, 2023; Higashikawa et al., 2023; Chen et al., 2023; Theis et al., 2022; Yousry et al., 2022; Xu et al., 2022; Bylak et al., 2024)
		A	(Canning et al., 2023; Odgaard et al., 2017; Kačergytė et al., 2023; Semeraro et al., 2015; Greenway, 2017)
		N	(Jing et al., 2023; Tiné et al., 2019; Han et al., 2021; Xi et al., 2023)

invertebrate. Additionally, a substantial number of studies target agro-ecosystems covering a wide range of species, with the exception of fish, invertebrates, and rare or endangered species. Fig. 5 illustrates that, fish and vegetation are the most frequently studied, followed by birds, ecosystem in general, to a lesser extent, invertebrates, mammals, amphibians, insects and reptiles, and rare or endangered species. Many studies offer diverse classification methods of the species, such as distinctions based on animal survival habits, biology, and whether the species are wild or commercial, or even consider different life stages. For instance, within the bird group, there are classifications like wetland birds, waterbirds, shorebirds, marine birds, terrestrial birds, migratory birds and bird chicks. Similarly, within the fish group, classifications include migratory fish—significantly affected by water infrastructure development — as well as indigenous and commercial fish, which are heavily influenced by local economic activities and industrialization. Plant groups primarily reflect their habitat relationships: seagrasses, phytoplankton, and algae thrive in seawater and freshwater; mangroves in wetlands; riparian meadows beside river corridors; and some are more general, such as wild plants and vascular plants. (the literature review in context to species detailed in Appendix 7).

Fig. 6 also highlights the varying focus of research across three groups: A, N, and H. The H group receives the most attention (64%), followed by the A group (21%), with the N group receiving the least focus (15%). Vegetation, invertebrate and fish are commonly researched across all three groups. Studies on birds and amphibians are predominantly found within the H group. In the A group, research on agro-ecosystems constitutes a significant proportion, with particular attention given to species that receive less focus in the other two groups, such as mammals, insects, and reptiles. Notably, research on mammals, birds, and amphibians is absent in the N group.

3.4. *The techniques and research scales*

The main techniques and their required datatypes (detailed in Appendix 8) applied among the articles summarized as follows:

Remote sensing (RS), refers to the acquisition and analysis of information typically using satellite or aerial sensors to capture data across various electromagnetic spectra for applications in environmental monitoring, GIS.

Machine learning (ML) represents a prominent contemporary technique, extensively applied across multiple scales for analyzing complex datasets and deriving insights from RS databases. Both spatial and spatial-temporal data are frequently used in RS-dominated techniques.

Observational commonly used in ecology research that contains monitoring, field surveys, species sampling, etc. These methods typically require the collection of textual, temporal, and numerical data.

Participation-based method, leverage public data collected through interviews, questionnaires, and citizen science metadata, emphasizing public involvement in collecting and analyzing diverse data types (textual, numerical, spatial, temporal, etc.).

Point cloud (PC) technologies, are employed for three-dimensional environmental capture primarily require spatial data and numerical data.

Optimization algorithms (OA) are mathematical procedures designed to find the best solution or maximum efficiency for a problem by iteratively improving candidate solutions based on a defined set of criteria. It mainly requires numerical data and also works with spatial, temporal data, etc. depending on the specific problem being addressed.

Cellular automata (CA) are computational models used for simulating complex systems that have been utilized for scenario modeling in planning.

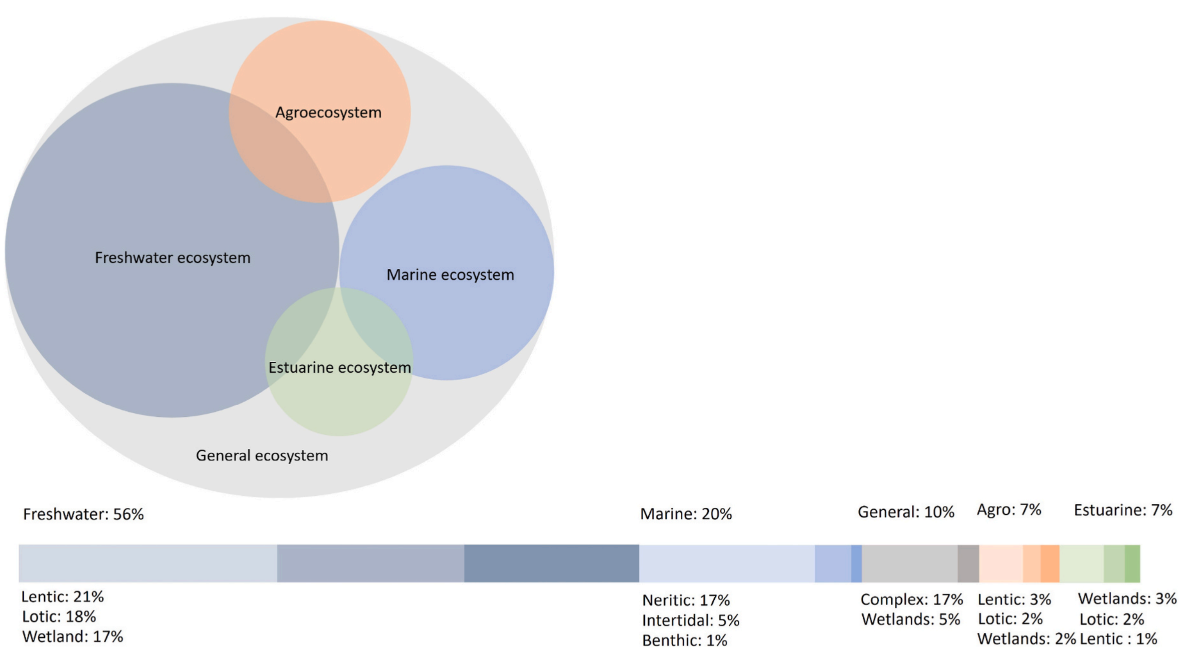

Fig. 3. The ecosystem and habitat types classification.

