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Morphometric Classification and GIS-Based Data Analysis in Coastal Modeling and Management

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Abstract: This paper describes how morphometric classification (based on openness, form, depth and size) and Geographic Information Systems (GIS) can be used for possible identification of coastal areas sensitive to pollution. Generalized maps of key water properties are then created for as large parts of Europe as possible using large amounts of empirical data. These maps give an overview of the general spatial pattern of the presented properties and offer identification of highly polluted coastal areas. They also provide input and reference data for two dynamic ecosystem models (CoastWeb and CoastMab) suitable for in-depth studies of individual coastal areas or regions. A modeling case study of coastal eutrophication is presented to illustrate that these general models may be practically applied for simulations related to the response of coastal ecosystems to various remedial scenarios using only the data presented in the morphometric coastal classification system and in the generalized overview maps.

Keywords: Coastal areas, morphometric classification, GIS, maps, ecosystem modeling.

INTRODUCTION

The coastal zone is of great importance for recreation, fishing, water planning and shipping and it is a zone where different conflicts and demands overlap. The natural processes (water transport, fluxes of material and energy and biological production) in this zone are of utmost importance for the entire sea. It may also be considered a “nursery and pantry” for the sea [1].

A coastal area may be defined and characterized in many ways, e.g., according to territorial boundaries, pollution status, water stratification, etc. Several coastal classification systems have been developed through the years (see, e.g., a review by Bird [2]). Many of these systems are specific and based on sea level changes [3], hydrographic regime [4], tectonics [5] or geological history [6]. Johnson [3] and Davies [4, 7] have presented coast type classifications based on geological considerations, e.g., according to form-creating processes. Valentin [8, 9] based a coastal classification on whether the coast is expanding or retreating. There are also different regional classification systems [10, 11] generally based on or related to the system of Davies. Coastal classification systems like these are useful to get a broad overview of the specific features and they can explain why the coastal geomorphology looks the way it does, but they do not provide the data necessary for ecological modeling or quantification, e.g., how and why a given coastal area functions as a “nursery and pantry” for the biological production or as a receiving system for water pollutants. The aim of the coastal classification and Geographic Information System (GIS) methodology discussed in this work is to address such issues.

In more recent time, several national classification systems have been developed that include both chemical variables and morphometry with examples in Sweden [12], Scotland [13] and Italy [14]. The Australian OzCoasts online database [15] provides easy access to coastal data, classifications, but also shows examples of how GIS can be useful in benthic habitat mapping. Another example of a similar initiative at the regional level is the Irish Sea Pilot [16], a project where the Irish Sea was used to test an ecosystem approach in marine management at the regional level. That project is a good example of how GIS can be successfully used to combine chemical, morphometrical, ecological and other data in comprehensive analyses. GIS has also been a component in several other coastal classification methods [17]. The trophic level classification system presented by Håkanson *et al.* [18] is based on practically useful, operational effect variables or bioindicators for coastal management. Such bioindicators should meet the following criteria [19-22]: (1) they should be measurable, preferably simply and inexpensively, (2) clearly interpretable and predictable by validated quantitative models, (3) internationally applicable, (4) relevant for the given environmental threat and (5) representative for the given ecosystem.

With a focus on eutrophication in marine coastal areas, Vollenweider *et al*. [23] developed a water quality index which was applied on the Adriatic Sea. The U.S. National Estuarine Eutrophication Assessment (NEEA; [24]) was a very comprehensive assessment of eutrophication in U.S. estuaries that considered many different stressors and indicators and included, e.g., a classification of the overall trophic conditions, based on different symptoms. Gazeau *et al.* [25] presented anthropogenic, geomorphic, oceanographic and terrestrial attributes for the whole European coastal zone, sub-divided into four regions, and reviewed available data on ecosystem metabolism in different regions and systems. The importance of using both

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morphometric as well as chemical information (salinity, chlorophyll-a and dissolved oxygen) when subdividing and classifying coastal systems was also addressed by Ferreira *et al.* [26]. They also included loading of nutrients into their methodology. Some of the presented regional systems ([15,16]) give an overview of the chemical and geo-physical situation in their region. It is however not easy to find similar overview maps of important operational effect variables and bioindicators for the whole European coastal zone. As an attempt to address this, such maps will be derived as a part of this work using data from public databases. The LOICZ project [27] is a good example of an effort to create a global coastal classification, or typology. One very useful output of the project is the global LOICZ/Hexacoral Environmental Typology Database [28]. This however sometimes lacks the detail needed in local or regional investigations. An important policy document that deals with both typology and classification of coasts is the EU Water Framework Directive [29]. This, and its Common Implementation Strategy for transitional and coastal waters [30] are meant to promote the development of new operational classification systems for a sustainable coastal management. This work is intended as a contribution towards such ends.

MODELING

Process-based dynamic mass-balance models are essential tools for gaining a deeper understanding of how a number of complex processes in an aquatic system together determine the concentration of a studied substance, e.g., a nutrient or a contaminant [31]. Mass-balance models have long been used as tools to study lake eutrophication [32, 33] and also in different coastal applications [34]. Such models make it possible to produce predictions of what will happen to the system if certain conditions change, e.g., a reduced discharge of a pollutant related to a remedial measure. Using dynamic ecosystem models, it is also possible to predict thresholds and points of no return before they have been reached, and hence to take actions to avoid them. Therefore, the use of mass-balance models is necessary in coastal management. To be cost-efficient, remedial measures should focus on the most sensitive systems [31]. So, identifying areas that potentially are the most sensitive to a given pressure is a vital task for coastal science.

Mass-balance modeling can be performed at different scales, depending on the purpose of the study and a large number of coastal models do exist, all with their pros and cons. For example, the 1D-nutrient model described by Vichi *et al.* [35] requires meteorological input data with a high temporal resolution, which makes forecasting for longer time periods than one week ahead very difficult. The 3D-model for the Baltic Sea used by Schernewski and Neumann [36] has a temporal resolution of 1 minute and a spatial resolution of 3 nautical miles, which means that it may be difficult to find reliable empirical data to run and validate the model. CoastMab is a general mass-balance model for entire coastal areas (the ecosystem scale), based on ordinary differential equations and a monthly time step to account for seasonal variations. It has been tested and applied for phosphorus [34, 37] and contaminants [38] with good results. CoastWeb [39, 40] is a dynamic foodweb model for coastal areas, also working on a monthly basis at the ecosystem scale and based on ten functional groups of organisms. These two general models are designed to be compatible with the coastal classification system discussed in this work. So, these two models may be run using readily accessible driving variables from maps and databases such as those used and discussed in this work. However, for all mass-balance models for coastal areas, data must be available both for the given coastal area and for the sea outside the given coastal area because the conditions outside a given coastal area will influence the conditions within a coastal area. This is most evident for open coasts, but also true for more enclosed systems. This explains why the topographical openness of coastal areas is a key attribute in this classifications system.

AIM OF THE STUDY

The first objective of this study is to present four morphometric parameters that can be defined for individual coastal areas and that are of practical use in coastal management. These parameters are easy to understand, simple to derive and three of the four are not common in the literature. Secondly we will present generalized overview maps of important environmental variables, based on data from public databases. Examples will be provided of how to use these maps for possible identification of "high priority" polluted areas and areas sensitive to pollution. Finally, it will be shown how the presented maps serve as input and reference data for two dynamic ecosystem models CoastMab and CoastWeb with a modeling example. These models aim to be useful in coastal management and science where the structure and function of coastal ecosystem are focal points.

METHODOLOGY

Coastal Classification and Mapping Using GIS

When classifying and mapping functional key parameters in GIS, the output can be used to give an overview of coastal areas that appear to be highly polluted, but also to identify areas sensitive to pollution (e.g., by using morphometric data). Generalized maps based on data from public databases also show in which areas data availability is scarce and hence where more should be done to gather data or make data available to the public. Depending on which parameters are selected, the resulting maps can also be used as a first input for dynamic ecosystem models suitable for in-depth studies of coastal areas at regional or local scale. A scheme illustrating this is shown in Fig. (**1**).

The methodology shown in Fig. (**1**) is performed in three steps:

1. Perform morphometric classification and use data-mining, GIS-based analysis and visualization to create generalized overview maps of chemical variables.
2. Use the output from step 1 to identify potential "high priority" areas, either sensitive and/or valuable (from morphometric classification maps) or highly polluted "hot-spots" (from chemical overview maps).
3. Use the output from step 1 as input to dynamic mass-balance models on the ecosystem scale and use these to investigate possible effects of different remedial measures.

