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REVIEW PAPER

The Use of Bathymetric Data in Society and Science: A Review from the Baltic Sea

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Abstract Bathymetry, the underwater topography, is a fundamental property of oceans, seas, and lakes. As such it is important for a wide range of applications, like physical oceanography, marine geology, geophysics and biology or the administration of marine resources. The exact requirements users may have regarding bathymetric data are, however, unclear. Here, the results of a questionnaire survey and a literature review are presented, concerning the use of Baltic Sea bathymetric data in research and for societal needs. It is demonstrated that there is a great need for detailed bathymetric data. Despite the abundance of high-quality bathymetric data that are produced for safety of navigation purposes, the digital bathymetric models publicly available to date cannot satisfy this need. Our study shows that DBMs based on data collected for safety of navigation could substantially improve the base data for administrative decision making as well as the possibilities for marine research in the Baltic Sea.

Keywords Bathymetry · Coastal environment · Mapping · Geospatial data · Baltic Sea

INTRODUCTION

Bathymetric data, in essence information about the water depth and underwater topography of oceans, seas and lakes, are important in many aspects of marine and lacustrine research, administration and spatial planning of marine and coastal environments and their resources. In the deep sea, most bathymetric data are collected primarily for such purposes. Even though bathymetric data are still sparse in many regions, significant international efforts are pursued in order to assemble all available data and make these available to the public. Examples of such efforts include the International Bathymetric Chart (IBC) projects, endorsed by the Intergovernmental Oceanographic Commission (IOC), or the General Bathymetric Chart of the Oceans (Hall 2006).

In the shallow waters and coastal areas of specific states, however, other societal needs are at the forefront: safety of vessel navigation is here the most prioritized rationale for bathymetric mapping close to the coast, around shoals and along shipping routes. This mapping is the basis for the production of nautical charts. In most countries, hydrographic surveying lies within the responsibility of national hydrographic offices or the navies. The detailed bathymetric measurements used for chart production are in some countries considered to be sensitive information, and access to the data may therefore be restricted. Published nautical charts are therefore often the best portrayal of the coastal seafloor readily available to the public, including the scientific community.

For a number of reasons, depth data displayed on nautical charts (hereafter referred to as chart depths) are, however, less than ideal in many research applications. Soundings on nautical charts are selected with a depth bias, as shoals generally are of greater importance for navigational safety than deeps (Zoraster and Bayer 1992; Haigang et al. 2005). Therefore, such data do not give a realistic portrayal of the seafloor morphology. Furthermore, the horizontal spacing of chart soundings is non-uniform, sparse, and often concentrated along common shipping routes.

Little research has been carried out on how bathymetric data primarily collected for safety of navigation are, or may be, used for other purposes in science and society. What potential problems may arise from the cross-disciplinary use of such data? Are there optimal ways to prepare and distribute bathymetric data so that their usefulness is maximized? If properly answered, this may result in better

possibilities to synchronize data collection and distribution efforts between the hydrographic authorities and the end users in research and administration.

This review builds on a questionnaire survey, carried out as part of an action plan for an updated digital bathymetric model (DBM) of the Baltic Sea. According to the Swedish government bill regarding the state's future maritime policy (Government of Sweden 2009), a consistent overview model of the Baltic Sea bathymetry shall be developed for maritime and environmental planning as well as for scientific research. A selection of Swedish state authorities, research institutes, and universities working with bathymetric data were contacted. They were asked a number of questions around their present use of bathymetric data in the Baltic Sea, the limitations of available data and their needs with regard to future data sets. Furthermore, the scientific literature was reviewed in order to acquire a more comprehensive understanding of the use of bathymetric data for research purposes. Here, we present a summary of the study, discuss the outcomes and provide an example for the potential of a new Baltic Sea DBM based on data not yet readily available to the public. More comprehensive details are listed in the technical project report (Broman et al. 2011).

We believe that the Baltic Sea may serve as a role model for highly exploited, shallow seas with a multitude of interests from different adjacent states. Assumedly, both common marine research questions and typical administrational tasks are not differing substantially between different states and regions. Therefore, we think that the essence of our findings may be applied to other regions in the world, too.

Available Bathymetric Data for the Baltic Sea

There are several publically available bathymetric data sets covering the Baltic Sea area (Fig. 1). In addition to such data sets, soundings may be extracted from paper or electronic nautical charts. All of these data have significant drawbacks concerning their spatial resolution and coverage or how up-to-date they are. At present, there is no homogeneous, quality controlled and continuously updated bathymetric model available for the Baltic Sea area, which can meet the demands indicated by Swedish government investigations (Miljödepartementet 2008).

Land elevation and underwater depth are usually measured with respect to different vertical datums, commonly mean sea level and the lowest astronomical tide (Gesch and Wilson 2002). Various applications rely on merging topography and bathymetry data sets, e.g., for the study of coastline changes or flooding phenomena. To date, there is no digital coastal terrain model available for the Baltic Sea accounting for the potential problems of such vertical datum issues.

Four important data sets are presented below.

GEOBALT

The GEOBALT project was a co-operation between the Swedish and Lithuanian geological surveys and resulted, among other outcomes, in a paper chart of the central Baltic Sea (Gelumbauskaitė 1998). Bathymetric contours (isobaths) are charted with an equidistance of 5 m, apart from an area on the northern map sheet with 10 m equidistance.

IOWTOPO

Seifert et al. (2001) at the Leibniz Institute for Baltic Sea Research, Warnemünde (IOW), published two DBMs of the Baltic Sea: IOWTOPO1 and IOWTOPO2. The IOWTOPO grids are by far the most widely used bathymetric portrayals of the Baltic Sea. The data are provided in two versions: the entire Baltic Sea area is covered at a grid cell size of 1′ (arc-minute) in latitude by 2′ in longitude (ca. 2 km in either direction). For the Southern Baltic Sea and Belts, a higher resolution data set exists at 30″ × 1′ (ca. 1 km) grid node spacing.

In the IOWTOPO grids, all at compilation time freely available depth information of the Baltic Sea was compiled. This includes mostly digitized nautical charts and soundings obtained for research purposes, but also other data sets based on measurements for safety of navigation purposes, e.g., in the Southern Baltic and the Belts. A total of 1.7 million water depth samples were incorporated in the final grids by calculating a weighted average for each grid cell. If no depth samples were present in a grid cell, a depth value was interpolated from adjacent cells using an averaging algorithm. Artifacts from interpolation over data gaps are visible in many of places.

