



Stepping Stones Along Urban Coastlines—Improving Habitat Connectivity for Aquatic Fauna with Constructed Floating Wetlands

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Abstract

Urban development along coastlines is accompanied by habitat fragmentation and loss of habitat connectivity, particularly affecting the habitat and nursery function of estuarine areas for migratory marine species. Constructed floating wetlands, deployed as ‘stepping stones’ along urban coastlines where natural wetlands are missing, offer the potential to partially replace lost ecosystem services. Originally developed for wastewater treatment, constructed floating wetlands are now used to improve landscape aesthetics or create habitats for aquatic fauna and birds. This study presents a toolkit to identify appropriate sites for stepping stones using open source data and open source software alone. The toolkit was used to identify 85 potential installation sites along the German Baltic Sea coast, a large proportion of which are located in protected areas offering synergies with nature conservation measures. Though the sites are often located in protected areas, the field investigation revealed that natural vegetation is largely absent from the estuaries near urban areas. Constructed floating wetlands can never replace ‘core areas’ in ecological networks, but they can serve as stepping stones improving habitat connectivity, especially for diadromous fish species such as the threatened European eel. To ensure not only structural connectivity, but also functional connectivity, restoration efforts at the land-sea interface must be holistic and include adequate hydrologic connectivity.

Keywords Constructed floating wetlands · Habitat connectivity · Stepping stones · Eel management, Baltic Sea

Introduction

Coastal wetlands provide a variety of ecosystem services such as nutrient regulation, shoreline protection and wildlife support (e.g. Borchert et al. 2018; Perillo et al. 2018). For aquatic species, the provision of a refuge habitat with a suitable physical–chemical environment for juveniles and the reduction of predator pressure are particularly important (Deegan et al. 2002). Especially the vegetated marsh edge plays a fundamental nursery role for transient nekton (Minello et al. 2003). Nektonic groups, including fish, cephalopods or decapod crustaceans, are able to swim independently from ocean currents (Dipper 2022), whereas transient means that the species have separate or not completely overlapping habitats for nursery, juvenile and adult stages (Minello et al. 2003). Coastal wetlands provide critical habitats for many transient fish and invertebrate species that are essential in commercial and recreational fisheries (Deegan et al. 2002; Moody et al. 2013). However, natural wetland loss due to urban expansion is a global phenomenon and various studies show

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how the anthropogenic overprinting of coastlines results in depletion of ecosystem services (e.g. Li et al. 2010; Lin et al. 2013; Carranza et al. 2020; Mao et al. 2018). Urban development along the coast is accompanied by habitat fragmentation, loss of habitat connectivity and an increase of artificial shorelines (Benzeev et al. 2017). Facing these circumstances, Krost et al. (2018) proposed ‘sublittoral wildlife corridors’ to connect isolated habitats in urban coastal waters and create a biotope network with restored shallow water habitats such as reefs, rocks, or eelgrass plantings. Constructed floating wetlands could provide another valuable option for creating artificial habitats along heavily modified urban shoreline, and serve as stepping stones (see Saura et al. 2014) that increase habitat connectivity to partially compensate for the lack of natural coastal wetlands.

Originally developed for wastewater treatment (Afzal et al. 2019), this technology is now used worldwide with a variety of goals including nutrient removal in highly eutrophic waters, enhancement of landscape aesthetics or habitats for birds (e.g. Yeh et al. 2015; Pavlineri et al. 2017; Colares et al. 2020). Common to all applications is the buoyant matrix, which is planted with emergent macrophytes. Recently the habitat-provision aspect under water has come into focus. The dense root network below the matrix serves as a shelter and refuge for fish and crustaceans (Huang et al. 2017; Karstens et al. 2021). Particularly surprising was the observation of large numbers of juvenile eels (*Anguilla anguilla*) utilizing floating wetlands in the brackish coastal waters of the Baltic Sea (Karstens et al. 2021). Within the last four decades, a drastic decline of the European eel population occurred (ICES 2020) and it has been designated as a critically endangered species on the HELCOM red list (HELCOM 2013). In addition to other factors such as hydropower use or commercial fishing, anthropogenic habitat loss and habitat degradation have been identified as possible causes of eel decline (ICES 2020). Accordingly, eel conservation efforts may also benefit additionally from measures aimed to restore lost aquatic habitats or improve habitat quality. Therefore, habitat improvements or measures to reduce migration barriers are components of various national eel management plans. Fishery authorities as well as nature conservation agencies throughout Europe are looking for management solutions off the conventional eel stocking.

Our study aims to investigate the potential of constructed floating wetlands (CFW) as stepping stones in ecological networks for transient marine species with a focus on the European eel and to identify potential sites along the German Baltic Sea. Further, this study provides a transferable open-source toolkit for other countries and targeted species.

