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Denmark's Depth Model: Compilation of Bathymetric Data within the Danish Waters

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Abstract: Denmark's Depth Model (DDM) is a Digital Bathymetric Model based on hundreds of bathymetric survey datasets and historical sources within the Danish Exclusive Economic Zone. The DDM represents the first publicly released model covering the Danish waters with a grid resolution of 50 m. When modern datasets are not available for a given area, historical sources are used, or, as the last resort, interpolation is applied. The model is generated by averaging depths values from validated sources, thus, not targeted for safety of navigation. The model is available by download from the Danish Geodata Agency website. DDM is also made available by means of Open Geospatial Consortium web services (i.e., Web Map Service). The original datasets—not distributed with the model—are described in the auxiliary layers to provide information about the bathymetric sources used during the compilation.

Keywords: digital bathymetric model; ocean mapping; open geospatial data

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1. Introduction

Ocean bathymetry refers to the depth measurements of the seafloor and, thus, represents the underwater equivalent of land topography [1]. Seafloor bathymetry is commonly distributed using a specialized type of digital terrain model called Digital Bathymetric Model (DBM), which is normally formatted as a regular grid and with depth values assigned to the grid cells [2]. A cursory glance at the available global and regional Digital Bathymetric Models (DBMs) may provide the false impression that the seafloor bathymetry of the oceans is largely known at full coverage. This impression is easily confuted by analyzing the content of these models. The General Bathymetric Chart of the Oceans (GEBCO)—a global DBM, with a resolution of 30 arc sec (e.g., about 926 m at the equator) [1]—lacks actual depth measurements for 80 percent of its coverage [3]. Similar considerations apply to other global compilations (e.g., the Global Multi-Resolution Topography (GMRT) [4]), as well as regional DBMs such as the International Bathymetric Chart of the Arctic Ocean (IBCAO) [5] and the European Marine Observation and Data Network (EMODnet) Bathymetry covering all European sea regions [6]. Although incorporating data derived from both single-beam echosounders (SBES) and modern high-resolution multibeam echo sounders (MBES), these models largely rely on interpolation and altimetry-derived data [1]. Altimetry-derived bathymetry is commonly used by global and regional compilations, but only provides a rough estimation of the seafloor, mainly due to upward continuation in deep waters and variations in sediment and crustal structure on shallow continental margins [7–9]. The depths estimated from altimetry have poor accuracy (i.e., a few hundred meters or worse) and quite low resolution, to the point that only very large seafloor features (in the order of a few kilometers) can be resolved [10].

For the subset of depths in the mentioned DBMs based on actual measurements, the density and the accuracy of the 'soundings' (i.e., bathymetric measurements) vary largely, and this heavily impacts the reliability of the estimated depths. Ocean mapping is limited by the intrinsic characteristics of the ocean environment, particularly by the high attenuation of the electromagnetic waves (i.e., multispectral images from satellites, lidar and radar) in water [11–14]. Thus, the sensors that are widely employed for land topography have limited application—often, just a few meters—in ocean mapping [3]. Instead other types of sensors—e.g., lead-lines and acoustical remote sensing such as SBES and MBES—play a critical role [3]. Historical depths are mostly derived from lead-lines; thus, they are sparse and obtained from a minimal seafloor area (i.e., the few-centimeter diameter of the used weight). When compared to lead-lines, a SBES provides depth measurements that are denser and represent the shallowest point of a fairly large area ensonified by the sonar. In fact, although the position of the measured depth is assumed at the nadir of the surveying platform, its actual location can be anywhere within the ensonified area [15]. Unquestionably, both density and resolution are higher than lead-lines and SBES when using a modern MBES that produces a significantly more accurate representation of the seafloor by electronically forming a set of narrow beams (usually, just a few degrees wide) [16,17]. Unfortunately, only a limited portion of the available models are based on soundings collected with a modern MBES [10]. This is mainly because a MBES for deep waters is physically large and heavy, requiring large platforms to be installed, and thus, relatively expensive to operate [10]. Acoustic geophysical methods also have a primary role in mapping shallow waters, but challenges associated with the coastal environment make it one of the most difficult in which to collect soundings [18] (e.g., the spatial and temporal variability of sound speed [19,20]). Furthermore, the collection of high-resolution bathymetry is not only expensive and frequently challenging, but also time-consuming, as it is only able to cover relatively small regions at a time [21]. Based on these considerations, it should not be surprising that the vast majority of the ocean is still inadequately mapped or even totally unexplored, in spite of centuries of ocean mapping efforts [3].