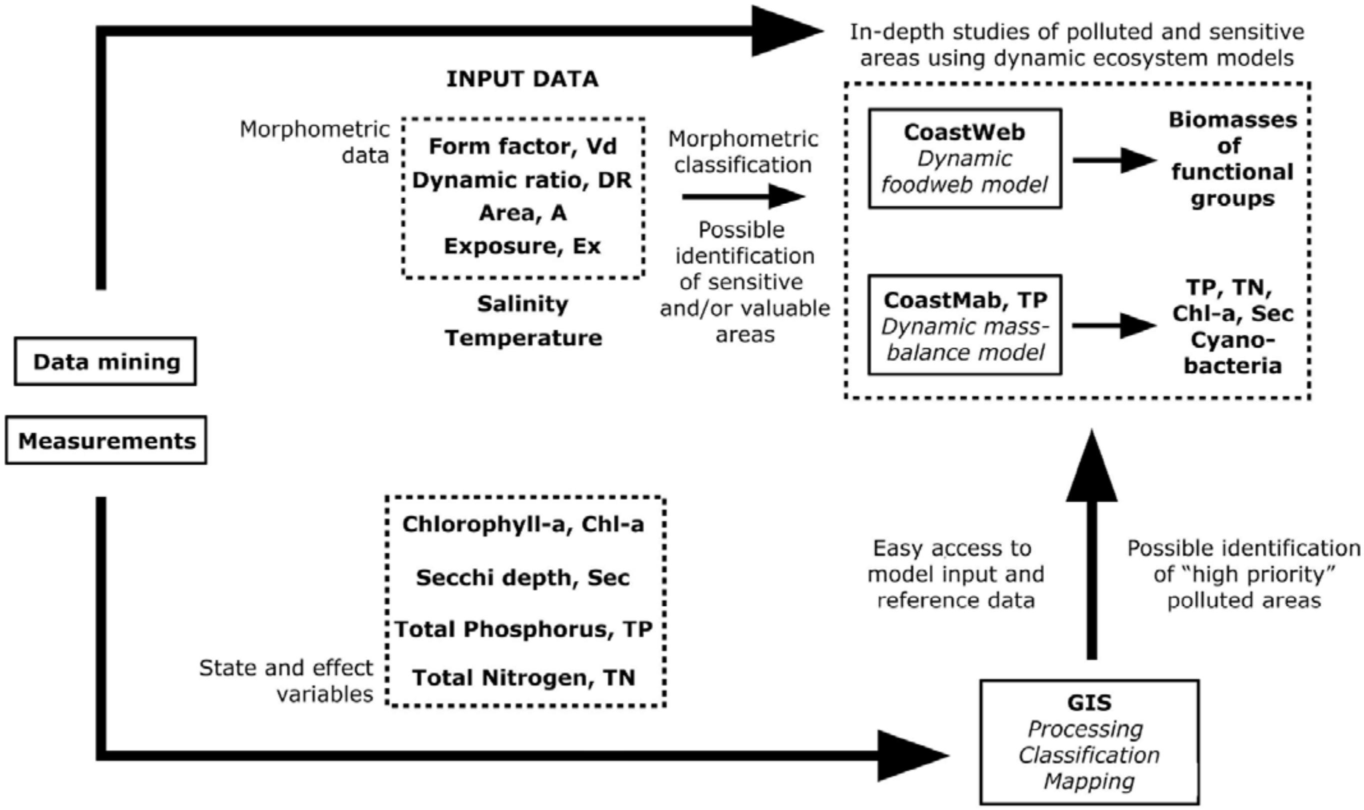

Fig. (1). Overview of the coastal classification, GIS-based data analysis and modeling workflow.

Fig. (**1**) also shows the parameters suggested for classification and mapping in this study. The main criteria for selecting these parameters is that they are functional ecosystem variables needed as input, or reference, when performing dynamic mass-balance or foodweb modeling using CoastMab and CoastWeb. The selected variables are described and motivated in detail in the following sections. The use of salinity, chlorophyll-a, Secchi depth, TP and TN for classification of coastal areas was discussed in detail by Håkanson *et al.* [18].

After having selected an interesting target ecosystem on the local or the regional level with a high load (pressure) and/or a high sensitivity, mass-balance and foodweb modeling can be performed. This gives an understanding of which processes are most important in that system so that the appropriate remedial actions may be taken and critical thresholds avoided. Several studies have been devoted to describe and test the CoastMab [34, 37, 38] and CoastWeb [39, 40] models in detail. Here, a modeling example will be included to show the potential of these models and to illustrate that the generalized maps presented in this paper are sufficient as model input.

Morphometric Classification

The morphometry of a coastal area, i.e., its size and form characteristics, can be crucial for its sensitivity to pollution. This is because morphometry influences sediment and bottom dynamic conditions [41], but also because morphometry influences the theoretical water retention time [42, 43]. The latter is significant since the in and outflowing sea water either dilutes ('purifies') or pollutes the coastal area [44]. To be practically useful, a coastal classification system should be based on variables that are easily accessible, e.g., from standard maps, databases and monitoring programs. Coastline data are available with worldwide coverage at a scale of 1:250000 in at least two datasets: The World Vector Shoreline (WVS; [45]) and the Global Self-consistent, Hierarchical, High-resolution Shoreline Database (GSHHS; [46]). For many regions of the world, coastline data are also available at greater detail from national sources. This means that down to a certain scale, coastal size and form parameters can be readily accessed. In a study of the coast of Britain, Andrle [47] concluded that coastline complexity varies in a continuous and systematic way with scale. Scale should be taken into account when analyzing geographical data in order to find enclosed and sensitive areas. An area that does not appear to be enclosed on a regional scale may, in fact, be enclosed and highly sensitive when studied at local scale. If the boundaries of a coastal area are known, also the surface area of the coastal area can be easily determined using GIS. Detailed coastline data are available because such data can be determined using remote sensing with good results [48]. Bathymetric information, however, can only partly be derived using remote sensing and hence bathymetric information is generally not available with the same detail as the coastline data. At least two global bathymetric datasets are freely available, ETOPO1 [49] and the GEBCO One Minute Grid [50]. These are both compilations from several sources and have a 1-minute resolution. Bathymetric datasets and maps with greater detail are available for parts of Europe, e.g., for the North Sea and the British isles (Digibath250; [51]), but they are not freely accessible. At a local scale, bathymetric information may be retrieved from sea charts or by performing measurements using echo-sounding techniques. A vital part of coastal mass-balance modeling at the ecosystem scale is to identify the boundaries between the coast and the sea. This is sometimes done in an arbitrary way, but should be done as objectively as possible, e.g., by identifying bathymetric sills [52, 53]. The location of the boundary directly influences the enclosed volume, which in turn has direct influence on the concentration of any substance.

Openness and Form

In coastal areas where the tidal amplitude is very small, e.g., all areas in the Baltic Sea (Fig. **2**), the topographical openness or exposure (Ex, Eq. 1.) has importance for sensitivity to pollution, since openness is a key regulator of water exchange for these areas [42].

$$Ex = 100 \cdot At/A \quad (1)$$

Here At is the cross section area (m^2) defined by the topographical bottleneck method so that the Ex-value is minimized and A is the enclosed surface area (m^2), see Fig. (**3**). The water exchange between the coast and the sea can affect the conditions in a coastal ecosystem in many profound ways, e.g., the concentration of pollutants and the recovering ability of coastal areas [54]. Open coastal areas are generally not very sensitive to pollution due to the short water retention times that usually characterize such systems [55], as compared to more enclosed areas. There are many examples of enclosed water bodies suffering from pollution problems including large systems at the international scale, such as the Black Sea [56, 57] and the Baltic Sea [58, 59]. At regional and local scales, similar examples are enclosed lagoons like the Oder Lagoon [60, 61] and Ringkobing Fjord [62]. Although exposure can be calculated for all semi-enclosed coastal areas at all scales, it has its primary use on local or regional scale.

Morphometric classification at the local scale requires detailed bathymetric data, which unfortunately generally are not freely available. Based on investigations on exposure and water exchange by [63] we suggest using the classes in Table **1** for exposure classification of coastal areas.