Materials and Methods

Study sites

This study focuses on urban areas and estuarine regions, including outlets of small streams, along the German Baltic coast. The Baltic Sea covers an area of over 400,000 km² and is a brackish, non-tidal shallow sea with an average depth of 52 m (Hupfer 2010; HELCOM 2010). Geologically it is a young sea (Snoeijs-Leijonmalm and Andrén 2017) and due to strong salinity gradients from west to east the biodiversity is relatively poor (Elmgren and Hill 1997). Characteristic for the German Baltic are the shallow bays, lagoons and estuaries called ‘Förden’, ‘Haffe’ and ‘Bodden’ that resulted from the morphological shaping during the last glaciation (Sterr 2008). Transitional coastal waters are particular important habitats for the threatened European eel (*Anguilla anguilla*) (ICES 2009; HELCOM 2013).

Mapping with Open-Source Data

The purpose of the toolkit was to identify potential locations to enhance biotope connectivity for diadromous fish species, particularly the European eel. The toolkit is based solely on open-source data and open-source software. The primary criteria in the site-search-tool development were easy methodology, free access to data, disclosure of GIS steps and transferability to other coastal regions. Data types, data sources and download links to the data used are summarized in Table 1. Workflow and data availability are easily transferable to other countries worldwide (for European datasets confer Table 1).

The selection criteria for potential sites were, first, proximity to urban areas (maximum distance 1 km) and, second, vicinity to a river mouth (including small streams), in order to include migration corridors for diadromous fish species (Fig. 1, Data used see Table 1). For the vicinity to river mouths a radius of 200 m was chosen, following the current legislation of Schleswig–Holstein which provides this distance for fish conservation zones (KüFVO SH 2020).

In addition, the sites were classified in terms of their location in NATURA 2000 sites, landscape conservation areas, and national parks or nature parks, as synergies with other nature conservation measures may result in these areas (Table 1). For fish conservation zones, national legislations were considered (KüFVO SH §7 Annex 2 (3)+ KüFVO M-V § 11 (5)). Vector geoprocessing tools in QGIS included buffering and intersecting (QGIS Geographic Information System. Open Source Geospatial

Table 1 Overview of open-source data used to map potential installation sites for constructed islands as fish refuges. In this case study, installation sites were required to be located at river mouths (including small streams) and in 1 km proximity to urban areas (derived from CORINE land cover data, © European Union, Copernicus Land Monitoring Service 2018, European Environment Agency (EEA))

What?	Why?	Source?	Link?	Transferability to other EU countries?
Urban areas	Anthropogenic overprinting; indicator of possibly degraded or missing natural wetlands	European Union, Copernicus Land Monitoring Service 2018, European Environment Agency (EEA)	https://land.copernicus.eu/pan-european/corine-land-cover	European dataset
River mouths	Particularity of estuarine areas for aquatic fauna, e.g. corridors for eel migration	German Federal Institute for Hydrology (BfG)	https://geoportal.bafg.de/inspire/download/HY/waterbody/dataset/feed.xml	Priority Dataset of INSPIRE (Infrastructure for Spatial Information in the European Community)— https://inspire-geoportal.ec.europa.eu – available for most countries Directive 2000/60/EC—Rivers (Water Framework Directive) Directive 2000/60/EC—Designated waters (Water Framework Directive)
Protected areas	Potential synergies with other nature conservation measures	German Federal Agency for Nature Conservation (BfN)	https://www.geoportal.de/Download/e2e51dc2-af22-486f-8e66-ebf12c3a2f77	Priority Dataset of INSPIRE (Infrastructure for Spatial Information in the European Community)— https://inspire-geoportal.ec.europa.eu – available for most countries Directive 92/43/EEC—Directive 92/43/EEC; Directive 92/43/EEC—Natura 2000 sites (Habitats Directive)
Fish conservation zones	Potential synergies with other fishery conservation measures	For MV: Mapping conducted by Volker Hucksdorf; For SH: Mapping by Svenja Karstens (part of this study)	German Legislations available at https://www.gesetze-rechtsprechung.sh.juris.de/jportal/?quelle=jlink&query=K%C3%BCFischV+SH&psml=bsshoprod.psml&max=true&aiz=time and https://www.landrecht-mv.de/bsmv/document/jlr-K%C3%BCFischVMV2006V3P1	National legislations vary. Another option would be to use Marine Protected Areas (MPA). However, fish conservation areas are often situated directly at the coast and thus more suitable as indicator for constructed floating wetland installation sites
City types (administrative areas with population)	Stronger anthropogenic influence in medium-to-big cities	German Federal Agency for Cartography and Geodesy (BKG)	Shapefiles on request https://gdz.bkg.bund.de/index.php/default/digital-geodaten/verwaltungsgebiete/verwaltungsggebiete-1-250-000-mit-einwohnerzahl-ebenen-stand-31-12-vg250-ew-ebenen-31-12.html	Priority Dataset of INSPIRE (Infrastructure for Spatial Information in the European Community)— https://inspire-geoportal.ec.europa.eu – available for most countries
Biotope mapping	Mapped neighboring shoreline vegetation (< 150 m) to potential installation sites	State Agency for Agriculture, Environment and Rural Areas Schleswig–Holstein (LLUR) Mecklenburg–Western Pomeranian Agency for the Environment, Nature Conservation and Geology	https://opendata.schleswig-holstein.de/dataset/biotopkartierung https://www.uis-mv.de/ (data only on request)	Habitat mapping for most NATURA 2000 networks available via European Union (EU) Habitats Directive (92/43/EEC)

Foundation Project. <http://qgis.osgeo.org>). The Biotope mapping of the state environmental agencies was used to obtain information about biotope types on adjacent shorelines near to potential installation sites. Processing steps 1 and 2 identify potential installation sites (Fig. 1), while step 3 offers additional site information to ensure long-lasting functionality and efficiency of CFWs. Data on adjacent vegetation can assist in selecting plant species suitable for CFW. The conservation status of the area informs decision makers whether synergies with other measures should be considered.

