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Review of environmental benefits and development of methodology for EUNIS habitat changes from nature-based solutions: Application to Denmark and the Netherlands

Samikshya Chhetri [a], Laddaporn Ruangpan [a,b,*], Yared Abayneh Abebe [a,c], Arlex Sanchez Torres [a], Zoran Vojinovic [a,d,e]

[a] IHE Delft Institute for Water Education, the Netherlands
[b] Faculty of Applied Science, Delft University of Technology, the Netherlands
[c] Department of Hydraulic Engineering, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, the Netherlands
[d] Faculty of Civil Engineering, University of Belgrade, Belgrade, Serbia
[e] College for Engineering, Mathematics and Physical Sciences, University of Exeter, UK

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ABSTRACT

Nature-Based solutions (NBS) are the measures supported by natural processes that can adapt to changing climates and generate diverse social, economic, and environmental benefits. Recognising the potential for additional NBS benefits, and quantifying these benefits is essential as it encourages decision-makers to implement and scale-up NBS initiatives. This paper presents findings from a systematic literature review. The review focused on tools and methodologies used for assessing the environmental benefits of implementing NBS. This review provides a detailed compilation of environmental indicators supported by assessment tools. It also includes a catalogue of tools for evaluating environmental benefits, thereby identifying research gaps. Moreover, this research proposes a methodology that uses an ArcGIS (Architecture of Geographic Information Systems) toolbox to identify habitat changes resulting from the implementation of NBS. The methodology translates CORINE (Coordination of Information on the Environment) land cover classes to EUNIS (European Nature Information System) habitat classes. The developed toolbox was applied to two case studies: Denmark (12 NBS) and the Netherlands (3 NBS). The assessment aimed to compare the habitat changes between 2000 and 2018 as two extreme time points for NBS implementation for both case studies. Results indicate that NBS implementation can change habitats leading to an increase in the Red-necked Grebe population in Denmark and a decline in the Black-tailed Godwit population in the Netherlands (two threatened species). The population change highlights the potential positive and potential negative impacts of NBS in their respective cases. These findings suggest Denmark could benefit from lake construction and restoration projects. At the same time, the Netherlands could invest in wetlands and meadows construction and restoration projects to protect the respective species. They could establish designated breeding zones to ensure their population does not decline rapidly.

1. Introduction

NBS are measures that imitate natural and semi-natural elements to tackle societal challenges by maintaining or rejuvenating the ecosystems (IUCN, 2021). Their characteristics make them attractive as part of adaptive processes for building resilient ecosystems that safeguard human welfare, the natural environment, and its biodiversity (Cohen-Shacham et al., 2016; IUCN, 2021). Therefore, NBS measures should be implemented either as stand-alone or coupled with traditional grey engineering structures to curb the apparent effects of climate change, for example, increased average temperature and erratic weather, which are expected to exacerbate in the future (Ruangpan et al., 2020).

NBS generate primary benefits that fulfil the main objective and co-benefits that are additionally generated while addressing a particular objective (Raymond et al., 2017). For example, green roofs can reduce the urban heat effect by regulating solar radiation through the vegetation layers (Fioretti et al., 2010). Here, the main objective is heat effect reduction. At the same time, they reduce runoff volume, attenuate peak

* Corresponding author at: Faculty of Applied Science, Delft University of Technology, the Netherlands
E-mail address: l.ruangpan@un-ihe.org (L. Ruangpan).

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and increase concentration time contributing to stormwater runoff generating co-benefits. Green infrastructures installed to purify water and provide flood protection can additionally provide wildlife support and recreation (Liquete et al., 2016). Quantifying benefits helps convince stakeholders and decision-makers that the conservation and sustenance of ecosystems are essential (Sagoff, 2011). A methodological framework that combines ecosystem services (flood protection, education, art/culture, recreation, and tourism) with economic analysis for selecting different measures has been proposed by Vojinovic et al. (2016). The present paper focuses on the assessment of environmental benefits from the implementation of NBS.

Environmental benefits are the positive impacts on ecosystems that help regulate and maintain ecosystem services. They can be evaluated by comparing the values of indicators such as land use change, biological diversity, and water quality before and after the implementation of NBS (>5-year period). While methodologies guide the evaluation of the implemented measures, tools provide means to quantify the environmental benefits. Here, the term tool refers to different computer programs such as stand-alone applications, web-based applications, plugins, and GIS toolboxes. This paper reviews the available tools and methodologies to quantify and evaluate environmental benefits, as environmental health is inextricably linked to human health and the economy.

There are several reviews on NBS, most of them focused on the effects of NBS implementation. For example, Oquendo-Di Cosola et al. (2022) reviewed the effect of NBS on urban comfort. The study by Farinha et al. (2021) focused on evaluation of ecosystem services provided by urban areas. Tang et al. (2021) reviewed constructed treatment wetlands for pollution removal from agricultural runoff. Some studies have focused on the additional benefits. For example, Raymond et al. (2017) developed a guideline to evaluate co-benefits obtained from the NBS. However, there needed to be a more comprehensive review of tools and evaluation methodologies to assess NBS benefits.

Therefore, the paper aims to address the research gap by conducting a systematic review, identifying existing gaps and addressing these gaps in tools and methodologies for assessing environmental benefits obtained from implementing NBS. The purpose of this review is to help other researchers understand the tools and evaluation methodologies available to conduct research. One of the gaps identified from the review was the need to develop an evaluation methodology to assess habitat change. Habitat monitoring can assess the forces and factors affecting biodiversity at a large spatial scale; hence they are advantageous over site or species-specific monitoring (Lengyel et al., 2008). The two primary methods for habitat monitoring are field mapping and remote sensing. Several studies use remote sensing to map and detect changes in land cover over a region, as mapping habitats is more challenging (Lucas et al., 2011). Therefore, to address the gap identified through the literature review, the paper proposed an evaluation methodology that uses the ArcGIS toolbox to assess habitat change. CORINE (Coordination of Information on the Environment) land cover data was acquired from the Copernicus website (Copernicus, 2022). The CORINE land cover classes were translated to EUNIS (European Nature Information System) habitat classes. The methodology was tested in Denmark and the Netherlands, with low-lying landscapes, making them susceptible to climate change. The impact of NBS was evaluated using the respective countries' freely available population data on commonly found bird species.

2. State-of-the-art review

To conduct a systematic literature review, we defined search terms following the guidelines from Siddaway et al. (2019). Firstly, we formulated three research questions:

i) How many and which environmental indicators of interest are supported by the tool?
ii) Which NBS measures can be evaluated by the tool?
iii) What are the gaps in the tools and methodologies?

Based on the research questions, we identified three sets of different terms used to search articles in the electronic databases: NBS, environmental benefits, and tools and methodologies. We used these root words and their synonyms to search relevant articles and compile their information. The method applied for the review has been discussed in the next section:

2.1. Review methodology

2.1.1. Search criteria

The term NBS is an “umbrella concept” referring to solutions based on ecosystem and nature for tackling societal and environmental challenges (Cohen-Shacham et al., 2016; IUCN, 2021). Over the years, new NBS terms have been introduced in literature to characterize different features of life processes and functions (Ruangpan et al., 2020, Kabisch et al., 2016). The commonly used NBS terms in literature have been used as search terms and noted in List 1 of Table A1 (Annex A).

The NBS terms used were nature-based solutions, low impact development, sustainable urban drainage systems, water sensitive urban design, best management practices, green infrastructure, green–blue infrastructure, ecosystem-based adaptation, ecosystem-based disaster risk reduction and green, and grey infrastructure. List 2 of Table A1 contains environmental benefits and its associated terms. Since literature might broadly include environmental benefits under benefits or co-benefits, these terms were used in addition to the term environmental benefit. Additionally, the specific environmental benefits of interest for the study, such as biodiversity, habitat structure, water quality and carbon sequestration were included in the list. Finally, List 3 of Table A1 comprises terms related to evaluation and assessment. Tools could also refer to guidance documents. However, this paper only considers computer-based programs as tools. Therefore, the term tool and other specific terms such as software and model were included in the list. The term methodology needed to be more specific and could refer to research methodology. The term framework was added to List 3 to narrow the search for including methodologies.