Due to the difficulties of mapping the seafloor through the water column, our knowledge of the topography of the oceans is largely lagging behind land topography [1]. However, the adoption of advanced techniques to improve the compilation of the available sparse soundings into a DBM has proven beneficial to many fields [21,22]. DBMs are commonly used to accurately describe critical boundary conditions for geophysical, geological, biological, and oceanographic systems [1]. Furthermore, DBM-based analysis is applied in several environmental and geological studies, such as the geohazard and geological analysis of morphologies, with increasing requirements of higher resolutions [23–26]. Elevation surface modelling of coastal areas or entire regions is often based on the integration of DBMs with various types of topographic data [27–29]. Although low-resolution DBMs may be used in global geomorphic features studies [30], they have limited applications in geomorphometric analyses (e.g., benthic habitat mapping) [18,31]. Detailed DBMs are essential to delineate coastlines for storm surges and sea level changes [11], and the morphology of the seafloor, controlling and constraining the bottom currents, and thus, global and regional heat transport [32,33]. Similarly, several aspects of marine geosciences (seafloor characterization, sedimentary studies, offshore engineering, etc.) require high-quality DBMs with meaningful associated metadata [34–36]. DBM's metadata and documentation, describing the main characteristics and limitations associated with a released DBM, facilitates researchers in discovering the bathymetry best fitting their specific purposes [32,37].

Since early 2020, the Danish Geodata Agency have made relevant efforts to organize available bathymetric datasets in Danish and Greenlandic waters into a modern geospatial data management system named DYBDB, and elaborate methodologies to compile these data sources into DBMs and other valuable products (e.g., hydrographic survey overviews) [38]. This paper focuses specifically on Denmark's Depth Model (DDM), the first bathymetric product created employing DYBDB. By improving the bathymetric coverage within the Danish Exclusive Economic Zone (EEZ) currently provided by the EMODnet Bathymetry, one of the major motivations for the creation of the DDM has been supporting environmental studies and other research efforts in the North Sea and in the Baltic Sea.

This paper starts by describing the management of the data sources (along with the main elements of DYBDB), then defines the methodological and technical steps underlying the creation of the DDM. Finally, the content of the publicly available DBM layers and services are presented, with the overall intent of facilitating the adoption of the DDM by researchers and other practitioners.

2. Materials and Methods

2.1. Management of Data Sources

DYBDB is a modern hydrographic data management system that has been designed and implemented by the Danish Hydrographic Office, which is a part of the Danish Geodata Agency.

The DYBDB system is based on several automated procedures (written in Python), task management mechanisms (based on the Atlassian's Jira™ issue-tracking product, https://www.atlassian.com/software/jira, accessed on 30 October 2022), and four types of geospatial databases (see Figure 1):

- **Smart DB**: The Survey Metadata and Raw data Tracker (Smart) database is used to manage an extensive collection of survey metadata, as well as for storing information used to track the integrity of the acquired raw data.
- **Point DB**: The Point database primarily contains the point cloud of cleaned soundings collected during the survey. When available in the data input, the soundings removed during the cleaning process are also stored, thus, replicating the original bathymetric content of the acquired raw data.
- **Grid DB**: Specially designed for dense datasets such as the ones collected by modern MBES, the Grid database contains a subset of the cleaned soundings stored in the Point database, at a spatial resolution tailored for nautical chart production.
- **Model DB:** Intermediate products and final DBMs are stored in the Model database.

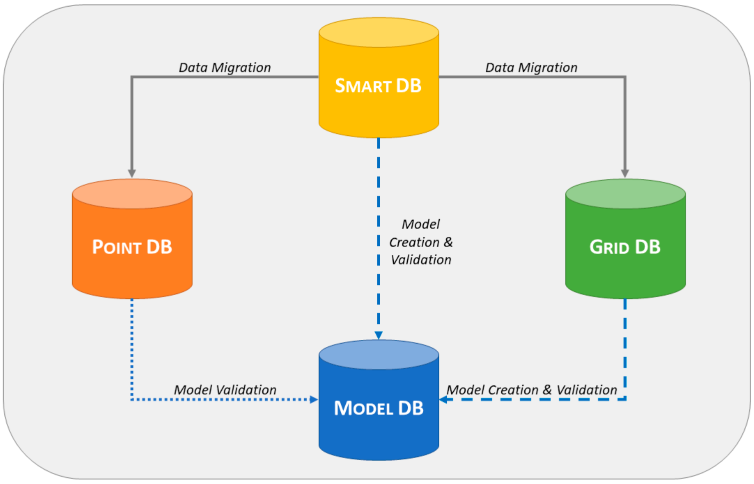

Figure 1. The four types of DYBDB databases (Smart DB, Point DB, Grid DB, and Model DB) and their interactions during key processes. The 'data migration' process (connectors shown in full grey) upload soundings to both Point DB and Grid DB based on the information stored on the Smart DB. The 'model creation' process (in dashed blue) combines soundings stored in Grid DB by retrieving the metadata information from the Smart DB. Once created, the 'model validation' (in dotted and dashed blue) is a semi-automated process that may require access to the point cloud of soundings at full resolution (shown in dotted blue).