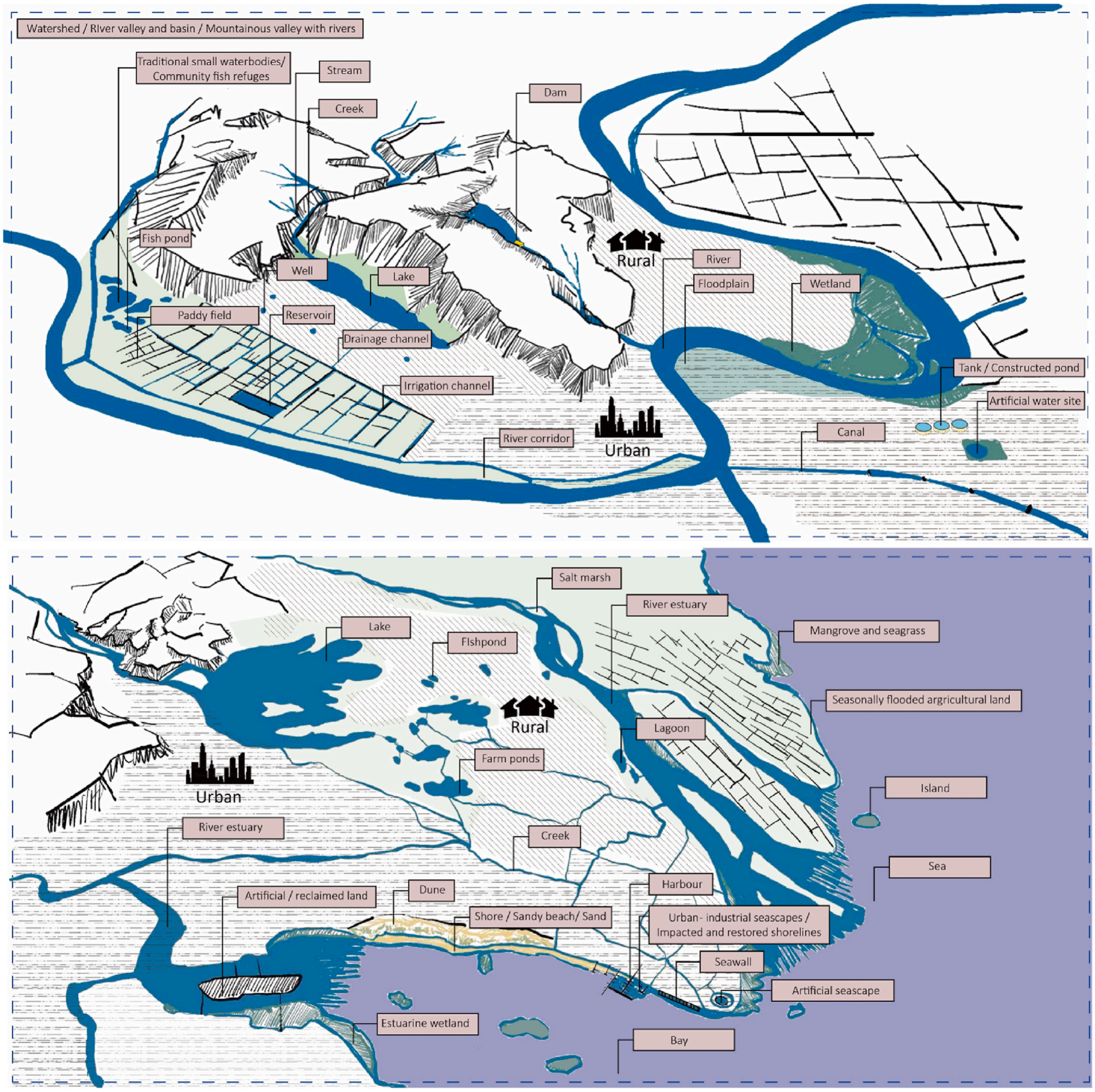

Fig. 4. The diverse habitats of the BHUS - **a.** Freshwater and Agroecosystem**, b.** Estuarine and Marine ecosystem (the specific habitat names derived/selected from the 93 articles).

Technologies such as cameras, sensors, sonar, and video tracking are used to capture and process specific types of data where people could use it to monitor, detect, and track specific species. Both techniques work with spatial, numerical, temporal and spatial-temporal data.

Fig. 7, along with the analysis table in, highlights several key findings. RS is the most widely utilized technique in spatial studies, dominating applications across various scales, except at the community scale, where it shares an equal proportion with observational techniques. Observational methods are predominantly applied in city scale or smaller scale research. Machine learning is employed across all scales, with its application at the continental scale being comparable to that of RS. Optimization algorithms, a newer technique, are used at the continental and regional levels.

Across the three disciplinary groups (Urbanism, Ecology, and Hybrid), observational methods, both alone and in combination with remote sensing (RS), are predominantly applied in ecological and hybrid research. Additionally, less common techniques, such as optimization algorithms, video analysis, sonar imaging, and sensor tracking, are employed in the ecology field. In urbanism, RS is the dominant research method, accounting for over half of the studies, with machine learning also playing a significant role; cellular automata techniques are uniquely prevalent in this field. Notably, one study combined observational methods to investigate freshwater ecosystems. In the hybrid group, point cloud technology is emerging as a novel tool for visualizing estuarine environments. Participation, reflecting the growing importance of community involvement and citizen science, is evident across all three groups, especially in ecology and hybrid groups.

4. Discussion

4.1. General observation

Despite the increasing focus on ecological issues, blue habitats remain underexplored in urban planning. Among the articles, are based on the truth that: Urbanization has created novel ecosystems, unprecedented in the natural world, through human intervention (Teixeira and Fernandes, 2020). For decades, as people began to notice the dramatic environmental degradation and its impact on human society, concepts such as sustainable development, green spaces, green infrastructure, ES emerged. However, research on urban & rural water systems has

