electronics

Brief Report

Concept of an Innovative System for Dimensioning and Predicting Changes in the Coastal Zone Topography Using UAVs and USVs (4DBatMap System)

Oktawia Specht [1], Mariusz Specht [1,*], Andrzej Stateczny [2] and Cezary Specht [3]

[1] Department of Transport and Logistics, Gdynia Maritime University, Morska 81-87, 81-225 Gdynia, Poland; oktawiaspecht@gmail.com
[2] Department of Geodesy, Gdańsk University of Technology, Gabriela Narutowicza 11-12, 80-233 Gdańsk, Poland; andrzej.stateczny@pg.edu.pl
[3] Department of Geodesy and Oceanography, Gdynia Maritime University, Morska 81-87, 81-225 Gdynia, Poland; c.specht@wn.umg.edu.pl
* Correspondence: m.specht@wn.umg.edu.pl

Abstract: This publication is aimed at developing a concept of an innovative system for dimensioning and predicting changes in the coastal zone topography using Unmanned Aerial Vehicles (UAVs) and Unmanned Surface Vehicles (USVs). The 4DBatMap system will consist of four components: 1. Measurement data acquisition module. Bathymetric and photogrammetric measurements will be carried out with a specific frequency in the coastal zone using a UAV equipped with a Global Navigation Satellite System (GNSS)/Inertial Navigation System (INS), Light Detection And Ranging (LiDAR) and a photogrammetric camera, as well as a USV equipped with a GNSS Real Time Kinematic (RTK) receiver and a MultiBeam EchoSounder (MBES). 2. Multi-sensor geospatial data fusion module. Low-altitude aerial imagery, hydrographic and LiDAR data acquired using UAVs and USVs will be integrated into one. The result will be an accurate and fully covered with measurements terrain of the coastal zone. 3. Module for predicting changes in the coastal zone topography. As part of this module, a computer application will be created, which, based on the analysis of a time series, will determine the optimal method for describing the spatial and temporal variability (long-term trend and seasonal fluctuations) of the coastal zone terrain. 4. Module for imaging changes in the coastal zone topography. The final result of the 4DBatMap system will be a 4D bathymetric chart to illustrate how the coastal zone topography changes over time.

Keywords: predicting changes in the coastal zone topography; Unmanned Aerial Vehicle (UAV); Unmanned Surface Vehicle (USV); topo–bathymetric measurements

check for updates

Citation: Specht, O.; Specht, M.; Stateczny, A.; Specht, C. Concept of an Innovative System for Dimensioning and Predicting Changes in the Coastal Zone Topography Using UAVs and USVs (4DBatMap System). *Electronics* **2023**, *12*, 4112. https://doi.org/10.3390/electronics12194112

Academic Editor: Sergio Trilles Oliver

Received: 10 August 2023
Revised: 11 September 2023
Accepted: 27 September 2023
Published: 30 September 2023

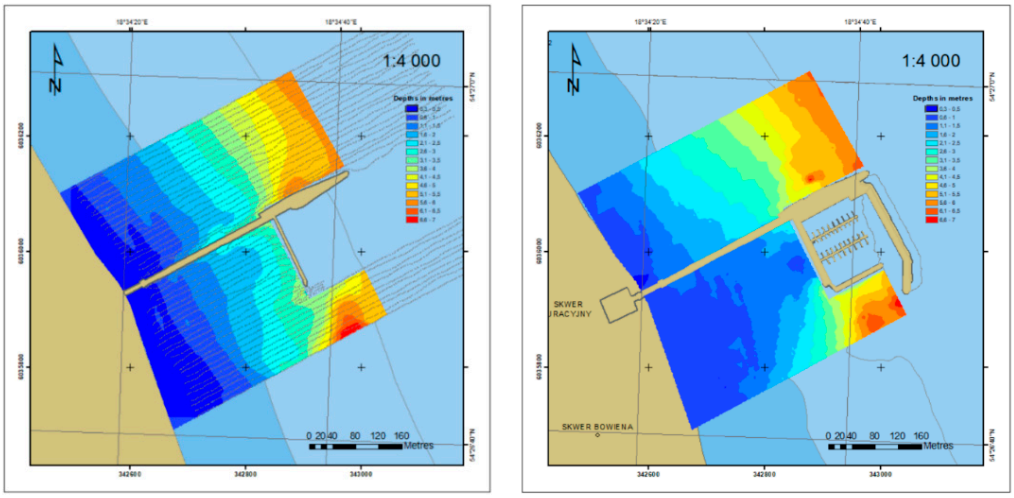
1. Introduction

1.1. Effects of a Lack of Dimensioning and Predicting Changes in the Coastal Zone Topography

Bathymetry is a branch of hydrology that deals with the measurements of depths and watercourses [1]. Bathymetric measurement results plotted on the waterbody map as depth points enable the determination of isobaths, i.e., isolines connecting points of equal depths of water areas, depicting the topography of the waterbody bottom [2]. The data made available by the General Bathymetric Chart of the Oceans (GEBCO) show that the global ocean floor has only been approx. 20% explored [3], despite the fact that the aquatic environment is among the most rapidly changing regions on the Earth, particularly in the coastal zone [4].

The coastal zone, i.e., the area encompassing the seashore and the adjacent parts of land and sea, is of particular importance from the perspective of economic and environmental policies of the coastal states. This is due to the fact that it is rich in natural resources, which is why approximately 50% of the world's population inhabit areas located within 100 km of the shoreline [5]. For this reason, it is essential to carry out continuous bathymetric monitoring and to predict the dynamically occurring changes in the coastal zone topography. These are determined by numerous anthropogenic and natural factors, which include biological activity, marine erosion, rising water levels [6], ocean currents, rock debris transport, tides, wave action [7], seawater intrusion [8], earthquakes, river regulation [9], ocean acidification, rising temperatures [10] and coastal flooding [11]. Studies on the influence of the above-mentioned factors on the course of landforms in the coastal zone were carried out on different waterbodies, e.g., deltas, estuaries [12,13], wetlands [14], bays [15,16] and other geographic formations situated along the coast [17,18]. Changes in topography occurring in the coastal zone can cause an adverse impact on the aquatic environment and humans [19–21].

Makar et al. [22] analysed changes in the seabed topography in the waterbody adjacent to the Sopot pier (Poland) that occurred in the years 2010–2018. In order to determine the temporal and spatial variability of the area topography, both archival and current bathymetric measurements were carried out using manned and Unmanned Surface Vehicles (USVs), on which Single Beam Echo Sounders (SBESs) and MultiBeam EchoSounders (MBESs) were mounted. For each of the four measurement campaigns conducted in the years 2010, 2012, 2014 and 2018, a Digital Bathymetric Model (DBM) was developed in an identical manner using the Inverse Distance Weighting (IDW), which is commonly applied for seabed modelling (Figure 1).



(**a**) (**b**)

Figure 1. A DBM model of the waterbody adjacent to the pier in Sopot, developed based on bathymetric measurements carried out in 2010 (**a**) and 2018 (**b**) [22].

The study demonstrated that the construction of the "Molo" marina in Sopot in 2011 caused a local inhibition in the debris (sand) transport along the coast, thus resulting in debris accumulation between the marina and the shore. The process of forming a tombolo, which refers to the connection of a peninsula to the mainland, began in Sopot as a result [23]. This phenomenon mostly shapes the course of beaches and coasts under natural conditions but can be the result of human activity, as is the case in Sopot [24]. After the construction of the marina, the area of the coastal strip increased by approx. 13,062 m^2, i.e., by 34.6%, and the shoreline moved towards the sea by 53 m [2020].

