Wetlands (2022) 42:76
https://doi.org/10.1007/s13157-022-01598-8

COASTAL WETLANDS

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

Svenja Karstens[1,2] · Malte Dorow[3] · Ralf Bochert[4] · Nardine Stybel[2] · Gerald Schernewski[5,6] · Martina Mühl[7]

Received: 18 February 2022 / Accepted: 6 September 2022 / Published online: 16 September 2022


## 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

✉ Svenja Karstens
svenja.karstens@ifg.uni-kiel.de

1 Center for Ocean and Society, University of Kiel, Neufeldtstr. 10, 24118 Kiel, Germany

2 EUCC – Coastal Union Germany, Technologiezentrum Warnemünde, Friedrich-Barnewitz-Straße 3, 18119 Rostock, Germany

3 Mecklenburg-Vorpommern Research Centre for Agriculture and Fisheries (LFA MV), Institute of Fisheries, Fischerweg 408, 18069 Rostock, Germany

4 Mecklenburg-Vorpommern Research Centre for Agriculture and Fisheries (LFA MV), Institute of Fisheries, Südstr. 8, 18375 Born/Darß, Germany

5 Leibniz-Institute for Baltic Sea Research (IOW), Seestrasse 15, 18119 Rostock-Warnemünde, Germany

6 Marine Research Institute, Klaipeda University, Universiteto ave. 17, Lt-92294 Klaipeda, Lithuania

7 CRM - Coastal Research & Management, Tiessenkai 12, 24159 Kiel, Germany

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 $km^2$ 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/datasetfeed.xml | Priority Dataset of INSPIRE (Infrastructure for Spatial Information in the European Community)—https://inspire-geoportal.ec.europa.eu – available for most countries<br>Directive 2000/60/EC—Rivers (Water Framework Directive)<br>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<br>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 Huckstorf;<br>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=true and https://www.landesrecht-mv.de/bsmv/document/jlr-K%C3%BCFischVMV2006V3P1<br>Shapefiles on request | 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) | https://gdz.bkg.bund.de/index.php/default/digitale-geodaten/verwaltungsgebiete/verwaltungsgebiete-1-250-000-mit-einwohnerzahlen-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)<br>Mecklenburg-Western<br>Pomeranian Agency for the Environment, Nature Conservation and Geology | https://opendata.schleswig-holstein.de/dataset/biotopkartierung<br>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 habitants) to big-sized cities (> 50,000 habitants) (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