The databases use the free and open-source PostgreSQL RDBMS (relational database management system) as backend (https://www.postgresql.org/, accessed on 30 October 2022). Snapshots of the critical content of DYBDB are obtained using the GeoPackage format (https://www.geopackage.org/, accessed on 30 October 2022). All the databases are currently managed through the CARIS' Bathy DataBASE Server™ software, and the CARIS' BASE Editor™ is used as the primary GIS client to access the content of DYBDB (https://www.teledynecaris.com/en/products/bathy-database/, accessed on 30 October 2022).

Since the DYBDB became operational at the beginning of 2020, the Point database and the Grid database have been populated by migrating about 1600 bathymetric datasets (see Figure 1), mainly from hydrographic surveys performed by the Danish Navy, other public agencies, industries, and academia. Most of these datasets have been acquired using SBES and MBES, with sounders generally hull-mounted or installed on a removable pole. Horizontal positioning of the soundings is mainly based on a Global Navigation System (often with corrections to improve accuracy) and, for MBES, an attitude sensor. The latter is required for collecting information on the dynamic movements of the survey platform (i.e., roll, pitch, heave, and yaw) used to spatially orient the acoustic swaths [15,16].

The primary key to uniquely identify a dataset in DYBDB is an encoded textual string named 'Survey ID'. The Survey ID is used not only to retrieve all the soundings belonging to a dataset from the Point DB and the Grid DB, but also to identify a dataset as a contributor to a specific depth value in the Model DB and, finally, in the DDM.

2.2. Compilation Approach

The latest EMODnet Bathymetry (released in December 2020) has a grid resolution of 1/16 arc minute (about 115 m) [39]. As such, to improve the resolution of the publicly available bathymetry within Danish waters, a regularly spaced grid resolution of 50 m was targeted for the DDM. A 50 m resolution was judged to represent a reasonable tradeoff between areas covered with high-resolution surveys (e.g., in the Kattegat area) and regions with only sparse historical soundings (e.g., a large part of the North Sea).

During the processes of model creation and model validation, the DYBDB provides access to datasets and related metadata—specifically, the Smart DB, the Point DB, and the Grid DB—as well as storage for the intermediate products and the finalized DBM in the Model DB (Figure 1). The overall compilation approach is made of the following main steps (Figure 2):

- *Creation/update of the model tiles for datasets in Danish waters.* The source datasets are retrieved from the Grid DB and related metadata from the Smart DB using the *Survey ID*. The sources are gridded by adopting a grid resolution of 50 m and a tiling scheme with a tile area of 1° of latitude by 1° of longitude (Figure 3). The tiles covered by at least one dataset are generated and stored in the Model DB. The bathymetric values are calculated as *representative average depth*, that is, an average of all water depths allocated from the relevant input source to a given grid cell. When multiple datasets overlap, the relevant input source is selected primarily based on the time of data collection. This step is periodically executed to update the tiles in the case of new datasets.
- *Combination of the model tiles into a continuous DBM.* All the populated DDM tiles stored in Model DB are combined into a continuous DYBDB-sources-only DBM.
- *Extension of the continuous DBM with historical soundings.* The DBM calculated in the previous step is extended by combining it with historical soundings available on published nautical products.
- *Interpolation using a Triangulated Irregular Network (TIN) and natural neighbors.* To fill areas with sparse soundings, an interpolated DBM is generated by first creating a Triangulated Irregular Network (TIN) from the extended DBM (generated in the previous step), then using the TIN to interpolate based on the 'natural neighbors' algorithm [40,41].
- *Coverage extraction based on Denmark's EEZ.* The interpolated DBM is updated to limit its coverage from the coastline (generalized at 1:100,000 scale) to the EEZ. The resulting DBM is uploaded to the Model DB.
- *Quality control*. The quality of the DBM resulting from the previous steps is extensively assessed by a team of reviewers. During this iterative process, the reviewers have access to all the direct and indirect DBM sources through Smart DB, Point DB, Grid

DB, and historical data. In case of issues, adjustments to the model may require the (partial or total) re-execution of the previous steps. Only when the outcomes of the quality control are satisfactory is the DBM finalized.