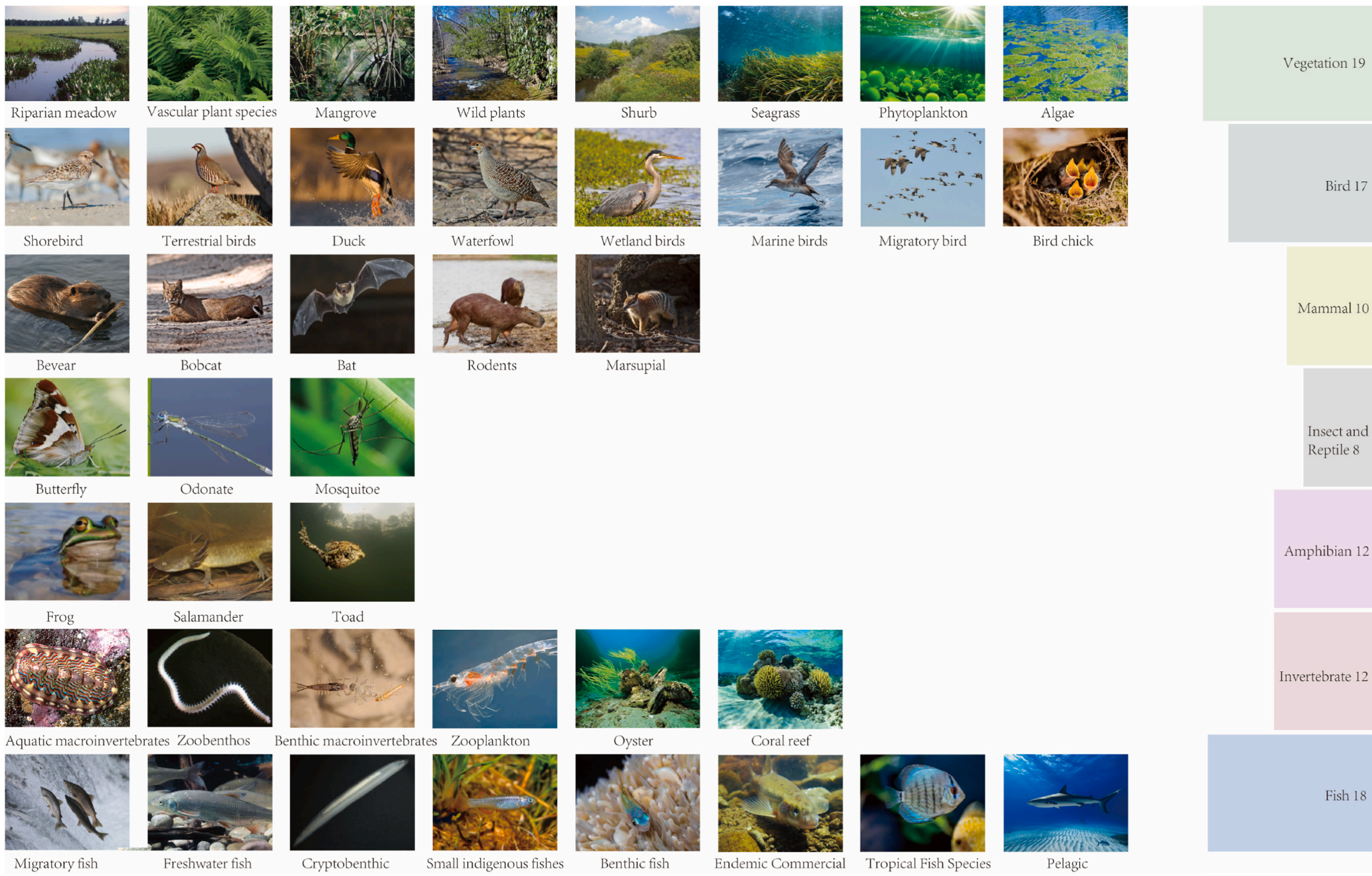

Fig. 5. The target species in the BHUS and the classification (The figures denote the number of articles in which the species were examined, figure reference detailed in Appendix 6).

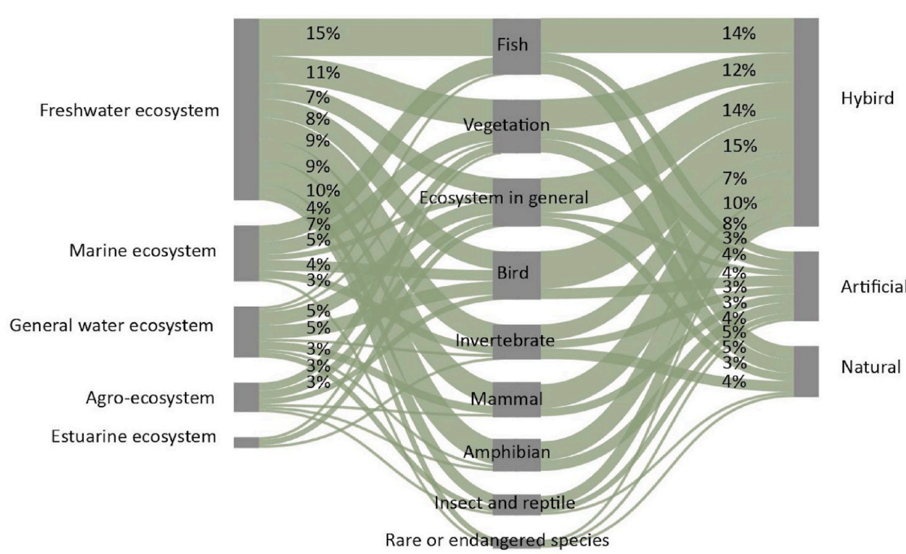

Fig. 6. Sankey diagram shows the species and habitat relation of the articles.

primarily focused on drainage, water supply, and flood management, with comparatively little attention given to the unique ecosystems within water bodies, their ecological interactions, and their value in the urbanized landscape.

Through a scoping review focused on urban and suburban water spaces and their biodiversity, the results revealed various BHUS types and the diverse species that depend on them. The review highlighted a phenomenon where, unlike land-based ecosystems, water systems are more challenging to accurately identify and study. Water systems can range from vast, interconnected networks that cross administrative boundaries and form diverse watersheds and estuaries, to small, isolated features such as ponds, lagoons, and reservoirs. These systems may also be highly integrated with land ecosystems, such as wetlands and seashores, and can change dramatically with the seasons, as seen in tidal

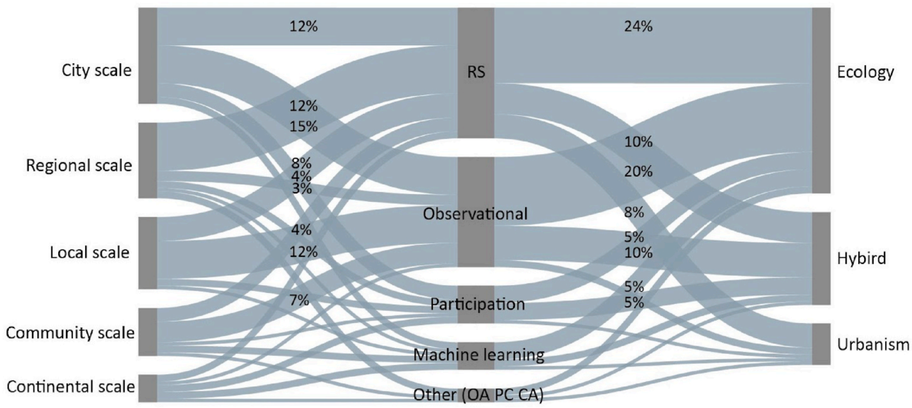

Fig. 7. Sankey diagrams for analysis main techniques, scales, and disciplines.

rivers and floodplains. This creates a dynamic and ever-changing landscape that is rich in diversity but presents significant research challenges.

Capturing the complexity of these systems is difficult from both satellite imagery, which is difficult to accurately capture their mixed and dynamic nature, and eye-level studies, which require specialized techniques to explore both surface and underwater environments. Consequently, the review identified the use of state-of-the-art techniques to study water systems, including the widespread application of machine learning and participatory methods (such as citizen science databases) to enhance accuracy and scalability. In ecological research, traditional methods like fieldwork, interviews, and camera tracking are increasingly being combined with newer techniques such as sensor tracking, video, and sonar to better identify and observe target spaces and species.

Therefore, it is important to discuss the main topics and methods through broad searching across disciplines and try to understand their application and potentials.

4.2. The gaps and limitations

Research on urban water biodiversity is limited, with more interdisciplinary studies needed. Within the field of urbanism, relevant studies accounts for 13%, 29% of researches are from a hybrid discipline perspective, and the majority (58%) is ecological. Bridging the divide between ecology and urbanism research is crucial for developing a more comprehensive understanding of sustainable development, especially in integrating water systems within spatial planning and design.

Biodiversity is a complex issue, with growing recognition of the need to incorporate human influence as a critical dimension. However, much of the existing research focused on spatial factors or species-specific observations, often overlooking the complexity of the BHUS as interconnected, dynamic systems. Additionally, the circularity of water systems—encompassing interactions between water flow, system functioning, human activities, and ecological factors — remains underrepresented in discussions of natural processes and biodiversity (Bobbink et al., 2022; Tsatsou et al., 2023).