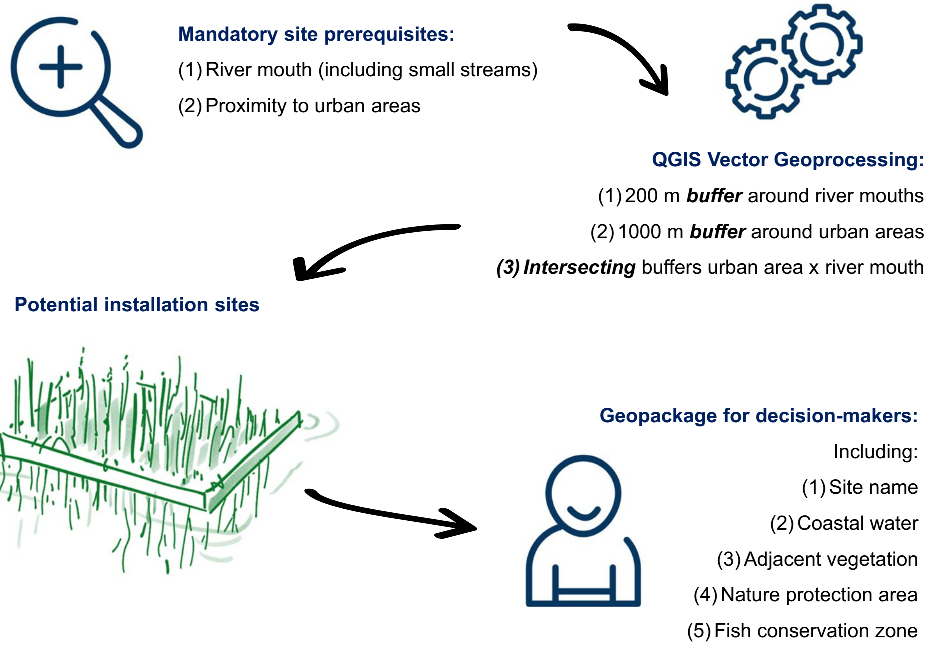


**Fig. 1** Work flow and geodata processing to identify suitable installation sites for constructed floating wetlands. All data used is freely available (see Table 1) and GIS procedures easy-to-use. Solely fish conservation zones were created manually for this study. (Symbols in Fig. 1 provided by Christian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