Another key morphometric feature of a coastal area is its form (shape). The form has direct impact on how much of the sediment surface that is influenced by wind and wave processes, i.e., the bottom areas where sediment resuspension occurs. This, in turn, is of importance for the internal loading and hence also for all concentrations of substances with a particulate phase. The form of the coast also affects the growth of macrophytes and benthic algae and hence the production potential of the coastal system [41]. Fig. (**4**) illustrates relative hypsographic curves (depth-area

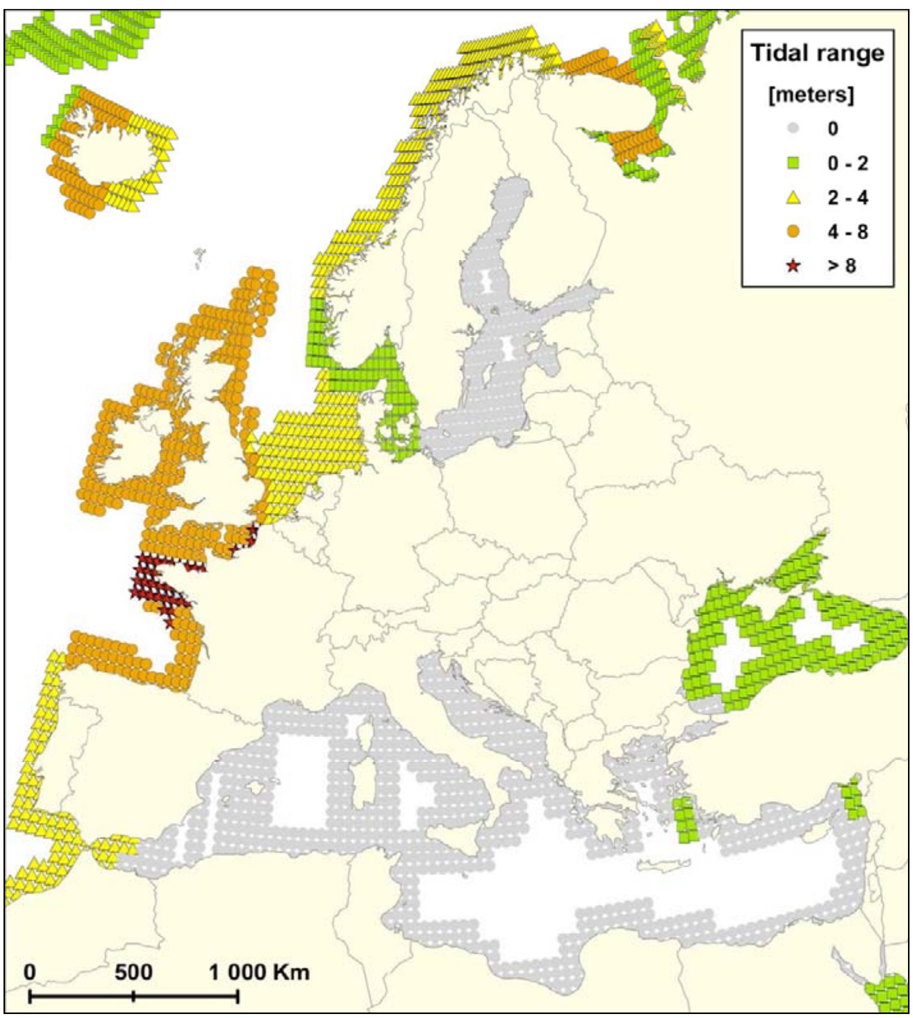

Fig. (2). Characteristic tidal ranges along the European coast. Based on data from LOICZ/Hexacoral Environmental Typology Database [28].

curves) for four systems with different form factors (Vd; see Eq. 2). Coast 1 has a large percentage of the bottom above the Secchi depth. Deep, U-formed coasts generally have smaller areas above the Secchi depth. Coastal areas with larger area above the Secchi depth enable higher primary production of phytoplankton, benthic algae and macrophytes. This gives them a higher potential biological value and they are thus important to protect and preserve.

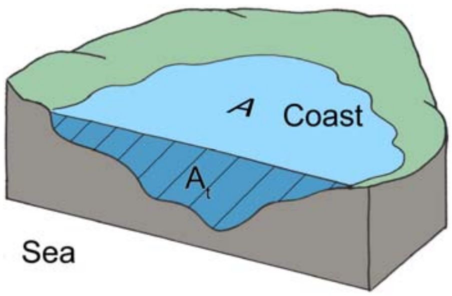

Fig. (3). A coastal area with cross section area (At) and the enclosed surface area (A).

Table 1. Classification Criteria for Openness (Exposure) of Coastal Areas

Ex	Openness	Typical Systems
0 – 0.02	Enclosed, very closed systems	Most coastal lagoons
0.02 – 1.3	Semi-enclosed systems	Bays, fjords, archipelagos
> 1.3	Open systems	Open coasts (cliff, sand, rock, man-made, etc.)

The form factor, or the volume development (Vd), Eq. 2, is a useful standard measure of the form of any aquatic system [64].

$$Vd = 3 \cdot D_{mv}/D_{max} \qquad (2)$$

where D_{mv} is the mean depth and D_{max} the maximum depth (both in meters). Since Vd is calculated from two general features, it can be applied to most systems at the ecosystem scale. Håkanson [64] also gave a classification scheme based on the form factor (Table **2**).

Table 2. Morphometric Classification for Aquatic Systems Based on the Form Factor, Vd (from [64])

Form of Lake or Coastal Area	Class Name	Vd
Very convex	VCx	0.05 – 0.33
Convex	Cx	0.33 – 0.67
Slightly convex	SCx	0.67 – 1.00
Linear	L	1.00 – 1.33
Concave	C	> 1.33

To illustrate how these morphometric classification schemes can be utilized to identify potentially sensitive and valuable coastal areas, a GIS-based analysis was made using data from the Swedish Water Archive (SVAR; [65]). In this analysis, Ex-values were calculated as an indicator of sensitivity to pollution using the classes in Table **1**. Vd-values were calculated and as an indicator of ecological value using the classes in Table **2**.

Depth and Size

Two other useful morphometric properties of coastal areas at the ecosystem scale are the dynamic ratio (DR) and the surface area (A). The depth of a coastal area is a central morphometric feature and has importance for sedimentation and resuspension. A useful form parameter describing the depth conditions is the dynamic ratio (DR), Eq. 3.

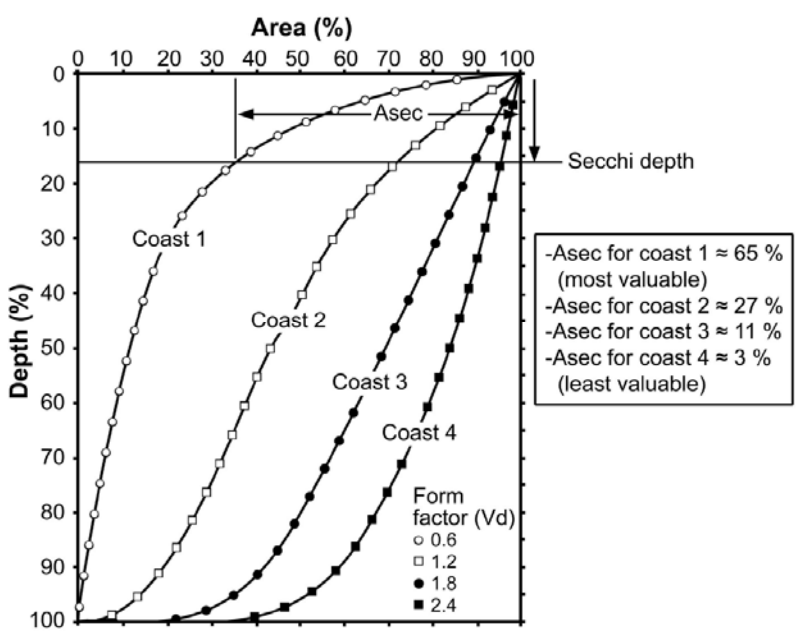

Fig. (4). Illustration of relative hypsographic curves that illustrates the depth-area relationship of four coastal areas with different shape (and form factor = volume development = Vd). The shape influences the area above the Secchi depth (Asec), which indicate the production capacity and “biological value” of the coastal system.

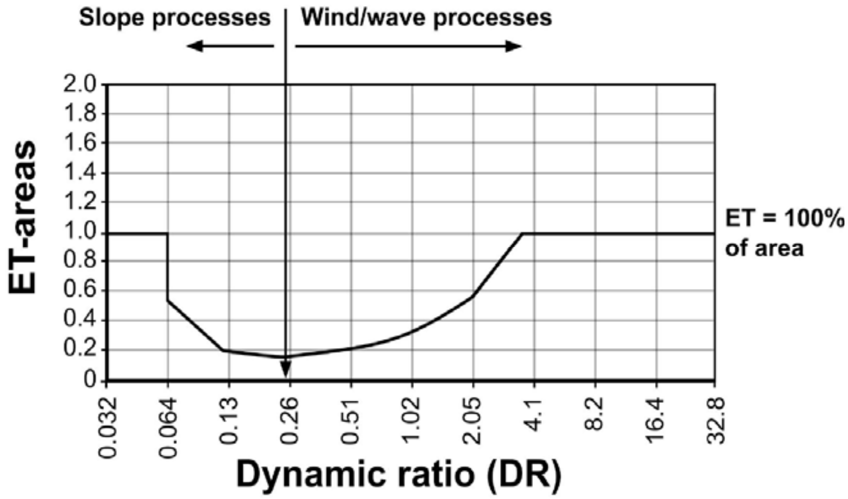

Fig. (5). The relation between the dynamic ratio (DR) and the proportion of bottom areas dominated by erosion and transport processes (ET). Redrawn from [41].

$$DR = \sqrt{(A)}/D_{mv} \quad (3)$$

where A is the enclosed coastal area in km^2 and D_{mv} the mean depth of the coastal area in m. A close relationship exist between the dynamic ratio and bottom dynamic conditions [41], see Fig. (**5**). Four different DR-classes can be derived (very deep, deep, intermediately deep and shallow) see Table **3**.