Human activities can profoundly and often irreversibly disrupt ecosystem stability by impacting key processes such as food chains, water flow, and other essential networks. Despite growing awareness and the valuable insights provided by frameworks like ES and NBS, a gap remains in the literature on comprehensively evaluating human influence on these interconnected systems. Another critical area requiring further study is how ecological and food chains function in urban and rural water environments shaped by human dominance. There is a shortage of in-depth research that examines these dynamic relationships holistically or introduces novel perspectives on their complexities.

At last, a limitation of the review is that the groundwater and the invisible water systems does not include. Besides, this review was limited to English-language studies, which may exclude important regional insights.

4.3. The potential of the main research topics and future trend

There are complex interactions between urbanization and biodiversity loss, particularly regarding water management. Knowing the main research directions and themes is important for exploring future trends and opportunities.

A group of scholars focuses on the study of habitat and ecosystem identification, with particular attention to their distribution and classification. This research encompasses the monitoring, mapping, and classification of habitats, as well as the detection of species (Casazza et al., 2021; Hamer, 2018; Law et al., 2017). Recent trends in this field have increasingly incorporated advanced techniques, such as machine learning and high-resolution satellite imagery, to enhance accuracy and expand the spatial scope of analysis. Some studies have employed cutting-edge methods, such as point cloud technology, to model the 3D structure of habitats. It provides a good chance for future, to establish a spatial-mate database system with comprehensive data sources for BHUS resources management and monitoring.

In addition, certain research initiatives are devoted to the spatial-temporal evolution of the "blue spaces," utilizing long-term data and historical records. These studies added the time dimension into the interactions and transformations within these spaces, offering a framework for understanding ecological processes and urban expansion, which can inform broader transformation studies (Bhagyanathan and Dhayanithy, 2023).

Not only considering the past, the future is another important topic. Research in future trend prediction and modeling has focused on developing predictive models, ecosystem vulnerability models (Hack et al., 2020), and scenario-based approaches to inform future planning and address potential threats. For example, climate change and sea-level rise are extensively discussed issues that have already had significant impacts and will continue to pose threats such as increased flooding, permanent inundation, and the loss of wetlands (Tiné et al., 2019). Consequently, future simulations and scenario testing have big potential for predicting outcomes and enabling adaptive planning under various conditions.

Since urban expansion has profoundly altered and destroyed numerous species, habitats, and ecosystems (Ossola and Niemelä, 2018). Many studies have focused on biodiversity assessment and conservation, with particular attention to the relationships between urban and rural habitats and species. These studies address a wide range of biodiversity concerns, often centering on the identification of habitats and the evaluation of urbanization's impact on habitat quality. Several papers approach this topic through the application of various assessment frameworks, such as CORINE (Coordination of Information on the

Environment), habitat classification system (Semeraro et al., 2015), InVEST (Integrated Valuation of Environmental Services and Trade-offs) habitat quality model (Hack et al., 2020), Habitat Suitability Modeling (C. Li et al., 2022), Species richness (Malerba et al., 2021), Landscape connectivity and heterogeneity (Higashikawa et al., 2023; Salviano et al., 2021), etc. There are also some researchers interested in specific habitat types, such as created wetlands or traditional small water bodies, or on particular species, like beavers (Bylak et al., 2024), to examine their influence on broader ecosystem benefits.

ES studies represent an emerging and increasingly significant area of research. ES refers to the benefits that humans derive from ecosystems, such as food, drinking water, and nutrient cycling (Martínez-Harms and Balvanera, 2012). Research on ES hotspots highlight the critical need to synthesize information on these services to balance human well-being with ecological preservation (Perrings et al., 2011). These hotspots typically encompass diverse ecosystems, such as wetlands and green and blue corridors, which support a wide range of ES and higher levels of biodiversity (Schwarz et al., 2017). The mapping of ES hotspots has become a widely used method to identify areas where ES are most concentrated or have high potential, offering crucial guidance for conservation and sustainable development initiatives (Hou et al., 2018).

In addition, many studies investigate the impacts of specific human activities on biodiversity, particularly those stemming from construction and restoration efforts, including tourism, agriculture, and infrastructure development. These studies examine the complex interactions between human constructions and natural systems. For instance, the impacts of dam construction on fish communities and habitat alterations have been a frequent subject of inquiry (Zhang et al., 2020). Similarly, coastal vulnerability assessments and river health are of growing concern, particularly due to their sensitivity to tourism development (Keys et al., 2016) and production activities such as fishing, farming, and industry.

Moreover, understanding the natural world within urban and rural environments poses significant challenges. There is a group of scholars who provided a new perspective: wilderness. They use wilderness mapping to explore and identify wilder regions in the urban context (Aznarez et al., 2022; Magle et al., 2019; Müller et al., 2015). This approach offers a fresh lens through which to examine ecological patterns in developed landscapes.

A few recent studies reveal emerging trends that offer more complex perspectives on the relationship between urban rural development and biodiversity. For instance, some research now integrates economic activities as key variables in evaluating habitat quality and ecological health, exploring the intricate interplay between ecological well-being and economic viability (Canning et al., 2023). Other studies investigate the willingness of stakeholders, such as fishermen, to support ecological policies, highlighting the socio-economic dimensions of ecosystem management (Roy et al., 2023).

Furthermore, there is growing interest in traditional practices and knowledge, particularly in water management (Bobbink and Loen, 2020; Sun et al., 2023). Increasingly, these practices are recognized for their alignment with the principles of natural water systems, often resulting in reduced biodiversity loss and enhanced water conservation in agroecosystems (Sánchez Martín et al., 2018; Zamora-Marín et al., 2024). These emerging research directions demonstrate that human activities, traditionally seen as socio-economic issues, also present critical ecological concerns. In the context of global urbanization, a significant future research trajectory involves deepening the exploration of the relationships between cultural and economic activities and ecosystem dynamics.

Four papers in the literature pool were published most recently in 2024. Three of these focus on species-specific studies: Beaver impacts on stream ecology, employing ML and RS; Small Waterbodies Supporting Terrestrial Birds, integrating observational methods with RS and programming tools; and Bobcat habitat investigation under urbanization, utilizing an ecological model enhanced by ML and RS (Bylak et al., 2024; Zamora-Marín et al., 2024; Zheng et al., 2024). The fourth paper emphasizes predictive modeling techniques based on ML to highlight the critical role of green belt conservation (Penfound and Vaz, 2024). Together, these studies demonstrate the growing integration of advanced computational tools and multidisciplinary approaches.

While the scope of research topics, methodologies, and applications within the studies is broad, there remains significant potential for further theoretical development and technical innovation in each area of inquiry. Future studies should explore how spatial planning and design can better integrate blue habitats for biodiversity conservation.

5. Conclusions

This article provides an extensive review of BHUS biodiversity research, examining 93 recent studies. The review identifies key types of BHUS and the species they support, highlights advanced techniques for biodiversity conservation.