Field Investigations Along Bigger Cities

Another classification criterion was proximity to cities with populations greater than 20,000 to identify sites that might have a stronger anthropogenic influence and thus a more pronounced impact on wetland connectivity and functionality. We assume that the anthropogenic influence is more pronounced in larger cities. On-site investigations were conducted along the coastline of Flensburg with 89,934 inhabitants, Eckernförde with 21,637 inhabitants, Kiel with 246,601 inhabitants (Statistikamt Nord 2020) and Rostock with 209,061 inhabitants (Statistisches Amt M-V 2020). Potential locations for CFW were documented by photos and notes on signs of anthropogenic influence (e.g. *culverts*, *stone groynes*, *concrete quay walls*), presence of natural wetlands (*yes*, *no*, *partly developed riparian vegetation*) and whether the land-sea connection is open for shipping (*maritime traffic*, *recreational boating*). Photos were then geotagged, imported in QGIS. Dependency analyses between categorical variables such as ‘natural vegetation’, ‘anthropogenic influence’ were conducted in RStudio Version 1.3.1073 (R Core Team 2021). Since the sample number was < 50, the Fisher's exact test for categorical variables was used instead of Pearson chi-square test to determine if there is a significant relationship between two variables.

Results

A total of 85 potential installation sites along the German Baltic coast were identified which are located in close proximity (max. 200 m) to estuaries (including small stream mouths) as well as within 1 km radius of urban regions (Fig. 2). Of those sites, 56 are located within areas that belong to the EU Natura 2000 network (66%), 42 within national landscape conservation areas (49%), and 38 in national parks or nature parks (45%). More than 30% of identified potential installation sites are located in fish conservation zones (28 sites).

Twenty-five sites were near cities with > 20,000 inhabitants (29% of all potential sites), located within the municipality boundaries of Flensburg (2 sites), Schleswig (3 sites), Eckernförde (3 sites), Kiel (3 sites), Lübeck (3 sites), Wismar (2 sites), Rostock (5 sites), Stralsund (2 sites) and Greifswald (2 sites). A list of potential installation sites is given in Annex A1, and a geopackage with the matching shapefiles can be downloaded (see SI 1). Adjacent shoreline vegetation at most sites is dominated (46 sites, 54%) by common reed (*Phragmites australis*). Biotope codes provided by the environmental state agencies are added to table A1, providing decision-makers with information on natural shoreline vegetation in the specific regions.

Field investigations were conducted at 24 sites along medium (20,000–50,000 inhabitants) to big-sized cities (> 50,000 inhabitants) (Figs. 3 and 4). Table 2 gives an overview of anthropogenic influences, presence of natural shoreline vegetation, potential conflicts with maritime traffic and whether the potential installation site is situated in a nature conservation area or fish conservation zone.

The field investigation revealed that natural riparian vegetation including emergent macrophytes is largely absent from the estuaries near urban areas (Table 2). The majority of sites were severely anthropogenically influenced. At 11 sites (46%) water flow was channeled through culverts. The variables ‘natural vegetation’, ‘culverts’ and adjacent city sizes were all independent with no significant relationship. A significant relationship existed between the two categorical variables ‘nature conservation’ (either NATURA 2000 or landscape conservation area) and ‘fish conservation zones’ ($p < 0.05$). However, both variables were independent from whether a natural coastal wetland was present or not.

Discussion

With our application-oriented approach based on open-source geodata, 85 potential sites along the German Baltic coast have been identified (Fig. 2). Transparency in data use and processing increases acceptance, empowers decision-makers, and may encourage fishery authorities to consider floating vegetation as an option for eel management by improving habitat connectivity. The ecological network approach aims to expand the integrity of environmental processes, facilitate the conservation of species and habitats and promote biodiversity (Bennett and Mulongoy 2006). Ecological networks consist of core areas, corridors and buffer zones (Jongmann 1995). Corridors can vary in shape and scale, e.g. from linear amphibian passages under a road to intercontinental corridors

Fig. 1 Work flow and geodata processing to identify suitable installation sites for constructed floating wetlands. All data used is freely available (see Table 1) and GIS procedures easy-to-use. Solely fish conservation zones were created manually for this study. (Symbols in Fig. 1 provided by Christian Ridder, Business-as-Visual)