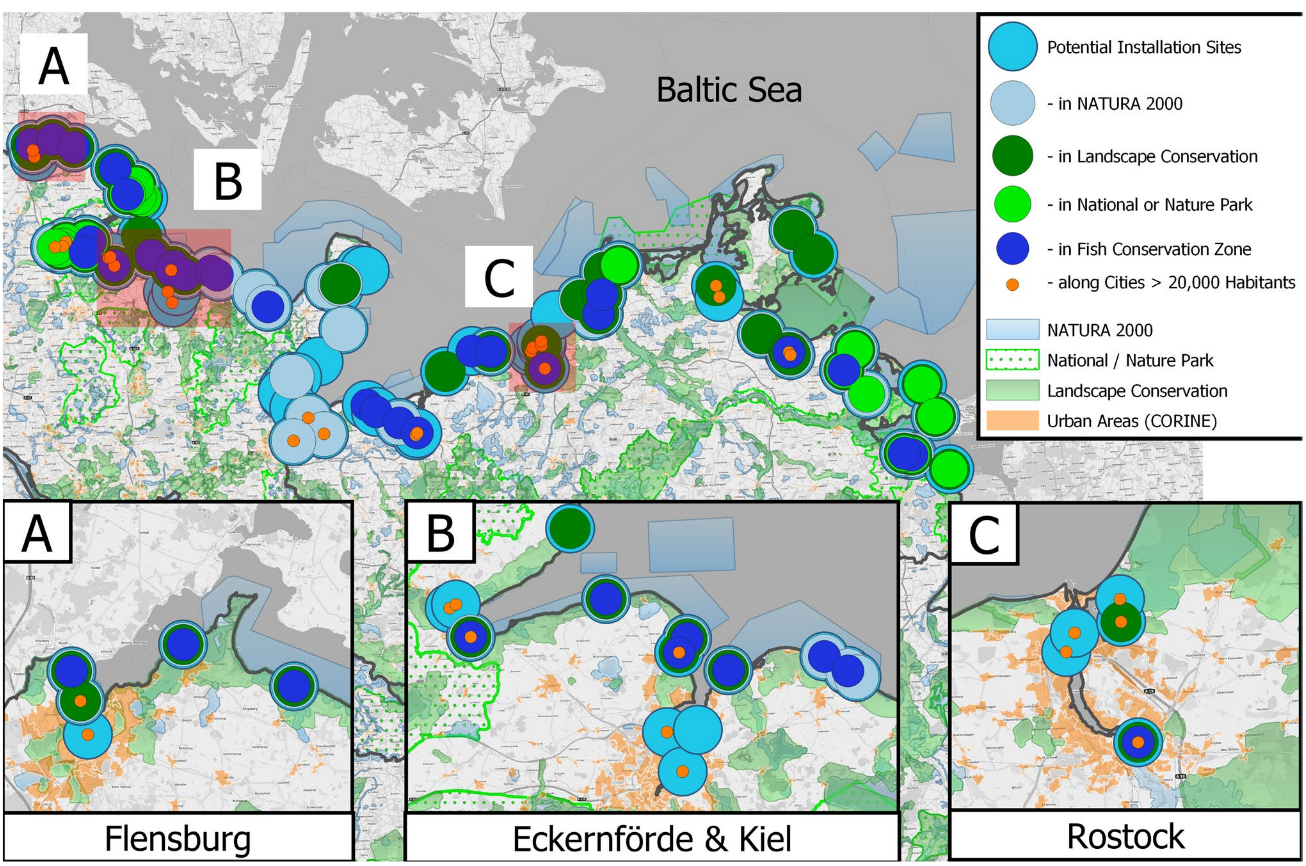


**Fig. 2** Mapping of potential installation sites of constructed floating wetlands along the German Baltic Sea that could potentially serve as refuges for aquatic fauna and stepping stones along urban coastlines. Zoom into **A** Flensburg Firth, **B** Eckernförde Bay and Kiel Bay, and **C** Rostock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