To conduct a literature review of NBS, we identified two popular electronic databases: Scopus and Web of Science (Chausson et al., 2020; Mendes et al., 2020; Ruangpan et al., 2020). The search terms from Table A1 (Annex A) were used to find research articles in both databases. Since the lists categorized the terms into different themes and each list consists of synonyms terms, the Boolean “AND” was used between the lists, and “OR” was used amongst the terms within each list. The search queries entered for the databases were:

Scopus – “TITLE-ABS-KEY ((”Nature-Based Solutions“ OR ”Low Impact Development“ OR ”Sustainable Urban Drainage Systems“ OR ” Water Sensitive Urban Design“ OR ”Best Management Practices“ OR ”Green Infrastructure“ OR ”Green-Blue Infrastructure“ OR ”Ecosystem-based Adaptation“ OR ”Ecosystem-Based Disaster Risk Reduction“ OR ”Green and Grey Infrastructure“) AND (”Biodiversity“ OR ”Habitat Structure“ OR ”Water Quality“ OR ”Carbon Sequestration“ OR ”Environmental Benefits“ OR ”Benefits“ OR ”Co-benefits“) AND (”Evaluation“ OR ”Software“ OR ”Framework“ OR ”Model“ OR ”Tools“ OR ”Assessment“))”.

Web of Science – “TS = ((”Nature-Based Solutions“ OR ”Low Impact Development“ OR ”Sustainable Urban Drainage Systems“ OR ” Water Sensitive Urban Design“ OR ”Best Management Practices“ OR ”Green Infrastructure“ OR ”Green-Blue Infrastructure“ OR ”Ecosystem-Based Adaptation“ OR ”Ecosystem-Based Disaster Risk Reduction“ OR ”Green and Grey Infrastructure“) AND (”Biodiversity“ OR ”Habitat Structure“ OR ”Water Quality“ OR ”Carbon Sequestration“ OR ”Environmental Benefits“ OR ”Benefits“ OR ”Co-benefits“) AND (”Evaluation“ OR ”Software“ OR ”Framework“ OR ”Model“ OR ”Tools“ OR ”Assessment“))”.

2.1.2. Selection process

Fig. 1 shows the PRISMA flow diagram (Page et al., 2021) for the systematic literature review and the number of articles left after each selection/ exclusion criteria. In both databases, additional criteria including research articles published in English between 2012 and 2021 were applied to study the recent trend. Then, they were reviewed and excluded/ included step-by-step.

The first search resulted in 3573 research articles (Scopus: 2017 and Web of Science: 1556). It is typical for a research article to feature in both databases. Identifying such articles as two separate ones is irrational as they contain the same information and are prone to overestimate in terms of the number of articles. Therefore, it was essential to identify and remove duplicate entries in the first step. We identified duplicate entries by comparing article titles and DOI information between the list of articles from the two databases. One of the articles was removed from the list when duplicate entries were found. We removed 1063 duplicated articles. The remaining articles were reviewed based on their titles, keywords, and abstracts. During the review, we searched for relevant terms in their titles and keywords from our search list, such as NBS and environmental benefits. Furthermore, we analysed abstracts to ascertain whether their primary emphasis pertained to evaluation methodologies and established a connection to environmental benefits. Upon discerning that they did not align with these criteria applied to titles, keywords, and abstracts, we eliminated the articles that fell short of the specified focus. Subsequently, we had a refined selection of 284 articles for full-paper review. This systematic review aimed to identify the gaps in tools and methodologies used to assess the environmental benefits obtained from implementing NBS. The articles that did not meet and contribute to the review's objectives were omitted. Following a comprehensive review and refinement process, we included data from 64 research articles in our study.

2.2. Findings of literature review

We reviewed 64 articles thoroughly, 56 of which focused on tools and eight on evaluation methodologies. The information from the articles has been discussed separately in the two sections.

2.2.1. Evaluation methodologies

The evaluation methodologies focused on selecting NBS measures, assessing NBS benefits, delivering NBS performance to potential investors, and assessing green infrastructure.

Of the eight, five were quantitative methodologies, and three were qualitative. The methodologies were majorly designed for the planning phase, specifically performance assessment of coupled-green blue systems, best management practices (BMPs), and urban stormwater

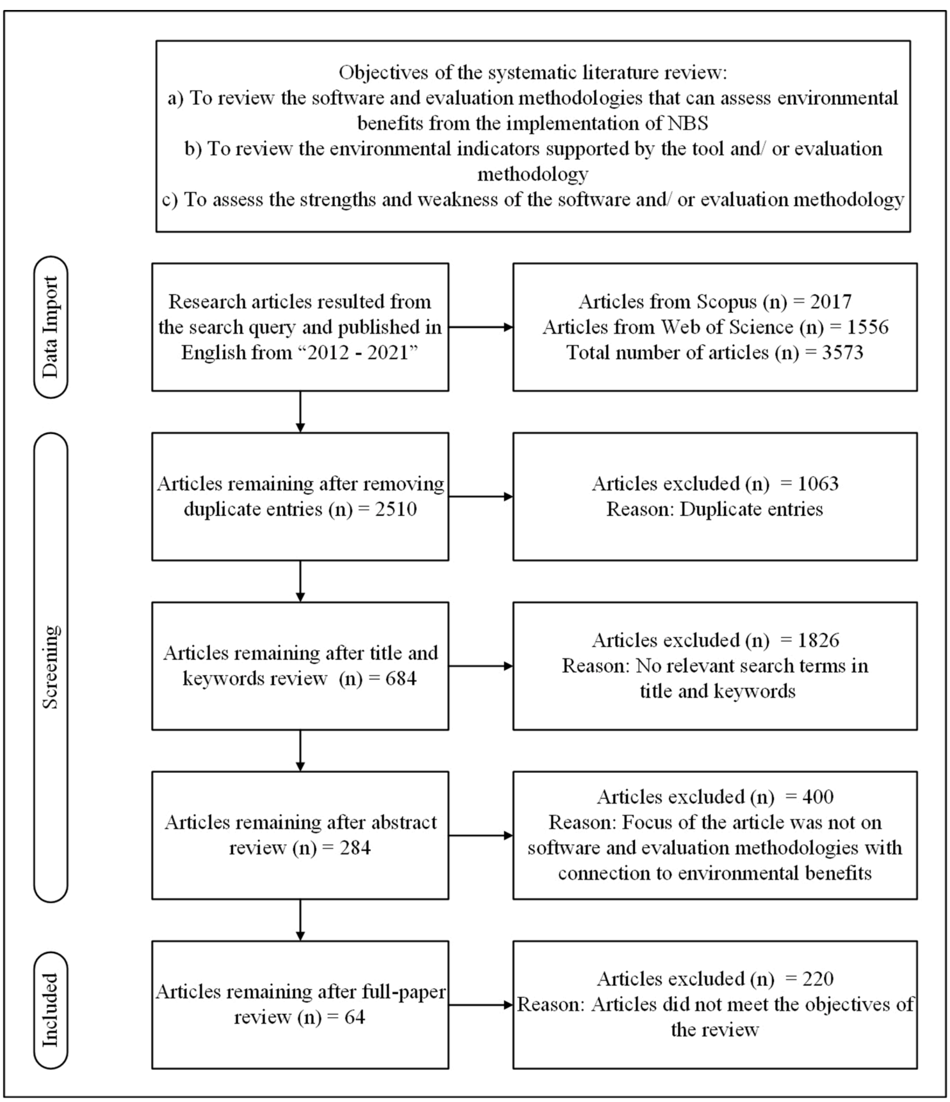

Fig. 1. A PRISMA flow diagram (Page et al., 2021) used for conducting the systematic literature review.

management systems. An exception was the methodology of Ruangpan et al. (2021), which concerned selecting measures instead of performance assessment. Watkin et al. (2019) proposed a post-implementation performance assessment methodology. Some methodologies were applied to overall phases. For example, Gordon et al. (2018) developed a project implementation and assessment methodology. Similarly, Wang et al. (2019)'s assessment methodology for green infrastructures considered the overall framework of the project from implementation to quantification of indicators for evaluating the methodology.