The coexistence of urban, suburban, and natural ecosystems within BHUS supports diverse species, effective biodiversity conservation here requires a context-sensitive approach within a unified framework.

Within a well-defined framework, there exists a significant opportunity to integrate the diverse methodologies, advanced technologies, and rich perspectives outlined earlier in this article. Such integration can be strategically applied to research on biodiversity in the BHUS, enabling more detailed and specialized investigations in future research directions, emphasizing the critical role of interconnected water systems in providing essential ES globally and the strategies of the BHUS's conservation. Furthermore, this approach has the potential to transcend the traditional boundaries between urban studies and ecology, fostering the development of innovative research methodologies through interdisciplinary collaboration.

CRediT authorship contribution statement

Pingyao Sun: Writing – review & editing, Writing – original draft. **Mingze Chen:** Writing – review & editing, Conceptualization. **Jingyi Chen:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix 1. Excluded topics

1	Urban & rural context (including regional infrastructure and corridor)
2	Multiple & individual/targeted species
3	Discipline: Landscape & urban ecology; Planning & landscape design; Ecology, zoology, botany & environmental science; Agronomy; Infrastructure & construction engineering
4	Exclude specific genetics research
5	Exclude no-spatial related research
6	Exclude animal diet research

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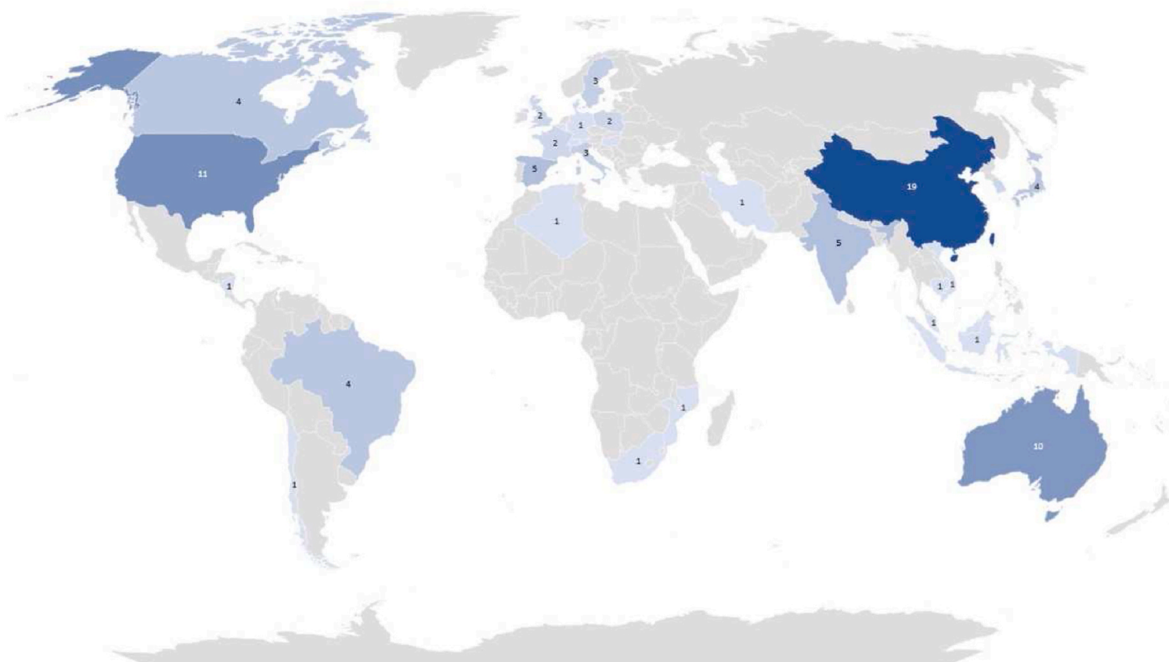
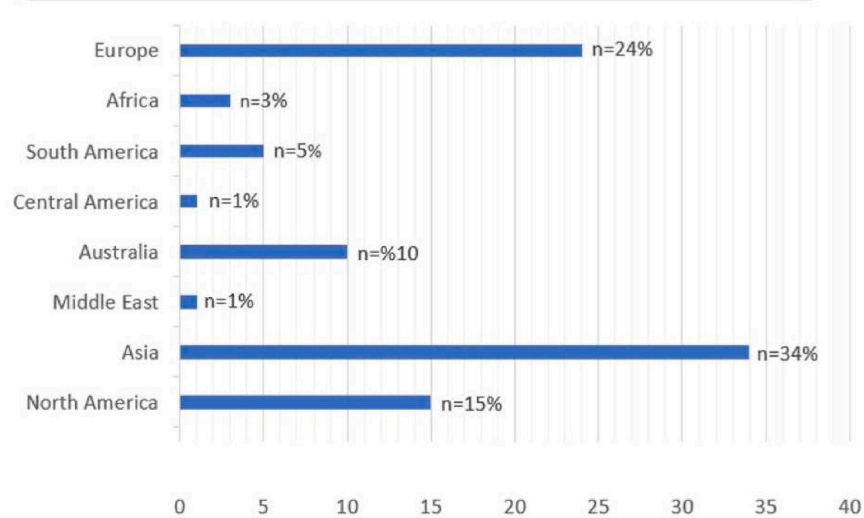
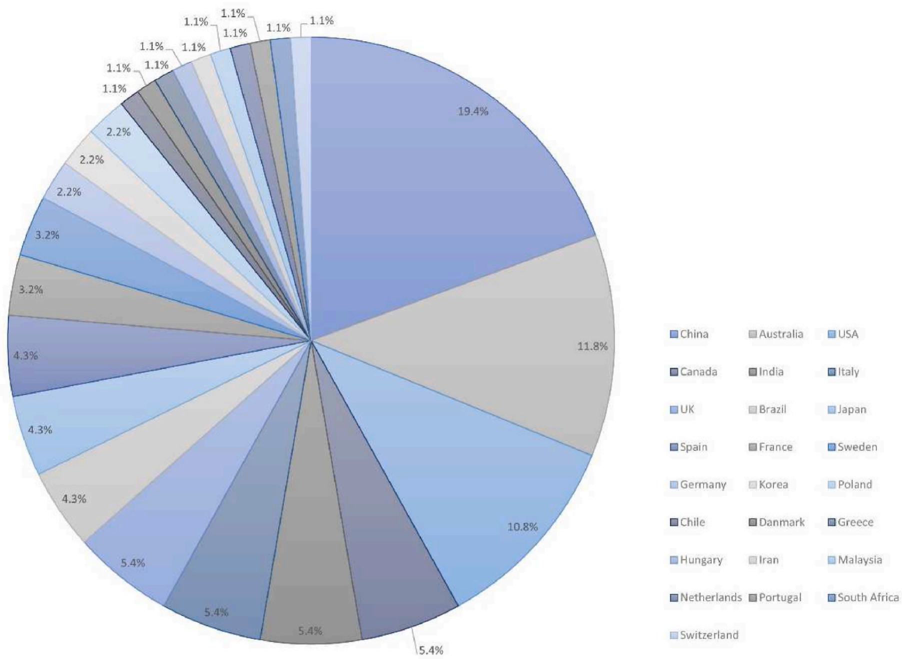
7	Exclude pet's impact for wildlife research
8	Exclude medical related research
9	Exclude animal tracking technology research
10	Exclude forest ecology research
11	Exclude Invasive species and microorganism research
12	Green & blue space and blue space
13	Technology: exclude below 2014 paper - advanced technology
14	Very special species exclude
15	Exclude urban environmental pollution/water quality pollution research
16	Exclude health risk assessment
17	Exclude noise Measurement
18	Exclude agrochemicals impact assessment
19	Exclude sewer System
20	Exclude metal/chemical pollution research
21	Exclude research focus on Wildfire
22	Exclude research focus on urban heat island effect