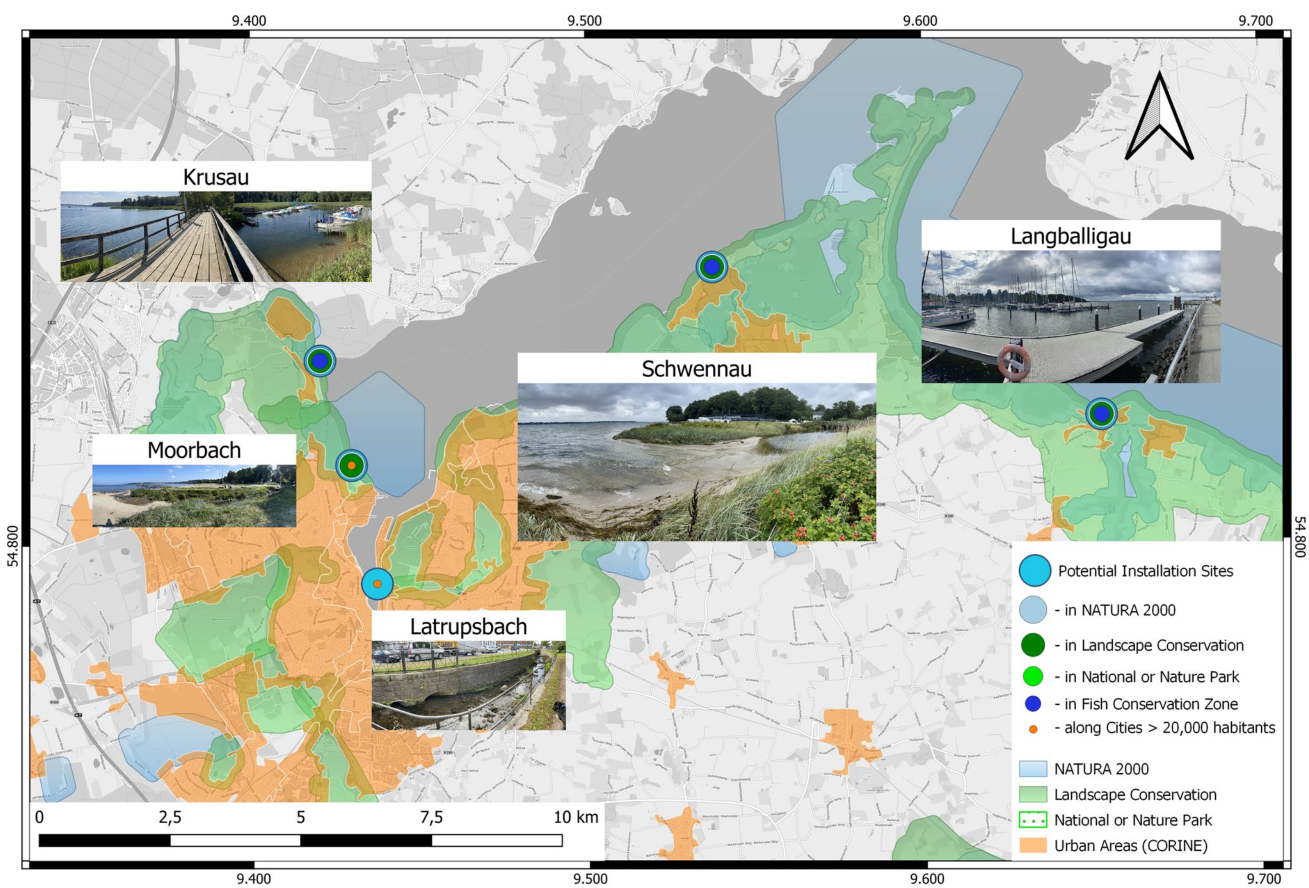


**Fig. 3** An overview of the mapped potential installation sites in the Flensburg Firth. Geotagged photos with site description (Table 2) are available as geopackages in the supplementary material. Points are only suggestions and the specific location should be determined on site. The overview of installation sites at Eckernförde, the other medium-sized town (habitants > 20,000), is in Supplementary Material