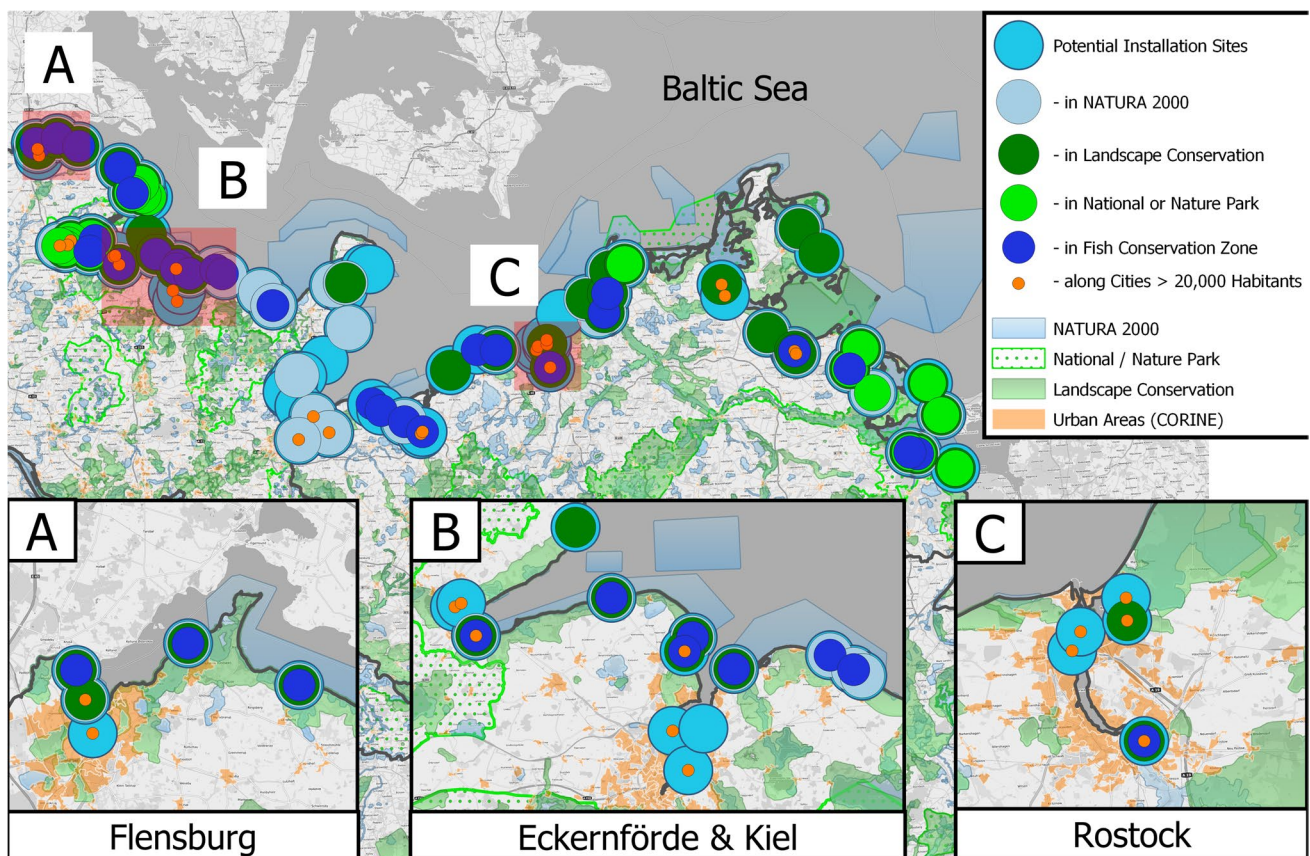
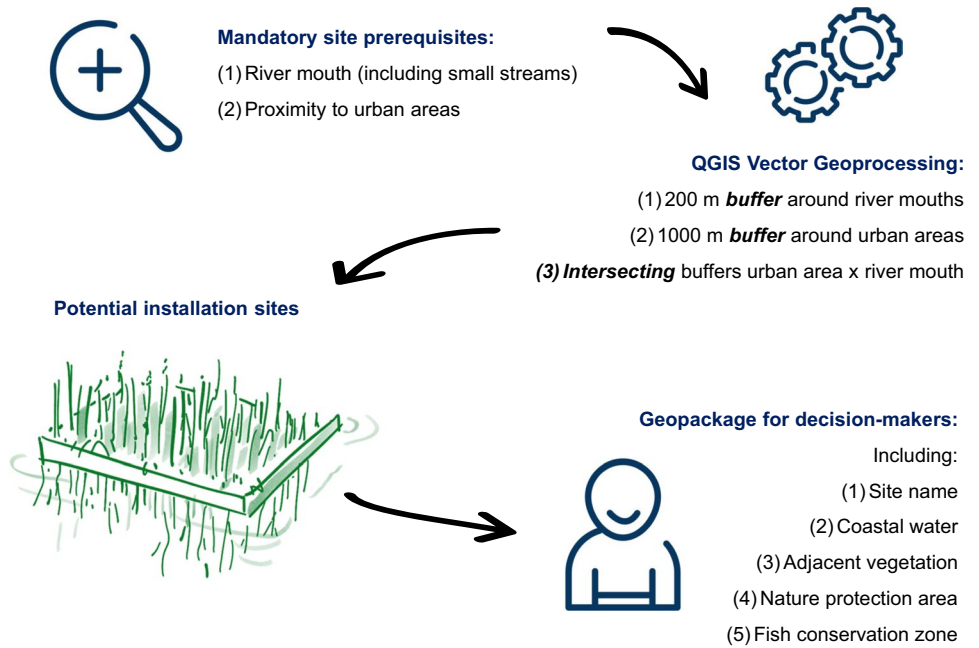