The tombolo phenomenon in Sopot has an adverse effect on the aquatic environment and on humans. Firstly, it poses a danger to navigation by both sailing and motor-powered vessels, particularly near the yacht marina, where the depths decreased, during the period under study, from approx. 3.5 m to 1.5 m. Secondly, research demonstrated that the tombolo phenomenon contributed to the occurrence of more stagnant water and to the faster heating of water, which created more favourable conditions for the blooms of cyanobacteria and other bacteria. Thirdly, every year the city of Sopot incurs millions of PLN in costs to curb the development of the phenomenon by commissioning dredging works.

The example of the waterbody adjacent to the Sopot pier proves that if accurate and periodic bathymetric measurements, as well as tools for predicting changes in the area topography, were available in this area, the adverse effect of the tombolo phenomenon on the aquatic environment and on humans could be inhibited or prevented.

Di Martino et al. [25] assessed the changes in the topography of a shallow waterbody with depths ranging from 2 m to 15 m, located in the Gulf of Pozzuoli in the eastern part of the Tyrrhenian Sea (Italy). Bathymetric measurements were carried out using manned hydrographic survey vessels with MBESs mounted on them. For each of the two measurement campaigns conducted in the years 2006 and 2017, a Digital Terrain Model (DTM) with a grid resolution of 1 m $\times$ 1 m was developed in an identical manner. The DTM models created in this way were then compared to produce maps showing the differences in the shallow waterbody depths.

The study demonstrated that the area of the waterbody affected by marine erosion increased by 38.91% (93,000 m^2) between 2006 and 2017. Considerable changes in the seabed topography (of more than 30 cm), as manifested by sand accumulation or depletion, are clearly seen within the 2–15 m depth range both in the central and the southern part of the water area under study. For example, a considerable accumulation of sand with a volume of 1254 m^3 was noted in area 1–2 with an area of 3406 m^2. As a result, the waterbody became shallower by up to 70 cm in some places. On the other hand, in area 2–1, with an area of 34,000 m^2, a significant loss of 15,000 m^3 of sand was noted. As a result, in some places the water area deepened by almost 1 m.

The authors of the publication claim that it was human activity (the construction of piers, coastal and shore protection works, etc.) carried out from the 1910s to 1990s that contributed to the considerable changes in the seabed topography in this area. In addition, these changes are affected by the marine erosion caused by coastal currents. The authors of this study recommend that periodic hydrographic surveys should be carried out in the coastal zone to analyse changes in the seabed topography. On the basis of these, it will be possible to plan dredging and silting works to prevent these changes and reduce their extent.

Mielck et al. [26] assessed the changes in the seabed topography that occurred over a short-term (6 months) and a long-term period (25 years) in the Westerland Dredging Area (WDA), where major dredging operations in Germany are carried out. This area is subject to severe water erosion caused by storms. Bathymetric measurements were carried out using survey vessels with MBESs and SBESs mounted on them. For each of the four measurement campaigns conducted in the years 1993, 2008/2009, 2016 and 2017, a DBM model was developed in an identical manner using the IDW method (Figure 2).

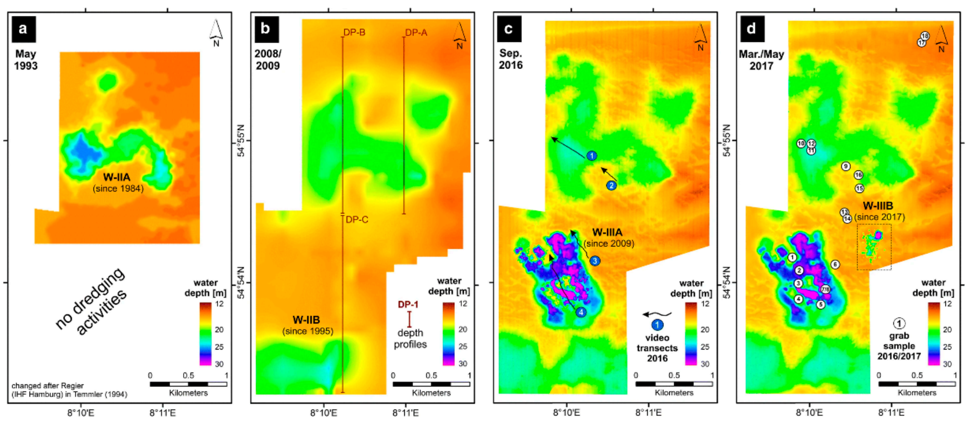


Figure 2. A DBM model in the WDA area in the years 1993 (**a**), 2008/2009 (**b**), 2016 (**c**) and 2017 (**d**) [26].

To assess the amount of sediment loss and gain over a longer period of time, it was decided to compare the depth data from 2017 with the bathymetric soundings conducted in the years 1993 and 2013. Figure 3 shows three bathymetric profiles crossing the area under study in a north–south direction. The locations of the cross-sections are shown in Figure 2b. Based on the analysis of the bathymetric profiles, a considerable sand loss of almost 5 m can be observed in the W-IIA area (Figure 3a,b) and a sand loss of approx. 8 m in the area W-IIIA (Figure 3c) due to the dredging works carried out in recent decades. Minor sediment losses were detected at the margins of the newly created dredge holes (Figure 3c). In addition, the sand accumulation was noted in dredge holes: ~3 m in the W-IIA area in the years 1993 and 2017 and ~0.5 m in the W-IIB area in the years 2013 and 2017.

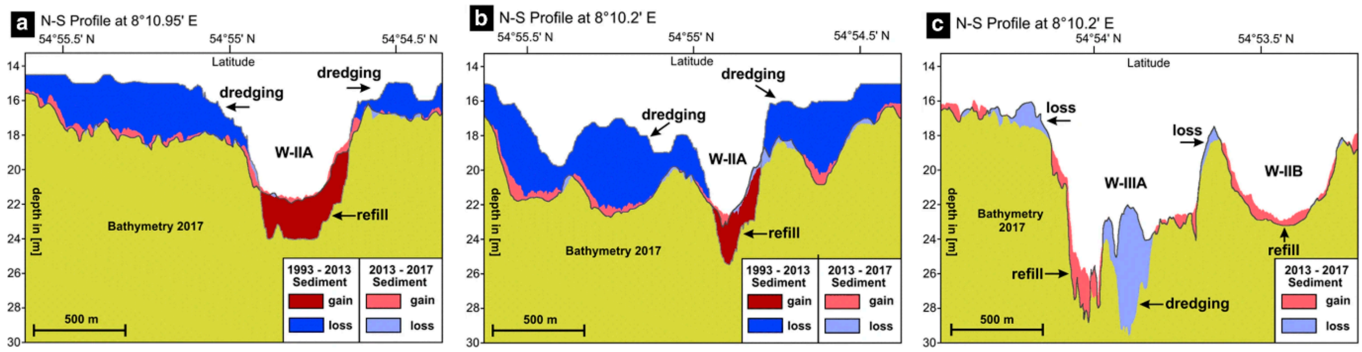
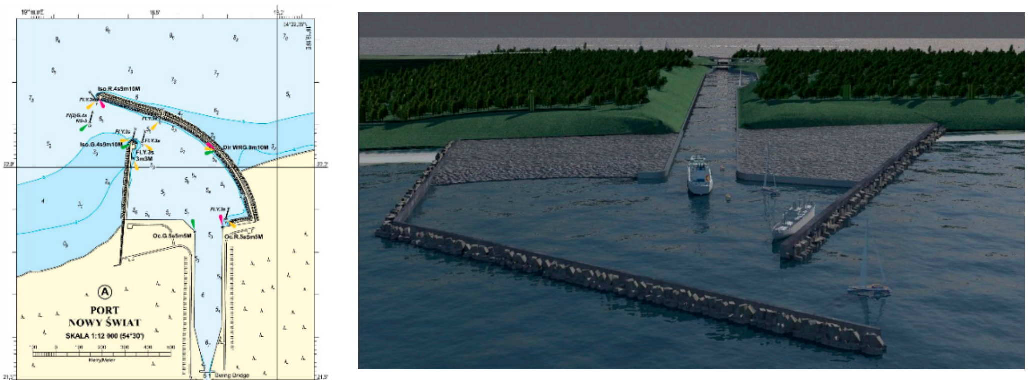