The reviewed methodologies used diverse stakeholders based on their studies to recognize the significant indicators for the study area and quantify them. Diverse stakeholders are essential throughout different phases of a project. For the planning phase, technical stakeholders can guide the selection of measures explicitly required in the study area. Non-technical stakeholders can identify indicators necessary for the case study and provide data on the economy, culture, and education (Ruangpan et al., 2021).

Benefits related to water quality from NBS can be assessed using existing modelling tools or by developing methods to update them. Leng et al. (2020) developed a methodology to assess the performance of green-grey-blue systems using coupled SWMM and EDFC models. On the other hand, Liu et al. (2018) developed a modelling methodology that can be adopted by tools such as SWAT and SWMM to assess the performance of BMPs. Though both methodologies were applied in case studies, Liu et al. (2018)'s methodology was not applied to the tools. The article notes that BMP performance can vary throughout the year due to changes in vegetation, and the methodologies take this into account. However, more detailed guidance would have helped other studies to apply Liu et al. (2018)'s methodology. Table 1 comprises a list of the reviewed tools and their description.

Assessing the sustainability of NBS against the United Nations Sustainable Development Goals (SDG) can inform decision-makers and encourage their implementation and upscaling. Sørup et al. (2019) developed a methodology that establishes links between local and SDG indicators. Although the methodology was designed for NBS for stormwater management, it identified other relevant services provided by NBS such as flood resilience, natural resource management, liveability, transition, and innovation. The methodology did not quantify the indicators but could be applied to other NBS by identifying relevant services.

Watkin et al. (2019) proposed a methodology to assess the positive and negative effects of NBS implementation for different indicators in general via the percentage change equation. This simple equation can help determine the change in multiple indicators. This simplistic approach of comparison can be applied to other cases as well. For their case study, they selected several indicators, such as biodiversity, carbon storage, historical flood mitigation, and habitat provision, based on stakeholders' needs. Besides, the methodology lists other indicators and provides information on data collection sources. However, the method of quantifying indicators needs to be more detailed.

The methodologies reviewed have incorporated various indicators. However, detailed quantification of parameters, such as, habitat structure, biodiversity, and carbon sequestration, is still needs to be included. Quantifying benefits shows the true potential of implementing NBS and attracts potential investors. The methodologies should be made applicable to broad regions using global datasets whenever possible because a lack of data can often be a problem in conducting research. Thus, there is potential for future research to develop methodologies to quantify the various environmental benefits of the NBS.

2.2.2. Tools for assessing environmental benefits

The review showed that most of the tools were hydrological and

Table 1
Description of hydrological, hydraulic, ecosystem and spatial tools used to quantify environmental benefits.

Tools	Type	Access	Descriptions	References
Benefits Estimation Tool (B£ST)	Excel	Open	• Benefits from green-blue infrastructure can be monetized without full-scale economic evaluation. Supports a wide range of benefits.	(Rizzo et al., 2021)
Chemicals, Runoff, and Erosion from Agricultural Management Systems CREAMS-PADDY	Integrated program	Commercial	• Extension of the CREAMS model. Modeling the environmental fate of pesticides, nutrients, and sediments in agriculture.	(Song et al., 2017)
Circuitscape	Standalone	Open	• Modeling heterogeneous landscapes and their outcomes.	(Zawadzka et al., 2019)
Corps of Engineers-Quality-Width Averaged 2D (CE-QUAL-W2)	Standalone	Open	• 2D Water quality and hydrodynamic modeling.	(Aalami, et al., 2018)
FRAGSTATS	Standalone	Open	• Analysis of spatial pattern and quantification of landscape structure.	(Han, et al., 2018)
Hydrologic Simulation Program- Fortran model (HSPF)	GIS-based program	Open	• Modeling watershed hydrology and water quality. Computationally time intensive.	(Risal et al., 2021)
i-Tree planting Tool	Web-based	Open	• Calculation of benefits from planting trees.	(Ariluoma et al., 2021)
i-Tree planting model	Standalone	Open	• Calculation of costs and benefits from urban trees.	(Reynolds et al., 2017)
Land Utilisation and Capability Indicator (LUCI)	ESRI ArcGIS Toolbox	Open	• Modeling the impact of land-use changes on ecosystem services. Supports a diverse range of ecosystem services.	(Dang et al., 2021)
Long-Term Hydrologic Impact Assessment-Low Impact Development (L-THIA-LID)	Web-based	Open	• Evaluation of benefits obtained from LID practices.	(Liu et al., 2015)
Model of Urban Stormwater Improvement Conceptualization (MUSIC)	Standalone	Commercial	• Modeling the effects of best management practices on stormwater runoff quality and quantity.	(Noh et al., 2018)
Soil and Water Assessment Tool (SWAT)	GIS-based program	Open	• Modeling hydrology and water quality. User Friendly. Moderate computational time.	(Risal et al., 2021)
Storm Water Management Model (SWMM)	GIS-based program	Open	• Modeling runoff water quality and quantity in urban environments.	(Dong et al., 2021)
System for Urban Stormwater Treatment and Analysis Integration (SUSTAIN)	Standalone	Open	• Modeling LID-BMPs.	(Daneshvar et al., 2017)
Topography-based Nitrogen Transfers and Transformations (TNT2)	Integrated program		• Modeling water movement and nitrogen transfer and transformation in small catchments.	(Casal et al., 2018)
Watershed Assessment Model (WAM)	GIS-based	Open	• Modeling hydrology and water quality.	(Khare et al., 2020)

hydraulic tools. The remaining were ecosystem services and spatial tools. Table 1 gives descriptions of these tools. B£ST, i-tree planting tool, and i-tree planting models are dedicated to calculating and monetizing the benefits. Tools such as Circuitscape, FRAGSTATS, InVEST, and LUCI (Table 1) can be used for spatial analysis. The advantage of using B£ST, InVEST, and LUCI is that they can be used for diverse indicators.

Hydrological and hydraulic tools such as SWAT, WAM, SWMM, and HSPF are GIS add-in programs, while standalone programs such as MIKE, DELT-3D, and SUSTAIN (Table 1) are also available. However, the latter are not freely available to users. B£ST, InVEST, and LUCI assessed multiple environmental benefits. The other tools were used for a single environmental benefit, mostly water quality.

Tools were selected based on research objectives. For example, a model's scale was considered to evaluate water quality. SWAT, SWMM, CE-QUAL-W2, Delft-3D, HSPF, and InVEST were used to model at watershed scales. InVEST calculated nutrients as a function of pixels (Singh et al., 2019); thus it produced precise results as a function of resolution. SWAT performed well at watershed scale (Risal et al., 2021) but showed poor performance for field-scale applications (Sommerlot et al., 2013). Field-scale simulation of nutrient loads was modelled with CREAMS-PADDY (Song et al., 2017).

Models were also selected based on the method. For water quality models, nutrient representation methods can differ. For example, TNT2 simulated the nitrogen cycling processes (Casal et al., 2018). InVEST calculated carbon sequestration based on the carbon pool values for each land use type at different scales (Zawadzka et al., 2019). Similarly, i-tree tools calculate sequestered carbon using allometric equations (Ariluoma et al., 2021; Reynolds et al., 2017).

Another criterion for tool selection was model data requirements and data availability because models can have similar yet specific requirements. For example, land use, land cover, topography, and soil information were common to SWAT and HSPF. However, the specific inputs were different as SWAT required daily precipitation, minimum and maximum temperature, relative humidity, and solar radiation, and HSPF needed hourly precipitation, cloud cover, dew point temperature, potential evapotranspiration and temperature (Risal et al., 2021). The data requirement could also be entirely different. InVEST used land use and land cover data to calculate carbon sequestration (Zawadzka et al., 2019). The i-tree planting tool used number and type of trees, condition of the trees, mortality, and amount of sun and shade, amongst others (Ariluoma et al., 2021).