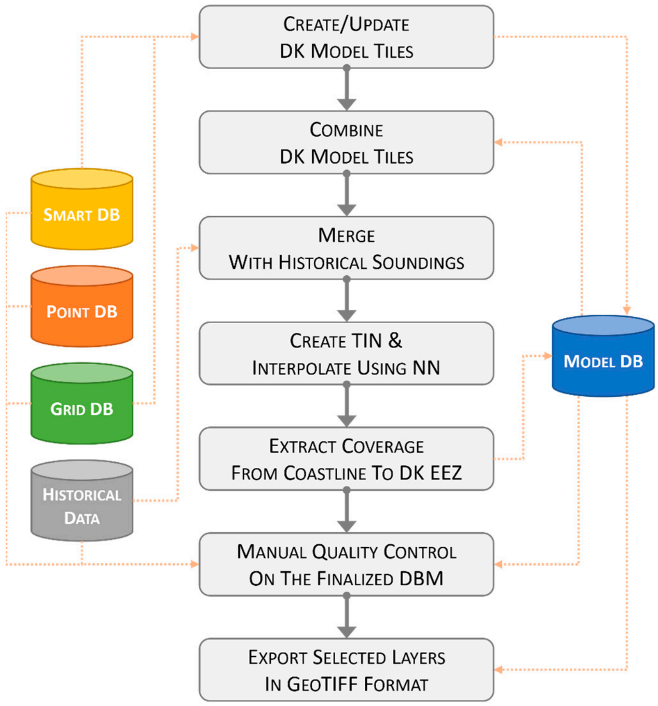

Figure 2. Workflow showing the main steps of the compilation approach (connected using grey arrows). The access (read/write) to DYBDB databases and the retrieval of historical data are shown using orange dotted connectors. Acronyms used in the workflow: DK for Denmark, EEZ for Exclusive Economic Zone, NN for the Natural Neighbor algorithm.

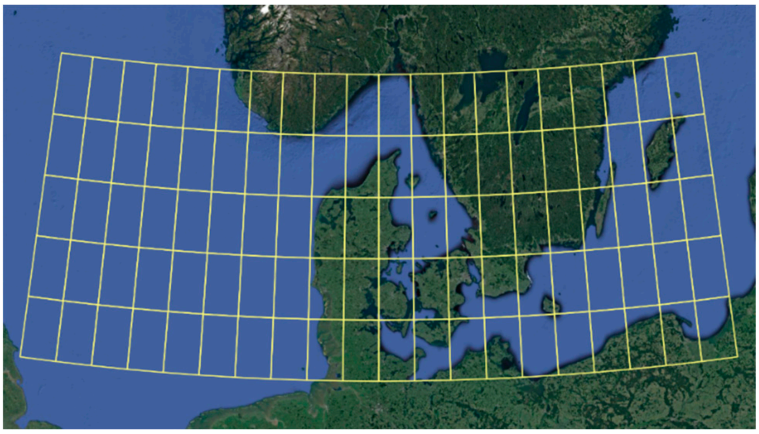

Figure 3. The tiling scheme (in yellow) used to divide the task of compiling the datasets available on the Grid DB. Each tile has an area of 1° of latitude by 1° of longitude. Background from Google Maps' Tile Map Service.

2.3. Model Products

Once the creation and validation processes are completed (following the steps described in the 2.2. *Compilation Approach* section and summarized in Figure 2), the layers listed in Table 1 are exported from the finalized DBM for public release.

Table 1. Layers extracted from the finalized DBM for public release.

Layer (in Danish)	Description
ddm_50m.dybde	The primary layer containing the depth values (in meters).
ddm_50m.kilde	An auxiliary layer providing the source of the depth data for each grid cell. The layer uses the following convention: 1. *DIGI*: The source is a digitalized survey fairsheet. 2. *SB*: The source depths were collected using a SBES. 3. *MB*: The source depths were collected using a MBES. 4. *Historical*: Historical depth values (e.g., lead-line). 5. *Interpolated*: Depth interpolation was applied.
ddm_50m.aar	An auxiliary layer providing the year at which the data collection has ended (only for *DIGI*, *SB* and *MB* dataset types).

The extract layers are projected in Lambert Conformal Conic (LCC)/ETRS89 (EPSG:3034). The vertical datum of the bathymetric layer is a combination of Mean Low Water Spring (MLWS), Lowest Astronomical Tide (LAT) and Dansk Vertikal Reference 1990 (DVR90). The two auxiliary layers (*ddm_50m.kilde* and *ddm_50m.aar*) are used to describe the type and the collection time of the source datasets used to estimate the DDM depths. The original source datasets are not distributed with the DDM. This approach is similar to the one adopted by EMODnet Bathymetry that does not distribute the sources, but provides metadata services (if any) [22].

The output format for the exported layers is GeoTIFF [42]. A *readme* document (in PDF format) with a succinct description on the DDM (i.e., how the model was generated and how to interpret the provided DDM layers) is also a part of the compressed archive containing the DDM release. The DDM layers listed in Table 1 are also made available as Open Geospatial Consortium (OGC) services (i.e., Web Map Service).

3. Results

The official publication of the first release of the DDM happened on 11 November 2022. Both compressed archives containing the material described in *2.3. Model Products* section and information to access the OGC services are available on the Danish Geodata Agency website (https://eng.gst.dk/danish-hydrographic-office/denmark-depth-model, accessed on 30 October 2022).

The released bathymetric layer (Figure 4) covers an area of 232,679 km^2. The largest majority (~97.5%) of the depth values are under 100 m; they present a skewed distribution with a modal depth range between 20 and 25 m and a median value of ~30.5 m (Figure 5).