Fig. 2 Mapping of potential installation sites of constructed floating wetlands along the German Baltic Sea that could potentially serve as refuges for aquatic fauna and stepping stones along urban coastlines. Zoom into **A** Flensburg Firth, **B** Eckernförde Bay and Kiel Bay, and

C Rostock with the Warnow estuary. Shapefiles with the potential installation sites are available as geopackage in the supplementary material. Points are only suggestions and the specific location should be determined on site

for migrating birds (Bennett and Mulongoy 2006). Stepping stones are a specific kind of corridor where small patches provide habitats for shelter, feeding or resting (Bennett and Mulongoy 2006). For coastal areas, Krost et al. (2018) proposed restored shallow water biotopes as stepping stones along heavily modified coastlines to restore habitat connectivity. CFWs could contribute to the development of stepping stone corridors along urban coastlines. Successfully improving habitat connectivity does not dilute the importance of core areas. Therefore, preserving remaining core areas and restoring natural habitats should remain the priority. Implementation of stepping stones can improve habitat connectivity and thus safeguard or even increase the value of core areas.

Optimal size, shape and distance between stepping stones themselves or to the next core area depend on objectives of the local conservation managers (Harrison et al. 2016). Structural and functional connectivity differ from each other. Structural connectivity is independent from any species behavior and interpreted in terms of landscape

structure (Collinge and Forman 1998; Tischendorf and Fahrig 2000). Functional connectivity, on the other hand, refers to ecological processes and is highly dependent on the target species (Harrison et al. 2016). Functional connectivity considers the species' response when leaving the habitat, such as the mortality risk outside the patches or their movement patterns. If ecological connectors, such as stepping stones (Jongmann 1995; Saura et al. 2014), between core areas in ecological networks do not match species behavior, structural connectivity may exist without the necessary functional connectivity (Tischendorf and Fahrig 2000). Consequently, it is not enough to replace missing wetland vegetation areas along urban shorelines with floating islands to provide structural connectivity. If estuaries are piped or otherwise inaccessible, so that juvenile eels cannot migrate upstream to their freshwater habitats, the functional connectivity is missing. The same holds true for other transient nekton species using coastal wetlands in different manners (e.g. nursery, feed or refuge habitat), including fish species like mullet (*Mugil spp.*) or