2.2.3. Environmental benefits assessed from the tools

Considering NBS benefits and co-benefits, our review also focused on tools assessing environmental benefits, precisely water quality, habitat quality, biodiversity, and carbon sequestration and storage. Most of the articles we reviewed focused on BMP, especially on agricultural practices and their effect on runoff water quality. As shown in Fig. 2, 50 research articles (86 %) focused on water quality assessment. Out of all the reviewed tools, only B£ST used water quality classification to assess the benefit achieved from implementing blue-green infrastructure. The tool uses local knowledge to define water quality classification and the area over which water quality has improved. Other tools assessed water quality changes based on water quality parameters.

Among all articles focused on water quality, the most common parameters were nitrogen and phosphorus, specifically as total nitrogen and total phosphorus (Fig. 2).

Total nitrogen and total phosphorus were simulated using tools: SWAT (Risal et al., 2021), InVEST (Di Grazia et al., 2021), MIKE-URBAN (Han et al., 2021), MIKE-FLOOD (Li et al., 2018), HSPF (Risal et al., 2021), DELFT-3D (Xiong et al., 2021), MUSIC (Noh et al., 2018), CREAMS-PADDY (Song et al., 2017), and L-THIA-LID (Liu et al., 2015). The research articles also assessed different forms of nitrogen and phosphorus, such as nitrate nitrogen (Dong et al., 2021; Lam et al., 2012) and soluble forms of phosphorus.

Water quality parameters such as water temperature, sediment, nitrate and dissolved oxygen could be selected as potential indicators of fish species. Triana et al. (2021) showed that fish biodiversity can be simulated by feeding values of water quality parameters into several regression models to predict changes in the fish population.

B£ST was also used to assess biodiversity. However, unlike the models by Triana et al. (2021), B£ST does not delve into the specifics of species. Rizzo et al. (2021) could also monetize the biodiversity benefit by using the change in wetland areas as a proxy.

Carbon sequestration was assessed using i-tree planting tool (Ariluoma et al., 2021), i-Tree Streets model (Reynolds et al., 2017), InVEST (Zawadzka et al., 2019) and LUCI (Dang et al., 2021). Finally, habitat quality and habitat connectivity were assessing with InVEST (Di Pirro et al., 2021; Hu et al., 2018) and LUCI (Nguyen et al., 2021).

2.3. Gaps and analysis of potential future research

The systematic review revealed that only a few studies carried out were on methodologies (13 %) as compared to the tools (87 %). This discrepancy could result from segregating articles into tools and methodologies sections. The studies categorized in the tool sections have their methodologies as well. However, this review did not reflect on those methodologies. Additionally, different tools can be used for the same methodology depending on data availability and project requirements. This could possibly lead to a high application of tools and

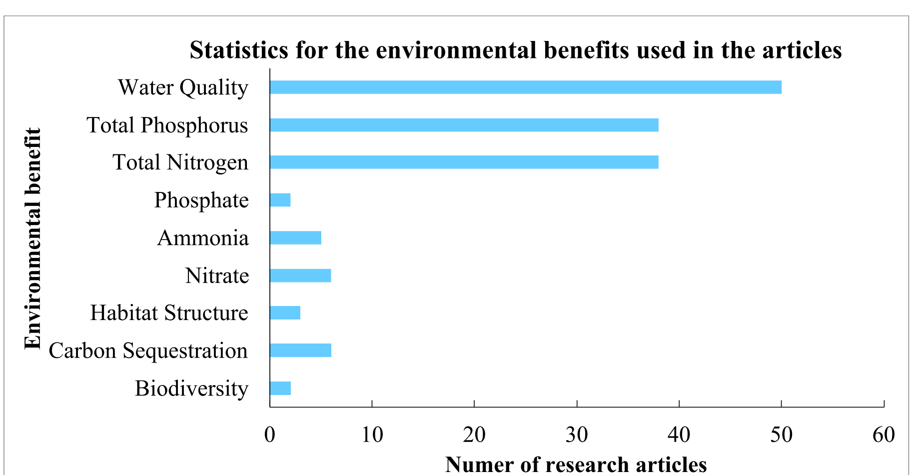

Fig. 2. The environmental benefits assessed by the research articles in the review.

methodologies. Since the categorization might have resulted in bias, future research can focus on evaluating methodologies for the tool sections.

Additionally, tools that can assess diverse benefits should be applied more in future research. Ecosystem services tools, such as InVEST, are valuable for assessing diverse benefits, particularly habitat quality. Such tools require land cover maps and threat data, which are only sometimes available. Therefore, future research should aim to create tools that can utilize globally available data to determine habitat changes.

There is an apparent gap in the articles assessing NBS as 86 % of the articles have focused on a single benefit, i.e., water quality. While water quality has been extensively studied in NBS, the ecological implications and the potential to sequester carbon, as well as other benefits such as biodiversity and habitat structure, require more attention (for example, the changes in agricultural practices can affect the biodiversity thriving on the farms themselves). These studies will provide a holistic insight into how the dynamic nature of the environment affects various environmental factors as a consequence of NBS implementation. The results could encourage stakeholders to invest in implementing and upgrading NBS to create a sustainable society. Hence, future research should focus on simultaneously assessing the multiple benefits of an NBS.

The reviewed articles assessed nitrogen and phosphorus in relation to nutrient runoff. Nutrient runoff may also lead to decreased dissolved oxygen in water bodies. Hence, in addition to nitrogen and phosphorus, dissolved oxygen could also be studied to show the suitability of a water body for thriving aquatic life. Most of the reviewed articles focused on surface water quality. Future research should study the effect of NBS on groundwater quality to assess the long-term impact.

3. Methodology to assess change in habitat area

One of the gaps identified from the systematic literature review was a need for a methodology for assessing change in habitat. This paper proposes such a methodology. It uses globally available remote sensing data. Remote Sensing has been extensively used for mapping and assessing changes in European habitats because of its strengths (Borre et al., 2011). However, mapping habitats is a more challenging task. Therefore, several studies map and detect changes in land cover over a region (Lucas et al., 2011). The proposed methodology translates CORINE Land Cover (CLC) classes to EUNIS habitat classes, two commonly used classification systems for land cover and habitat, respectively. The following section provides a detailed description of the methodology and the classification systems:

3.1. Data description

CORINE stands for Coordination of Information on the Environment. It is an inventory of Europe's land cover divided into 44 distinct land cover classes and provides land cover data for the years 1990, 2000, 2006, 2012 and 2018 (EEA, 2021). CORINE nomenclature is a 3-tiered hierarchical classification system with 44 classes at Level III. We acquired CORINE land cover data (CLC) for Europe from the Copernicus website (Copernicus, 2022).

EUNIS stands for European Nature Information System. EUNIS habitat classification provides an all-encompassing approach for detailing terrestrial and marine habitats in European ecosystems (Moss, 2008). It categories the habitats hierarchically. Level I is the highest, with ten habitat categories at this level (Davies et al., 2004). The marine habitats have been categorised up to level IV, while the terrestrial habitats are divided into level III. For this research, only habitats of level I defined by Davies et al. (2004) have been considered due to a lack of data that prevented detailed categorisation. Other versions are also available, but detailed information could be found only for 2004. Additionally, there were no significant changes in the latest reports besides the codes.

3.2. Crosswalk from CLC class to EUNIS habitat type

The habitat categories defined by the EUNIS report are (Davies et al., 2004):

i) A – Marine habitat
ii) B – Coastal Habitat
iii) C – Inland Surface waters
iv) D – Mires, bogs and fens
v) E – Grasslands and land dominated by forbs, mosses or lichens
vi) F – Heathland, scrub and tundra
vii) G – Woodland, forest and other wooded lands
viii) H – Inland unvegetated or sparsely vegetated habitats
ix) I – Regularly or recently cultivated agricultural, horticultural and domestic habitat
x) J – Constructed, industrial and other artificial habitats
xi) X – Complex habitats

A brief description of each habitat type is listed in Supplementary 1. The last category consists of the amalgamation of other habitats.