Appendix 2. Geographical distribution of the studies

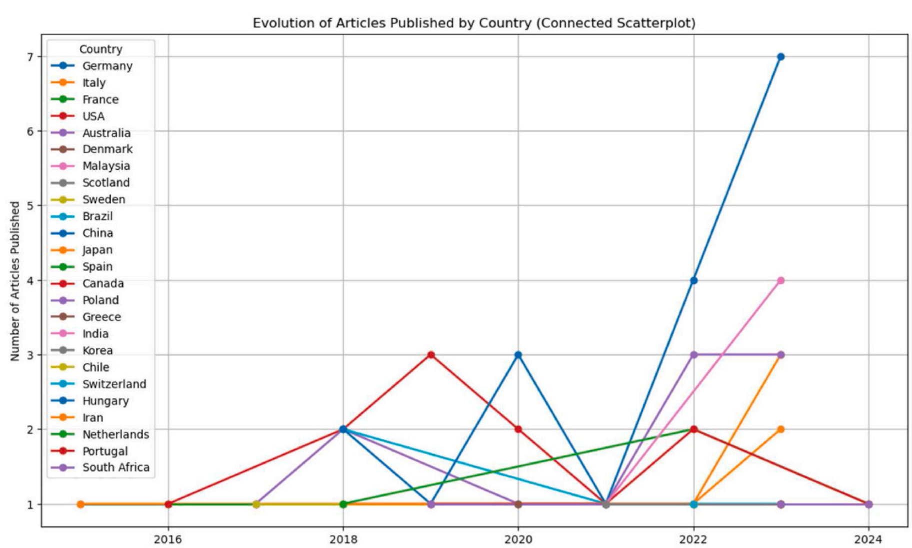




Appendix 3. Corresponding authors' sampling locations across all nations



Appendix 4. The occurrence of countries for the last decade



Appendix 5. The diverse habitat types studied in the papers

Publication	Habitat name in paper
Bhagyanathan and Dhayanithy (2023)	Urban wetlands, canal
Hack et al. (2020)	Urban rivers
Wikramanayake et al. (2020)	Tidal flats, Coastal mangroves, Marshes, Fishponds
O'Brien et al. (2021)	Glacial and constructed ponds
Hou et al. (2018)	Lake watershed

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Publication	Habitat name in paper
Semeraro et al. (2015)	Constructed Treatment Wetlands (CTWs)
Malerba et al. (2021)	Farm dam
Keys et al. (2016)	River corridors
Molina et al. (2023)	Touristic coastal, Dune
Shipley et al. (2020)	Lakes and rivers in agricultural watershed
Wang et al. (2022)	Urban surface water bodies
Shi et al. (2021)	Green Infrastructure: water
Howard et al. (2018)	Freshwater conservation areas
Datry et al. (2016)	Intermittent rivers
Yu et al. (2018)	Coastal wetlands
Lopes et al. (2023)	Urban greenway: water bodies
Odgaard et al. (2017)	Reconstructed wetlands
Myers et al. (2019)	Sandy beaches, Salt marshes
Aznarez et al. (2022)	Urban green and blue spaces (UGBS): blue space
Müller et al. (2015)	Wilderness
Fitoka et al. (2020)	Water-related ecosystem: Freshwater wetland ecosystems, Non-freshwater ecosystems, Wider water-related habitats
Casazza et al. (2021)	Managed wetland, Permanent water, Tidal marsh, Channel, Pond
Andrade et al. (2018)	Urban riparian corridors
Jing et al. (2023)	Floodplain wetlands
Brown et al. (2018)	Mangrove
Law et al. (2017)	Agriculturally-degraded wetlands
(Perschke et al., 2023)	Seashore: dunes, shores, estuaries
Hamer (2022)	Urban blue green network: pond
Beaujean et al. (2021)	Urban ecological networks
Dou et al. (2020)	Estuarine wetland
Świtek et al. (2019)	Farm: ponds, diches, watercourses
Pham et al. (2022)	Estuarine wetland: Intertidal forested wetlands, intertidal marshes, farm ponds, sand, shingle or pebble shores outside the river mouth, tributaries/tidal creeks, estuary waters; seasonally flooded agricultural land
Liu et al. (2023)	River basin: the main stream of river, major tributaries, minor tributaries
Sordello et al. (2022)	Urban water area: DI, BI, GI
De Santis et al. (2023)	Reclaimed coastal areas
Guilherme et al. (2018)	The dune-beach interface
Hatamkhani and Moridi (2023)	Agricultural Basin wetlands: dam, river, irrigation network, waterbasin
Yousry et al. (2022)	River valley and basin: river, inland wetlands, inland waters
Xiu et al. (2017)	Urban green networks: river (or blue) network
Li et al. (2022)	Coastal zone
Yang et al. (2019)	Lake watershed
Hamer (2018)	Peri-urban freshwater wetlands
Lee et al. (2021)	Modified and natural wetlands, Constructed stormwater ponds
Magle et al. (2019)	Urban: open water
Xu et al. (2022)	Mountainous valley with Rivers
Fiorella et al. (2019)	Community fish refuges
Romano et al. (2023)	Artificial water sites (AWS): Drinking-troughs, tanks, wells
Bylak et al. (2024)	River, Water reservoirs, Streams, Wetlands, Channel and drainage Ditches, Dam, Pond
Parisi et al. (2022)	Coastal lake lagoon
Graells et al. (2022)	Coastal Areas
Chen et al. (2023)	Blue-green infrastructure: River, Reservoir, Ditch, Paddy field
Graells et al. (2022)	Island coastal wetland
Rawal et al. (2021)	Capital ponds
Han et al. (2021)	Riverine wetlands
Hyseni et al. (2021)	Urban ponds
Bento et al. (2023)	Mangrove and seagrass of bay
(C. Zhang et al., 2020)	Downstream of dam
Bennett and Agpalo (2022)	Swimming pool
Kim et al. (2023)	Wetlands
Liao et al. (2023)	Bay
(Schulz et al., 2020)	Natural, impacted and restored shorelines
Kačergytė et al. (2023)	Created wetlands
Malerba et al., 2021)	Farm dam
Canning et al. (2023)	Constructed Wetlands
Zheng et al. (2024)	Reservoir: wetland, irrigation and channel network, stream, riparian zone
Roy et al. (2023)	Coastal-saline zone: network of tidal rivers, creeks and channels
Javaid et al. (2023)	Urban wetland and rural wetland
Salviano et al. (2021)	Riparian corridors
Keppeler et al. (2018)	Tropical lakes
Kasada et al. (2022)	Paddy fields (previous floodplain)
Damastuti et al. (2023)	Coastal lowland
Bohus et al. (2023)	Streams
Sánchez Martín et al. (2018)	Water channels used for irrigating
Sheergojri et al. (2023)	Urban lake
Theis et al. (2022)	Freshwater ecosystems
Pinel-Alloul et al. (2021)	Urban waterbodies: artificial ponds, lakes, natural marshes
Zamora-Marín et al. (2024)	Small waterbodies: artificial pools, cattle ponds, drinking troughs
Tiné et al. (2019)	Open wetlands
Kidera et al. (2018)	Rice field
(Y. Zhang et al., 2023)	Bay: water body, sea