In the central Baltic Sea the underlying data are sparse, and IOWTOPO2 is in large areas almost exclusively based on the GEOBALT contour map. As a result, depth values evenly divisible by 5 m are grossly over-represented in the data set, as indicated by a histogram of the data set (Fig. 1). Usually, this becomes manifest in terracing artifacts. However, in IOWTOPO2, such artifacts cannot be clearly identified.

Danish DMU Bathymetry

The Danish National Environmental Research Institute (DMU) has published a series of environmental data sets, including the bathymetry of Danish parts of Baltic Sea and Belts (Nielsen et al. 2000). Bathymetric data are released as a Triangulated Irregular Network (TIN) model with facet sizes on the order of 50 m, accompanied by a coastline data

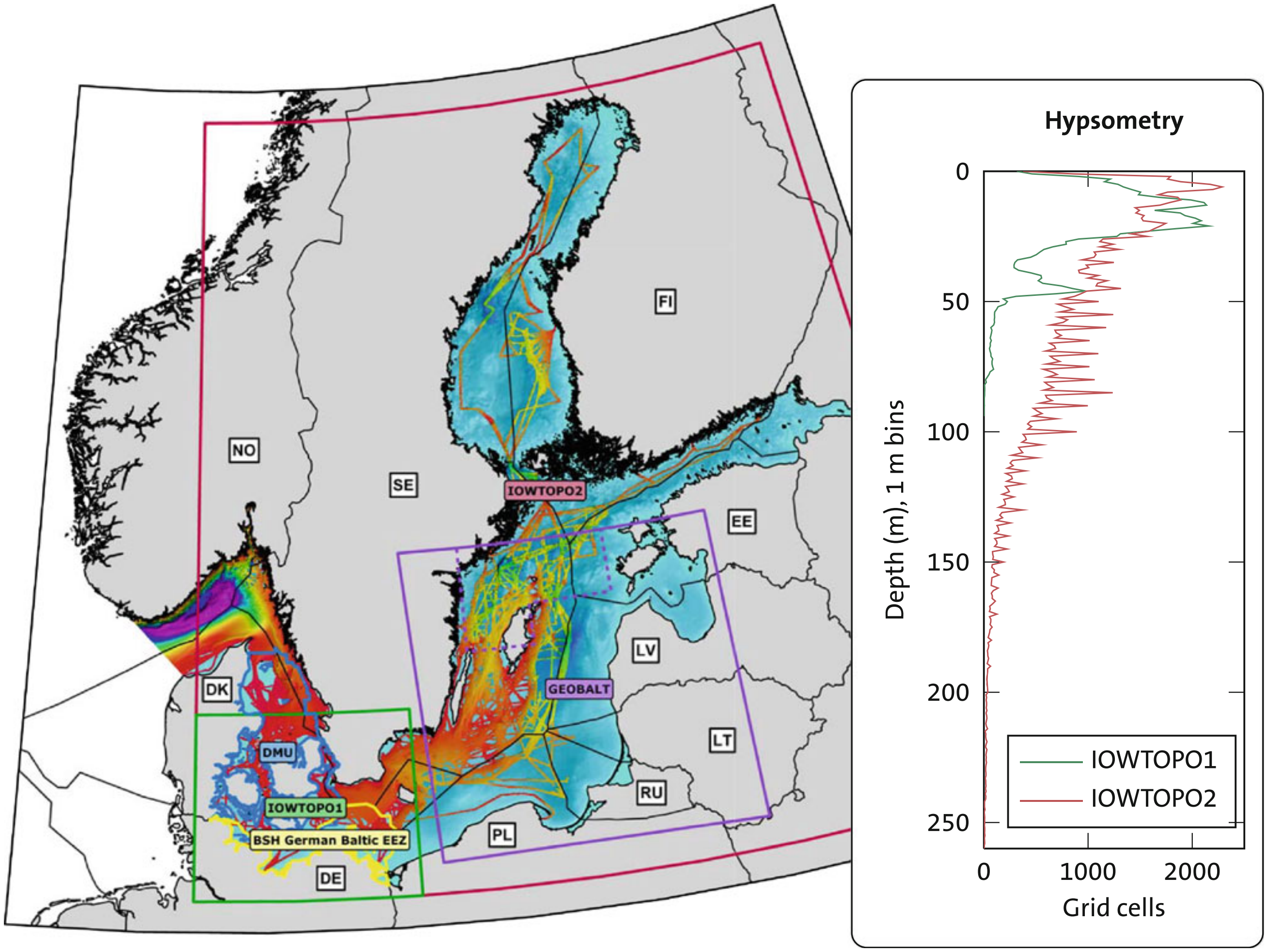


Fig. 1 Publically available bathymetric data sets for the Baltic Sea and Skagerrak. The Swedish-Lithuanian GEOBALT project resulted in a map of the central Baltic Sea depicting isobaths with an equidistance of 5 m in most places. For the German Baltic EEZ, the responsible hydrographic office has released a bathymetric grid with a cell size of ca. 200 m. A TIN model of the Danish Kattegat, Sound and Belts bathymetry with facet sizes in the order of 50 m is available from the Danish National Environmental Research Institute (DMU). IOWTOPO1 and IOWTOPO2 are DBMs compiled of all publically available depth data from the Baltic Sea at the time of compilation, among others including the above-mentioned maps and data sets (partly in now outdated versions). The southern Baltic Sea and Belts grid has a cell size of ca. 1 km (see text), and the entire Baltic Sea is covered at ca. 2 km cell size. Olex data (see "Discussion" section) cover a continuously growing part of mostly the Southern Baltic Sea (highlighted with *rainbow tints*; the data is not freely available). Maritime boundaries delineate the EEZs of the circum-Baltic states. The *inset* shows a histogram of the depth values (hypsogram) in the IOWTOPO grids, indicating terracing artifacts in IOWTOPO2

set. Most of the bathymetric data were acquired before 1988 with single beam echo sounders and at a measurement line spacing of typically 25 m. Only small parts of the TIN model are based on better and more recent multibeam measurements. There are relatively few interpolated gaps, but the data quality and spatial resolution vary within the data set.

