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Defining a typology for Danish coastal waters

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Abstract

A typology has been developed for the Danish coastline, most of which is located in a region with a strong physical and biological gradients. It was found necessary to use different criteria for characterizing the open water coast and estuaries. The open water coast was characterized with respect to salinity, depth, wave exposure and tidal influence, whereas estuaries were characterized with respect to bottom salinity, degree of stratification, the ratio of residence time to surface runoff and sluice-control. The approach results in dividing the Danish coastal waters into 15 different types. It, however, still remains to be analyzed whether this typology is useful when considering different biological quality elements as indicators of water quality.

1 Introduction

The European Water Framework Directive (WFD, EUROPEAN UNION 2000) requires characterizing of coastal waters into types defined by distinctive hydromorphological and physical conditions. These physical conditions are specified in Annex II of the WFD and include salinity, tidal range, wave exposure and substrate type, depending on which conditions are the most defining for the biology in a given area. The idea is that physical conditions define distinct biological features in the coastal zone, with a known quality, if no other pressures are present in the area. Further, the WFD requires that reference conditions for a number of biological quality elements are developed for each type, i.e. areas of a given type has the same set of reference conditions associated with them. These reference conditions ideally describe the undisturbed state of a given type. Consequently, successful implementation of the WFD requires that the typology in fact does reflect the geographical differences among the biological quality elements.

The Danish coastline can be divided into the North Sea/Skagerrak Coast and the Kattegat and Belt Seas located in the transition area between the North Sea and the Baltic Sea. The North Sea/Skagerrak Coast is a high-energy coast, which in the southern part is also influenced by tides. The Kattegat and Belt Seas have characteristics similar to a large estuary: dynamic and large water exchange driven by meteorological conditions, and as a consequence of this exchange a large salinity gradient is present between the northern and southern parts, and the water column is almost permanently stratified. In addition to the open coastline, a number of estuaries are located along the coast. The variability of the open water is also reflected in the estuaries both in terms of salinity gradients and stratification.

The large physical gradients found in both coastal waters and estuaries means that the ecological conditions are also highly variable in both time and space. Accordingly, the coastline has been divided into a large number of types that reflect this variability. Here we discuss the criteria used for selecting physical factors used for defining these types.

2 Results

The Danish waters that are encompassed by the WFD are shown in Figure 1. The coastline is divided into two major types: open water and estuarine types. The open water coastline tends to be more exposed to waves and tides and less affected by run-off, which creates environmental conditions that are very different from those found in estuaries. The freshwater run-off to Danish estuaries means that a strong salinity gradient may exist within an estuary. Residence times are typically much longer than along the open coast, suggesting a stronger response to landbased river inputs (typically nitrogen and phosphorous load) in estuaries.

2.1 Criteria for selection of Open Water Types

The open water category comprises the Danish part of the Wadden Sea, the Danish North Sea/Skagerrak Coast, the exposed coastline of the Kattegat and Western Baltic Sea, and the coast of Bornholm. The open water category is characterized with respect to salinity, depth, exposure, and tidal regime. In most cases the biological response to these physical pressures represent a continuum of responses and consequently, only few clearly defined boundaries for biological communities exist. This lack of clearly defined boundaries often makes it difficult to argue for why one boundary should be chosen over another.

In the case of salinity, the boundaries specified in the WFD were used, resulting in three salinity categories: euhaline ($S>30$), polyhaline ($S>18$ & $S\leq30$) and mesohaline ($S>5$ & $S\leq18$). In large parts of the Danish open water coast, salinity also varies with depth. It was chosen to use bottom salinity because the WFD requires that biological response is measured in terms both benthic macro fauna and submerged aquatic vegetation, indicators that both respond more strongly to bottom salinity than to mean or surface salinity. The euhaline category is found along the North Sea/Skagerrak coast, the polyhaline category is found within the Kattegat. Apart from in the Sound, a well-defined geographical boundary between the polyhaline and mesohaline category does not exist due to the large variability in salinity in the Danish waters. In the Sound, the Drogden Sill defines the boundary between the polyhaline and mesohaline category. Here we have drawn the boundary in the Little Belt, Great Belt and the Drogden Sill in the Sound.