Figure 3. The temporal and spatial variability of the seabed topography in the WDA area in the years 1993–2017 along the bathymetric profile DP-A (**a**), DP-B (**b**) and DP-C (**c**) [26].

The authors of the publication identified the effect of dredging works on the natural regeneration of the seabed in the WDA. The study showed that steep slopes gradually eroded in the newly created holes, which was followed by a slide of sand into the holes. Slow bottom currents in the holes prevent the transport of debris (sand), which results in mud deposition. It is difficult to estimate the time required to restore the seabed to its natural form on the basis of available data. Even more than 30 years after the dredging works were finished, deeper holes are still clearly recognisable. The authors of this study claim that the natural regeneration of the seabed may take many decades or even several centuries.

Shallow waterbodies with a high temporal and spatial variability of the seabed topography are often the subject of numerous tenders invited by public institutions. One of the most recent such procedures was the “Monitoring of sea shores based on data obtained by LiDAR, orthophotomap and transverse profiles of the sea shore”, commissioned by the Maritime Office in Gdynia in 2020. The subject of the contract was the assessment of the seashore condition by analysing the topography of the seashore and all features of the coastal zone, natural or artificial, that have an effect on the maintenance of a 417.5 km long seashore. In addition, port areas with a total area of 5433 ha were covered by bathymetric monitoring. As part of this tender, photogrammetric surveys of ports and the Hel Peninsula were to be carried out by the Airborne Laser Scanning (ALS), resulting in the preparation of an orthophotomap. In addition, bathymetric measurements of coastal protection structures were to be carried out using at least one vessel equipped with an MBES or SBES, resulting in the development of DBM models. Four tenderers applied for the open tender procedure: AirborneHydroMapping GmbH, GISPRO Sp. z o.o., MEWO S.A. & MGGP Aero Sp. z o.o. and Geo Ingenieurservice Polska Sp. z o.o. & OPEGIEKA Sp. z o.o. The most favourable tender offer in the public procurement procedure was submitted by Geo Ingenieurservice Polska Sp. z o.o. & OPEGIEKA Sp. z o.o., and it received the highest score based on the offer evaluation criteria, which included the price, a weight of 60%; the extent and depth of Light Detection And Ranging (LiDAR) scanning, a weight of 30%; and the experience, a weight of 10%. The price of the selected tender offer was PLN 2.643 million gross, which was less than the Contracting Authority's budget of PLN 3.874 million [27].

Another important project from Poland's economic and strategic perspective is the Vistula Spit canal, which enables entering the Baltic Sea from the port in Elbląg without crossing Russian territory, thus reducing the previous route by approx. 100 km. Currently, the canal provides access to Elbląg for seagoing vessels with a length of 100 m (or 180 m for a set of barges), a width of 20 m and a draft of 4.5 m. It should be noted that the min. depth of the canal is 5 m. Hence, the max under-keel clearance is only 50 cm [28]. Therefore, continuous seabed topography monitoring appears to be necessary to ensure the safety of marine shipping. In addition, it seems important to predict depths at the entrance to the canal from the Gulf of Gdańsk due to the shallow water conditions found there, with depths of less than 3 m (Figure 4a) [29]. As demonstrated by the results of studies by other authors [22,25], the construction of hydrotechnical structures, e.g., a breakwater near the Vistula Spit canal, may result in sand accumulation in its area (Figure 4b). Therefore, it is necessary to monitor the debris transport that may pose a navigational hazard to vessels.



(**a**) (**b**)

Figure 4. A bathymetric chart of the Vistula Spit canal (**a**) [29] and a view of the canal from the Gulf of Gdańsk (**b**).

1.2. Current State of Knowledge

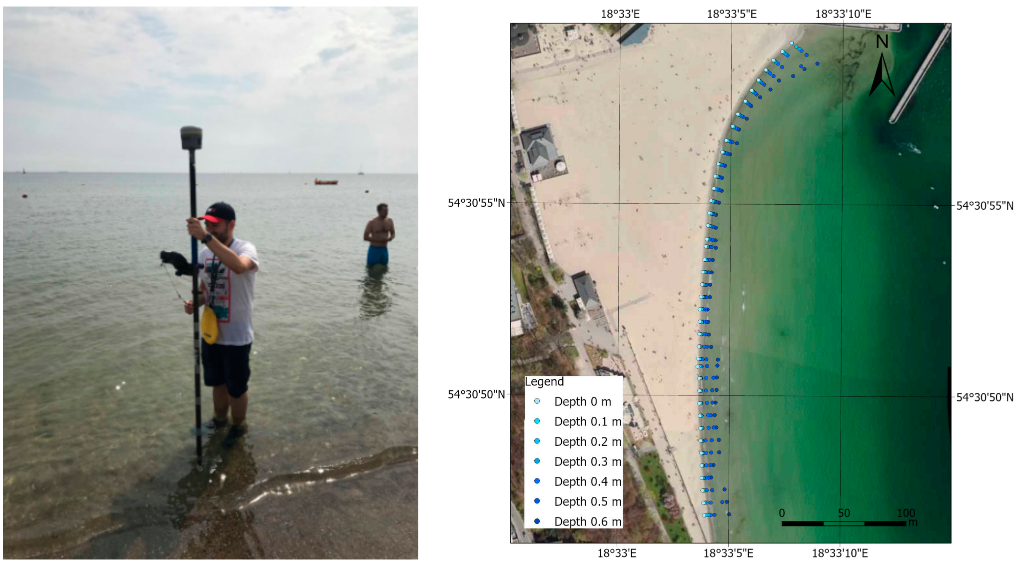
The survey devices and methods used in bathymetric measurements in shallow waterbodies (with depths of less than 1 m) are characterised by a low accuracy of the position coordinate measurement in terms of the accuracy requirements provided for the most stringent International Hydrographic Organization (IHO) Orders (Exclusive and Special) [30], and a low bottom coverage with surveys. This can result in a misinterpretation of the topography and the processes occurring in the coastal zone [31,32].