German BSH Data

The German hydrographic authority provides a Web Map Service (BSH 2007), which serves a bathymetric data set of the German Exclusive Economic Zone (EEZ) at a grid cell size of 6″ × 10″ (ca. 200 m). The displayed values are average depths in the grid cells and most likely based on measurements for chart production.

METHODS

Questionnaire Survey

In order to assess the needs for depth data in today's society, including scientific research, a questionnaire was sent to Swedish public authorities, administrative bodies, research institutes and universities, asking about their

specific needs and use of bathymetric data. More specifically, the questionnaire included questions about the depth data presently used and on the needs regarding resolution, uncertainty, consistency, coverage, and accessibility of bathymetric data.

The responses were qualitatively analyzed with special emphasis on developing appropriate categories to classify the details given in the answers.

The questionnaire was sent out to 12 public authorities and state organizations, 11 universities and research institutes, six county administrative boards, primarily the ones doubling as River Basin District Authorities, and three non-governmental organizations. The questionnaire was also distributed to the private company AquaBiota, which mostly works under public contract. The recipients were chosen because they matched at least one of the following criteria: (1) known users of depth data; (2) known to be performing marine research; (3) mandate in the administration of water resource aspects of the Baltic Sea; (4) known to be dealing with marine protection questions; (5) interest in one of the above criteria as expressed in their response to the outcome of the Marine Environment Inquiry (Miljödepartementet 2008); and (6) own initiative to participate in the survey.

The addressees thus represent a broad variety of users of digital bathymetric data in Sweden, although this selection is biased toward the administrative and research communities.

Detailed bathymetric data are presently classified information in Sweden. Producing, keeping, and publishing such information needs approval by Swedish authorities and the Armed Forces. This imposes severe restrictions on how bathymetric data may be used. As the questionnaire was designed to find out in which form bathymetric data should ideally be available, the addressees were asked not to have their answers limited by such classification issues.

Literature Analysis

A review of the available scientific literature was carried out in addition to the questionnaire, in order to further assess the use of Baltic Sea bathymetric data for research applications. The review includes scientific articles, both peer-reviewed and non-peer-reviewed, as well as reports published until 2009. The literature review is restricted to research-related publications, although many publications exist that are related to administration, industry, or spatial planning.

Of a total of 144 references, 18 are not readily available in full text and have been excluded from this study. Another 20 references were not strictly research related and also excluded. Each of the remaining 106 references was analyzed with regard to the questions asked in the questionnaire survey. The complete list of references is available in the project report (Broman et al. 2011).

RESULTS

Questionnaire Survey Response

Of the 32 addressees, 21 answered the questionnaire. The distribution of the different groups and their response frequencies are shown in Fig. 2a. Because most of Swedish relevant public authorities are included in the answers, one may assume that the results are representative for administrative uses of bathymetric data in Sweden. The research community is less well represented as this group is more heterogeneous and the response frequency is lower. The literature analysis indicates that the range of research topics being carried out with the help of depth data (Fig. 2b and results below) is more comprehensive than what is indicated by the limited number of questionnaire answers from the research community.

Countries Performing Research Involving Bathymetric Data

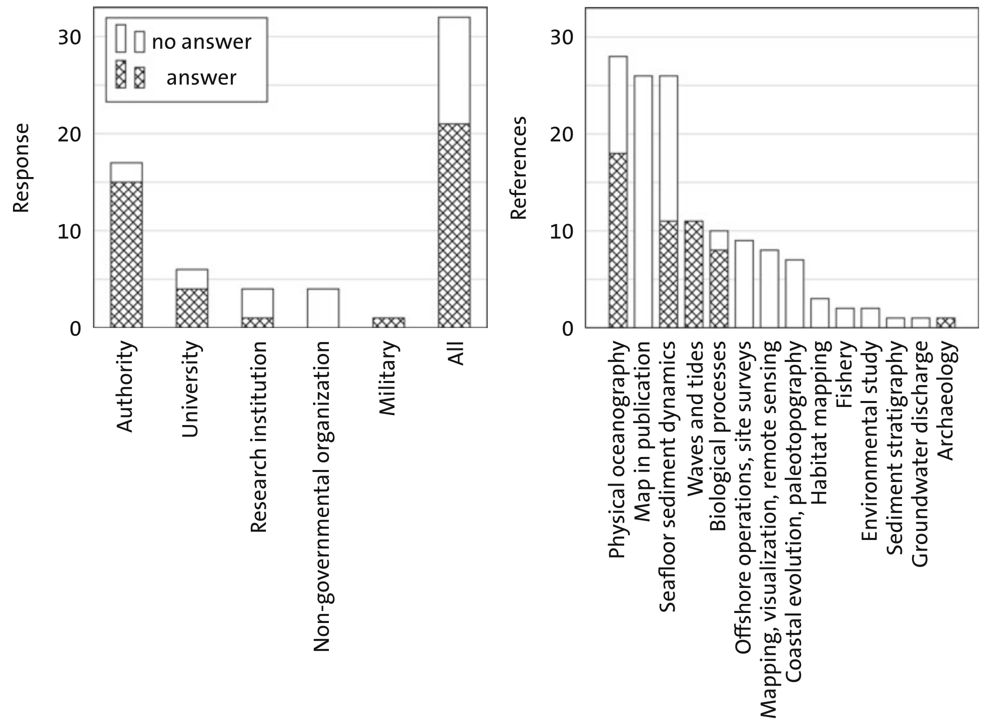
A few countries dominate Baltic Sea research involving bathymetric data (Fig. 3), judging from the affiliations of lead authors in the published literature. It is not surprising that almost half of the publications are of German origin, as the most used DBM of the Baltic Sea, IOWTOPO, was published by a German research institute. Sweden has the longest shoreline of all Baltic countries and a strong record of Baltic Sea research. The somewhat unexpected third position of Estonia in terms of publication quantity is partly due to a single researcher contributing half of the Estonian articles alone.

Within the countries, the activities are rather evenly distributed between the respective university departments active in marine research. Some public authorities, namely the geological surveys, have also published research results. One research institute is overrepresented: IOW, where IOWTOPO was compiled.