Based on the *ddm_50m.kilde* auxiliary layer, 18% of the populated grid cells are derived from MBES surveys, and about 75% are derived from interpolation (Figure 6). Based on the *ddm_50m.aar* auxiliary layers, the first MBES-type contribution to the DDM occurred in 1993, and the following years present a significant increase in DDM coverage (Figure 7). The large variability in data density based on the types and years of the DDM sources determined areas with detailed bathymetry derived from MBES surveys (Figure 8), and others that were heavily smoothed because of the interpolation estimating the depth among the sparse soundings (Figure 9).

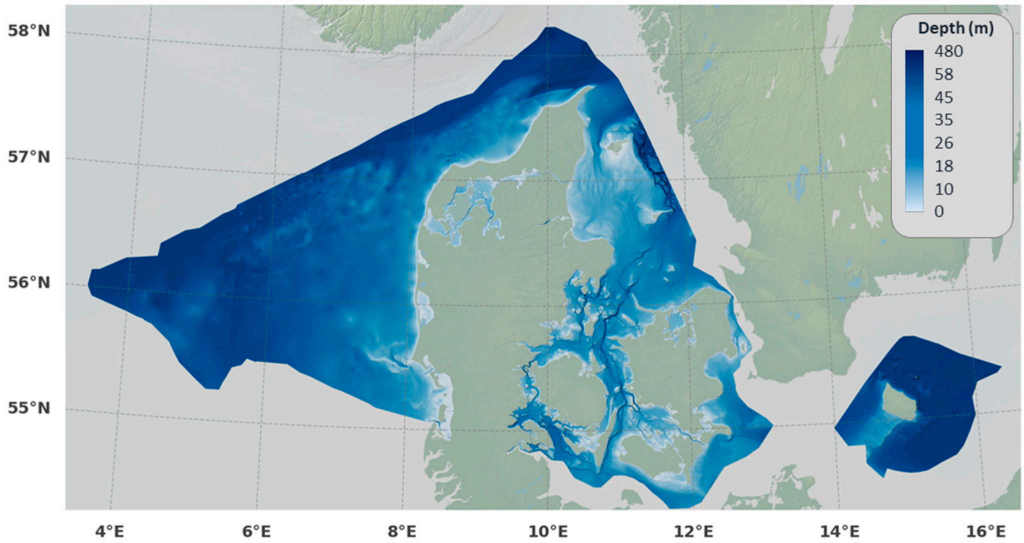

Figure 4. The bathymetric layer of Denmark's Depth Model. The depth values in the color legend are in meters. The Global Multi-Resolution Topography (GMRT) version 4.0 is shown in the background.

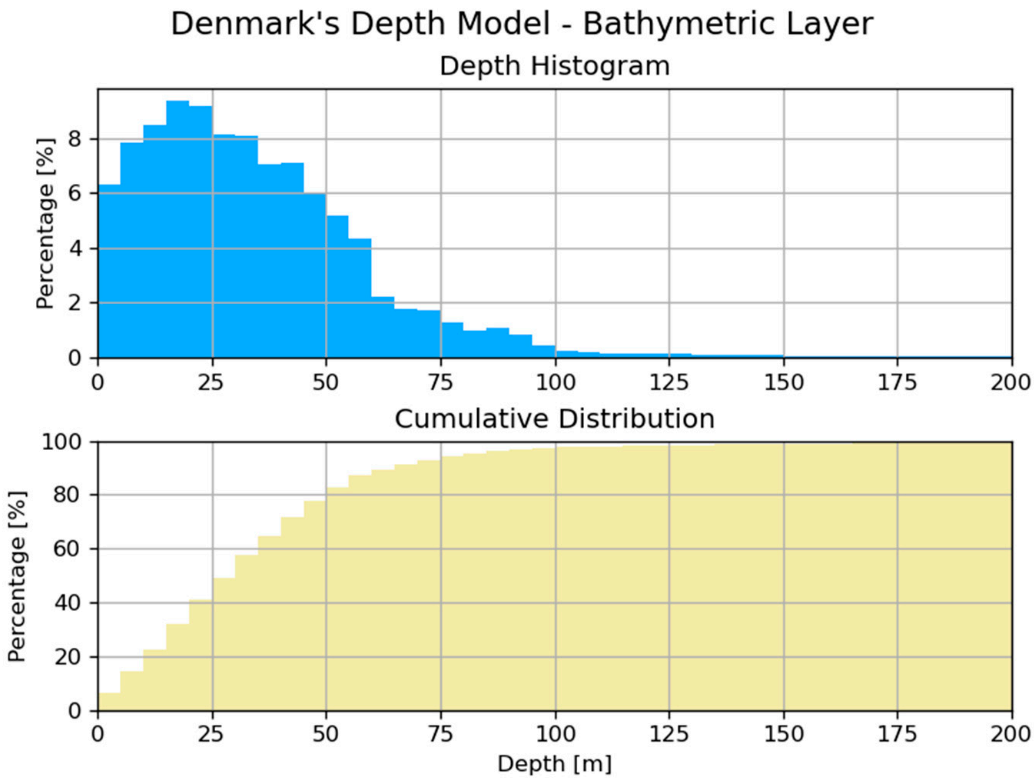

Figure 5. Depth histogram (upper pane) and related cumulative distribution (lower pane) for Denmark's Depth Model's bathymetric layer. For better visualization, an upper limit of 200 m has been applied to the axis of the depth values.