The methods and survey equipment most commonly used in hydrography include:

1. The tachymetric method involves determining the position of a depth point based on the measurement of horizontal and vertical angles and distances, usually carried out using an electronic total station. This method is characterised by a high position measurement accuracy (<1 cm). However, its main disadvantage is the low coverage of the bottom with measurements, which is determined by the depth to which the surveyor with a pole can enter [31,33].
2. The geodetic method involves a surveyor entering marine water depths to a preset depth using a Global Navigation Satellite System (GNSS) receiver mounted on a pole. Similarly to the tachymetric method, it is characterised by a high positioning accuracy (1–2 cm when using a GNSS Real Time Kinematic (RTK) receiver) and a low coverage of the bottom with measurements [34,35] (Figure 5).
3. The hydrographic method involves performing a bathymetric survey using a manned vessel with a measurement set comprising a hydroacoustic device (SBES) and a positioning system (maritime Differential Global Positioning System (DGPS) receiver)

usually mounted on it. This method has a limited range of operation due to the draft of hydrographic vessels (approx. 1 m and more) and the echo sounder transducers mounted on their bows. It can be assumed that bathymetric measurements down to a depth of 1 m are virtually not carried out using the hydrographic method. In addition, it should be noted that hydrographic surveys of this type involve considerable financial outlays [36,37].

4. Satellite-Derived Bathymetry (SDB) involves the determination of the waterbody depth by measuring light intensity using high-resolution (0.5–2.5 m) multi-spectral images derived from DubaiSat, IKONOS, QuickBird and WorldView satellites, or moderate-resolution multi-spectral images derived from Landsat satellites [38]. Undoubtedly, the advantages of satellite bathymetry include the lack of costs associated with the performance of hydrographic surveys, the considerably shorter time it takes to carry out the measurements as compared to the traditional methods and the possibility of conducting research in remote and inaccessible areas. The disadvantage of the SDB method is the unsatisfactory accuracies of depth measurements (of several metres), which are strongly determined by water transparency [39,40].
5. Airborne LiDAR Bathymetry (ALB)/Airborne LiDAR Hydrography (ALH) involve determining the depths of a waterbody by measuring the time difference between the moments of reception of two pulses recorded by the on-board sensors of a manned aircraft [41]. The advantage of the ALH/ALB systems is the full coverage of the bottom with measurements, the accuracy of which, however, depends on water transparency [42]. A study conducted by [43] proved that these systems failed to meet the accuracy requirements provided for the most stringent IHO Orders (Exclusive and Special). The disadvantages of the ALB/ALH systems also include the relatively low resolution that is largely determined by the local hydrometeorological and hydrological conditions, as well as the considerable financial outlays for the research.



(**a**) (**b**)

Figure 5. A surveyor during bathymetric measurements in a shallow waterbody (**a**) [35] and the coverage of the area surveyed (**b**) by the geodetic method.

The literature research revealed that the existing hydrographic solutions used in bathymetric measurements in shallow waterbodies (with depths of less than 1 m) are characterised by low accuracy of the position coordinate measurement and a low bottom coverage with surveys. Therefore, the aim of this article is to present a concept of an innovative system for dimensioning and predicting changes in the coastal zone topography using Unmanned Aerial Vehicles (UAVs) and USVs. It will allow dimensioning and predicting of the terrain in accordance with the accuracy requirements provided for the IHO Special Order.

Section 2 describes measurement methods and tools (UAVs, USVs and a method for determining the depth of shallow waterbodies) that will be used to create an innovative system for dimensioning and predicting changes in the coastal zone topography using UAVs and USVs. This chapter also presents how the geospatial data recorded by the 4DBatMap system will be processed. Section 3 presents the concept of an innovative system for dimensioning and predicting changes in the coastal zone topography using UAVs and USVs, including the final result of the system, i.e., a 4D bathymetric chart to illustrate how the coastal zone topography changes over time. In Section 4, existing solutions similar to the 4DBatMap system were made, such as MIKE 21. In Section 5, potential application areas of this system were discussed.

2. Materials and Methods

2.1. Measurement Aspect

To develop a prototype of dimensioning and predicting changes in the coastal zone topography that uses autonomous unmanned flying and floating measurement platforms, two main research aspects should be considered:

- The measurement aspect, which will involve the optimal selection of equipment, survey methods and techniques for acquiring geospatial data that meet the accuracy requirements provided for the IHO Special Order.
- The mathematical modelling aspect, which will involve the analytical processing of geospatial data for predicting changes in the coastal zone topography. As a result, an optimal method will be determined to describe the temporal and spatial variability of the coastal zone topography and criteria for the assessment of these changes will be determined.

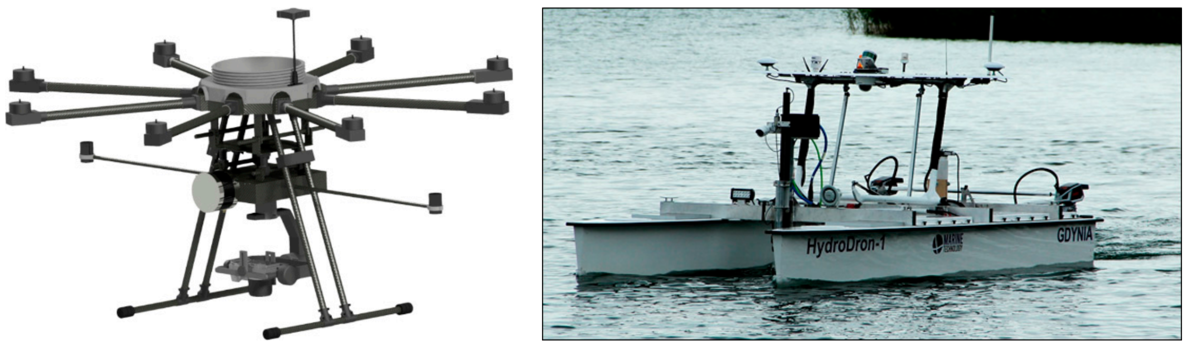
The aspect related to mathematical modelling will largely determine the scientific value of the system under development. However, in order to implement it, it is necessary to acquire precise geospatial data with a high measurement coverage of the area using unmanned survey platforms (measurement aspect). These will enable the prediction of changes in the coastal zone topography to be carried out in a reliable manner.

To conduct the proposed study, the system will use the following measurement methods and tools:

- A UAV is an aircraft capable of performing a flight with no pilot on-board. Therefore, the flight of the aircraft must be performed autonomously, in pre-programmed mode or using remote control [44,45]. Aerial drones are characterised by their high manoeuvrability, small size and high accessibility, and they enable the performance of complex photogrammetric surveys with an accuracy of up to several centimetres thanks to the possibility of mounting high-resolution digital cameras or 3D laser scanners on them [46–50]. The system will use an Aurelia X8 UAV, on which a prototype optoelectronic module comprising the following nine components will be mounted: a camera (Sony A6500 + Sony E 35 mm f/1.8 OSS), communication module, gimbal (Gremsy T3V3), GNSS/Inertial Navigation System (INS) (SBG Ellipse-D), Internet modem, LiDAR (Velodyne VLP-16 Puck LITE), module supporting camera and gimbal control, power control module and a single-board computer (PICO-WHU4) (Figure 6a). A UAV will enable the performance of photogrammetric surveys of the coastal zone onshore topography and the determination of the depths between the shoreline of the shallow waterbody and the min. isobath recorded by the echo sounder [51]. The prototype optoelectronic module to be mounted on the UAV was designed during the implementation of a research project entitled "Innovative autonomous unmanned system for bathymetric monitoring of shallow waterbodies" (INNOBAT system), funded by the National Centre for Research and Development (NCBR) in Poland under the LIDER XI programme [35]. Photogrammetric measurements using a UAV will be carried out under appropriate weather conditions, i.e., sunny and windless weather.