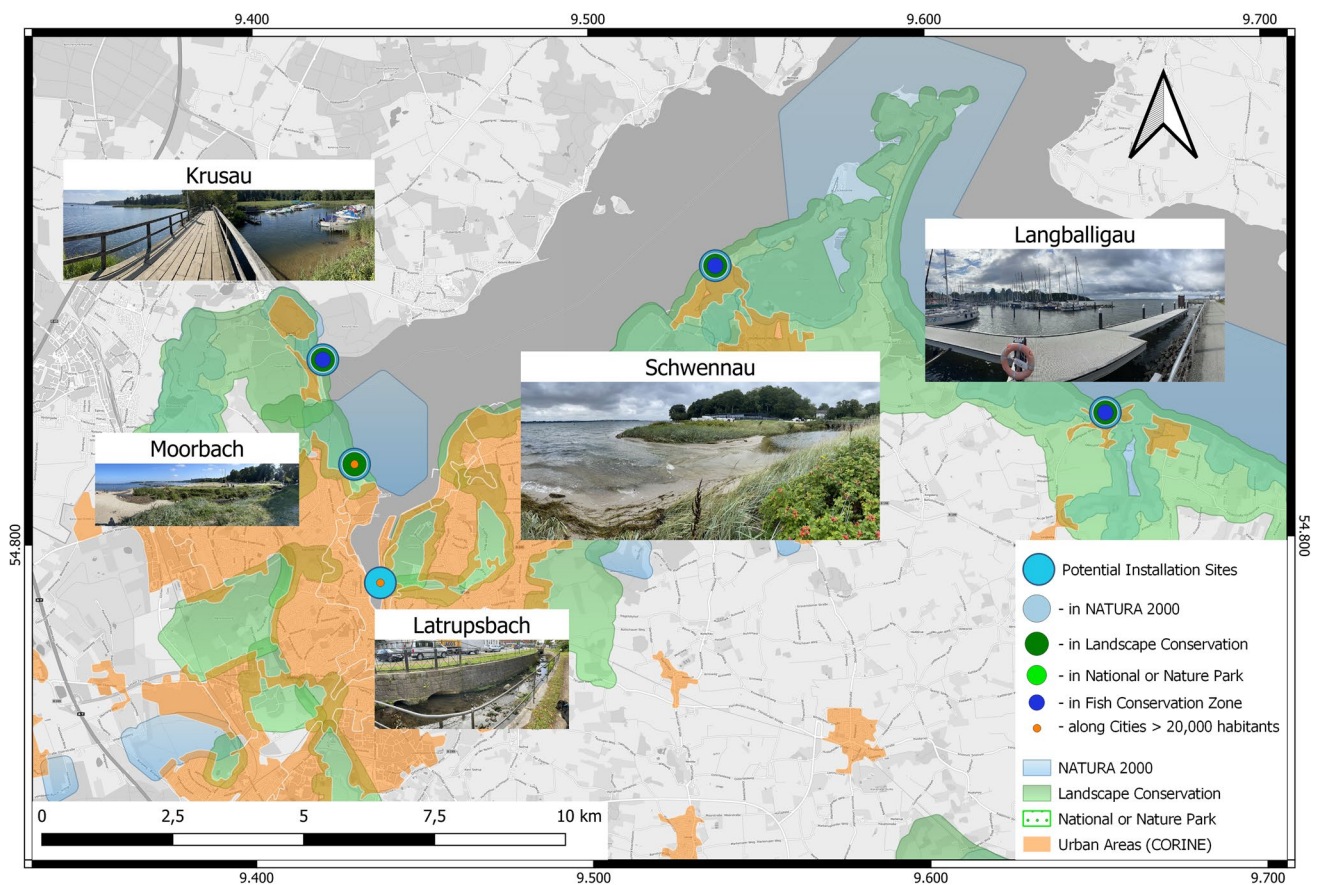


Fig. 3 An overview of the mapped potential installation sites in the Flensburg Firth. Geotagged photos with site description (Table 2) are available as geopackages in the supplementary material. Points are only suggestions and the specific location should be determined

on site. The overview of installation sites at Eckernförde, the other medium-sized town (habitants > 20,000), is in Supplementary Material