The Present Use of Depth Data

Purposes Depth Data is Used for

The questionnaire answers reveal a wide range of applications for bathymetric data, which mostly fall into three categories: (1) geographical planning tasks mentioned in 12 answers are mostly performed by state authorities and including energy and water resource related work, environmental protection, and exploration. (2) Numerical modeling is listed in 11



(a) Survey response **(b)** Study purpose

Fig. 2 **a** Questionnaire survey response. Overall about two-thirds of the addressees answered the questionnaire. Almost all contacted public authorities responded, whereas the response frequency was lower for the research community and zero for non-governmental organizations. **b** Depth data of the Baltic Sea is used in a variety of research fields. Shown are the numbers of published articles and research reports within a certain research field mentioning the use of bathymetric data. The *filled bars* indicate uses in a modeling context

answers. Typical applications include circulation modeling, hydrologic transport mechanisms, habitat and ecosystem mapping, as well as nutrient and sediment transport. Modeling is carried out at administrative level, especially at the River Basin District Authorities and in county administration, where it is often related to planning matters. Modeling is primarily research oriented at universities and research departments. (3) Marine scientific research is mentioned in 11 answers and often carried out at universities. The most common research questions are concerned with ecology, climate change mitigation and geomorphology.

The published literature provides a more detailed insight into the kind of research questions that are addressed (Fig. 2b). In about one quarter of the references, bathymetric data are exclusively used for illustration in a map of the study area.

Two research fields dominate in the literature, namely physical oceanography and marine geology. Physical oceanography, mentioned in 37 references, includes studying the water masses, their circulation, currents, climate as well as waves and tides. The 33 publications related to marine geology deal with sedimentation, erosion, and seafloor dynamics as well as coastal evolution, sea level change, and paleotopography questions.

Biology and environmental studies follow far behind oceanography and geology, with 10 references concerning biological processes and three publications dealing with habitat mapping. Planning of fieldwork, site surveys, and underwater vehicle operations are mentioned in nine references. The remaining 25 publications deal with more exotic topics (Fig. 2b).

Data Sets Used

The most commonly used data in the Swedish questionnaire survey are nautical charts of Sweden's territorial waters and its EEZ. These are mentioned in 11 answers, mainly by users having interests in the coastal zone. The second most used data set is IOWTOPO, listed by eight addressees, primarily for circulation modeling applications. Despite the low resolution of IOWTOPO, the data set is also used for purposes that would benefit from more detailed bathymetry, such as habitat mapping. In seven occasions dealing with geotechnical applications, habitat mapping, environmental protection and geological mapping, the users have collected their own data. Some other bathymetric data sets are mentioned in a few answers.

In the scientific literature, IOWTOPO is by far the most used data set (Table 1). IOWTOPO is referenced in 65 publications, both for the entire Baltic Sea (IOWTOPO2) and the southern Baltic (IOWTOPO1). Chart depths or similar data obtained from a hydrographic authority were used in 10 references. For another 10 studies, bathymetric data were specifically collected.

Other data sets are occasionally used in research, but such data is often not properly referenced in the publications.

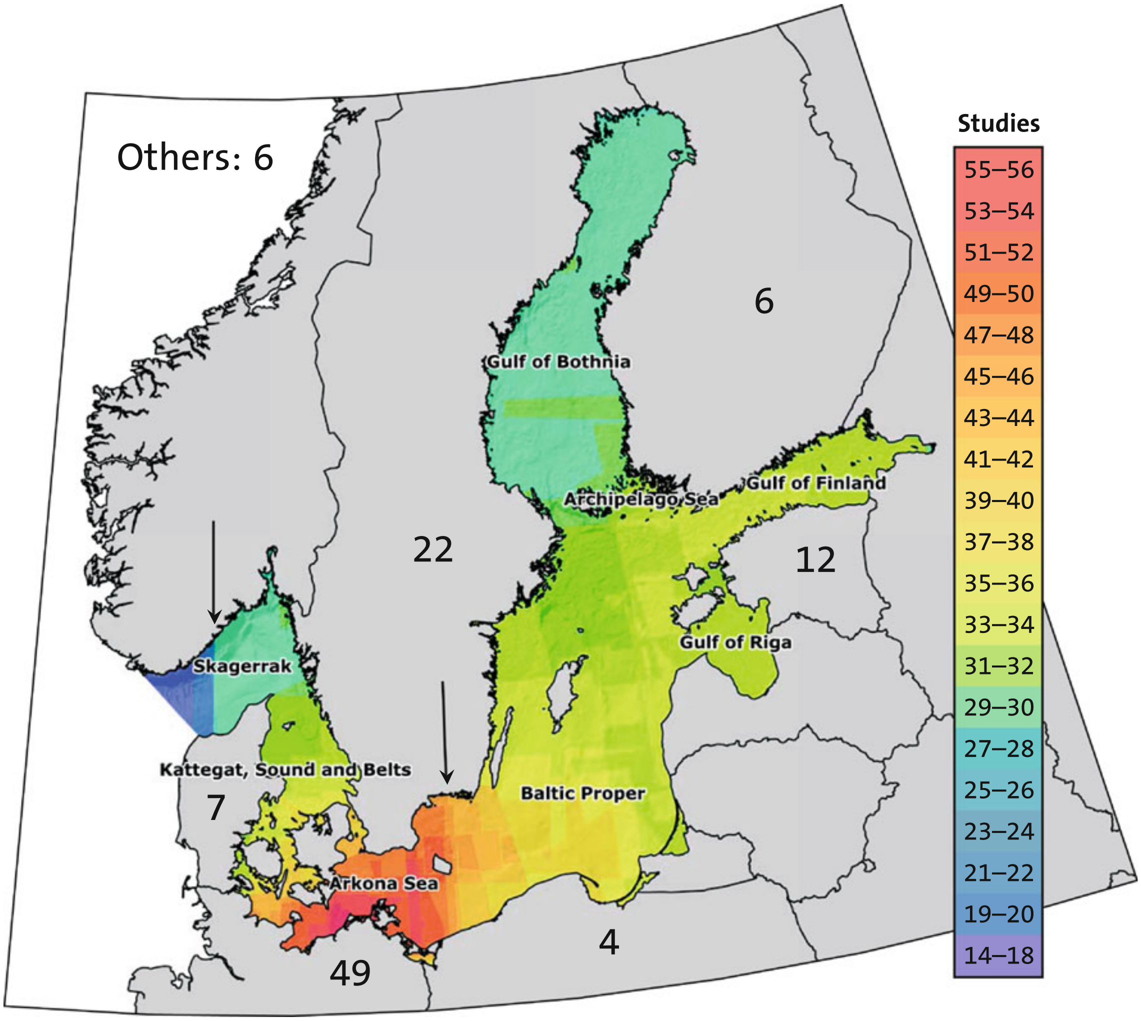


Fig. 3 Intensity of research utilizing bathymetric data in the Baltic Sea, as shown by the number of bathymetry related scientific publications at a certain place. Research is carried out most intensively in the Southern Baltic, with about twice as many studies carried out than in the Gulf of Bothnia, where research intensity is lowest. The area around the Leibniz Institute for Baltic Sea Research in Warnemünde (IOW) features the highest concentration of research studies in the entire Baltic. Since the IOWTOPO data set was published at IOW, this bias is not surprising. Discontinuities may be observed at the edge of IOWTOPO2 in the Skagerrak and the edge of IOWTOPO1 on a line through Bornholm (*arrows*; compare Fig. 1 for outlines of these data sets). The *numbers* indicate the amount of first author affiliations to the respective country