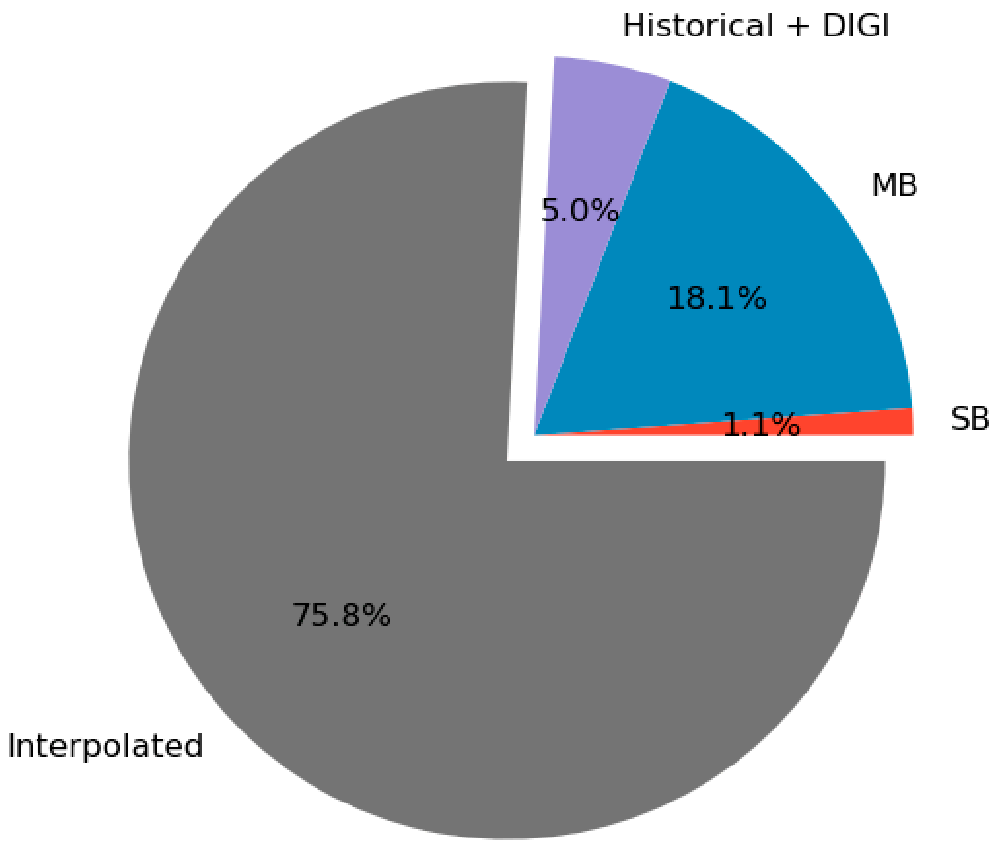

Figure 6. Percentage distribution of the different source types. The labels follow the convention described in Table 1 for *ddm_50m.kilde*.

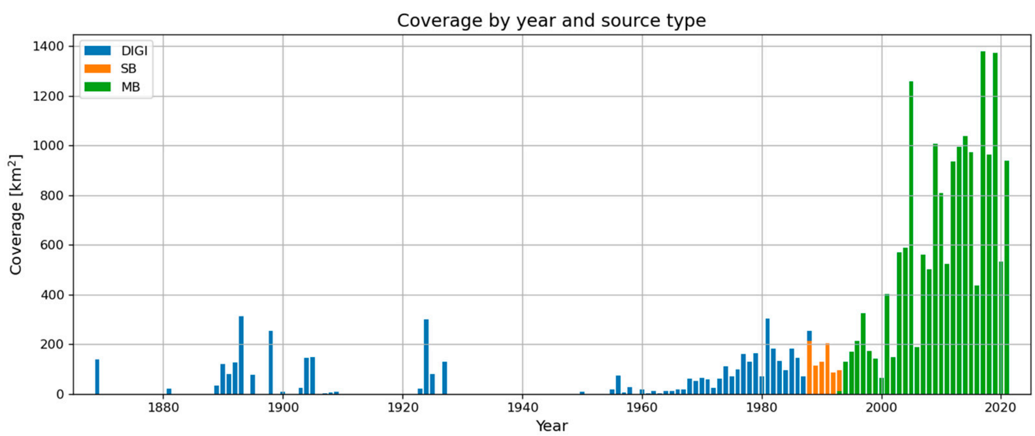

Figure 7. Coverage in km^2 by year and source type. The DDM shows the transition to modern SBES surveys (in orange) in 1988 and the transition to MBES surveys (in green) in 1993.