Table 3. Classes for the Dynamic Ratio (DR)

Class	DR	Description
1 Very deep	< 0.064	Areas dominated by slope processes and erosion and transport processes for fine particles
2 Deep	0.064 – 0.25	Areas influenced by slope processes were erosion, transport and accumulations for fine particles occur
3 Intermediate	0.25 – 4.1	Areas more influenced by wind and wave processes were erosion, transport and accumulations for fine particles occur
4 Shallow	> 4.1	Area dominated by wind and wave processes and erosion and transport processes for fine particles

The size of a coastal area is of importance for a number of reasons. The water area together with the mean depth defines the water volume, which in turn is essential for calculating the concentration of any substance. We suggest that coastal areas may be classified into size classes according to the system given in Table **4** (very large, large intermediate, small and very small). These classes correspond to the A-F categories used in the Swedish Marine Area Registry (SHR; [66]).

Generalized GIS-maps of Key Water Variables

Generalized GIS-maps of key water variables can both be used for identification of areas sensitive to pollution and areas under high environmental pressure. They can also provide input data to mass-balance and foodweb models of local target ecosystems. To provide an overview and background information of such data, generalized overview maps of salinity, temperature, total phosphorus (TP in µg/l), total nitrogen (TN in µg/l), chlorophyll-a (Chl in µg/l) and Secchi depth (Sec in m) have been created for the whole, or parts of, the European coastal zone using data mining of public databases and GIS-based analysis.

Table 4. Surface Area Classification

Surface Area (km^2)	Class Name
> 10 000	Very large
1 000 – 10 000	Large
100 – 1 000	Intermediate
10 – 100	Small
< 10	Very small

There are many ways to separate a water mass into different layers, e.g., by following differences in temperature (thermocline) and salinity (halocline). To be able to compare values at larger regional and national scales, a simplified system is needed. Hence, in this work only data from the surface-water layer, defined as the upper 10 m of the water mass, have been used for all water variables. The reason for focusing on surface values is that this is the biologically most important part with the highest biological value, as calculated by the production potential (the ratio between the biomass and the production; see [1]). In this work, individual data have been used as much as possible. However, in some areas only average values were available and to avoid large areas being represented by few data, also averaged data were accepted in the analysis. To minimize the uncertainty of individual measurements, only points with at least three measurements were used. The maps show mean values of all included variables for the whole year. For chlorophyll, however, only data from the growing season, defined here by the period between the beginning of May to the end of September, were used. To ensure good data coverage, data should come from a sufficiently long period. At the same time, we would like to show the present situation. As a tradeoff, only data from 1990 and onwards were used in this work, except for Secchi depth where data from 1980 and onwards were used, since the number of data from 1990 to present was not sufficient. It has not been the focus here to study temporal trends and with the used approach long-term trends cannot be seen

Occasionally, the databases overlap, which may result in the same data being used more than once. To avoid this all data from the most extensive database were first used. Then, using GIS, only the data with different geographical locations were selected from the second largest database, etc., until all available data were either included or rejected. Inverse distance weighting (IDW) was then applied to obtain a continuous map from the available data. Maps were only created for areas where the data cover was considered sufficient.

The following sections briefly describe the importance of each water variable as well as the data availability and considerations made in each individual case.

Salinity and Water Temperature

The salinity is of vital importance for the biology of coastal areas, e.g., influencing the number of species in a system [67], and also the reproductive success, food intake and growth of fish [68, 69]. A higher salinity has been shown to increase the flocculation and aggregation of particles [41] and hence affect the rate of sedimentation. This does not only influence the concentration of particulate matter, but also the concentration of any substance with a substantial particulate phase such as, e.g., phosphorus and many pollutants. The salinity also affects the relationship between total phosphorus and primary production (chlorophyll-a; [18]). The salinity is easy to measure and the availability of salinity data for the European coastal zone is better than for most other water variables. The salinity map was created using data from ICES [70]. In total, about 413 000 surface water data (d<10m) were used.

The water temperature regulates many important processes and functions in aquatic systems. Primary and secondary production increase with increasing temperatures, and so does bacterial decomposition of organic matter, and hence also the oxygen consumption. Water temperature influence the stratification and hence also mixing across the thermocline. In total, about 410 000 temperature data (d < 10m; [70]) were used to create the temperature maps. The data coverage was rather good for the whole European coastal zone. Since temperature has a distinct seasonal variation (more than most other water variables), maps were created not only for average annual surface-water temperatures (using all available data), but also for the growing season (the beginning of May to the end of September) and for two individual months (January and July to represent a wide temperature range). When creating maps for individual months, data coverage was not sufficient for the whole European coastal zone, so the North Sea and parts of the Baltic Sea were chosen as an example.

Chlorophyll, Nutrients and Secchi Depth

Chlorophyll is a standard measure of phytoplankton biomass and has a direct influence on foodweb characteristics in a given coastal area. The phytoplankton biomass also influences the photic zone and hence also the primary production of phytoplankton, benthic algae and macrophytes. Since bacterial decomposition of dead phytoplankton is an oxygen consuming process the phytoplankton biomass also affects the oxygen conditions in the system. Deep-water oxygen conditions in turn influence the habitat for benthic organisms and important biogeochemical processes in the sediment-water interface, e.g., diffusion of phosphorus from sediments to water. The searched databases [70-73] included about 123 000 chlorophyll data from depths < 10 m and from the growing season (May to September).

Phosphorus is well known to be the limiting nutrient for primary production in most lakes [74-81]. Nitrogen is regarded as a key nutrient in many marine areas [80, 82-87]. However, Guildford and Hecky [88] showed that total phosphorus (TP) is of importance also for algal growth in marine systems, a conclusion also supported by Håkanson and Lindgren [89] in a study of a large number of systems from different parts of the world. Hence TP should be considered an important nutrient also in many marine coastal areas. In total, about 126 000 data were available from water depths < 10 m in the accessed databases [70-72]. Data were only sufficient for map construction for the Baltic Sea and parts of the North Sea.

As mentioned, nitrogen is often considered to be of special importance for primary production in marine systems [83, 86]. It is well established [90] that plankton cells have a typical atomic composition of $C_{106}N_{16}P$, which means that 16 times as many atoms (and 7.2 times as many grams) are needed of N than of P to produce phytoplankton. There are many different chemical forms of the nutrients (nitrate, phosphate, DIP, DIN, etc.) and the interaction between these can be complex, but only total nitrogen (TN) and total phosphorus (TP) are considered here. The available number of TN data from depths < 10 m was about 93 000 [70-72]. Also for these data, the coverage was only sufficient for the Baltic Sea and parts of the North Sea.

Secchi depth is an indicator of water clarity and has a direct link to the depth of the photic zone [91], which in turn influences the primary production, both phytoplankton in the water phase and the benthic vegetation. Secchi depth is also a good indicator of water quality for swimming and tourism. In a data-mining study of Secchi depth in the North Sea and Baltic Sea by Aarup [92] over 40 000 data were gathered, mainly from individual studies. These data are now available from ICES [93]. Since the number of data was less for this variable after 1990 and because the number of available data from the period between 1980 and 1990 was very large, all data from 1980 and onwards were used in this work (about 30 500 data).

Example of Mass-Balance and Foodweb Modeling in a Target Ecosystem at the Local Scale

The practical use of this ecosystem-oriented coastal mapping and classification approach and the selected parameters will be illustrated with a modeling example. The idea is to illustrate how the presented parameters and maps can serve as input data to perform dynamic foodweb and mass-balance modeling at the local scale. This is done using a foodweb model for functional groups of organisms

(CoastWeb [39, 40]) which also includes a phosphorus mass-balance model (CoastMab [34]). A scenario will be given, where the CoastWeb model is used to quantify how one of the most acute threats to many coastal areas of the world, eutrophication, will likely influence the structure and function of coastal foodwebs. The idea is to study how a hypothetical stepwise (3-year steps) increase of the TP-concentration in the sea outside a coastal area would likely influence phosphorus concentration, target bioindicators, chlorophyll-a concentration and Secchi depth in the area. The effect on the structure and function of the coastal foodweb is also studied, as this is quantified for the production and biomasses of the functional groups of organisms included in the CoastWeb-model (phytoplankton, benthic algae, macrophytes, bacterioplankton, herbivorous zooplankton, predatory zooplankton, jellyfish, zoobenthos, prey fish and predatory fish). In this case, data have been used from the Haverö coastal area (in the Finnish Archipelago Sea). Note that only the data in Table **5** are needed to run the model and that all these data may be accessed from the system discussed in this work. More details about this scenario are given by Håkanson and Lindgren [39].

Table 5. Data for the Studied Coastal Area, Haverö, Finland, at Latitude 61 °N (data from [94])

Water Area	D_{max}	D_{mv}	At	Chl	Salinity	C_{TP}	Sec
(km^2)	(m)	(m)	(km^2)	(µg/l)	(psu)	(µg/l)	(m)
2.3	22.5	8.6	0.0172	2.1	6.5	27	3.4

D_{max} = maximum depth; D_{mv} = mean depth; At = section area; Chl = concentration of chlorophyll-a; C_{TP} = TP-concentration; Sec = Secchi depth.