The tidal regime along the Danish coast ranges from micro-tidal (range < 30cm) in the Kattegat and Western Baltic Sea to mesotidal (range > 30 cm & < 1.5 meters) along the North Sea coast. The largest tidal range is found the Wadden Sea, and this area has been assigned its own type, which is expected to be the same as the German and Dutch Wadden Sea types.

Most of the open Danish coast is characterized by shallow water (depths<15m). It was none the less decided to use depth as one of the defining physical criteria because one of the most clearly defined separations of biological communities in open water exists with depth. The stratification that arises in the Kattegat due to low salinity water flowing out of the Baltic and high salinity water flowing in from the Skagerrak typically has a halocline depth of 15 meters. In areas of the Kattegat where the seafloor is at depths greater than 15 meters, salinity is typically at oceanic levels, in the euhaline range and at this depth the *Amphiura* fauna community is found. At sea floor depths shallower than 15 meters, the *Macoma* fauna community is found.

An overview of the open water types is shown in Table 1 and the distribution of open-water types is shown in Figure 1.

Table 1: Open water types in Danish coastal waters.

Salinity	Mesohaline (S>5&S≤18)	Polyhaline (S>18&S≤30)	Euhaline (S>30)		
Other physical pressures		Depth < 15 meters	Depth > 15 meters	Wave exposed	Tidal influence
Type	ow3	ow2	ow1	ow4	ow5

2.2 Criteria for selection of estuary types

The Danish coast includes a large number of shallow water estuaries. For an overview see CONLEY et al. (2000). JOSEFSON & RASMUSSEN (2000) have documented that in addition to salinity regime, estuary residence time may be important for defining the biomass of benthic macro fauna in a particular area, and unpublished observations have also shown the influence of stratification on biomass of benthic macro-fauna. Consequently the typology for Danish estuaries is based those three physical pressures. In addition, two sluice-controlled estuaries are found on the West Coast of Denmark. This man made control provides unique conditions in both estuaries and they have been characterized as their own type. The estuaries have thus been characterized in terms of salinity, stratification, a sensitivity index, defined as the ratio between run-off and residence time, as well as sluice-control at the estuary mouth.

2.3 Salinity and stratification

Salinity profile measurements made for up to 20 years in 33 estuaries were used to determine surface and bottom salinity in each set of measurements. Benthic fauna and submerged aquatic vegetation that are used as biological indicators respond to bottom salinity. Consequently, bottom salinity is used to characterize salinity of the estuary. In several estuaries, the permanent monitoring stations are located at the deepest point, which is often unrepresentative of estuary depth. Thus, we have chosen to define the depth, where 80% of the estuary has a depth more shallow than this depth, as the bottom. The limits of the salinity boundaries are the same as those used for open water. In many cases, the fresh water run-off creates a horizontal salinity gradient within an estuary, but only in 4 cases is the gradient strong enough to require division of the estuary into two or even three types.

A stratification index ΔS, has been calculated as the difference between bottom and surface salinity because the degree of stratification expresses the availability of food to bottom fauna. In a well-mixed estuary, the food supply is independent of depth, but in a stratified estuary, food availability may be very different above and below the halocline, thus providing habitat for different types of communities with depth. Further the strength of the stratification is an indicator of the estuary sensitivity to oxygen depletion events. When $\Delta S > 1$ in 50% or more of the profile measurements, the location corresponding to those measurements is considered stratified.