Needs Regarding Bathymetric Data

Problems with Currently Available Data Sets

Three common problems with the available bathymetric data sets are identified in the questionnaire answers: (1) almost three quarters of the users, especially those engaged in shallow water work, complain about a lack of spatial resolution or small bathymetric details; (2) more than one-third raise complaints concerning a general lack of measurements, i.e., the need for additional mapping efforts; (3) the confidentiality of detailed depth data in Sweden results in problems getting access to bathymetric data and difficulties when working with classified data sets. This was pointed out in more than one quarter of the answers, mostly by state authorities. Some users referred to other problems, such as accuracy deficits, lack of metadata, or poor harmonization between different data sets.

In the published literature, it is difficult to find clearly expressed problems and shortcomings of the bathymetric data used, probably because scientific research is published only once the data basis is sufficiently adequate for the performed task.

Required Coverage

Both the questionnaire survey and the published literature reveal that the areas where bathymetric data is needed vary

Table 1 Bathymetric data sets referenced in the reviewed literature

Data set	Reference	Comment	Used by
IOWTOPO	Seifert et al. (2001)	See "Introduction" section	65
Chart depths		Digitized nautical charts, ENCs or hydrographic office data	10
Own measurements			10
ETOPO5	NGDC (1988)	Depth model based on ETOPO5	4
GEOBALT	Gelumbauskaitė (1988)	See "Introduction" section	3
Satellite altimetry	Smith and Sandwell (1997), U. S. Department of Commerce et al. (2006), Becker et al. (2009)	Bathymetry derived from Satellite altimetry measurements	2
	Babenerd and Gerlach (1987)	Bathymetry of the Bay of Kiel	2
DHI DYNOCS	Weiergang (1995)	Danish waters, 1′ grid cell size	2
Olex		See "Discussion" section	1
SMHI		Bathymetry from Swedish Meterological and Hydrological Institute model	1
IOWTOPO 1995		1995 predecessor of IWOTOPO	1
BSH North Sea		German hydrographic office North and Baltic Sea model at 6″×10″	1
BSH Coast		German hydrographic office Baltic coast model at 1′ × 1′40″	1
DMU		See "Introduction" section	1
SYKE		Finnish ca. 50 m TIN model from chart data	1
SWAN		Military data (?)	1
TRIMGEO		Circulation model with 10 km resolution	1
RDANH Bornholm		Bathymetry around Bornholm from the Royal Danish Administration of Navigation and Hydrography, 200 m grid cell size	1
	Wieser (1987)		1
Unknown		Not stated which DBM was used in study	9

depending on the use of the data (Figs. 3, 4). Most users defined priority areas with regard to the coastline, base line, or certain isobaths (lines of constant depth), which may be grouped into the following categories (Fig. 4): (1) areas within the base line and archipelagos; (2) very shallow coastal areas within the ca. 10 m isobath or within a line up to three nautical miles (nmi) beyond the base line as well as protected areas; (3) coastal waters and shoals shallower than 40 m or within a line about 6 nmi beyond the base line as well as shipping routes; and (4) the Swedish EEZ or the remaining deeper parts of the Baltic Sea. The interest in coastal waters and shallow areas is higher than in the deeper regions of the Baltic. Fourteen answers fit into the two first categories, another seven in the third, and only three, all of them research institutions, were interested in the deeper regions of the fourth category.

The shallowest category was most interesting for marine archaeology and the River Basin District Authorities, whereas the second and third categories are interesting for a larger variety of applications. The two categories furthest away from the coast are primarily demanded by the remaining research institutes and authorities dealing with oceanographic questions. In 14 answers, interest in major inland waters is expressed, mostly in the lakes Vänern, Vättern, Mälaren, and Hjälmaren.

The number of published studies about any specific location in the Baltic Sea and Skagerrak is shown in Fig. 3. The "research intensity" is highest in the Arkona Sea, close to where IOW is located, publication wise the most active research institute. It decreases toward Skagerrak and the Baltic Proper. Most publications contributing to the areas with low "research intensity" deal with the entire Baltic Sea and there are few published studies focusing explicitly on these areas. Less than 10% of the publications extend into areas beyond the Baltic Sea and Skagerrak.

At the western edge of IOWTOPO2 and the eastern edge of IOWTOPO1 discontinuities in "research intensity" may be observed. In contrast, area subdivisions, such as the border between the Baltic Sea and North Sea or between different states' EEZs, are not prominent in the map.

From the questionnaire answers, the majority of the users would appreciate a seamless coastal elevation model