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Publication	Habitat name in paper
Strain et al. (2020)	Seawalls
Chee et al. (2017)	Reclamation land and artificial island
Tian et al. (2023)	Canal estuary
(Zingraff-Hamed et al., 2018)	Urban river
Matsuzawa et al. (2023)	Small spring-fed river
Penfound and Vaz (2024)	Urban wetlands: lakes
Donati et al. (2022)	Blue-green infrastructure: water bodies
Xi et al. (2023)	River basin
Greenway (2017)	Stormwater wetlands: ponds, creeks, wetlands
Liang et al. (2022)	Reservoirs
Higashikawa et al. (2023)	Freshwater: rice paddy fields, marshy wetlands, rivers, ponds and lakes, agricultural channel, stream
Zamora-Marín et al. (2022)	Traditional small waterbodies (SWB)
Bradley et al. (2023)	Urban-industrial seascapes

Appendix 6. Fig. 5 figure reference link

https://sciencing.com/list-seedless-vascular-plants-5811189.html
https://oceanographicmagazine.com/news/mangrove-forests-flood-protection/
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https://www.sdherps.org/species/ambystoma_tigrinum
https://kentarg.org/amphibians/great-crested-newt/
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https://en.wikipedia.org/wiki/Caribbean_reef_shark.

Appendix 7. The literature review in context to species

Species types	Specific species studied in the papers	Publication
Ecosystem in general		Malerba et al. (2021)
		Shipley et al. (2020)
		Brown et al. (2018)
		Świtek et al. (2019)
		Xu et al. (2022)
		(Penfound and Vaz, 2024; Hou et al., 2018)
		Hack et al. (2020)
		Bhagyanathan and Dhayanithy (2023)
		Tiné et al. (2019)
		(Wang et al., 2022; Shi et al., 2021; Müller et al., 2015; Fitoka et al., 2020) (Y. Zhang et al., 2023)
		(Molina et al., 2023; Perschke et al., 2023)
Vegetation		Hatamkhani and Moridi (2023)
	Wild plants	Świtek et al. (2019)
	Vascular plant species	Sánchez Martín et al. (2018)
	Mangrove *Acanthus ilicifolius* (AI), Sonneratia apetala (SA), *Aegiceras corniculatum* (AC), *Kandelia candel* (KC), Cyperus malaccensis (CM)	Tian et al. (2023)
	Aster altaicus var. uchiyamae	(Han et al., 2021; Kasada et al., 2022; Jing et al., 2023)
	Riparian meadow, Shrub	Semeraro et al. (2015)
	Aquatic vegetation, Phytoplankton	(Sheergojri et al., 2023; Pinel-Alloul et al., 2021)
	Algae	Xi et al. (2023)
		Keys et al. (2016)
		O'Brien et al. (2021)
		Kim et al. (2023)
	Sporobolus virginicus, Sarcocornia quinqueflora, Suaeda australis/Red mangrove (Rhizophora mangle), black mangrove (Avicennia germinans), white mangrove (Laguncularia racemose), black needlerush (Juncus roemerianus), cordgrass (Spartina sp.), sawgrass (Cladium jamaicense), and Brazilian pepper (Schinus terebinthifolius)	(Li et al., 2022; Lanceman et al., 2022; Schulz et al., 2020)
	Mangrove, Seagrass	Chee et al. (2017)
	Mangrove	Damastuti et al. (2023)
Bird	Waterbird	Hatamkhani and Moridi (2023)
		Zamora-Marín et al. (2024)
		Chen et al. (2023)
	Non-wetland birds/Terrestrial birds	(Rawal et al., 2021; Liang et al., 2022)
	Waterbird	Zamora-Marín et al. (2022)
	Bird pare and bird chick (Ducks, grebes, gulls, geese, swans, terns and rallids)/Riparian meadow, Shrub	(Kačergytė et al., 2023; Semeraro et al., 2015)
	Waterbird	Andrade et al. (2018)
		(Lopes et al., 2023; Aznarez et al., 2022; Sordello et al., 2022)
	Wetland birds	Kim et al. (2023)
	Shorebird, Migratory bird/Waterfowl, Duck/Terrestrial and marine birds	(Wikramanayake et al., 2020; Yu et al., 2018; Casazza et al., 2021; Graells et al., 2022)
Mammal	Rodents	Świtek et al. (2019)
	Beaver	(Yousry et al., 2022; Bylak et al., 2024)
		O'Brien et al. (2021)
	Bat	Bennett and Agpalo (2022)
	Local small mammals: Rodents, Marsupials	Salviano et al. (2021)
	Riparian meadow, Shrub	Semeraro et al. (2015)
	Beaver	Law et al. (2017)
	Bat	(Aznarez et al., 2022; Sordello et al., 2022)
	Bobcat	Zheng et al. (2024)
Insect and Reptile		Świtek et al. (2019)
	Turtles, Snakes and Lizards	Howard et al. (2018)
	Butterflies, odonates	Kasada et al. (2022)
	Riparian meadow, Shrub	Semeraro et al. (2015)
	Mosquitoes	Greenway (2017)
	Odonata (dragonflies and damselflies)	Higashikawa et al. (2023)
	Butterflies	(Aznarez et al., 2022; Sordello et al., 2022)
Amphibian	Frogs (*Rana japonica*)	Kidera et al. (2018)
	Litoria aurea (green and golden bell frog)/Frogs	(Hamer, 2018; Kasada et al., 2022)
	Boreal chorus frog, Wood frog, Tiger salamander	Lee et al. (2021)
	Triturus carnifex, Lissotriton sp., Pelophylax lessonae, *Bombina variegata*	Romano et al. (2023)
	Frog	(O'Brien et al., 2021; Hamer, 2022)
	Bufo calamita/Frogs and Toads, Salamanders and Newts	(Beaujean et al., 2021; Howard et al., 2018)
	Common toad, Moor frog, Common frog, Smooth newt, Great created newt/Riparian meadow, Shrub	(Kačergytė et al., 2023; Semeraro et al., 2015)
		Donati et al. (2022)
Invertebrate	Macroinvertebrate	Dou et al. (2020)
	Aquatic invertebrate	Bylak et al. (2024)
	Zoobenthos	Xi et al. (2023)
	Macroinvertebrates	Greenway (2017)
		O'Brien et al. (2021)
	The orders Odonata, Trichoptera (larvae), Coleoptera, Hemiptera (larvae and adults), Adult-stage freshwater snails (class Gastropoda)/Zooplankton, Macroinvertebrates	(Hyseni et al., 2021; Pinel-Alloul et al., 2021)
	Aquatic macroinvertebrates	Bohus et al. (2023)