The run-off to most estuaries is small relative to their volume and water residence time is typically controlled by exchange at the estuary mouth rather than by the magnitude of catchment surface water discharge. Most estuaries border the inner Danish waters that are micro tidal and consequently the water exchange between the estuary and adjacent sea is driven more by morphology of the estuary mouth and by meteorological conditions than by tidal elevation.

A sensitivity index (F) has been calculated as the ratio between run-off and residence time to identify the sensitivity to freshwater inputs and thus nutrient inputs. An estuary with a long residence time will be more sensitive to nutrient inputs, but if the run-off to that estuary at the same time is small, the effect will be less. When calculating the sensitivity index, run-off in m^3s^{-1} and residence time in days was used. This provided values ranging from 10^{-4}to14 $m^3 s^{-1}$ day^{-1}, and the median value rounded off to the nearest decade was used as boundary between two categories.

The residence times used to calculate the sensitivity index are estimated from the following two relations:

$$T = \frac{V}{Q+R} \qquad \text{and} \qquad Q = \frac{\frac{S}{Sm}}{\left(1-\frac{S}{Sm}\right)} R$$

where V is estuary volume, Q is salt water supply, R is run-off, S is surface salinity in the estuary and Sm is salinity at the estuary mouth (RASMUSSEN OG JOSEFSON, 2002). This relation provides an estimate of residence time that is within the right order of magnitude, but also one that may deviate from other estimates for example calculated using hydraulic models. It will also only provide the correct result in those situations where the salinity is lower inside than outside the estuary and uncertainty increases when run-off is very small.

An overview of the estuary types is shown in Table 2.

The criteria defined in the previous section have been used to characterize both open water and the 33 largest estuaries in Danish coastal waters. Types O1, O2, and O3 are not present in any of the selected estuaries. The geographical distribution of types is shown in Figure 1.