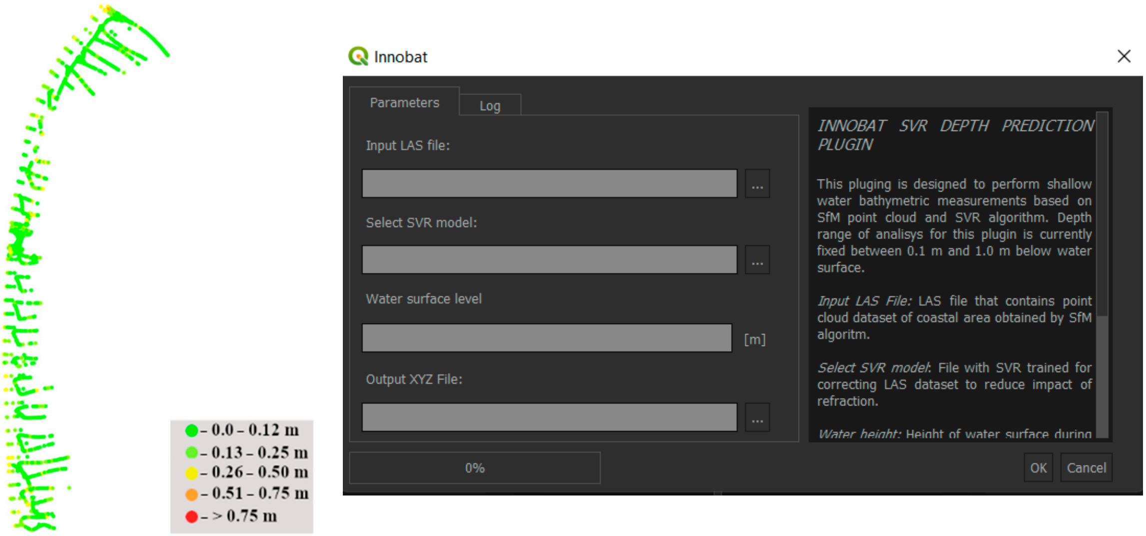
In order to obtain LiDAR data and low-altitude images, the research will be conducted along previously planned flight profiles parallel and perpendicular to the coastline, spaced every 10 m from each other, with a longitudinal and transverse coverage of approx. 80%. To fully cover the area with photos, the flight will be carried out at a speed of 10 km/h at a height of 70 m. Thanks to this, it will be possible to obtain the Ground Sample Distance (GSD) of approx. 2–3 cm [45,52].

- A hydrographic USV is a remotely, radio-controlled surface vessel that enables hardware integration with a GNSS receiver and a vertical echo sounder (min. equipment), designed to carry out hydrographic surveys in harbour basins, lakes, rivers and small waterbodies [53–57]. The main advantage of USVs is their shallow draft (10–20 cm in certain cases). This allows them, in contrast to manned hydrographic vessels, to carry out bathymetric measurements on shallow water areas with depths of up to 1 m. The system will use a hydrographic "HydroDron" USV (Figure 6b) [58,59], built during the implementation of a research project entitled "Development of an autonomous/remotely controlled surface platform dedicated to hydrographic surveys in restricted waterbodies", funded by the NCBR in Poland under the INNOSBZ programme [60]. This is undoubtedly a solution that meets the highest global standards for the performance of hydrographic surveys. Thanks to the state-of-the-art equipment, the "HydroDron" vessel allows bathymetric, LiDAR and sonar measurements to be carried out in autonomous mode. The "HydroDron" USV enables the implementation of hydrographic surveys of fixed and floating objects, aids to navigation, features above the vertical reference significant to navigation, coastline, overhead clearances, water flow direction, water flow speed and angular measurements in accordance with the accuracy requirements provided for the most stringent IHO Order, i.e., the Exclusive Order. Hydrographic surveys using a USV will be carried out under appropriate hydrometeorological conditions, i.e., no waves and no wind. For depths exceeding 1 m, bathymetric measurements will be performed with the use of the "HydroDron" USV equipped with an MBES parallel to the coastline. However, at depths of up to 1 m a shallow-draft USV equipped with a SBES will be used. Hydrographic surveys will be conducted along main and control profiles. In places where it is impossible to obtain bathymetric data at depths, the geodetic method will be applied, which will enable full coverage of the bottom with measurements [52,61].
- A method for determining the depth of shallow waterbodies, which involves acquiring aerial images from the UAV and then processing (interpreting) them in post-processing mode. The Support Vector Regression (SVR) algorithm [62] will allow the depth of a shallow-water area to be determined based on the radiometry of the field pixel image [63]. As part of the INNOBAT project, a validation study of this method was carried out on two waterbodies: marine and inland. In the marine water area, the 2σ depth measurement accuracy (p = 0.95) was 0.16 m (Figure 7a), while in the inland waterbody, the 2σ depth measurement error (p = 0.95) ranged from 0.22 to 0.24 m. It should be noted that the above results were obtained for a depth range of up to 1 m. The study demonstrated that the proposed method for determining the depth of shallow water areas within a range of 0.1 to 1 m met the accuracy requirements provided for the IHO Special Order [30]. In addition, the INNOBAT project implemented this method in the form of the "Depth prediction" plug-in in the QGIS software (Figure 7b).



(**a**) (**b**)

Figure 6. Aurelia X8 UAV with the mounted prototype optoelectronic module (**a**) and the "Hydro-Dron" USV (**b**).



(**a**) (**b**)

Figure 7. A graphic representation of the differences between the actual depths and the depths obtained by using the SVR algorithm for the depth range of 0.1 m to 1 m on the waterbody at the public beach in Gdynia (**a**) [52] and the user interface of the "Depth prediction" plug-in in the QGIS software (**b**).

2.2. Analysis of Time Series

The above-mentioned measurement methods and tools will allow reliable dimensioning and predicting of changes in the coastal zone topography. Without the measurement aspect, it would not have been possible to achieve the main scientific objective of the system under development, namely the development of an optimal mathematical method to enable predicting changes in the coastal zone topography showing long-term tendencies (trends) [64–66] and seasonal fluctuations (seasonality) [67,68].

The mathematical modelling aspect will be solved by carrying out an analysis of time series, which has been gaining increasing importance recently, and is being used with undiminished success in many areas of science, business and industry [69,70]. The time series itself is an observation of an interesting quantity recorded at consecutive (usually regular) time intervals, e.g., consecutive months or years. The analysis of time series in this system is aimed at developing a model to describe the temporal and spatial variability of the coastal zone topography well. The model will later be used to predict the future (unknown) values of the depths/heights of coastal zone points [71].