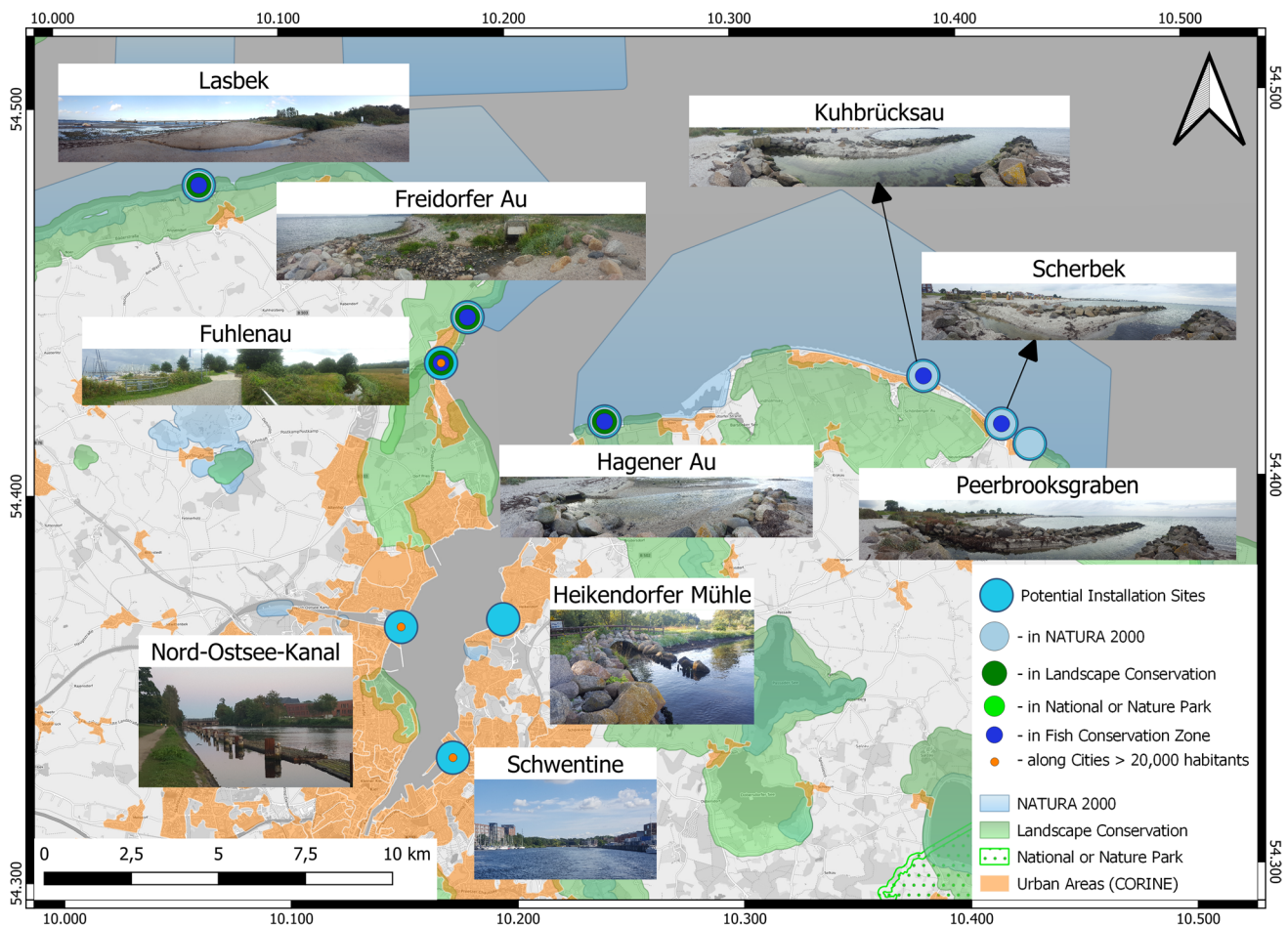


Fig. 4 An Overview of the mapped potential installation sites in the Kiel Fjord. Geotagged photos with site description (Table 2) are available as geopackages in the supplementary material. Points are

only suggestions and the specific location should be determined on site. The overview of installation sites at Rostock, the other big city (habitants > 100,000), is in the Supplementary Material.

crustaceans like shrimp (*Palaemon* spp.) (Deegan et al. 2002; Wolanski & McLusky 2011). Our field investigations showed that the open water flow is restricted at more than 40% of mapped potential installation sites (Table 2). Land and sea are connected via culverts of different shapes and sizes. In some cases, the stream was completely piped (Fig. 4). Not only vegetation on CFWs need to be adopted in accordance to prevailing species, but even more the culvert constructions. Hydrologic connectivity in undersized and poorly designed culverts are not sufficient to maintain habitat quality, up- and downstream movement of different sized fishes as well as the exchange between spawning and feeding grounds (Layman et al. 2004). In order to enhance resilience along the seascape-landscape interface, stream restoration is needed considering culvert modifications with consideration to flow turbulence and impact on fish migration (Colombano et al. 2020). Our toolkit, based on European open-source data, allows to

narrow down potential CFW installation site. However, subsequent field investigations are necessary. In case of undersized culverts, decision-makers should begin by assessing hydrological barriers before installing CFWs.

Conclusions

More than half of the mapped potential sites for CFWs are located either in NATURA 2000 areas, in national landscape conservation zones, or within national or nature parks. This offers a tremendous potential of synergies with nature conservation measures and underlines the importance of combining actions. In addition, more than 30% of the mapped sites along the German Baltic coast are located already in fish conservation zones where fishing activities (both commercial and recreational fisheries) are restricted. Our toolkit enables decision-makers to identify these overlapping areas

Table 2 Overview of field investigations of 24 potential installation sites, including anthropogenic influence, natural vegetation and conservation areas

Coastal water	Stream name	Anthropogenic influence?		Natural shoreline vegetation?		Bordering directly cities with > 20,000 habitants?	Potential conflict with maritime traffic?	Inside nature pro- tection area?	Inside fishery sanctu- ary?
		Seaside	Landside	Seaside	Landside				
Flensburg Firth	Krusau	Bank reinforcement with stones	Boat berths	Yes	Yes	No	Recreational boat- ing	Landscape con- servation area, NATURA 2000 area	Year-round, 600 m radius (KüFVO SH §7 Annex 2 (6) 1)
Flensburg Firth	Moorbach	Minor	Culvert	Partly	Partly	Yes	No	Landscape con- servation area, NATURA 2000 area	No
Flensburg Firth	Latrupsbach	Piped	Culvert	No	No	Yes	No	No	No
Flensburg Firth	Schwennau	Bank reinforcement with stones	Pedestrian bridge	Yes	Yes	No	No	Landscape con- servation area, NATURA 2000 area	1st of October— 31st of December, 200 m radius (KüFVO SH §7 Annex 2 (3) 2)
Flensburg Firth	Langballigau	Stone groynes	Straightened and fortified bank structure	No	Partly	No	Recreational boat- ing	Landscape con- servation area, NATURA 2000 area	1st of October— 31st of December, 200 m radius (KüFVO SH §7 Annex 2 (3) 2)
Eckernförde Bay	Hökholz Au	Minor	Culvert	No	Yes	No	No	Landscape con- servation area, NATURA 2000 area	No
Eckernförde Bay	Lachsenbach	Stone groynes	Culvert	Partly	Partly	Yes	No	No	No
Eckernförde Bay	Marina adjacent to Windebyer Noor	Concrete quay walls	Concrete quay walls	No	No	Yes	Recreational boat- ing Maritime Traffic	No	No
Eckernförde Bay	Drainage of Goos- see	Minor	Culvert	Partly	Partly	Yes	No	Landscape con- servation area, NATURA 2000 area	1st of October— 31st of December, 200 m radius (KüFVO SH §7 Annex 2 (3) 2)
Eckernförde Bay	Lasbek	Minor	Minor	No	Yes	No	No	Landscape con- servation area, NATURA 2000 area	1st of October— 31st of December, 200 m radius (KüFVO SH §7 Annex 2 (3) 2)