To assess the change in habitat type and area before and after implementing NBS, the CLC classes were first transformed into EUNIS habitat types. The crosswalk chart has been adapted and modified from the EUNIS habitat categorization for Level 1 habitat types (Davies et al., 2004). The chart allows a practitioner to crosswalk from CLC level III to EUNIS habitat level I. CLC level III was chosen because the classes in level III provide the least vagueness in definitions and descriptions. Meanwhile, EUNIS level I was selected because CLC classes were not detailed enough to segregate them into further classes. The crosswalk will result in each CLC class corresponding to EUNIS habitats. Fig. 3 provides the crosswalk chart adapted from Davies et al. (2004), and the explanation and criteria for the crosswalk chart are in Supplementary 2.

3.3. Habitat type and area change toolbox

The CLC classes to the EUNIS habitat translation concept were adopted into an ESRI ArcGIS toolbox. The toolbox used ArcGIS's Model Builder feature, which facilitates the combination of various tools to automate spatial workflow. A screenshot of the developed toolbox is in Appendix B. The toolbox used CLC maps as inputs to generate EUNIS habitat maps. For our study, the inputs were study boundary area and CLC data for 2000, 2006, 2012, and 2018. The CLC map was masked using the boundary data and fed into the next tool. The overall toolbox working methodology is shown in Fig. 4. We selected 2000 and 2018 as two extreme time points for NBS implementation. Depending on the study objective, it can be adapted for different years.

We vectorized the CLC as a query-based selection that allowed habitat change identification. Using Python code, the CLC classes were converted to EUNIS habitat classes. Consequently, a habitat map for each year was obtained. The resultant EUNIS habitat maps for two years were merged using the Union tool. It stored information on overlapping and non-overlapping areas of all areas with attributes. Another Python code was run to identify the areas where habitat changes had occurred. The pixels were styled into diverse colors and patterns to indicate if an area had been altered by NbS implementation. The automated process facilitated by ArcGIS Model Builder helped acquire the results efficiently. Future research could explore ways to apply the methodology using open-source software, as ArcGIS is a proprietary software.

4. Habitat type and area changes toolbox application to case studies

The developed GIS toolbox has been applied to two European cases: Aarhus, Denmark, and Noord Brabant, the Netherlands. The European case studies were chosen because our methodology used European land cover and habitat classification systems. We selected the countries based

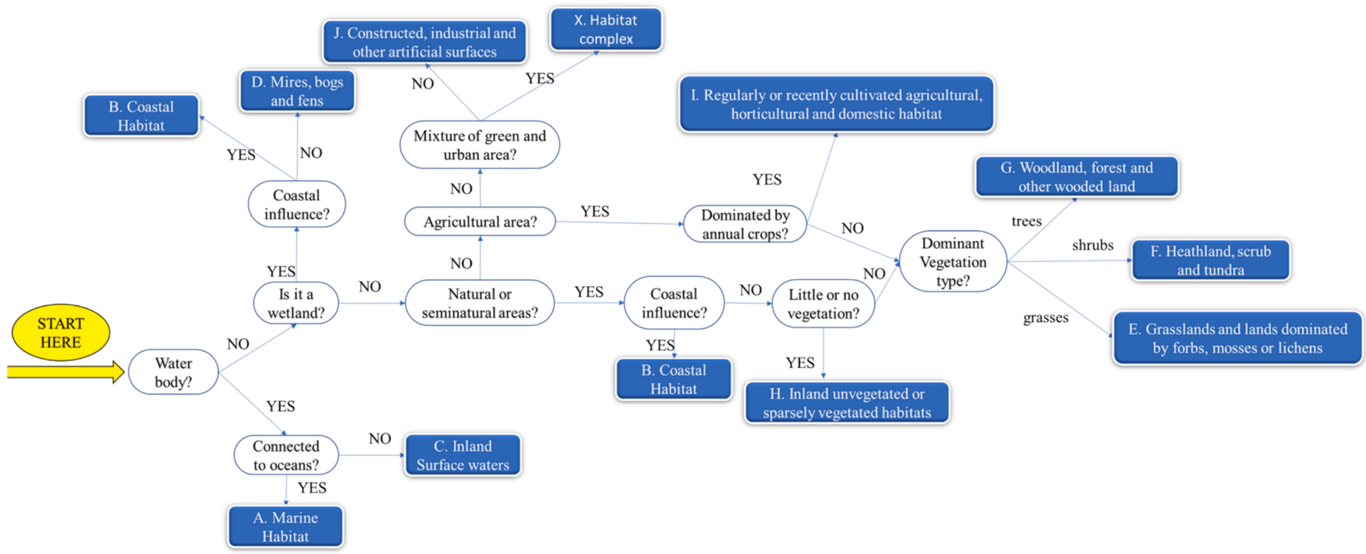

Fig. 3. Chart to crosswalk from the CLC class and EUNIS habitat type (. Adapted from (Davies et al., 2004)

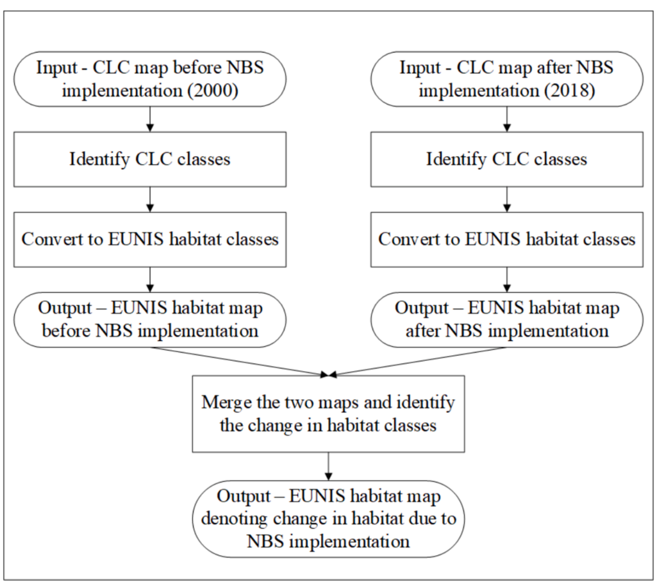

Fig. 4. Flowchart showing the process involved in the toolbox.

on their similar low-lying landscape and their vulnerability to changing climate. The following sessions provide case studies information, finding of the toolbox and discussions.

4.1. Description of the case studies

4.1.1. Aarhus case Study, Denmark

Aarhus is the second largest city in Denmark – and fast growing – with approximately 270,000 inhabitants. It is densely populated, low-lying, and at risk of flooding under increased precipitation. The project has two locations: Lystrup and Egå Engsø, lying in River Egå's catchment (Fig. 5A). Lystrup is a suburb on a hillslope just north of Egå Ensø in the catchment area of River Egå. Between Lystrup and Egå Engsø, the landscape is intersected by a highway that acts as a barrier disturbing the biological and hydrological systems. The main problem is the lack of hydrological connectivity between Lystrup and Egå Engsø. It is addressed by two sub-projects (two big pipes) that improve the passage of surface water below the highway.

In the upper part of Lystrup, the main problem is that during intense rainfall, the relatively steep and impervious surface (paved areas and clay soil) leads to surface runoff that might exceed the capacity of the sewage system.

The NBS in the area has been installed to reduce hydrometeorological hazards, particularly flooding. Egå Engsø is an artificial lake and wetland covering an area of 115 ha, surrounded by 35 ha of grazed meadows (Hansen). It was established in 2006 to reduce the nitrogen concentration entering Aarhus Bay, protect the surrounding areas from the flooding of River Egå, and provide natural benefits.