The system will involve an analysis of the time series, to be conducted in four steps [71–75]:

- Step I: Analysis of the basic properties of the series. In this step, the measurement data will be presented as graphs. They will enable the determination of a long-term tendency (trend) and seasonal fluctuations (seasonality). In addition, a graph will be produced to assess whether a temporal correlation is occurring in the data and how strong it is (the so-called autocorrelation).
- Step II: Necessary transformations. Before starting the proper analysis and predicting of time series, the measurement data must be prepared in an appropriate way. To this end, transformations are used to simplify the modelling and predict the construction process. These include:
    - ○ Box–Cox transformation (power transform) is applied when variance in the data under analysis increases or decreases with the series level. Very importantly, the application of this transformation allows the effect on the analysis results, occurring in the series of atypical (outlier) observations, to be mitigated, and the data distribution more similar to the normal one to be obtained (a typical assumption for classical models for time series).
    - ○ Differentiation is used to transform data to the stationary form, i.e., one whose properties do not change over time (no occurrence of a long-term trend and seasonality). If a stationary series is obtained following the elimination of the trend and seasonality, it will then be possible to fit a suitable model from an extensive family of stationary models, e.g., AR, MA and ARMA models.
    - ○ The division of data into a training set and a test set. In order to be able to reliably assess the accuracy and to compare the performance of different prediction methods, the measurement data will be divided into two parts: the training set and the test set. Forecasts will be constructed based on the training set, while the assessment of their accuracy will be carried out using the test set.
- Step III: Model fitting and diagnostics. When analysing time series, the choice of an appropriate mathematical model for the measurement data is of vital importance. To this end, the following models will be used to predict changes in the coastal zone topography:
    - ○ Stationary models, e.g., AR (p), MA (q) and ARMA (p,q).
    - ○ Non-stationary models to account for the differentiation operations, e.g., ARIMA (p,d,q).
    - ○ Seasonal models, e.g., ARIMA (p,d,q) $(P,D,Q)_s$.
    - ○ Models based on ExponenTial Smoothing (ETS).
    - ○ Decomposition models to account for the breakdown of the series into seasonality, trend and random fluctuations.
    - ○ Basic information will be presented for each model and diagnostic charts will be produced to confirm the model fit correctness.
- Step IV: Prediction. Forecasting future values based on historical data is among the main tasks of time series analysis. The choice of an appropriate prediction method is determined by many factors, e.g., long-term trends occurring in the series under analysis and seasonality. In order to assess the actual suitability of the prediction construction methods applied, it is advisable to also take into account simple reference methods in the comparison to assess whether the forecasts determined using advanced methods are more accurate and how much more accurate they are.

The main criterion in selecting the appropriate method for predicting changes in the coastal zone topography will be the accuracy of the forecasts constructed. It can be determined using the following statistical measures:

- ○ Criteria based on prediction methods, e.g., Mean Absolute Error (MAE), Mean Square Error (MSE) and the Root Mean-Square Error (RMSE).
- ○ Criteria based on percentage prediction methods, e.g., Mean Absolute Percentage Error (MAPE), Mean Percentage Error (MPE) and the Maximum Absolute Percentage Error (MaxAPE).

- ○ Criteria based on scaled errors, e.g., Mean Absolute Scaled Error (MASE).
- ○ Criteria using reference forecasting methods, e.g., Theil and Theil's U indexes.

The statistical measures determined enable an assessment of the risk associated with decisions taken based on the selected prediction methods. Based on these, an optimal method will be then determined to describe the temporal and spatial variability of the coastal zone topography.

3. Results

The final effect of the implementation of the proposed research will be the 4DBatMap system, i.e., an integrated system using autonomous unmanned flying and floating measurement platforms designed to dimension and predict changes in the coastal zone topography. It will enable the dimensioning and forecasting of the area topography in accordance with the accuracy requirements provided for the IHO Special Order (horizontal position error $\leq$ 2 m (p = 0.95), vertical position error $\leq$ 0.25 m (p = 0.95)) [30]. Bathymetric and photogrammetric surveys will be carried out using UAVs and USVs within the coastal zone, both in the onshore area adjacent to the shallow waterbody and in the underwater area to a depth of several metres.

- The 4DBatMap system should be understood as a system that provides a service:
- The performance of bathymetric and photogrammetric surveys with an appropriate frequency using unmanned flying and floating measurement platforms for studying short-term (seasonal) and long-term changes in the coastal zone topography.

Predicting changes in the coastal zone topography based on geospatial data, resulting in the compilation of a 4D bathymetric chart to illustrate how the coastal zone topography changes over time.

As compared to other existing solutions, the 4DBatMap system will allow the entire coastal zone topography to be surveyed in an accurate and precise manner based on the geospatial data acquired by UAVs and USVs. The system will comprise four main modules (Figure 8).

1. Measurement data acquisition module. For the purposes of this module, bathymetric and photogrammetric surveys will be carried out with an appropriate frequency (ascertained on the basis of research) to identify short-term (seasonal) and long-term changes in the coastal zone topography. To this end, a UAV with a prototype optoelectronic module comprising a GNSS/INS system, LiDAR and a photogrammetric camera mounted on it, as well as a USV equipped with an MBES and a GNSS/RTK receiver will be used.
2. Multi-sensor geospatial data fusion module. In this module, the geospatial data recorded using autonomous unmanned measurement platforms will be processed. LiDAR data will allow a land area model to be developed. The images taken by the photogrammetric camera will enable the determination of the waterbody shoreline and the determination of the water area depth between its shoreline and the min. isobath recorded by an echo sounder mounted on an unmanned vessel, which is approx. 1 m. The remaining part of the seabed will be surveyed by an integrated hydrographic system (MBES + GNSS/RTK receiver) mounted on the USV. For the processing of geospatial data, three plug-ins for the QGIS software, developed as part of the INNOBAT project implementation, will be used:
    - ○ "Shoreline extraction"—a module designed to extract the shoreline based on LiDAR data using the algorithms proposed by Xu S. et al. [76] and the contour method [77].
    - ○ "Depth prediction"—a module designed to determine the shallow waterbody depth based on the Structure from Motion (SfM) point cloud using the SVR algorithm [62].

- ○ "Data integration"—a module designed to integrate hydroacoustic and opto-electronic data using the method proposed by Dąbrowski P.S. et al. [78] and also to use the algorithms designed to model the coastal zone topography.

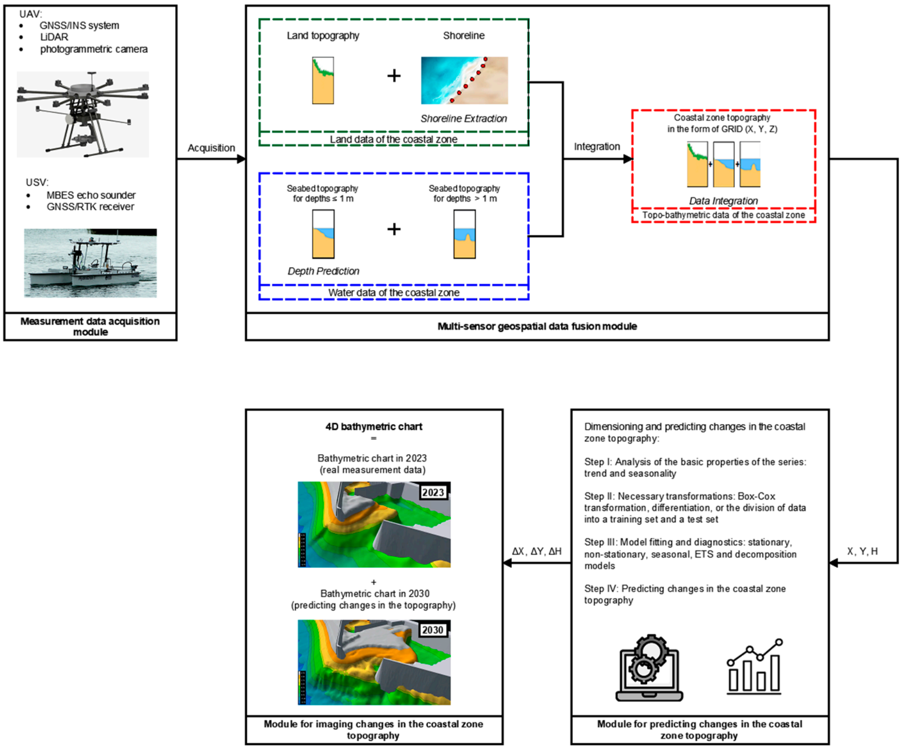


Figure 8. A diagram of the operation and functioning of an innovative system for dimensioning and predicting changes in the coastal zone topography using UAVs and USVs.