RESULTS AND DISCUSSION

Morphometric Classification

Fig. (**6**) shows exposure values calculated at a local scale, using Blekinge archipelago in southern Sweden as an example. Here two more enclosed and possibly more sensitive sub-areas can be seen (areas with Ex = 0.086 and 0.073). In Fig. (**7**) some coastal areas in Stockholm archipelago have been classified using a combination of openness (Ex) as an indicator of sensitivity and hypsographic form (Vd) as an indicator of potential ecological value. This map shows that only one of the mapped areas (Horsfjärden) is classified as both 'Most valuable' and 'Sensitive', thus potentially interesting for further investigation and maybe protection. A map like the one in Fig. (**7**) offers a way to help coastal managers identify potential areas of high interest. When looking at the morphometric statistics of all Swedish coastal areas (Table **6**), the number of very sensitive coastal areas according to the Ex-criterion is 35 (closed or very enclosed systems; Ex < 0.02). The results in Table **6** also show that the dominating coastal form for all Swedish areas is slightly convex (SCx) and that 10 areas are classified as very convex, i.e., potentially most valuable. Table **6** also includes statistics of depth (DR) and size (A) characteristics of all Swedish coastal areas.

Generalized Overview Maps

Salinity and Temperature

A salinity map for the entire European coastal zone is shown in Fig. (**8**). The salinity gradients in the Baltic Sea and the transient areas of Kattegat and the Danish straits are clearly seen. A gradient with slightly less saline water closest to the coast can also be observed for almost the whole Norwegian coast, as well as the eastern coasts of the North Sea and the Irish Sea. This is due to extensive freshwater input from large drainage areas. In the case of the Norwegian coast, it is also because of the coastal currents transporting brackish water from the Baltic Sea. Similar generalized global maps have been presented in the oceanographic literature (e.g., [95]) and can also be produced with global coverage by using the 0.5 deg salinity grid, available in the LOICZ Typology dataset [28]. The general features of the map presented here correspond well with these. Those maps and databases are global, but do not provide the great detail

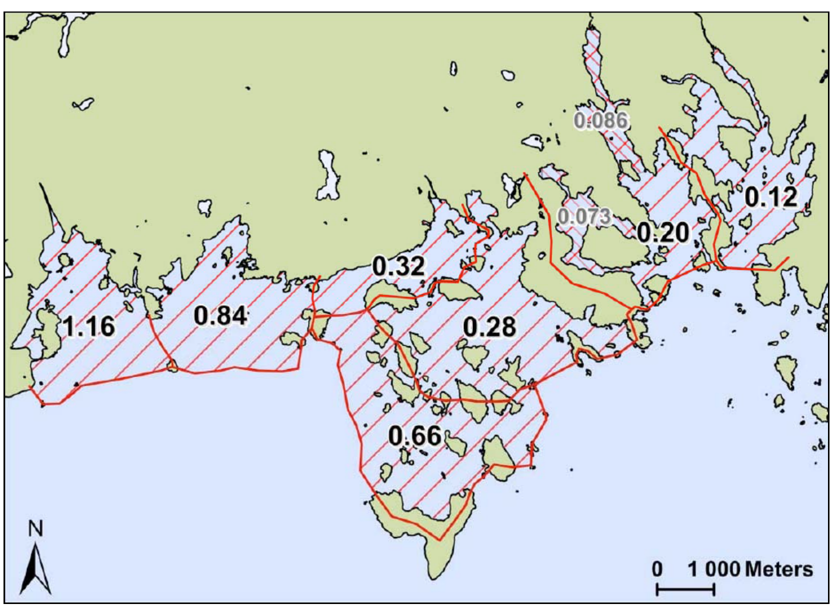

Fig. (6). Exposure (Ex) values calculated on a local scale, example from Blekinge Archipelago, Sweden.

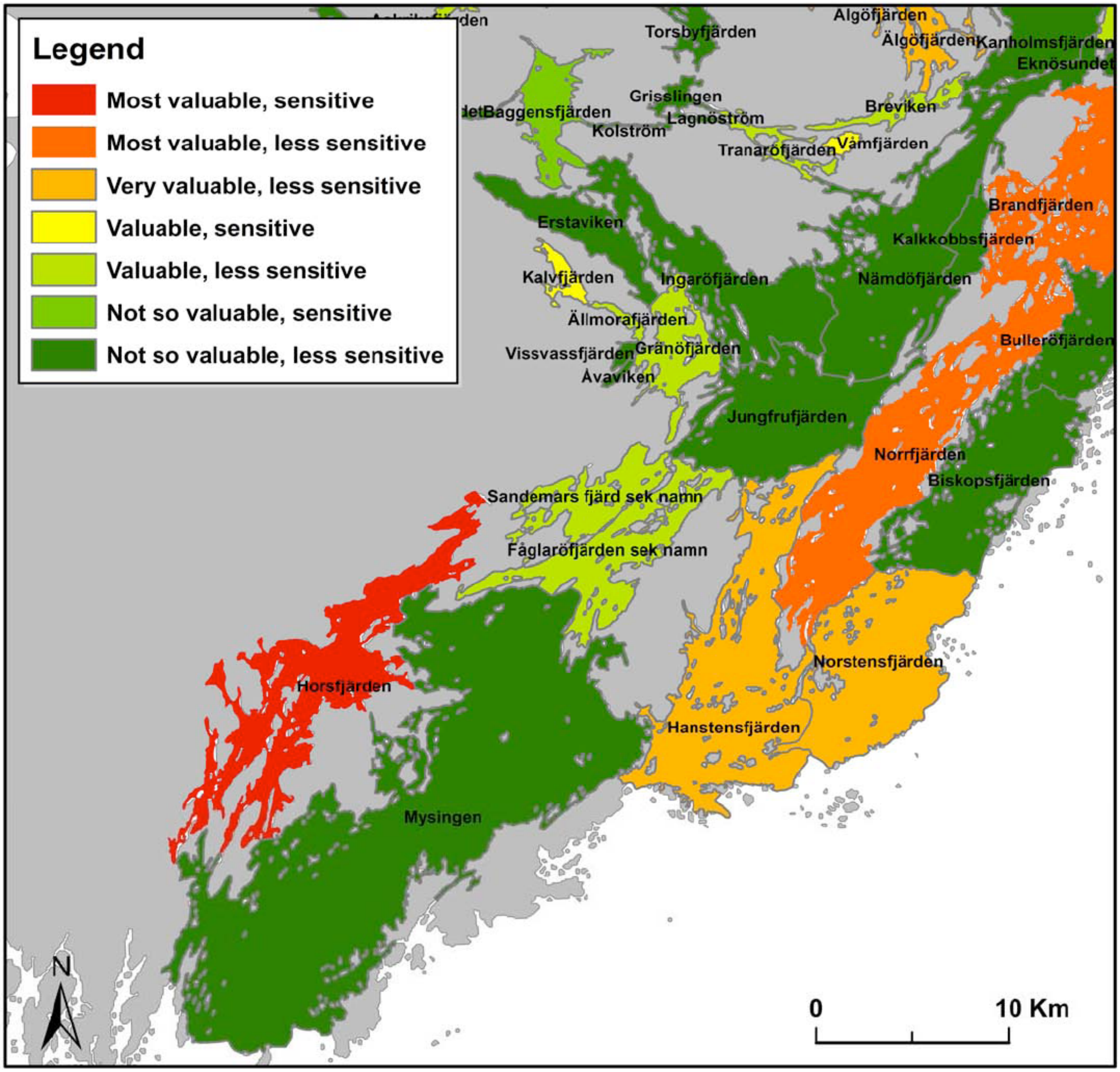

Fig. (7). Classification of coastal areas in Stockholm archipelago based on sensitivity and potential ecological value.

on local scale that was achieved here by using much data in a GIS. When zooming in on the created GIS-map, local areas can be studied in more detail. When doing so, salinity gradients are clearly depicted for most big European estuaries. Estuaries and fjords are affected by fresh-water discharges from land and such systems often have marked seasonal variations in salinity. The generalized map presented here only shows the general spatial pattern in surface-water salinity and does not address seasonal variations.

Fig. (**9A**) gives an overview of annual mean surface-water temperatures along the entire European coastal zone, Fig. (**9B**) gives the corresponding data for the growing season (May to September), Fig. (**9C**) gives average data from January (generally the coldest month) and Fig. (**9D**) data for July. Note that sufficient data were not available from the entire European area for individual moths so Fig. (**9C**, **D**) give the information using data from the North Sea. From Fig. (**9**), one can note the marked geographical variation in surface-water temperatures. These temperature differences are fundamental for the geographical variations in primary, and hence also in secondary production (of zooplankton, zoobenthos and fish). The low temperatures in parts of the Bothnian Bay and the Gulf of Riga seen in Fig. (**9B**) are probably a result of uneven temporal distribution of the used data in those areas.