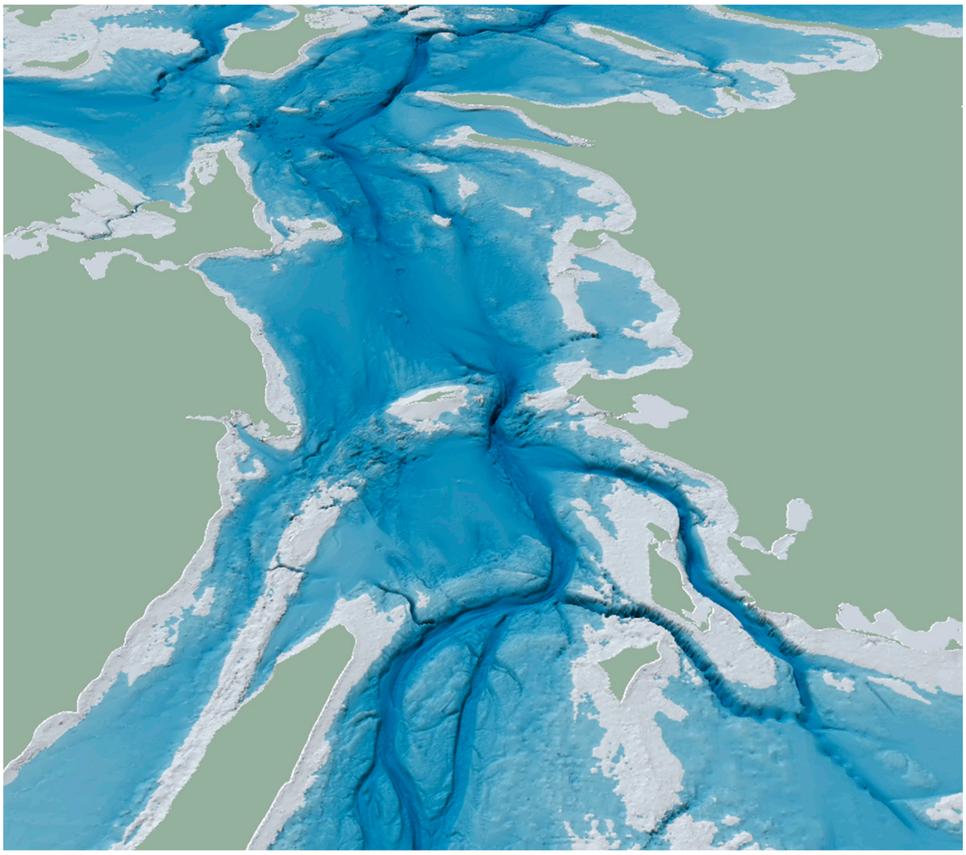

Figure 8. Perspective view of Denmark's Depth Model at the Great Belt facing north. The area is located between the greater islands, Funen (west) and Zealand (east), and is a heavily trafficked route to the Baltic Sea. The model hill-shading is rendered using a depth exaggeration of 25 times. The maximum model depth in the area is ~70 m.

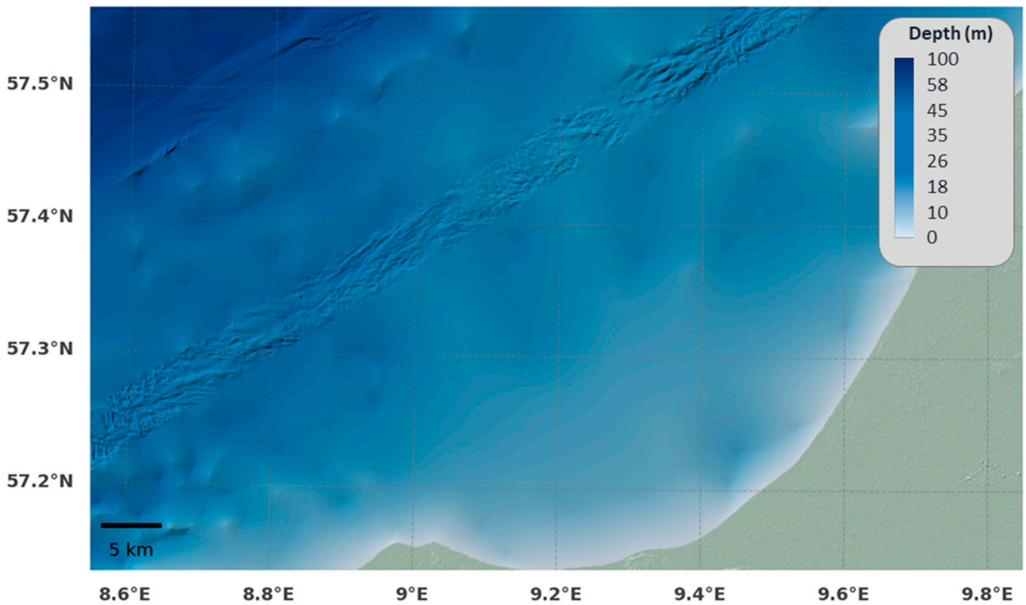

Figure 9. Bathymetry of an area of about 50 km offshore the city of Hirtshals (North Jutland, Denmark). The maximum model depth in the area is ~100 m. The oblique strip with detailed bathymetry is derived from a MBES source. The Global Multi-Resolution Topography (GMRT) version 4.0 is shown in the background.