4.1.2. Noord Brabant case Study, the Netherlands

The second case study area is Biesbosch National Park, located in Noord Brabant, in the southern part of the Netherlands. The park is in between the tributary of the Rhine (Nieuwe Merwede) and Meuse (Amer) rivers, converging in the Hollands Diep (Fig. 5B). Part of the case study area is a nature conservation area and the largest European freshwater tidal region comprising about 8,000 ha of small rivers and streams. It has an open connection to the sea via the Nieuwe Waterweg. The tides influence Biesbosch due to its location. During flood tide, the seawater holds back the water from the rivers, and the water level is then at its highest. Conversely, river water freely drains into the sea during ebb tide, resulting in the lowest water level. Historically, the fluctuation between the highest and lowest water levels in the Biesbosch was recorded at two meters.

Biesbosch is known for its rich biodiversity and a haven for numerous bird species, making it a popular destination for birdwatchers and nature enthusiasts. The wetland ecosystem is also vital for various fish species and is recognized for its ecological significance. The park also serves as a recreational haven, attracting visitors for birdwatching, boating, hiking, and nature exploration. Integrating human activities with nature conservation is a notable aspect of the socio-ecological dynamic within the park.

Since the late 1950 s, depletion management actions have been carried out in the region because unwanted vegetation was removed. Multiple NBS projects were implemented in the region as part of the Room for the River project. Noordwaard polder covers nearly 2500 ha (Van Alphen, 2020), and depoldering was carried out as a part of the Room for the River project between 2009 and 2015 (Restoring River for effective catchment management (REFORM), 2013). Overdiepse polder was depoldered by from 2010 to 2013 (Roth and Winnubst, 2014).

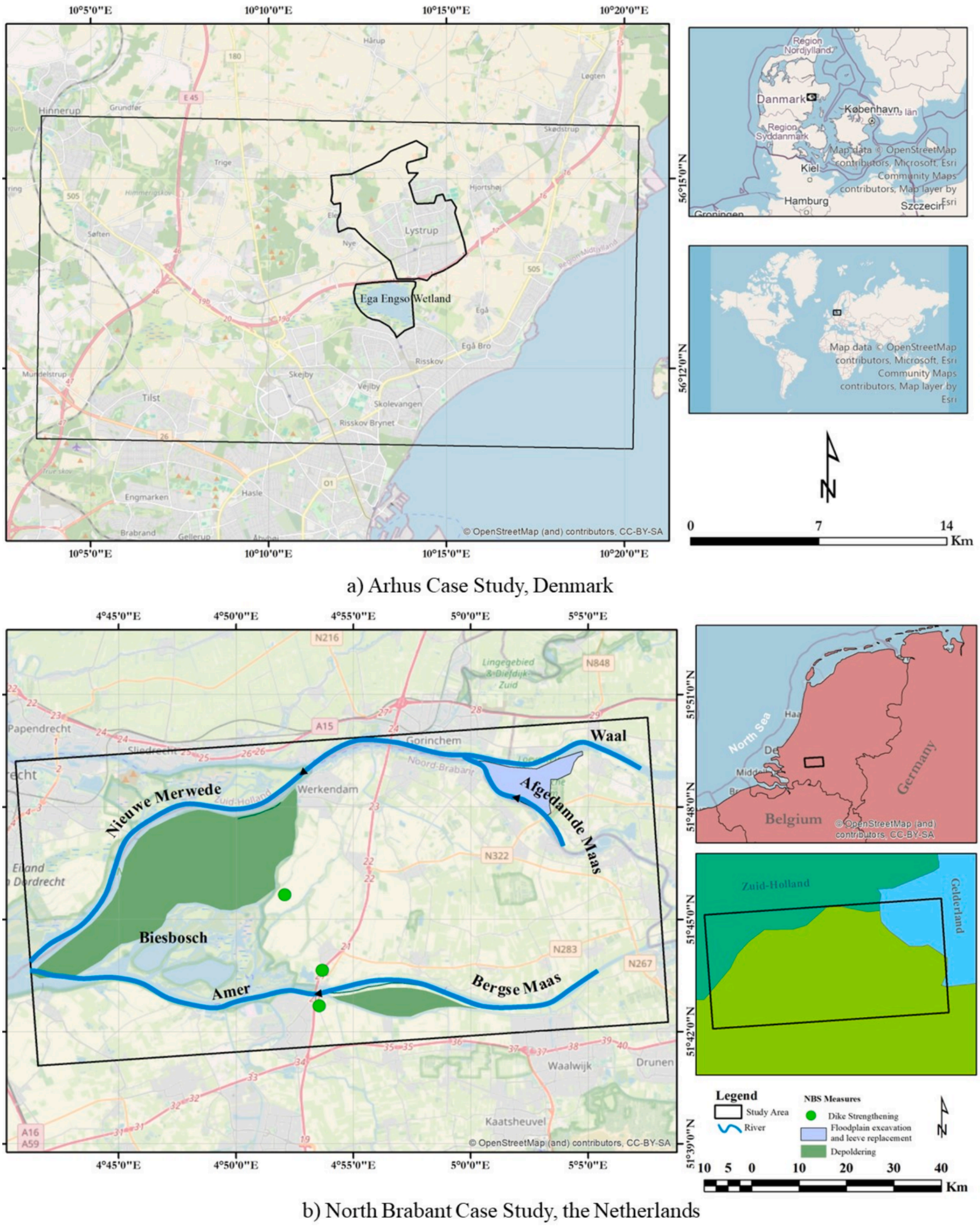

Fig. 5. Location of the case studies: A) Aarhus, Denmark and B) Noord Brabant, the Netherlands.

4.2. Findings of the toolbox

The changes in the habitat area of Denmark before (2000) and after the implementation of NBS (2018) can be seen in Fig. 6. Over the years, changes in habitat area can be seen dispersed throughout the study area as indicated by the colored patterns. The two bordered areas in Fig. 6ii highlight the regions Lystrup and Egå Engsø where NBS were implemented. Although areas outside the border have changed over the years, the measures implemented in those sections are unknown. Therefore, we only considered the specific locations where NBS were installed.

In the southern region (Egå Engsø), one distinct change was the conversion of a cultivated habitat to an inland surface water habitat.