The final result of this module will be the coastal zone topography, accurate and completely covered with measurements in the form of a regular grid of squares (GRID). It will be generated using the "Data integration" plug-in.

3 Module for predicting changes in the coastal zone topography. For the purposes of this module, an analysis of the time series will be carried out in four steps:

- ○ Step I: Analysis of the basic properties of the series. In this step, the measurement data will be presented as graphs in order to identify long-term tendencies and seasonal fluctuations.
- ○ Step II: Necessary transformations. Before starting the proper analysis and predicting of time series, the measurement data must be prepared in an appropriate way on the basis of, e.g., Box–Cox transformation, differentiation or the division of data into a training set and a test set.
- ○ Step III: Model fitting and diagnostics. When analysing time series, the choice of an appropriate mathematical model for the measurement data is of vital importance. To this end, the following models will be used to predict changes in the coastal zone topography: stationary, non-stationary, seasonal, ETS and decomposition models.
- ○ Step IV: Prediction. The main criterion in selecting the appropriate method for predicting changes in the coastal zone topography will be the accuracy of the forecasts constructed. The statistical measures will enable an assessment of the risk associated with decisions taken based on the selected forecasting methods. Based on these, an optimal method will be then selected to describe the temporal dynamics of the variation in the coastal zone topography.

4 Module for imaging changes in the coastal zone topography. The final result of the 4DBatMap system will be a 4D bathymetric chart to illustrate how the coastal zone topography changes over time. Among other things, it will help in investigating navigability conditions, anchorages, fairways and other usable waterbodies, determining safe depth parameters for fairways in the vicinity of ports, as well as taking proper navigational and hydrographic decisions.

One of the effects of the research activities will be the development of a unique 4DBatMap computer application that will enable the solution of an optimal method to describe the temporal dynamics of the variation in the coastal zone topography, followed by the generation of a 4D bathymetric chart on its basis.

4. Discussion

The proposed solution is an innovative product with no equivalent on the domestic or foreign market. A system that is functionally most similar is the MIKE 21 software distributed by a Danish company DHI, which has more than 50 years of experience in modelling and numerical simulations in the field of water, environment and natural resources [79]. The main task of the MIKE 21 software is not the dimensioning and predicting of changes in the coastal zone topography but the numerical modelling of various hydrodynamic processes occurring in coastal waters, lakes and rivers [80–82].

As compared to the 4DBatMap system, the MIKE 21 software is devoid of two essential modules: measurement data acquisition and multi-sensor geospatial data fusion. Hence, the application prevents the acquisition and processing of geospatial data recorded using UAVs and USVs in the coastal zone that would meet the accuracy requirements provided for the IHO Special Order (horizontal position error $\leq$ 2 m (p = 0.95), vertical position error $\leq$ 0.25 m (p = 0.95)) [30]. Another significant disadvantage of the MIKE 21 software is that it has the ability to predict changes in the coastal zone topography based exclusively on a single set of bathymetric data and not on a series of periodic bathymetric and photogrammetric surveys. Therefore, this software forecasts changes in topography based primarily on computer simulations that account for phenomena such as currents, sediment transport, tides and waves, as well as interactions between water and built structures, and not on the basis of historical, more reliable, actual measurement data. This also enables the identification of short-term (seasonal) and long-term changes in the coastal zone topography.

In addition, the 4DBatMap system will include the following novelty elements as compared to the existing solutions:

- A new methodology for carrying out bathymetric and photogrammetric surveys, using unmanned aerial and surface measurement platforms for predicting changes in the coastal zone topography.
- A computer application for predicting changes in the coastal zone topography based on the geospatial data acquired using UAVs and USVs.
- A new method for predicting changes in the coastal zone topography based on the geospatial data acquired using unmanned aerial and surface measurement platforms, which meets the accuracy requirements provided for the IHO Special Order.

5. Conclusions

This publication presents a concept of an innovative system for dimensioning and predicting changes in the coastal zone topography using UAVs and USVs. It will allow dimensioning and predicting of the terrain in accordance with the accuracy requirements provided for the IHO Special Order.

The target recipients of the services provided using the system for dimensioning and predicting changes in the coastal zone topography will include:

- Investors in construction projects in port and inland waterbodies.
- Hydrographic companies performing work on waterway sections that are involved in measurement data acquisition.

- Public administration offices, including the Geodetic Bureaus of Marshal's Offices, Hydrographic Office of the Polish Navy, Maritime Offices, Offices of Inland Navigation, port authorities and the State Water Holding Polish Waters (Regional Water Management Authorities).

In summary, the final recipients of the system outcomes can be all units that are involved in coastal zone monitoring, e.g.,

- Carrying out hydrographic surveys, investigating navigability conditions, anchorages, fairways and other usable waterbodies, as well as determining safe depth parameters for fairways in the vicinity of ports.
- Surveying the watercourse and waterbody bottom topography. This particularly applies to the Great Masurian Lake district, whose bathymetric charts are based on measurements carried out in the 1950s and 1960s and therefore include outdated and insufficiently detailed data on the water area bottom topography.
- Bathymetric measurements of inland marinas.
- Inventory of the bottom before the commencement and after the completion of dredging and silting works.
- Performance of hydrotechnical works, e.g., the construction of breakwaters and groynes.
- Checking the capacity of waterbodies.
- Regeneration of sea beaches.
- Shore protection and strengthening.

It should be noted that all the above-mentioned operations should be carried out periodically every five years or so.

Testing of the 4DBatMap system will be carried out on various measurement areas, such as the inland waterbody, open sea, public beach and river mouth at different times of the year. The factor determining bathymetric and photogrammetric measurements will be the transparency of water. The conducted research will determine the possibilities of using the 4DBatMap System, i.e., in which waterbodies and at what water clarity this type of measurement can be carried out. Based on the measurement data recorded in this way, an optimal mathematical method will be selected based on the analysis of time series, allowing for predicting changes in the coastal zone topography showing long-term tendencies (trends) and seasonal fluctuations (seasonality). The advantage of the 4DBatMap system will be the ability to acquire and process geospatial data recorded using the most modern solutions, i.e., unmanned flying and floating measurement platforms in the coastal zone, which would meet the accuracy requirements provided for the IHO Special Order (horizontal position error $\leq$ 2 m (p = 0.95), vertical position error $\leq$ 0.25 m (p = 0.95)) [30].