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Species types	Specific species studied in the papers	Publication
	Benthic macroinvertebrates	Kim et al. (2023)
	Marine macroinvertebrates (Annelida, Arthropoda, Cnidaria, Echinodermata and Mollusca)	Bento et al. (2023)
	Oyster, Sessile taxa, Mobile invertebrates	Strain et al. (2020)
	Coral reef	Chee et al. (2017)
Fish	Migratory fish	(Bylak et al., 2024; Yousry et al., 2022)
		Xi et al. (2023)
	Freshwater fish	Higashikawa et al. (2023)
	Anadromous Salmonids, Resident Freshwater Fish	Howard et al. (2018)
		Fiorella et al. (2019)
	Migratory Species and lentic species/Chondostroma nasus L.	(C. Zhang et al., 2020; Zingraff-Hamed et al., 2018)
		Matsuzawa et al. (2023)
		Keppeler et al. (2018)
		Javaid et al. (2023)
		Semeraro et al. (2015)
	Small indigenous fishes	Roy et al. (2023)
	Branchiostoma belcheri	Liao et al. (2023)
		Bradley et al. (2023)
	Cryptobenthic, Pelagic	Strain et al. (2020)
	Tropical Fish Species, Endemic Commercial Species	Parisi et al. (2022)
		(Schulz et al., 2020)
Rare or endangered species	Imperiled aquatic species	Theis et al. (2022)
		Odgaard et al. (2017)
		Myers et al. (2019)

Appendix 8. The main techniques and their required datatypes

Main Technique	Data types	Publication
RS/Camera track	Spatial data, Numerical data, Textual data, Spatial – temporal data	(Müller et al., 2015; Xu et al., 2022; Aznarez et al., 2022; Magle et al., 2019)
RS/Observational	Spatial data, Textual data, Spatial – temporal data, Temporal data	(Hack et al., 2020; Chen et al., 2023)
RS/Participation	Textual data, Numerical data, Spatial data, Temporal data, Sound & video data	(Graells et al., 2022; Malerba et al., 2021)
RS, Observational	Spatial – temporal data, Spatial data, Textual data, Temporal data, Sound & video data	(Rawal et al., 2021; Kačergytė et al., 2023; Bylak et al., 2024; Fiorella et al., 2019)
RS, Point cloud	Spatial data, Numerical data	Tian et al. (2023)
RS/Observational	Spatial data, Numerical data, Textual data, Spatial – temporal data, Temporal data	(Kasada et al., 2022; Zamora-Marín et al., 2022; Wikramanayake et al., 2020; Yu et al., 2018; Romano et al., 2023; Higashikawa et al., 2023; Schulz et al., 2020)
Machine learning	Textual data, Spatial data, Spatial – temporal data	(Zheng et al., 2024; Matsuzawa et al., 2023)
RS/Observational	Sound & video data, Spatial data, Spatial - temporal data, Numerical data, Textual data	(Semeraro et al., 2015; Donati et al., 2022; Lopes et al., 2023; Parisi et al., 2022)
Participation	Textual data, Numerical data, Spatial data, Spatial – temporal data	Lee et al. (2021)
RS, Zonation (Optimization Algorithm)	Textual data, spatial data	Howard et al. (2018)
RS	Spatial data, Numerical data	Hyseni et al. (2021)
RS/Observationl	Spatial data, Numerical data, Spatial-temporal data, Textual data	(O'Brien et al., 2021; Shi et al., 2021; Odgaard et al., 2017; Perschke et al., 2023; Beaujean et al., 2021; Lanceman et al., 2022; Greenway, 2017)
Participation	Textual data, Spatial data	Molina et al. (2023)
RS	Spatial-temporal data, Spatial data	(Hack et al., 2020; Myers et al., 2019; Liao et al., 2023; Salviano et al., 2021; Theis et al., 2022; Tiné et al., 2019; Sordello et al., 2022)
RS, Participation	Textual data, Numerical data, Spatial-temporal data, Spatial data	Sheergojri et al. (2023)
RS, ACO (Optimization Algorithm)	Spatial data, Textual data, Temporal data, Numerical data	(Y. Zhang et al., 2023)
Machine learning/Cellular automata	Spatial-temporal data, Spatial data, Textual data	(Penfound and Vaz, 2024; Wang et al., 2022)
Sensor tracking	Raster image, Spatial data	Casazza et al. (2021)
RS/Observational	Spatial-temporal data, Textual data, Numerical data	(Andrade et al., 2018; Law et al., 2017; Hamer, 2022)
RS	Spatial data, Spatial-temporal data, Textual data, Numerical data	(Dou et al., 2020; Bento et al., 2023)
Camera track	Spatial-temporal data, Spatial data, Numerical data	Malerba et al. (2021)
RS	Raster image, Spatial data, Spatial-temporal data, Numerical data	(Fitoka et al., 2020; Datry et al., 2016)
Machine learning	Spatial data, Spatial-temporal data, Temporal data, Numerical data, Textual data	(Jing et al., 2023; Świtek et al., 2019; Guilherme et al., 2018; Kim et al., 2023)
RS, Video, Sonar imaging	Spatial data, Sound & video data, Temporal data	Bradley et al. (2023)

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Main Technique	Data types	Publication
RS, Participation	Textual data, Numerical data, Spatial data, Spatial – temporal data	(Canning et al., 2023; Roy et al., 2023; Damastuti et al., 2023)
RS, Observational	Numerical data, Textual data, Spatial data, Temporal data, Spatial-temporal data	(Zingraff-Hamed et al., 2018; Bohus et al., 2023; Xi et al., 2023; Liang et al., 2022; Zamora-Marín et al., 2024; Han et al., 2021; Keppeler et al., 2018; Keys et al., 2016) (C. Zhang et al., 2020; Xiu et al., 2017; Kidera et al., 2018; Hamer, 2018; Hatamkhani and Moridi, 2023; Li et al., 2022)
Participation	Textual data, Numerical data, Spatial data	(Świtek et al., 2019; Bennett and Agpalo, 2022; Yousry et al., 2022)
Observational	Textual data, Numerical data, Temporal data	(Sánchez Martín et al., 2018; Strain et al., 2020)
Machine learning	Spatial data, Spatial-temporal data, Numerical data	Semeraro et al. (2015)
RS/Observational/ Participation	Spatial data, Spatial-temporal data, Textual data	(Javaid et al., 2023; Liu et al., 2023; De Santis et al., 2023; Brown et al., 2018; Chee et al., 2017; Yang et al., 2019; Bhagyanathan and Dhayanithy, 2023)

Data availability

No data was used for the research described in the article.

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