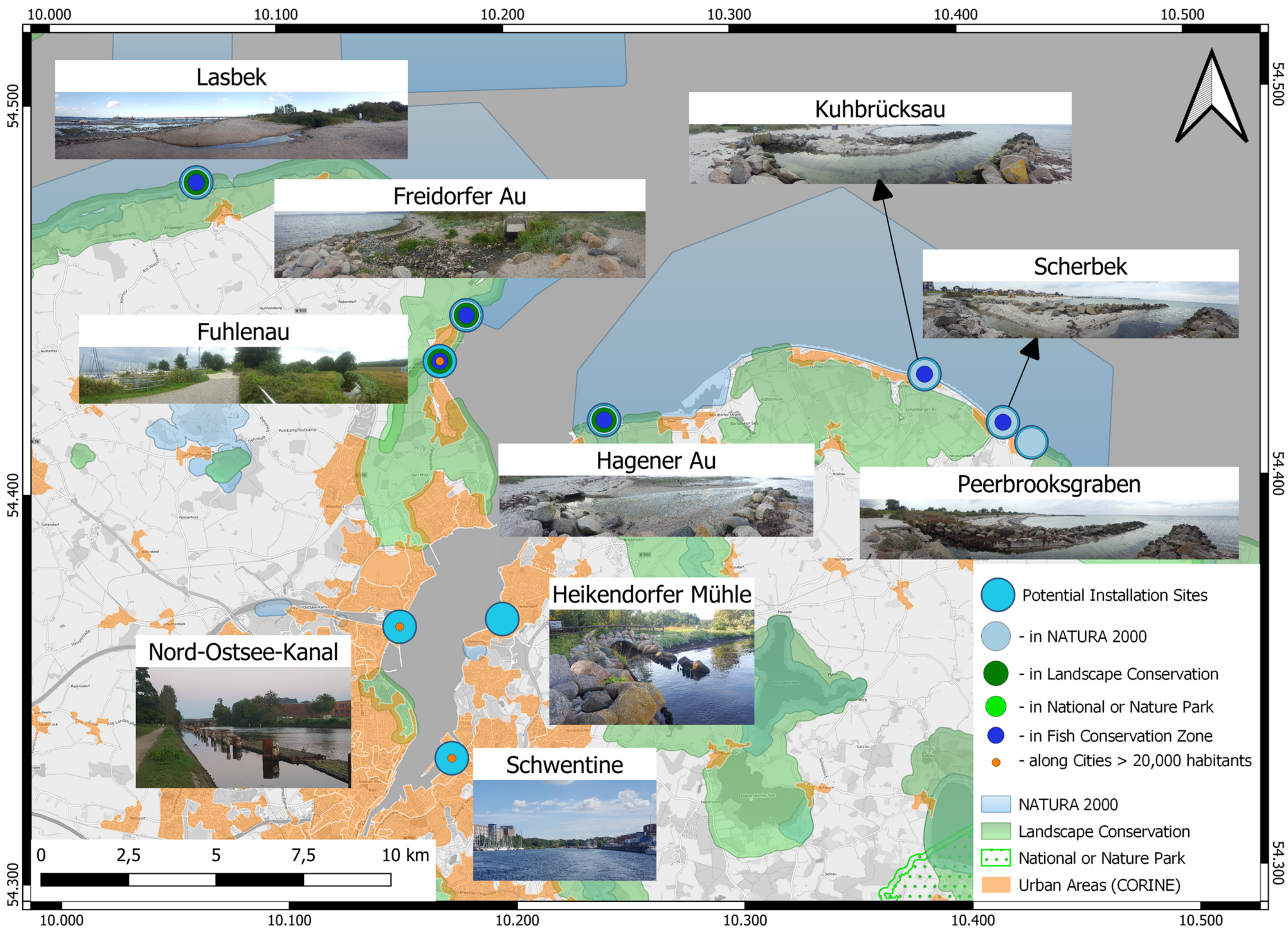


**Fig. 4** An Overview of the mapped potential installation sites in the Kiel Fjord. Geotagged photos with site description (Table 2) are available as geopackages in the supplementary material. Points are only suggestions and the specific location should be determined on site. The overview of installation 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 protection area? | Inside fishery sanctuary? |
|---|---|---|---|---|---|---|---|---|---|
| | | Seaside | Landside | Seaside | Landside | | | | |
| Flensburg Firth | Krusau | Bank reinforcement with stones | Boat berths | Yes | Yes | No | Recreational boating | Landscape conservation 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 conservation 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 conservation 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 boating | Landscape conservation 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 conservation 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 boating<br>Maritime Traffic | No | No |
| Eckernförde Bay | Drainage of Goossee | Minor | Culvert | Partly | Partly | Yes | No | Landscape conservation 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 conservation 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 habitants? | Potential conflict with maritime traffic? | Inside nature protection area? | Inside fishery sanctuary? |
|---|---|---|---|---|---|---|---|---|---|
| | | Seaside | Landside | Seaside | Landside | | | | |
| Kiel Fjord | Freidorfer Au | Stone groynes | 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 groynes | Culvert | Partly | Yes | No | No | No | No |
| Kiel Bay | Hagener Au | Stone groynes | 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 groynes | 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 groynes | 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 | Peerbrooksgraben | Stone groynes | Culvert | No | Yes | No | No | NATURA 2000 area | No |
| Warnow 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)) |
| Warnow 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 habitants? | 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 | Moorgraben | 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 $m^2$ (EUCC-D 2021) higher than material costs for seagrass restoration (40US$ per $m^2$, Bayraktarov et al. 2016 – plus high personnel costs), artificial reefs (30–90 US$ per $m^2$, pers. comm. Krost 2022), saltmarsh restoration (180 US$ per $m^2$, Bayraktarov et al. 2016) or the creation of oyster reefs (39 US$ per $m^2$, 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.

**Authors' Contributions** SK developed the article concept, analyzed the data, and drafted and substantially edited the article. MD, RB, NS supported the article concept development, data analysis and the writing. GS and MM supported the analysis and commented on the paper.

**Funding** Open Access funding enabled and organized by Projekt DEAL. This research is part of following projects: (1) 'The use of active barriers for the nutrient removal and local water quality improvement in Baltic lagoons (LiveLagoons)', funded by EU South Baltic Interreg Program (STHB.02.02.00-LT-0089/16). (2) "Innovationsraum: BaMS-HaFF – Halophyten und andere Makrophyten zur Filtration von nährstoffbelasteten Ab- und Oberflächenwasser in Freilandkultur" (Constructed wetlands and floating cultivation of marsh plants for treatment and bioremediation of saline waters and waste waters) (FKZ031B0915C2), funded by the German Federal Ministry of Education and Research.