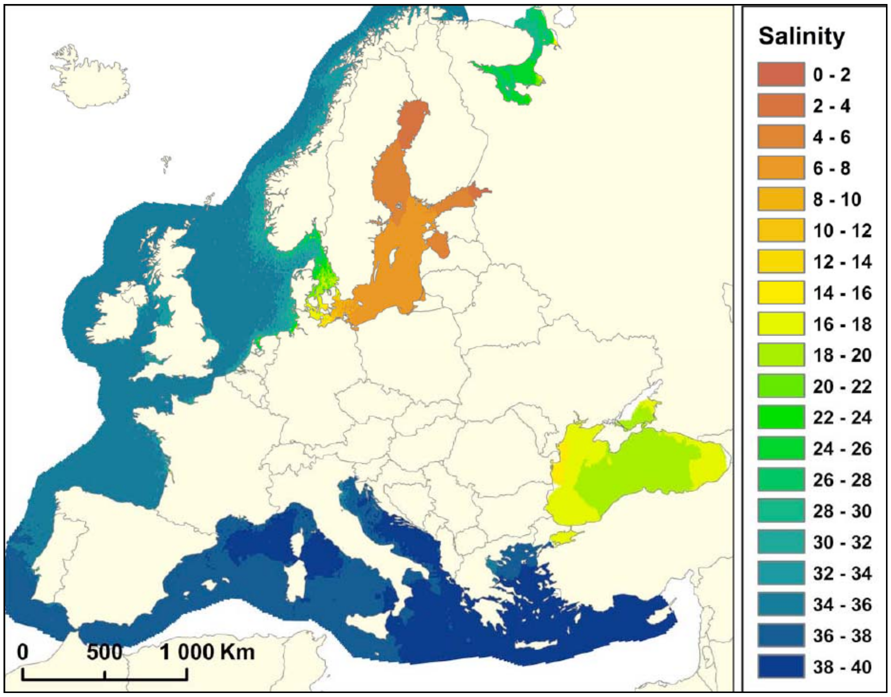

Fig. (8). Average annual surface water salinities in the European coastal zone in the upper 10 m water column for the period from 1990 to 2005.

Table 6. Results of the Morphometric Classification of Swedish Coastal Areas

Parameter	Class	Number of Areas	Mean	St.dev.	CV
Exposure, Ex	All	572	0.33	0.42	1.27
	Enclosed	35	0.010	0.0057	0.57
	Semi-enclosed	518	0.29	0.24	0.81
	Open	19	2.06	0.66	0.32
Form factor, Vd	All	537	0.93	0.36	0.39
	Very convex	10	0.24	0.091	0.38
	Convex	117	0.54	0.087	0.16
	Slightly convex	215	0.84	0.090	0.11
	Linear	145	1.15	0.098	0.09
	Concave	50	1.67	0.36	0.22
Dynamic ratio, DR	All	537	0.74	0.67	0.91
	Very deep	1	0.061	-	-
	Deep	91	0.18	0.048	0.27
	Intermediate	443	0.83	0.53	0.64
	Shallow	2	7.1	0.64	0.09
Area, A (km^2)	All	572	55.7	146.6	2.63
	Very large	0	-	-	-
	Large	3	1 536.2	696.7	0.45
	Intermediate	68	244.2	147.8	0.61
	Small	282	33.9	21.8	0.64
	Very small	219	4.8	2.6	0.54

Chlorophyll, Nutrients and Secchi Depth

Typical chlorophyll-a concentrations for the Baltic Sea and parts of the North Sea are shown in Fig. (**10**). Values lower than 2 µg/l (oligotrophic conditions) are found in the northern parts of the Bothnian Bay and the outer parts of the North Sea, while values higher than 20 µg/l (hypertrophic conditions) and more are found in the Vistula and Oder lagoons. The hotspots shown on the map outside the British coast may be a result of data from situations with algal blooms being over-represented.

Fig. (**11**) shows the generalized map of TP-concentrations derived for the Baltic Sea and parts of the North Sea. The eastern North Sea coast, especially the areas around the mouths of the rivers Weser and Elbe, show the highest average values, over 90 µg/l. In the Baltic Sea, the lowest values are found in the Bothnian Bay and hotspots are found in the Vistula and Oder lagoons. The generalized map of typical TN-concentrations for the Baltic Sea and parts of the North Sea is shown in Fig. (**12**). Also here, the eastern North Sea coast shows many high values between 700-1000 µg/l. In the Baltic Sea, the Bothnian Bay and the Bothnian Sea have the lower values between 200-300 µg/l, while the Gulf of Riga and the eastern part of the Gulf of Finland show higher values, ranging from 400 up to 800 µg/l.

The generalized map of average Secchi depth for the Baltic Sea and the south-eastern parts of the North Sea is presented in Fig. (**13**). Some areas with lower Secchi-depths can be observed in the Gulf of Riga and along the North Sea coasts of Holland, Belgium and Germany. Although some of the observed patchiness may be a result of the interpolation method rather than a true patchiness, it seems from this analysis that Secchi depth shows more spatial patchiness than the other analyzed variables.

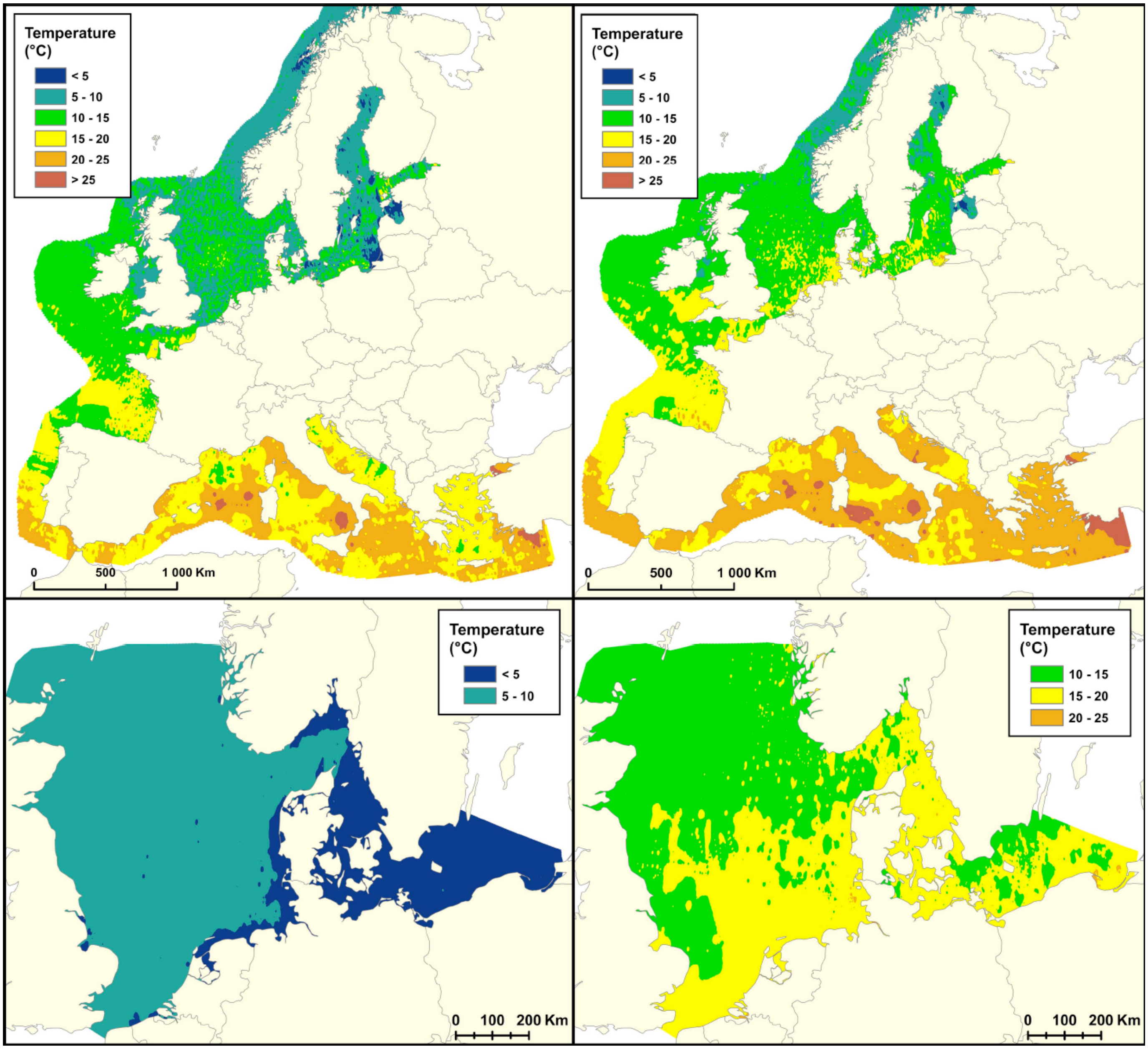

Fig. (9). (**A**) Average annual surface-water temperatures, (**B**) average surface-water temperatures for the growing season (May-September) along the European coastal zone, (**C**) surface-water temperatures for January for the North Sea and parts of the Baltic Sea and (**D**) surface-water temperature for July, all in the upper 10 m water column for the period from 1990 to 2005.