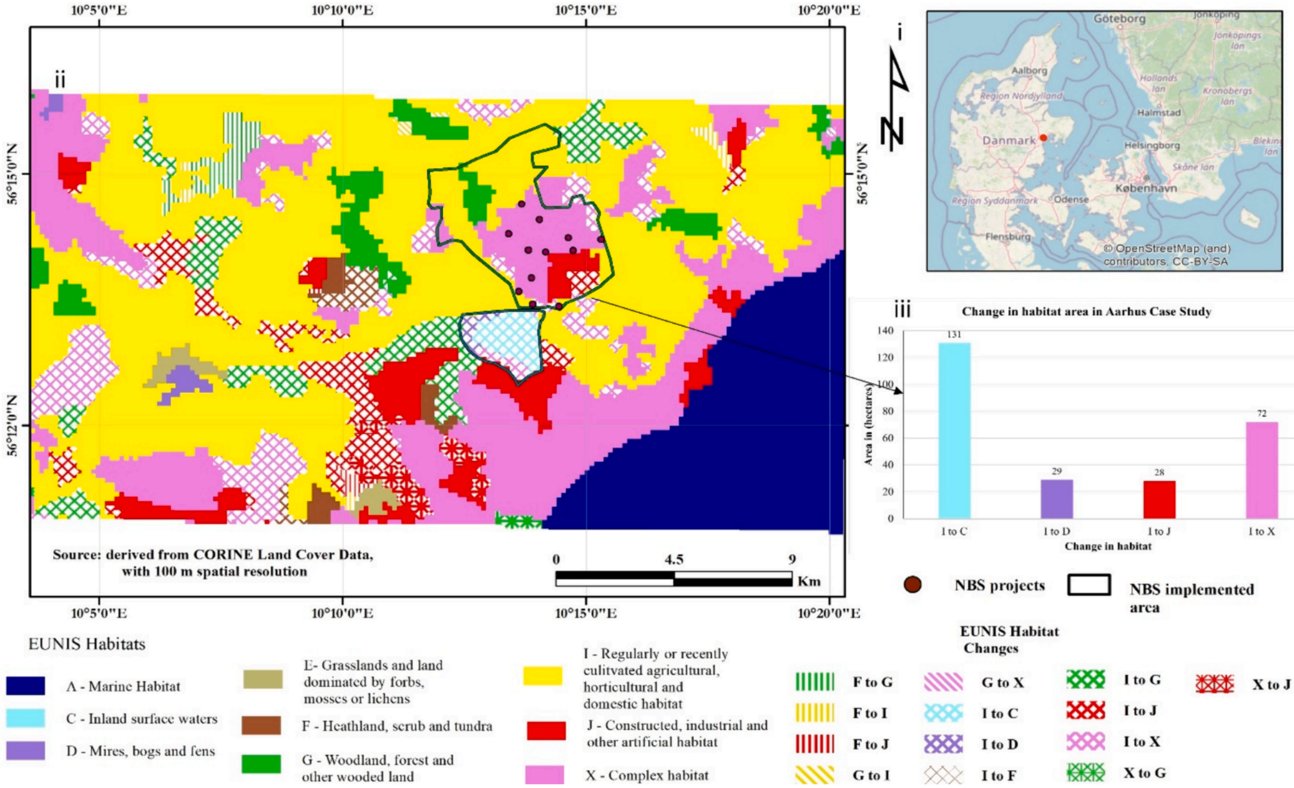

Fig. 6. Application of the proposed methodology to Aarhus, Denmark. i) Geographical location of the study area, ii) Change in habitat area before (2000) and after (2018) NBS implementation and iii) Quantification of change in habitat area.

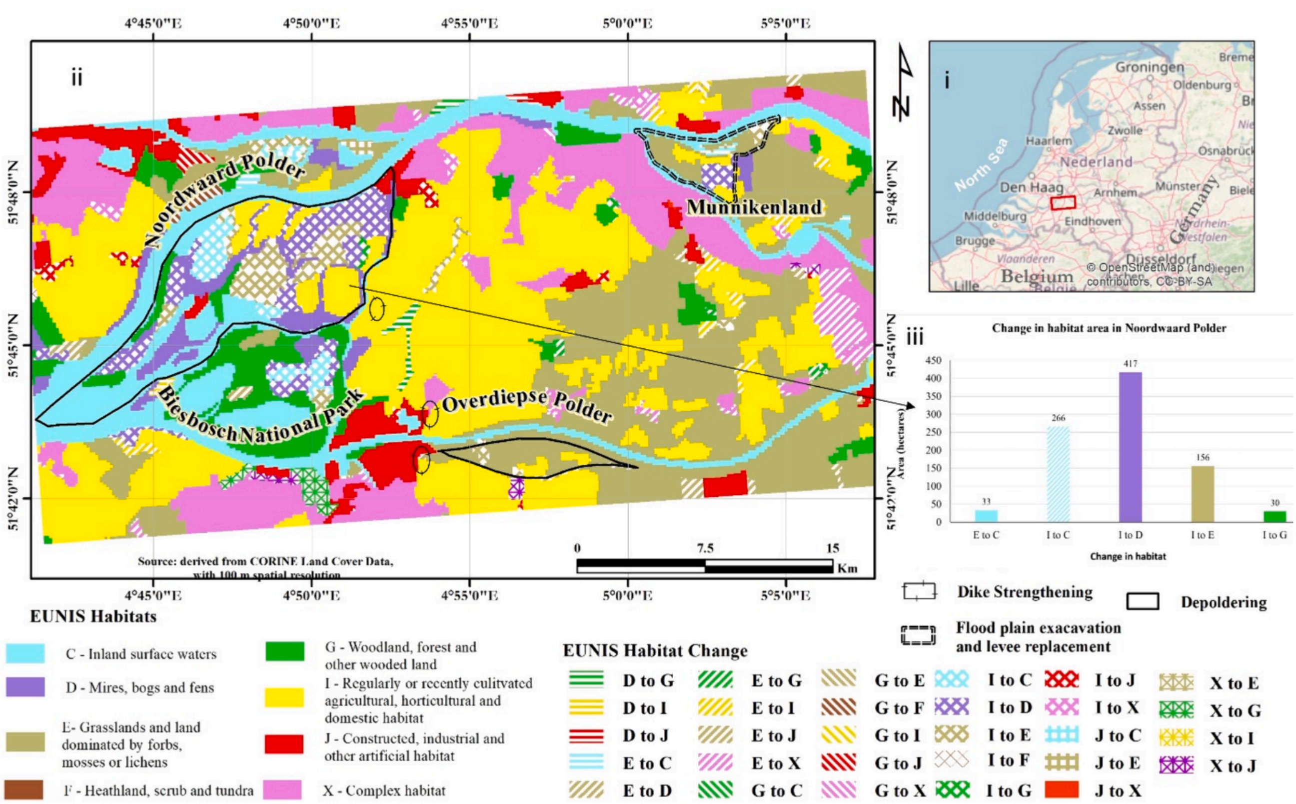

Fig. 7. Application of proposed the methodology to Noord Brabant, the Netherlands. i) Geographical location of the study area, ii) Change in habitat area before (2000) and after (2018) NbS implementation and iii) Quantification of change in habitat area.

Similarly, bogs, mires, and fens habitat (D) had emerged to the west of the wetland. The region probably got saturated from the lake to form a wetland. In the southwest of the wetland, agricultural area (I) had changed to a complex habitat (X), and the south of the region was surrounded by an artificially dominated habitat (J). It may have been a transitional zone between wetland and artificial areas. In the southeast of the wetland, complex habitat (X) changed to a constructed habitat (J).

Despite the installation of several NBS projects in the Lystrup urban section, habitat changes had not significantly altered. Most of the changes occurred outside the region where NBS had been implemented, except for minor changes in the south. It can be implied that the NBS measures probably did not cause habitat changes in Lystrup.

Fig. 6 iii) quantifies the cumulative changes in the areas where the NBS projects were implemented. It can be noticed that the agricultural and domestic habitat (I) had transformed into other habitats in all cases. The most significant change in the area was the establishment of the artificial lake of 131 ha (C). Another big change was the transformation of complex habitat (X) by 72 ha. The shift in mires, bogs, and fens habitat (D) and the constructed habitats (X) were 29 and 28 ha, respectively.

The results of the toolbox application in the Netherlands case can be seen in Fig. 7. As evident in the figure, there had been significant changes in the area. In the Noordpolder, the space for water increased by moving the dike inland. As a result, the habitats in the region were changed to inland surface water and mires, bogs, and fens habitats (D) immediately to the river. The agricultural habitat had also transformed into a grassland habitat (G).

Almost no change occurred in Overdiepse polder due to depoldering in contrast to Noordwaard polder. In Munnikenland, the mire habitat has been affected by the flood plain excavation. Outside the regions, there have been another habitat changes as well. However, NBS measures were not implemented there. So, habitat alteration probably occurred due to other reasons.

Fig. 7iii shows the change in habitat area in the Noordwaard polder. The largest change had occurred from agricultural area (I) to bogs (D) habitat by 417 ha. More agricultural land was changed into a water body (C), grassland (G), and forest (F) by 266 ha, 156 ha, and 30 ha, respectively. The river area was also increased by 33 ha as it changed from grassland (G).

4.3. Discussions

In Lystrup, Denmark, habitat alterations were not observed in the locations where NBS projects were installed. This suggests that the NBS did not exert a discernible influence on the habitat. It is also possible that toolbox could not record the NBS-induced implementation as the area was a complex habitat characterized by a heterogeneous blend of different habitats. One limitation of this method could be that it is challenging to delineate changes within habitat complexes.