**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.

## References

Afzal M, Arslan M, Müller JA, Shabir G, Islam E, Tahseen R, …, Khan QM (2019) Floating treatment wetlands as a suitable option for large-scale wastewater treatment. Nature Sustainability 2(9):863–871

Bayraktarov E, Saunders MI, Abdullah S, Mills M, Beher J, Possingham HP, …, Lovelock CE (2016) The cost and feasibility of marine coastal restoration. Ecological Applications 26(4):1055–1074

Bennett G, Mulongoy KJ (2006) Review of experience with ecological networks, corridors and buffer zones. In: Secretariat of the convention on biological diversity, Montreal, Technical Series (Vol 23, p 100)

Benzeev R, Hutchinson N, Friess DA (2017) Quantifying fisheries ecosystem services of mangroves and tropical artificial urban shorelines. Hydrobiologia (incorporating JAQU) 803(1):225–237

Borchert SM, Osland MJ, Enwright NM, Griffith KT (2018) Coastal wetland adaptation to sea level rise: Quantifying potential for landward migration and coastal squeeze. Journal of Applied Ecology 55(6):2876–2887

Carranza ML, Drius M, Marzialetti F, Malavasi M, de Francesco MC, Acosta AT, Stanisci A (2020) Urban expansion depletes cultural ecosystem services: an insight into a Mediterranean coastline. Rendiconti Lincei Scienze Fisiche e Naturali 31(1):103–111

Colares GS, Dell'Osbel N, Wiesel PG, Oliveira GA, Lemos PHZ, da Silva FP, …, Machado ÊL (2020) Floating treatment wetlands: A review and bibliometric analysis. Science of the Total Environment 714:136776

Collinge, S. K., & Forman, R. T. (1998). A conceptual model of land conversion processes: predictions and evidence from a microlandscape experiment with grassland insects. Oikos 66–84

Colombano DD, Manfree AD, Teejay AO, Durand JR, Moyle PB (2020) Estuarine-terrestrial habitat gradients enhance nursery function for resident and transient fishes in the San Francisco Estuary. Marine Ecology Progress Series 637:141–157

Deegan LA, Hughes JE, Rountree RA (2002) Salt marsh ecosystem support of marine transient species. In Concepts and controversies in tidal marsh ecology. Springer, Dordrecht, pp 333–365

Dipper F (2022) Elements of Marine Ecology. Butterworth-Heinemann

Elmgren R, Hill C (1997) Ecosystem function at low biodiversity—the Baltic example. Marine biodiversity: patterns and processes, 319–336

EUCC-D (2021) Stellungnahme zu den Gewässermanagementplänen M-V, 21.06.2021

Harrison, L. J., White, P. C. L., & Odell, S. (2016). Connectivity and ecological networks: Technical Information Note 01/2016.

HELCOM (2010) Ecosystem Health of the Baltic Sea 2003- 2007: HELCOM Initial Holistic Assessment. In: Baltic Sea environment proceedings, vol 122, no 63. Baltic Marine Environment Protection Commission, Helsinki (Finnland), p 2010

HELCOM (2013) HELCOM red list of baltic sea species in danger of becoming extinct. Baltic Sea Environment Proceedings, No, p 140

Huang X, Zhao F, Song C, Gao Y, Geng Z, Zhuang P (2017) Effect of stereoscopic artificial floating wetlands on nekton abundance and biomass in the Yangtze Estuary. Chemosphere 183:510–518

Hupfer P (2010) Die Ostsee - kleines Meer mit großen Problemen. Borntraeger, Stuttgart

ICES (2009) Report of the Study Group on Anguillid Eels in Saline Waters (SGAESAW), 16–18 March 2009, Sackville, Canada; 3–5 September Gothenburg, Sweden. ICES CM/DFC:06, 183 pp. Copenhagen: International Council for Exploitation of the Seas

ICES (2020) Joint EIFAAC/ICES/GFCM Working Group on Eels (WGEEL). ICES Scientific Reports, 2:85, 223 pp

Jongman RH (1995) Nature conservation planning in Europe: developing ecological networks. Landscape and Urban Planning 32(3):169–183

Karstens S, Langer M, Nyunoya H, Čaraitė I, Stybel N, Razinkovas-Baziukas A, Bochert R (2021) Constructed floating wetlands made of natural materials as habitats in eutrophicated coastal lagoons in the Southern Baltic Sea. Journal of Coastal Conservation 25(4):1–14

Krost P, Goerres M, Sandow V (2018) Wildlife corridors under water: an approach to preserve marine biodiversity in heavily modified water bodies. Journal of Coastal Conservation 22(1):87–104