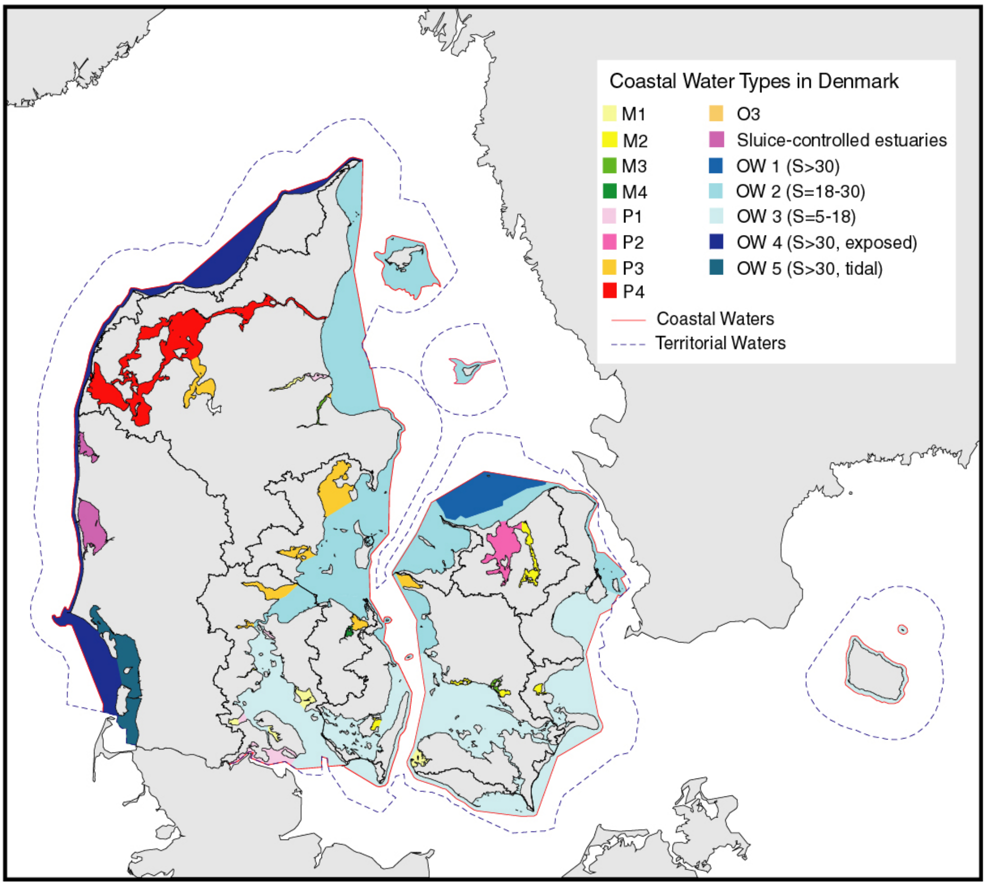

Figure 1. Open water and estuary types in Danish coastal waters.

Table 2: Estuary types in Danish coastal waters.

Oligohaline (S≤5)				Mesohaline (S>5&S≤18)				Polyhaline (S>18&S≤30)			
Stratified ΔS>1		Mixed ΔS≤1		Stratified ΔS>1		Mixed ΔS≤1		Stratified ΔS>1		Mixed ΔS≤1	
F≤0.1	F>0.1	F≤0.1	F>0.1	F≤0.1	F>0.1	F≤0.1	F>0.1	F≤0.1	F>0.1	F≤0.1	F>0.1
O1	O3	O2	O4	M1	M3	M2	M4	P1	P3	P2	P4

3 Discussion

Here we have presented a simple method for developing a typology for coastal waters in an area with large geographical differences, which results in 15 different open water and estuary types. While these 15 different types represent a wide range of physical conditions, it is still unclear to which extent they also represent the variability within biological communities.

The biological quality elements specified in the WFD are abundance and sensitive species of benthic macro fauna, species composition, abundance and biomass of phytoplankton, and abundance, distribution and biomass of bottom vegetation. All of these quality elements have been systematically monitored at a large number of stations in Danish waters since 1989, and thus, a large base of information is available for linking biological quality to types in this area. There are, however, a number of difficulties related to establishing agreement between type and ecological quality, and while ongoing work aims at relating biological quality elements to the typology, this work has not yet been completed.

The lack of clear boundaries between biological communities makes it difficult to establish a "reasonable" number of types. For example, preliminary work shows that this typology describes differences in species diversity of benthic macro fauna, but the analysis also suggests that using different values to describe the boundary between two types may describe this measure of environmental quality equally well. Types have also been defined where no or only few measurements of biological elements have been made, making it difficult to determine whether the type is relevant.

The physical environments relevant for the different biological elements are very different. The definition of types used here is based on bottom salinity because benthic macro fauna and aquatic vegetation are expected to respond to local bottom conditions. Bottom salinity is, however, not the relevant salinity for phytoplankton in stratified environments. Phytoplankton are only associated with the photic zone, which is very shallow in this area (8-10 meters deep). In addition, phytoplankton and other pelagic organisms are transported over large distances in this region, and thus, phytoplankton communities may not necessarily be different in areas of different type.

Eelgrass (*Zostera marina*) is the most widespread angiosperm in the Danish coastal waters, and it is regarded as a useful indicator of water quality because water clarity regulates its extension towards deeper waters. In a study where the depth limit of eelgrass was used as an indicator of ecological quality, KRAUSE-JENSEN et al. (2004) found that it was not possible to establish sufficiently accurate reference conditions for depth limit within a distribution of types that was based on salinity and depth. The eelgrass depth limit also responds to other pressures such as exposure levels and sediment composition that are also not included in the typology presented here. Including those factors in the typology would mean developing types that would have very small geographical extent, which is not the intent of the WFD.

This study represents a method for developing a typology in a region with a highly variable physical and biological environment. The approach results in dividing the Danish coastal waters into 15 different types. It, however, still remains to be defined how useful this typology is when considering different biological quality elements as indicators of water quality.

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