Utilizing the Data for Modeling

Data from the presented maps were used as input for the CoastWeb model and the results of the modeling example are presented in Fig. (**14**). The default TP-concentration in the sea outside this coastal area is 24 µg/l (see Fig. **11**). Tests were carried out to see how changed TP-values of 0.75·24, 24, 1.5·24 and 2·24 would change modeled values of TP within the coastal area for (A), chlorophyll (B), Secchi depth (C), oxygen saturation in the deep-water zone (D), the normal and actual biomasses of zoobenthos (E), herbivorous zooplankton (F), prey fish (G) and predatory fish (H). Modeled values of TP, chlorophyll, Secchi depth and oxygen saturation were also compared with empirical data and the uncertainty bands for the empirical data (MV = mean value, SD = standard deviation). Fig. (**14**) shows that:

- There is generally very good correspondence between modeled and empirical data. Note that the empirical chlorophyll value is the mean value for the growing season.
- The increased eutrophication of the sea outside the coastal area will drastically increase TP also in the given coastal area (which is logical because the retention time of the surface water in Haverö is only 3-5 days; [39]. This leads to higher chlorophyll values, reduced water clarity (Secchi depth) and significantly lower oxygen saturation, which will influence zoobenthos more than, e.g., zooplankton.
- Since there is much more zoobenthos in the system than zooplankton (about 50 t ww as compared to

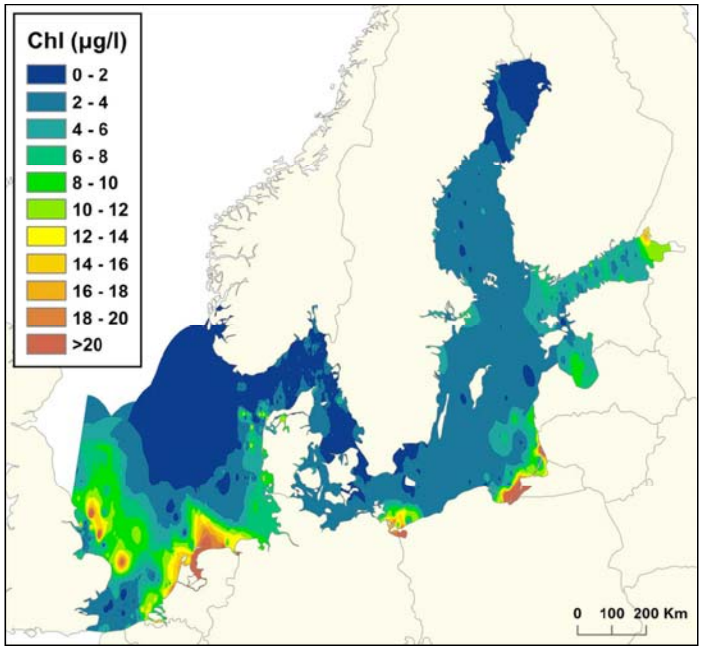

Fig. (10). Typical chlorophyll concentrations in the Baltic Sea and parts of the North Sea during the growing season (May-September) in the upper 10 m water column for the period from 1990 to 2005.

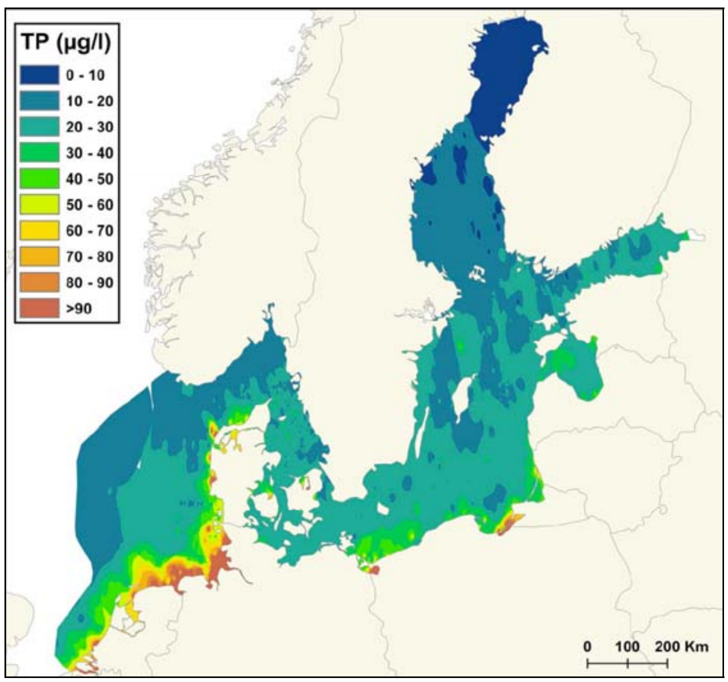

Fig. (11). Typical annual surface-water TP-concentrations for the Baltic Sea and parts of the North Sea in the upper 10 m water column for the period from 1990 to 2005.

about 3-5 t ww), zoobenthos is an important source of food for prey fish and reductions or changes in zoobenthos biomass will have clear effects on the prey fish. Changes in prey fish biomass will in turn influence the predatory fish.

- The zoobenthos within the areas of continuous fine sediment accumulation will die if the oxygen saturation is lower than 20%, but the oxygenation of the areas dominated by fine sediment erosion and transport will maintain a low biomass of zoobenthos in the more shallow parts of the coastal area.

So, the increased eutrophication will imply several changes to the water quality and foodweb characteristics of this coastal area. Many of these changes could be expected without a model, but here they have been quantitatively predicted using a general comprehensive foodweb model that includes a dynamic mass-balance model for phosphorus. This model accounts for many abiotic and biotic interactions and is meant to give the "normal" response of the system to the given change of the TP-concentration in the sea. The model accounts for different types of compensatory effects that would be difficult to quantify without a model. Note

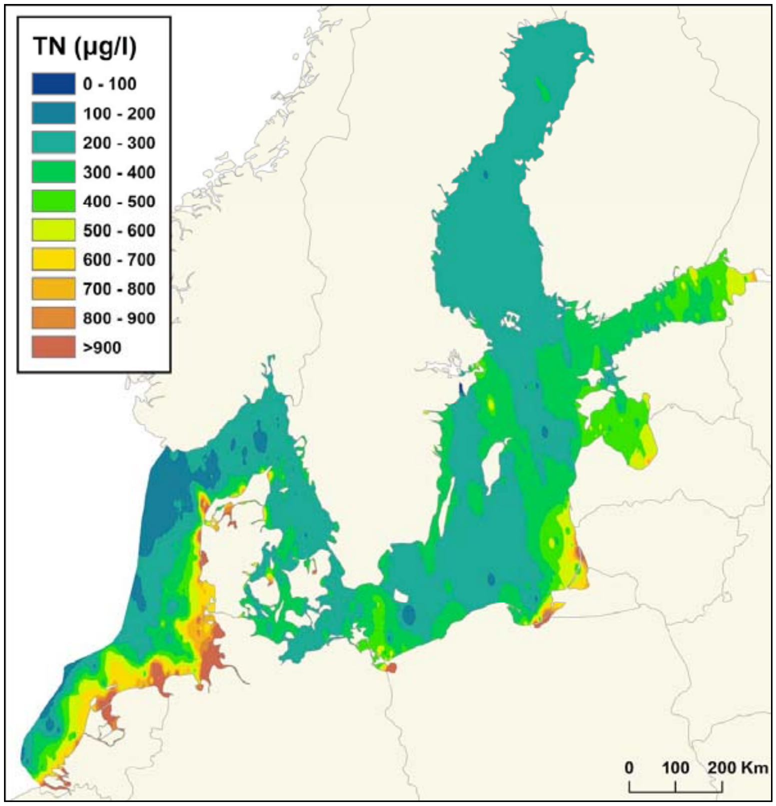

Fig. (12). Typical annual surface-water TN-concentrations for the Baltic Sea and parts of the North Sea in the upper 10 m water column for the period from 1990 to 2005.