KüFVO SH (2020) SH § 7 Annex 2 (3) 2. https://www.gesetze-rechtsprechung.sh.juris.de/jportal/?quelle=jlink&query=K%C3%BCFischV+SH&psml=bsshoprod.psml&max=true&aiz=true. Last accessed 2022/02/07

Laffaille P, Feunteun E, Baisez A, Robinet T, Acou A, Legault A, Lek S (2003) Spatial organisation of European eel (Anguilla anguilla L.) in a small catchment. Ecology of Freshwater Fish 12(4):254–264

Layman CA, Arrington DA, Langerhans RB, Silliman BR (2004) Degree of fragmentation affects fish assemblage structure in Andros Island (Bahamas) estuaries. Caribbean Journal of Science 40(2):232–244

Li Y, Zhu X, Sun X, Wang F (2010) Landscape effects of environmental impact on bay-area wetlands under rapid urban expansion and development policy: a case study of Lianyungang. China Landscape and Urban Planning 94(3–4):218–227

Lin T, Xue X, Shi L, Gao L (2013) Urban spatial expansion and its impacts on island ecosystem services and landscape pattern: A case study of the island city of Xiamen, Southeast China. Ocean & Coastal Management 81:90–96

Mao D, Wang Z, Wu J, Wu B, Zeng Y, Song K, Luo L (2018) China's wetlands loss to urban expansion. Land Degradation and Development 29(8):2644–2657

Minello TJ, Able KW, Weinstein MP, Hays CG (2003) Salt marshes as nurseries for nekton: testing hypotheses on density, growth and survival through meta-analysis. Marine Ecology Progress Series 246:39–59

Moody RM, Cebrian J, Heck KL Jr (2013) Interannual recruitment dynamics for resident and transient marsh species: evidence for a lack of impact by the Macondo oil spill. PLoS One 8(3):e58376

Pavlineri N, Skoulikidis NT, Tsihrintzis VA (2017) Constructed floating wetlands: a review of research, design, operation and management aspects, and data meta-analysis. Chem Eng J 308:1120–1132

Perillo G, Wolanski E, Cahoon DR, Hopkinson CS (Eds) (2018) Coastal wetlands: an integrated ecosystem approach. Elsevier, Amsterdam

R Core Team (2021) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna. https://www.R-project.org/

Saura S, Bodin Ö, Fortin MJ (2014) EDITOR'S CHOICE: Stepping stones are crucial for species' long-distance dispersal and range expansion through habitat networks. Journal of Applied Ecology 51(1):171–182

Snoeijs-Leijonmalm P, Andrén E (2017) Why is the Baltic Sea so special to live in? Biological oceanography of the Baltic Sea. Springer, Dordrecht, pp 23–84

Statistikamt Nord – Bevölkerung der Gemeinden in Schleswig-Holstein 4. Quartal 2020 (XLSX-Datei), https://www.statistik-nord.de/fileadmin/Dokumente/Statistische_Berichte/bevoelkerung/A_I_2_S/A_I_2_vj_204_Zensus_SH.xlsx Last accessed 2021/10/05

Statistisches Amt M-V – Bevölkerungsstand der Kreise, Ämter und Gemeinden 2020 (XLS-Datei), https://www.laiv-mv.de/static/LAIV/Statistik/Dateien/Publikationen/A%20I%20Bev%C3%B6lkerungsstand/A123/2020/A123%202020%2022.xls Last accessed 2021/10/05

Sterr H (2008) Assessment of vulnerability and adaptation to sea-level rise for the coastal zone of Germany. J Coast Res 24(2):380–393

Tischendorf L, Fahrig L (2000) On the usage and measurement of landscape connectivity. Oikos 90(1):7–19

Wolanski E, McLusky DS (Eds) (2011) Treatise on estuarine and coastal science. Academic, Cambridge

Yeh N, Yeh P, Chang Y-H (2015) Artificial floating islands for environmental improvement. Renew Sust Energ Rev 47:616–622

**Publisher's Note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.