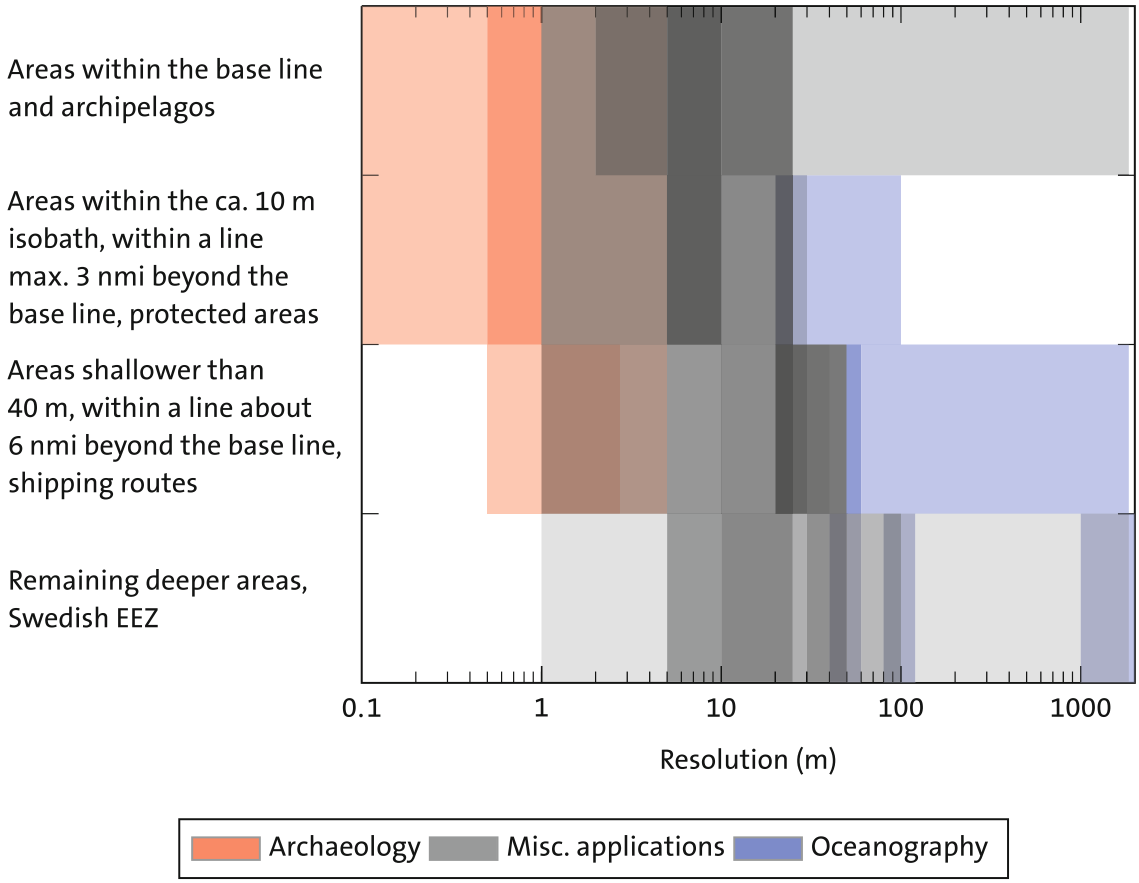


Fig. 4 Requirements regarding geographic coverage and spatial resolution. Each questionnaire answer is represented by a transparently shaded rectangle. Accordingly, the darker the areas in the plot, the more users are interested in such data. The bulk of the user requirements would be satisfied with a DBM covering areas shallower than 40 m with a spatial resolution on the order of 5–25 m. Only users working in archaeology express extremely high resolution requirements. Oceanographic uses generally have the lowest requirements with regard to resolution, but need extensive geographic coverage

integrating bathymetry with land elevations. This is of particular interest for geotechnical problems and coastal dynamics, such as studies of habitats characterized by recurring flooding events, coastline changes due to land rise and sea level changes, coastal erosion, paleo-landscape changes or water quality issues.

Required Spatial Resolution, Accuracy, and Metadata

There is much interest in the shape and structure of the seafloor, far beyond the details shown on nautical charts. In general, the spatial resolution of a DBM should be as high as possible, but different applications have different needs (Fig. 4). Marine archaeology and geotechnical users ask for the highest spatial resolutions, on the order of decimeter to meter level. Grid resolutions of 2–50 m are generally sufficient for applications in habitat mapping, fishery, or infrastructure and water resource administration. It was stated that resolutions coarser than 25 m are not sufficient for species and habitat modeling. Circulation modeling applications generally have the lowest needs concerning spatial resolution, on the order of one hundred meters or coarser. In many answers the possibility of variable grid resolutions are mentioned. Shallow waters and complex areas generally need to be portrayed at higher resolutions than deeper and less complex regions (Fig. 4).

The data accuracy needed for different applications varies, but generally the questionnaire answers indicate high standards. The answers include: vertically 0.1 m in shallow waters and 0.25 m otherwise; 0.5 m positioning in shallow waters; that small scale structures such as sand waves should be resolved; and compliance with the hydrographic standard S-44 (IHO 2008). A mean or median value of all measured depths within each grid cell satisfies the needs of most applications. If the grid resolution is significantly lower than the measurement spacing, other quantities may be interesting, such as a measure of sea floor roughness, minimum and maximum depth or various statistical parameters.

Thirteen users stated that the uncertainty of the grid should be specified in detail, for example, with a map showing relative or absolute uncertainty for each grid cell. Twelve users asked for information about the source data, or lack thereof, at a certain place. This could be implemented by showing the number of aggregated soundings for each grid cell, flagging of interpolated values, or specifying the distance from the grid node to the closest sounding.

The Capabilities of High-Resolution DBMs in Comparison to Commonly Used Data Sets

To assess the potential improvements with a DBM according to some of the specifications expressed in the questionnaire answers, a comparison of several data sets was carried out. The northern entrance of the Great Belt was chosen as a sample area. This area features a complex bathymetry with important details of relatively small size. The narrow and deep trough through the Great Belt is the pathway where most of the inflow from the Atlantic to the Baltic Sea takes place (Döös et al. 2004). Resolving its shape is therefore of particular importance for circulation modeling.

The DMU data set of the Danish Belts is based on data measured for chart production and provides a spatial resolution on the order of 50 m. This area is almost exclusively mapped using pre-1988 single beam measurements. Both versions of the IOWTOPO grids cover at least partially the same area, as does the legacy data set ETOPO5 (NGDC 1988).

For this area, four similar grids based on these data sets were prepared. Using a Geographic Information System, the grid nodes were extracted from the data and transformed into Lambert Equal Area projection coordinates optimized for Europe (Annoni et al. 2003). The points were then interpolated onto a regular 50 × 50 m lattice using the GMT programs *surface* and *blockmedian* (Smith and Wessel 1990). The land areas of the grids were masked out using high-resolution coastline data. The resolution of the original data is much lower than 50 m in most cases: ca. 1 km for IOWTOPO1, ca. 2 km for IOWTOPO2, and about 10 km in the case of ETOPO5. The resulting DBMs are compared in Fig. 5.