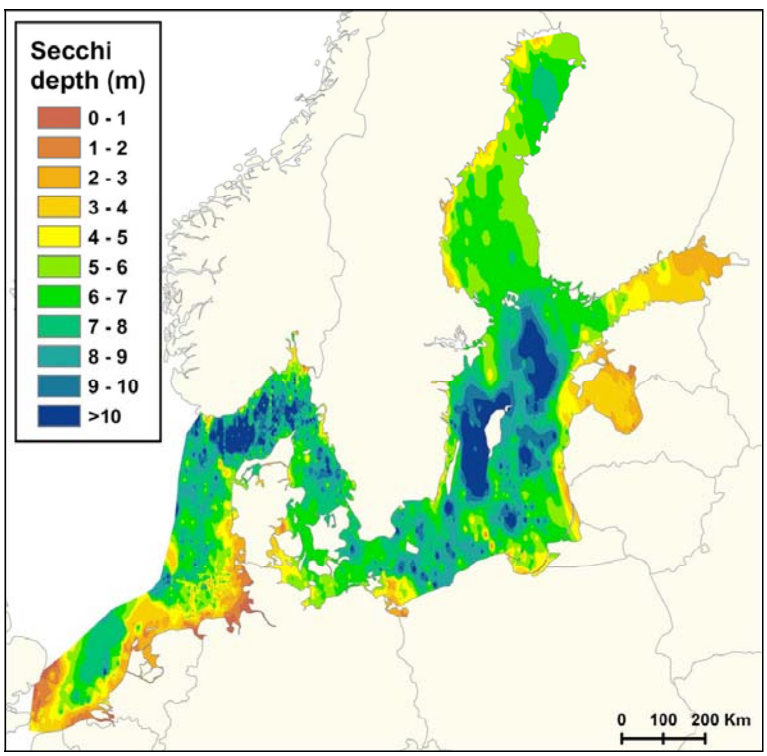

Fig. (13). Average annual Secchi depths in the Baltic Sea and parts of the North Sea for the period from 1980 to 2005.

that, the CoastWeb-model simulates functional groups and hence does not include responses related to individual species, see [39] and [40] for more details. Again note that all input needed to run the model was available from the previously presented morphometric classification and generalized maps.

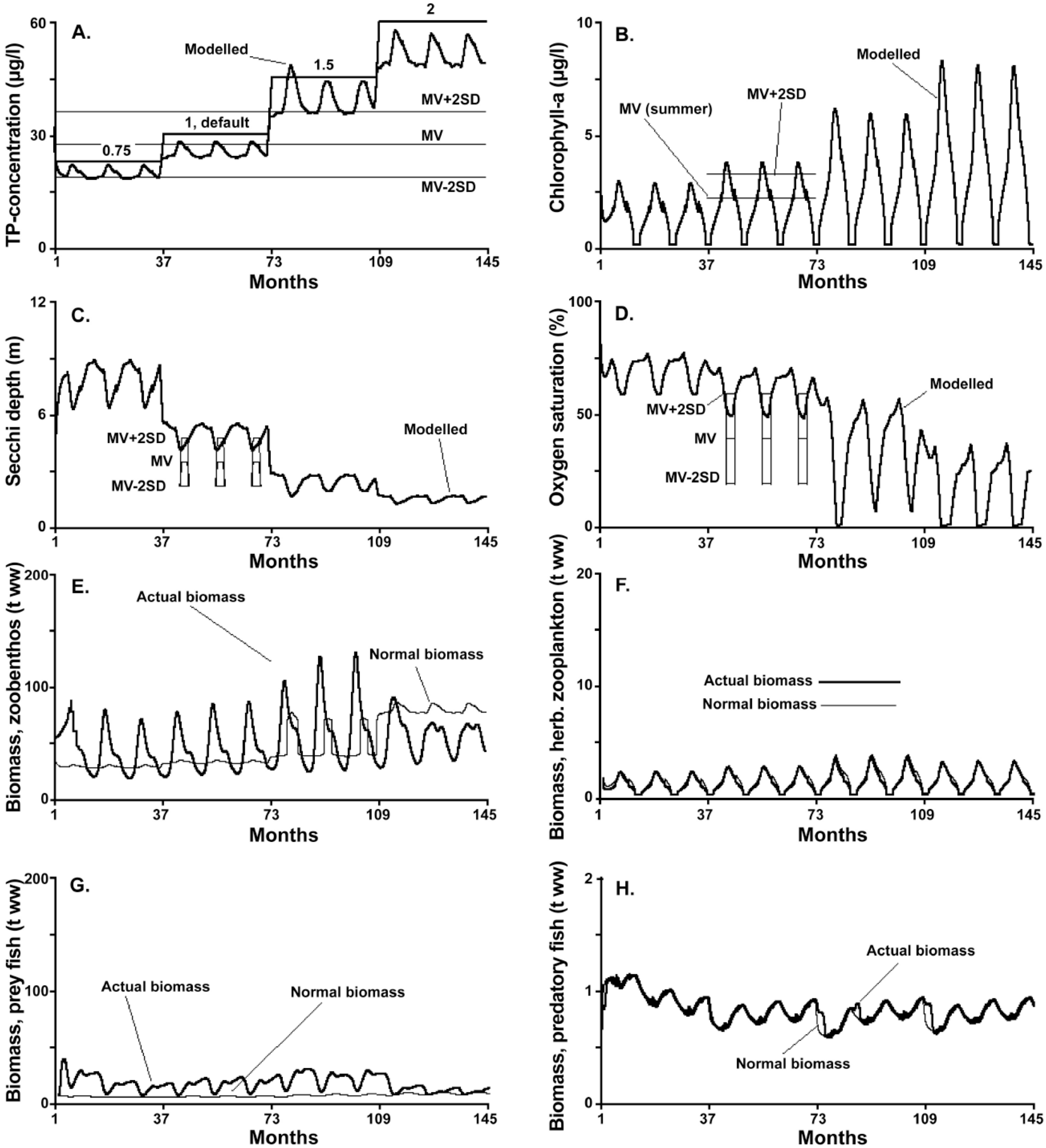

Fig. (14). Case-study on coastal eutrophication using data from the Haverö coastal area. There are changes in 3-year steps in the TP-concentration in the sea adjacent to the coastal area. The default TP-concentration in the sea is 24 µg/l and this value has been set to 0.75·24, 24, 1.5·24 and 2·24 (i.e., 18, 24, 36 and 48 µg/l) and the consequences calculated for (**A**) the TP-concentration in the given coastal area, (**B**) chlorophyll, (**C**) Secchi depth, (**D**) oxygen saturation in the deep-water zone (all compared to empirical mean values and inherent uncertainties in the mean values; the chlorophyll mean value is for the summer period) and actual and normal biomasses of (**E**) zoobenthos (**F**) herbivorous zooplankton, (**G**) prey fish and (**H**) predatory fish. From [39].

CONCLUDING REMARKS

We have presented several morphometric parameters that can be utilized to make a first identification of coastal areas that are potentially ecologically valuable or sensitive to pollution. Although these parameters have been used in limnology for some time, they are not commonly used in coastal sciences. It was also shown how data from public databases and GIS can be used for morphometric classification and generalized overview maps of environmental variables in coastal waters. Such maps of the studied variables were created for as large parts of the European coastal zone as possible (restricted only by data availability). These maps give a good overview of average values in different regions and spatial differences between them. A similar compilation of maps for many relevant parameters, based on very extensive empirical data, is hard to find in previous literature. The classification and maps can serve as tools to find target ecosystems that are sensitive to pollution, but also to analyze the status of different systems and find areas under a heavy load. The presented maps show several examples of this, both at local and regional scale. The maps also provide input data to dynamic ecosystem models. Such models help to gain a deeper understanding of what factors control the environment in a coastal area, and what will happen when taking different remedial actions. This has been illustrated in a practical coastal ecosystem modeling case-study.

This work has focused on standard variables used in coastal science and management at local, regional and national levels in many countries. Naturally, there are also other important variables and following the methodology presented here; similar maps may also be derived for those variables. It was, e.g., desirable to include suspended particulate matter (SPM) in the analysis (see [41]), but unfortunately no data were available on this variable in any of the major databases that we could access. It would also be interesting to expand this study and include different fractions of TP and TN (e.g. phosphate, nitrate, DIN, DIP), and also other nutrients, like Si, which is known to be of importance for primary production in marine systems [96, 97].

The maps presented in this work are generalized and provide a general overview of spatial differences in surface water conditions. At the local scale and over shorter time-scales, major variations may occur in all these water variables. Hence, more local or regional data should be consulted for such modeling applications. The generalized overview maps presented in this work were created mainly using data from the European Environment Agency (EEA) and the International Council for the Exploration of the Sea (ICES). Naturally, it would be desirable to include also other data sources. One example of such a comprehensive database is The World Ocean Database 2005 [98]. However, we did not find enough raw data of the variables used in this work and for the investigated area in that database. At the time of writing, the most recent version of that database (World Ocean Database 2009) has not yet been finalized and was hence not used. A time-consuming, but interesting, option would be to search national databases for data from the areas where the used databases have insufficient coverage.

Hopefully, this work has shown the potential use of morphometric parameters like exposure (Ex) and form factor (Vd) at the ecosystem scale as indicators of sensitivity to pollution and ecological value. It has also shown how generalized overview maps can be derived and that these maps can provide useful information, both for selection of focus areas, and as input for dynamic modeling at the ecosystem scale. We hope that more effort will be put into collecting data from coastal areas currently lacking data. This would enable even better maps to be created in the future for gaining a better understanding of the spatial variation of the various variables and to provide a better foundation for coastal managers and modelers.

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