Table 2 (continued)

Coastal water	Stream name	Anthropogenic influence?		Natural shoreline vegetation?		Bordering directly cities with > 20,000 inhabitants?	Potential conflict with maritime traffic?	Inside nature protection area?	Inside fishery sanctuary?
		Seaside	Landside	Seaside	Landside				
Kiel Fjord	Freidorfer Au	Stone groyne	Culvert	Partly	Partly	No	No	Landscape conservation area, NATURA 2000 area	1st of October—31st of December, 200 m radius (KüFVO SH §7 Annex 2 (3) 2)
Kiel Fjord	Fuhlenau	Piped	Pedestrian bridge	No	Yes	Yes	Recreational boating	Landscape conservation area	1st of October—31st of December, 200 m radius (KüFVO SH §7 Annex 2 (3) 2)
Kiel Fjord	Nord-Ostsee-Kanal	Concrete quay walls	Concrete quay walls	No	No	Yes	Maritime traffic	No	No
Kiel Fjord	Schwentine	Concrete quay walls	Concrete quay walls	No	Yes	Yes	Maritime traffic	No	No
Kiel Fjord	Heikendorfer Mühle	Stone groyne	Culvert	Partly	Yes	No	No	No	No
Kiel Bay	Hagener Au	Stone groyne	Culvert	No	Yes	No	No	Landscape conservation area, NATURA 2000 area	1st of October—31st of December, 200 m radius (KüFVO SH §7 Annex 2 (3) 2)
Kiel Bay	Kuhbrücksau	Stone groyne	Culvert	No	Partly	No	No	NATURA 2000 area	1st of October—31st of December, 200 m radius (KüFVO SH §7 Annex 2 (3) 2)
Kiel Bay	Scherbek	Stone groyne	Culvert	No	Partly	No	No	NATURA 2000 area	1st of October—31st of December, 200 m radius (KüFVO SH §7 Annex 2 (3) 2)
Kiel Bay	Peerbrooksgaben	Stone groyne	Culvert	No	Yes	No	No	NATURA 2000 area	No
Warmow estuary	Mühlendamm	Straightened and fortified bank structure	Straightened and fortified bank structure	Partly	Partly	Yes	Recreational boating	Landscape conservation area	Year-round, 100 m radius, (KüFVO M-V § 11 (5))
Warmow estuary	Schmarler Bach	Straightened and fortified bank structure	Minor	No	Yes	Yes	Recreational boating	No	No

Table 2 (continued)

Coastal water	Stream name	Anthropogenic influence?		Natural shoreline vegetation?		Bordering directly cities with > 20,000 inhabitants?	Potential conflict with maritime traffic?	Inside nature protection area?	Inside fishery sanctuary?
		Seaside	Landside	Seaside	Landside				
Warnow estuary	Laak Kanal	Straightened and fortified bank structure	Minor	No	Yes	Yes	Recreational boating	No	No
Warnow estuary	Peezer Bach	Minor, except harbor infrastructure	Minor	Partly	Yes	Yes	Maritime traffic	Landscape conservation area	No
Warnow estuary	Moorgaben	Concrete quay walls	Boat berths	Yes	Yes	Yes	Recreational boating	No	No

and identify priority areas. Harrison et al. (2016) point out that the implementation of stepping stones would be most efficient if carried out simultaneously with other measures that improve habitat provision, such as artificial reefs or restoration of submerged vegetation (Krost et al. 2018). The European eel, a critically endangered species that would profit from CFW, would also benefit from other structurally diverse habitats such as seagrass meadows or stone reefs. Juvenile can be found in shallow coastal waters with an abundance of aquatic vegetation (Laffaille et al. 2003). Construction costs of plastic-free floating wetlands are with 185 US\$ per m² (EUCC-D 2021) higher than material costs for seagrass restoration (40US\$ per m², Bayraktarov et al. 2016 – plus high personnel costs), artificial reefs (30–90 US\$ per m², pers. comm. Krost 2022), saltmarsh restoration (180 US\$ per m², Bayraktarov et al. 2016) or the creation of oyster reefs (39 US\$ per m², Bayraktarov et al. 2016 – plus high personnel costs). However, actions aiming to restore sublittoral habitats are limited by light availability and thus water depth. In urbanized areas with quay walls and deeper water with muddy sediments, CFW could restore some functions of shallow water habitats or wetlands such as structural diversity, shelter from predators or food availability. Using our toolkit, 85 potential sites along the German Baltic coast were identified. The identification relied solely on information provided by EU INSPIRE Priority Datasets, in line with data driven strategic conservation management. Therefore, processing steps and site-search can be easily transferred to other countries and other target species than the European eel.

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Data Availability All data generated during this study are included in this published article and its supplementary information files.

Declarations

Competing Interests 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.

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