In Egå Engsø, significant transformation from an agriculturally dominated landscape to lakes and wetlands was evident. The result supports the claim that the applied toolbox can assess habitat area changes. Egå Engsø could be a suitable breeding ground for species breeding in freshwater. The Red-necked Grebe breeds in shallow freshwater habitats and takes shelter during winters in shallow estuarine and marine habitats (Kloskowski et al., 2019). According to the International Union Conservation for Nature, Red-necked Grebe is a vulnerable species (IUCN, 2022). We tested the habitat changes against the population data of Red-Necked Grebe. The population data from the Danish Ornithological Society (https://www.dof.dk/en) recorded 857 observations in June 2007, immediately after the lake installation. It can be inferred that the wetland could attract the Red-necked Grebe population for the breeding seasons.

In the Netherlands study case, the most significant changes were increased rivers and wetlands habitats. It can be implied that depoldering successfully widened the river channel, and the toolbox modelled it as a change to water habitats. These habitat changes could affect the population of the Black-tailed Godwit, a meadow bird common to the Netherlands. It is categorized as Near Threatened by IUCN (IUCN, 2022). They are mostly found in the Netherlands in agricultural areas (Groen et al., 2012). They breed in grassland areas with a high water table and use wetlands for foraging and wintering (Gill et al., 2007). Given that most of the agricultural area were lost and the species arrived in the Netherlands for breeding, the change in habitat area in Noordwaard Polder could negatively affect the Black-tailed Godwit. The bird database Waarneming (https://waarneming.nl/) recorded 29,319 observations in 2009, 52,475 in 2012 and 67,173 in 2018. A potential negative impact could be implied by the decrease in the trend of observations between 2012 and 2018 compared to 2009 and 2012.

This paper used CORINE land cover classes and EUNIS habitat classes, which are applicable to Europe. The developed methodology offers the advantage of being applied in cases with limited local information. The translation methodology could be modified using regional land cover and habitat classes. However, validation of the methodology is essential as the limitation arises from translating the land cover classes to habitat classification. The methodology can be validated with field data to classify the habitats. A limitation of the developed ArcGIS toolbox is that ArcGIS is proprietary software, so it might only be available to some.

5. Conclusions

A systematic literature review was conducted to review on tools and methodologies to assess environmental benefits from the implementation of NBS. Sixty-four articles were selected after the application of different keywords and filters for data extraction and analysis. The results showed that the most used tools were hydrological and hydraulic tools focused on water quality assessment. Further, it revealed a need to develop methodologies, especially for quantitative assessment of benefits such as habitat structure, biodiversity, and carbon sequestration. The existing tools can be updated or simple tools can be developed to use global datasets to quantify the indicators when specific data are unavailable.

A GIS toolbox was developed to change the land cover classes to habitat classes and was applied to case study areas in Denmark and the Netherlands. In Egå Engsø of Denmark, the lake's construction changed the agricultural to surface water habitat by 131 ha. The increase in the breeding population of Red-necked Grebe showed a potential positive impact of NBS on the bird. In the Netherlands, multiple NBS measures of depoldering, dike strengthening, and floodplain excavation were implemented. The most significant habitat change was in Noordwaard Polder, where depoldering had been done. The decline in the Black-tailed Godwit population indicated a potential negative impact on the bird species due to river depoldering. Quantification of benefits helps identify the effect of implementing NBS in a region. The positive impacts encourage investments in NBS, while the negative impacts could be used as a lesson to find suitable alternatives.

CRediT authorship contribution statement

Samikshya Chhetri: Formal analysis, Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **Laddaporn Ruangpan:** Supervision, Visualization, Writing – review & editing. **Yared Abayneh Abebe:** Conceptualization, Supervision, Writing – review & editing. **Arlex Sanchez Torres:** Conceptualization, Supervision, Writing – review & editing. **Zoran Vojinovic:** Conceptualization, Funding acquisition, Supervision, Visualization, 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.

Data availability

Data will be made available on request.

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Appendix A

Table A1
Set of different terms used to search the articles in the electronic databases.

List 1 – NBS related terms	List 2 – Environmental benefit related terms	List 3 – Evaluation related terms
Nature-Based Solutions	Biodiversity	Evaluation
Low Impact Development	Habitat Structure	Software
Sustainable Urban Drainage Systems	Water Quality	Framework
Water Sensitive Urban Design	Carbon sequestration	Model
Best Management Practices	Environmental benefits	Tools
Green Infrastructure	Benefits	Assessment
Green Blue Infrastructure	Co-benefits	
Ecosystem-Based Adaptation		
Ecosystem-Based Disaster Risk Reduction		
Green and Grey Infrastructure		

Appendix B

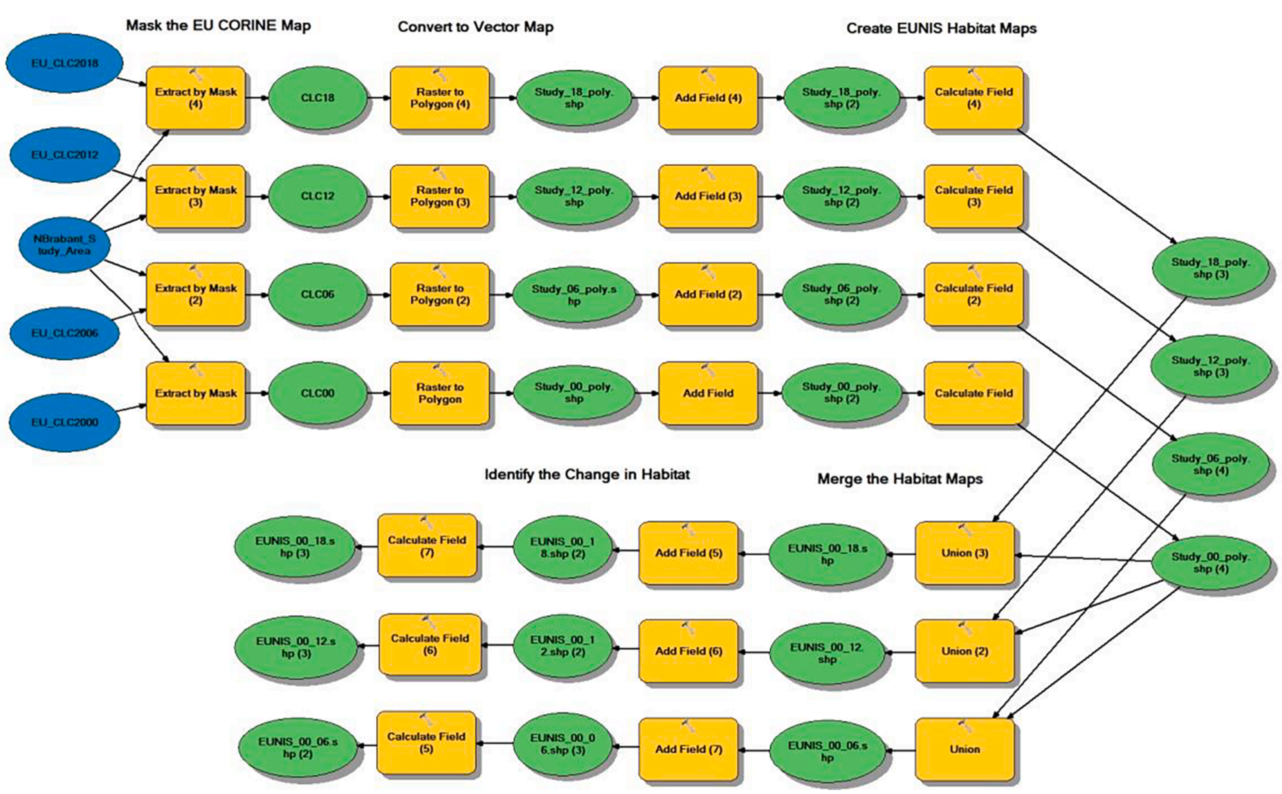

Fig. B1. A screenshot of the toolbox that translates the CLC maps into EUNIS habitat maps. The toolbox prepares EUNIS habitat maps before and after the NBS implementations, merges them and identifies where habitat change has occurred.

Appendix C. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2024.112189.

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