4. Discussion

Denmark's Depth Model represents the first publicly released model covering the Danish waters with a grid resolution of 50 m. This paper describes the compilation process adopted in the creation of the DDM, as well as its distribution through publicly available products (Figure 4). Both aspects may be of interest for hydrographic offices and other national agencies aiming to actively support research and modeling efforts, given the variety of applications in which DBMs are used. The DDM is generated using an averaging approach, thus, not targeted for safety of navigation. However, several of the steps described in the compilation workflow (Figure 2) can be re-used for future works targeting the development of a navigation surface to streamline the production of nautical charts [43].

The DDM is based on hundreds of bathymetric survey datasets and historical sources within Denmark's EEZ. Unfortunately, less than 20% of the DDM coverage is based on surveys executed with modern SBES and MBES (Figure 6). Significantly increasing this percentage in the coming years is resource-intensive, also because the acoustic swath of MBES is limited by the relatively shallow depths surrounding Denmark (Figure 5). This consideration is one of the main drivers to explore alternative data sources, such as bathymetric lidar and satellite-derived bathymetry—both limited to shallow waters in coastal areas—as well as crowd-sourced bathymetry (CSB). The potential of CSB is large, but its adoption requires practical solutions to overcome a few challenges (i.e., data validation and quality assessment, variable credibility of the collectors) [44].

When modern datasets are not available on a given area covered by the DDM, historical sources are used, or, as the last resort, interpolation is applied. The adopted interpolation approach based on the Natural Neighbor algorithm [40] shows positive results in preserving the details of the areas with dense MBES-type data (Figure 8), as well as in transitioning between areas of wildly different density (Figure 9). However, future works may explore alternative interpolation approaches for introducing further improvements in the DDM [45,46]. Next, releases of the DDM will also likely reduce the interpolated areas, extend the coverage of the inner waters (i.e., fjords, rivers, and lakes), and reduce all the depth values to a common vertical datum (e.g., Mean Sea Level).

The mechanism to compile the hundreds of sources from Grid DB—the "Create/Update DK Model Tiles" step in Figure 2—permits reducing the computation time by requiring updating only the model tiles interested by source changes. More generally, the creation of a robust workflow facilitates the integration of new data sources in the DBM, while preserving a consistent way to present the finalized product. Future work may also explore automated procedures to improve the efficiency of the current quality control of the finalized DBM (Figure 2) [27,47].

DDM has the potential to be beneficial for many scientific applications, from geological studies to oceanography and biology [10,23,48]. Several aspects of marine geosciences—seafloor characterization, sedimentary studies, offshore engineering, etc.—require high-quality DBMs such as the DDM [18,27,35,49]. The metadata and documentation associated with the DDM aims to facilitate its discovery by researchers when searching for the bathymetry best fitting their specific purposes. The downloading services are available on the Danish Geodata Agency website (https://eng.gst.dk/danish-hydrographic-office/denmark-depth-model, accessed on 30 October 2022). The DDM is also made available by means of OGC web services (i.e., Web Map Service).

The original datasets, which are not distributed with the model, are described in the auxiliary layers to provide clear information about the bathymetric sources locally in use by the DBM. Facilitating access to marine data is a critical component of the EU Marine Strategy Framework Directive and the EU Marine Knowledge 2020 agenda, including the already mentioned EMODnet initiative [6,22]. The DDM is also a prospective data source for a future release of the EMODnet Bathymetry. In fact, the EMODnet Bathymetry can receive 'composite grids'—that is, gridded product composed from multiple sources—

as input, by using the SeaDataNet Sextant catalogue service that has been extended for providing details about this type of submission [22].

5. Conclusions

The creation of Denmark's Depth Model (DDM) is based on hundreds of modern datasets (described in the auxiliary layers), historical sources, and interpolation. The resulting DBM represents the first publicly released model covering the Danish Exclusive Economic Zone at a resolution of 50 m.

The current poor knowledge of the ocean seafloor limits our understanding of critical ocean processes providing resources and goods for humanity, controlling the climate, and, more generally, sustaining life on Earth [10]. The DDM improves the bathymetric coverage within the Danish Exclusive Economic Zone (EEZ), which is currently provided by the EMODnet Bathymetry. As such, in times of increasing environmental concerns, the DDM provides a relevant contribution, as described in the United Nations Sustainable Development Goal 14, which aims to "conserve and sustainably use the oceans, seas and marine resources for sustainable development" [50].

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