The DMU data show much more of the morphological seafloor details compared to all other data sets, whereas the difference between IOWTOPO1 and IOWTOPO2 is a lot less obvious. An analysis of the depth distributions (hypsometry) of the various data sets reveals similar histograms for the IOWTOPO and the DMU data sets. However, bathymetric profiles over both IOWTOPO data sets are smoothed and extreme values are missing, for example, deeps. Nevertheless, the general trend of the seafloor surface in IOWTOPO1 is more or less correct. The formerly widely used but now outdated ETOPO5 data set gives a poor portrayal of this area.

For many applications, water volumes are of special interest. A volumetric calculation for the area shown gives 71.4×10^9 m^3 for the DMU data set. The other data sets yield lower volumes at 69.1×10^9 m^3 (IOWTOPO1), 66.5×10^9 m^3 (IOWTOPO2), and 49.8×10^9 m^3 (ETOPO5). Accordingly, the mean water depths are 3.3–30.3% too shallow for the three lower resolution data sets.

DISCUSSION

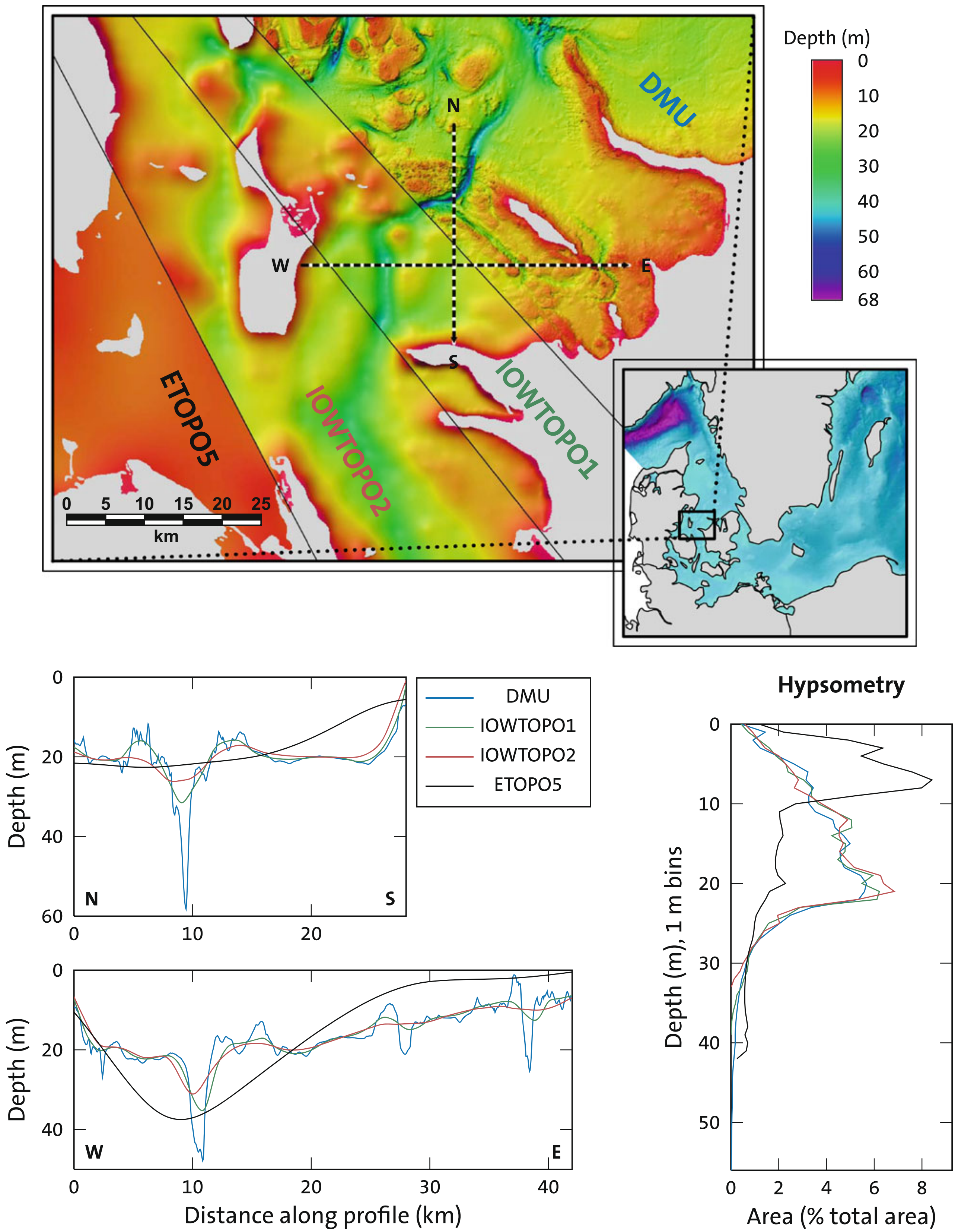
Our review underlines the general need for depth data in today's society. The relevance of depth data will persist in the future, considering the importance of the marine resources. This study also shows that there are problems with the quality and availability of bathymetric data for most of the Baltic region.

For many users, the lack of sufficient bathymetric data imposes limits on the quality and scope of their performed work. Several public authorities point out that bathymetric data are used for administrative decision making. Insufficient data are a less-than-optimal foundation for often costly decisions. This bears consequences, or in extreme cases risks, for the environment, the efficiency of costly offshore operations, material or safety at sea.

According to the Swedish Board of Fisheries, the lack of detailed depth data is the single most limiting factor for the mapping of the marine environment. Political commitments such as the Marine Strategy Framework Directive (European Parliament and Council 2008) or the HELCOM Baltic Sea Action Plan (HELCOM 2007) include mapping and documenting the marine nature, for which a bathymetric model of high quality and resolution is a prerequisite.

The restrictions imposed on detailed depth data in Sweden as well as the complexities in obtaining and working with classified information is a limiting factor in work involving Baltic Sea bathymetry. The company AquaBiota works to a large extent on projects commissioned by the Swedish Environmental Protection Agency. They stated that based on nautical charts one cannot obtain habitat maps sufficient for managing the marine environmental resources. Using classified depth data of higher resolution and quality, their habitat modeling was more successful. Offshore operations by the Swedish Geological Survey have been carried out less efficiently, more expensively and with worse results, as would have been the case with better bathymetric data. The classification issues caused them extra work and increased costs.

Presently, the focus of most authorities lies on coastal areas and shallow waters. Nevertheless, several of them



Depth (m)
0
10
20
30
40
50
60
68
DMU
N
W
E
S
IOWTOPO1
ETOPO5
IOWTOPO2
0 5 10 15 20 25
km
DMU
IOWTOPO1
IOWTOPO2
ETOPO5
Depth (m)
N
S
Distance along profile (km)
W
E
Hypsometry
Depth (m), 1 m bins
Area (% total area)

◀ **Fig. 5** Comparison of the commonly used IOWTOPO data sets with higher resolution data provided by the Danish Environmental Research Institute (DMU) for the Danish Belts. The level of detail is significantly higher for the higher resolution DMU data, whereas the difference between the two IOWTOPO data sets is much less obvious. The hypsograms of DMU and IOWTOPO data are quite similar. However, profiles over distinct morphological features show that the IOWTOPO data sets are prone to missing extreme values in the bathymetry. The legacy and now outdated ETOPO5 data set gives only a poor portrayal of this area

underline the importance of deeper areas for exploration in the future. Already today, authorities such as the Swedish Geological Survey or the Swedish Meteorological and Hydrological Institute are limited by the quality of depth data for the deeper parts of the Baltic Sea.

Despite evidence for problems with the data used in scientific studies being rare in the literature, one may assume that similar problems also have a negative impact on scientific research work. For tasks such as habitat mapping, detailed sedimentology studies, studies of paleocoastlines or certain modeling questions, the spatial resolution of the commonly used data sets is often too low. Clear indications for this are given by: Harff and Meyer (2001), who upsampled the low resolution of the ETOPO5 bathymetry for a coastal geology evolution study; Jakobsson et al. (2007), where a 500 m grid was interpolated from IOWTOPO; and Milbradt and Lehfeldt (2002), who performed modeling of littoral processes on nodes spaced at as little as 10 m along the German Baltic coast.

The discontinuities visible in Fig. 3 indicate that the geographical extents of a number of studies are determined by data availability rather than natural regimes, administrative boundaries or the official limits of sea subdivisions.

Our data comparison shows that higher resolution bathymetric data have a great potential for improvements over the currently widely used DBMs. Even data collected for chart production with now outdated technology more than two decades ago features a level of detail far beyond of what low-resolution scientific compilations can provide.

For modeling applications, resolving small but extreme bathymetric features may be very important. She et al. (2007) had to modify bathymetric data when modeling transport mechanisms through the Great Belt using a low-resolution DBM, in order to preserve the effect of the narrow and deep channel not resolved. Higher resolution bathymetry prevents such modeling problems (Bendtsen et al. 2009).

Possibilities in Data Collection

Besides the Swedish Maritime Administration, the Coast Guard, and the Geological Survey represent Swedish authorities that have capacities for seafloor mapping. In both latter cases, however, the depth measurements collected are not systematically saved and preserved for uses beyond the respective offshore operations. The data is not quality controlled to the same standards as in hydrographic production environments. In most cases, the amount of data collected is small. Nevertheless, if quality aspects were considered properly, such data could be shared and incorporated in DBMs.

The offerings of the Norwegian company Olex are an example of the efficiency of concerted mapping efforts. Olex provides a navigation and mapping solution targeted primarily toward the fishery industry. Using the echo sounders and GPS receivers of the fishing vessels, the Olex client systems continuously collect bathymetric data, which is uploaded to a central server, automatically processed and merged with data from other clients. The final gridded data are then distributed to all Olex clients, where the fishermen can use them to support decision making.

Olex operates worldwide, and data cover significant parts of the European continental shelf seas and many areas far away from the major shipping routes. The coverage in the Baltic Sea as of early 2010 is shown in Fig. 1. Data quality, coverage and resolution vary, but in many places the data provide a better portrayal of seafloor morphology than the data from nautical charts.

CONCLUSIONS

In contrast to administration and economy, where predefined goals prevail and highlight the need for a better data basis, research is often driven by the quality of the base data. Considering the variety of research topics presently published on a comparatively weak data base, it is likely that easily available, detailed bathymetric data of both high quality and high spatial resolution would amplify and simplify marine research. This conclusion is drawn from the literature review, and strongly supported by the questionnaire answers from the scientific community. As suggested by the answers from the state authorities, improved bathymetric data would also increase the efficiency of maritime administration. In general, the answers highlight a need for improved bathymetric data of the Baltic Sea in comparison to what is presently available, especially in the shallow, coastal zone.

Five key points of this review may be summarized as follows:

(1) Managing the marine environment and its resources is becoming increasingly important. Therefore, the value of high-resolution bathymetric data for administrative purposes may be expected to significantly increase in the future.

(2) Many applications require a level of detail that cannot be satisfied by navigational charts, for example, mapping habitats or archaeological studies. Many areas are mapped at high resolution, but the data are not available beyond the hydrographic offices. Other areas have only lower resolution data or show a complete lack of data. Therefore, releasing existing data is one priority but resurveying previously mapped areas with modern equipment is also important.
(3) The shallow waters in the immediate vicinity of the coast are the areas where data is most needed. However, the ship time needed for mapping increases with decreasing water depth. Airborne LiDAR measurements may be a valuable complement to ship soundings.
(4) Improved collaboration with regard to acquisition, management, and distribution of bathymetric data will lead to a more efficient use of the available resources and better data sets will become available to the end users. The ongoing efforts to establish international Spatial Data Infrastructures, such as the European INSPIRE directive, are a step in the right direction.
(5) Legal and military restrictions regarding handling and using detailed bathymetric data, as implemented in some countries, are severe hinders for administrative duties, research and the overall usefulness of depth data.

Typical administrative duties and marine research questions may be considered to be quite similar in most parts of the World, as is the lack of high-resolution coastal elevation models. Therefore, most of the conclusions drawn here may probably be applied to coastal areas and shallow seas other than the Baltic as well, even though they are strictly based on findings from the Baltic Sea.

All hydrographic authorities in the circum-Baltic and many other states keep bathymetric data similar to the DMU data set discussed above, at least for parts of their EEZs. Taken the enormous improvements possible in the portrayal of seafloor morphology with these data, their potential for societal needs strongly indicates that these data should be made publicly available for high-resolution DBM compilations.

All mapping efforts should be harmonized between countries, authorities, businesses, and the research community. Even if data quality may be an issue in some cases, the usefulness of a limited data set increases in combination with other data, and much data of varying quality are better than no data at all.

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