Author Contributions: Conceptualization, O.S. and M.S.; methodology, A.S. and C.S.; investigation, O.S., M.S., A.S. and C.S.; writing—original draft preparation, O.S. and M.S.; writing—review and editing, A.S. and C.S.; visualization, O.S. and M.S.; supervision, A.S. and C.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded from the statutory activities of Gdynia Maritime University, grant number WN/2023/PZ/05.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Christ, R.D.; Wernli, R.L. Chapter 17—Navigational Sensors. In *The ROV Manual (Second Edition). A User Guide for Remotely Operated Vehicles*; Elsevier: Amsterdam, The Netherlands, 2014; pp. 453–475.
2. NOAA. 3-D Bathymetric Chart Activity: An Introduction to the Nautical Chart. Available online: https://web.archive.org/web/20090509101307/http://channelislands.noaa.gov//edu/pdf/chartlesson.pdf (accessed on 8 August 2023).
3. CCOM. Bathymetric Globe. Available online: http://ccom.unh.edu/project/bathymetry-globe (accessed on 8 August 2023).
4. Yunus, A.P.; Dou, J.; Song, X.; Avtar, R. Improved Bathymetric Mapping of Coastal and Lake Environments Using Sentinel-2 and Landsat-8 Images. *Sensors* **2019**, *19*, 2788. [CrossRef] [PubMed]

5. Li, Z.; Zhai, J.; Wu, F. Shape Similarity Assessment Method for Coastline Generalization. *ISPRS Int. J. Geo-Inf.* **2018**, *7*, 283. [CrossRef]
6. Mury, A.; Jeanson, M.; Collin, A.; James, D.; Etienne, S. High Resolution Shoreline and Shelly Ridge Monitoring over Stormy Winter Events: A Case Study in the Megatidal Bay of Mont-Saint-Michel (France). *J. Mar. Sci. Eng.* **2019**, *7*, 97. [CrossRef]
7. Mahamud, U.; Takewaka, S. Shoreline Change around a River Delta on the Cox's Bazar Coast of Bangladesh. *J. Mar. Sci. Eng.* **2018**, *6*, 80. [CrossRef]
8. Fu, Y.; Guo, Q.; Wu, X.; Fang, H.; Pan, Y. Analysis and Prediction of Changes in Coastline Morphology in the Bohai Sea, China, Using Remote Sensing. *Sustainability* **2017**, *9*, 900. [CrossRef]
9. Nikolakopoulos, K.; Kyriou, A.; Koukouvelas, I.; Zygouri, V.; Apostolopoulos, D. Combination of Aerial, Satellite, and UAV Photogrammetry for Mapping the Diachronic Coastline Evolution: The Case of Lefkada Island. *ISPRS Int. J. Geo-Inf.* **2019**, *8*, 489. [CrossRef]
10. Zhang, Y.; Hou, X. Characteristics of Coastline Changes on Southeast Asia Islands from 2000 to 2015. *Remote Sens.* **2020**, *12*, 519. [CrossRef]
11. Kanwal, S.; Ding, X.; Sajjad, M.; Abbas, S. Three Decades of Coastal Changes in Sindh, Pakistan (1989–2018): A Geospatial Assessment. *Remote Sens.* **2020**, *12*, 8. [CrossRef]
12. Chu, Z.X.; Yang, X.H.; Feng, X.L.; Fan, D.J.; Li, Y.K.; Shen, X.; Miao, A.Y. Temporal and Spatial Changes in Coastline Movement of the Yangtze Delta during 1974–2010. *J. Asian Earth Sci.* **2013**, *66*, 166–174. [CrossRef]
13. Cowart, L.; Corbett, D.R.; Walsh, J.P. Shoreline Change along Sheltered Coastlines: Insights from the Neuse River Estuary, NC, USA. *Remote Sens.* **2011**, *3*, 1516–1534. [CrossRef]
14. Kuleli, T.; Guneroglu, A.; Karsli, F.; Dihkan, M. Automatic Detection of Shoreline Change on Coastal Ramsar Wetlands of Turkey. *Ocean Eng.* **2011**, *38*, 1141–1149. [CrossRef]
15. Martínez, C.; Quezada, M.; Rubio, P. Historical Changes in the Shoreline and Littoral Processes on a Headland Bay Beach in Central Chile. *Geomorphology* **2011**, *135*, 80–96. [CrossRef]
16. Pattanshetti, S.S.; Chauhan, O.S.; Sivakholundu, K.M. Quantification of Changes in Seabed Topography with Special Reference to Hansthal Creek, Gulf of Kachchh, India. *J. Coast. Res.* **1993**, *9*, 934–943.
17. Specht, M.; Specht, C.; Lewicka, O.; Makar, A.; Burdziakowski, P.; Dąbrowski, P. Study on the Coastline Evolution in Sopot (2008–2018) Based on Landsat Satellite Imagery. *J. Mar. Sci. Eng.* **2020**, *8*, 464. [CrossRef]
18. Zhang, X.; Pan, D.; Chen, J.; Zhao, J.; Zhu, Q.; Huang, H. Evaluation of Coastline Changes under Human Intervention Using Multi-temporal High-resolution Images: A Case Study of the Zhoushan Islands, China. *Remote Sens.* **2014**, *6*, 9930–9950. [CrossRef]
19. Paull, C.K.; Dallimore, S.R.; Jin, Y.K.; Caress, D.W.; Lundsten, E.; Gwiazda, R.; Anderson, K.; Clarke, J.H.; Youngblut, S.; Melling, H. Rapid Seafloor Changes Associated with the Degradation of Arctic Submarine Permafrost. *Proc. Natl. Acad. Sci. USA* **2022**, *119*, e2119105119. [CrossRef] [PubMed]
20. Specht, M.; Specht, C.; Mindykowski, J.; Dąbrowski, P.; Maśnicki, R.; Makar, A. Geospatial Modeling of the Tombolo Phenomenon in Sopot Using Integrated Geodetic and Hydrographic Measurement Methods. *Remote Sens.* **2020**, *12*, 737. [CrossRef]
21. Wlodarczyk-Sielicka, M.; Stateczny, A. Clustering Bathymetric Data for Electronic Navigational Charts. *J. Navig.* **2016**, *69*, 1143–1153. [CrossRef]
22. Makar, A.; Specht, C.; Specht, M.; Dąbrowski, P.; Burdziakowski, P.; Lewicka, O. Seabed Topography Changes in the Sopot Pier Zone in 2010–2018 Influenced by Tombolo Phenomenon. *Sensors* **2020**, *20*, 6061. [CrossRef]
23. Mohamed, A.S. 2D and 1D Numerical Model Simulations for the Effect of a Single Detached Breakwater on the Shore. MSc Thesis, Delft University of Technology, Delft, The Netherlands, 1997.
24. Institute of Oceanology of the Polish Academy of Sciences. Conducting Research and Modeling of the Seafloor and Sea Shore Near the Pier in Sopot. Available online: https://bip.umsopot.nv.pl/Download/get/id,32756.html (accessed on 9 June 2019). (In Polish)
25. Di Martino, G.; Innangi, S.; Sacchi, M.; Tonielli, R. Seafloor Morphology Changes in the Inner-shelf Area of the Pozzuoli Bay, Eastern Tyrrhenian Sea. *Mar. Geophys. Res.* **2021**, *42*, 13. [CrossRef]
26. Mielck, F.; Hass, H.C.; Michaelis, R.; Sander, L.; Papenmeier, S.; Wiltshire, K.H. Morphological Changes due to Marine Aggregate Extraction for Beach Nourishment in the German Bight (SE North Sea). *Geo-Mar. Lett.* **2019**, *39*, 47–58. [CrossRef]
27. Maritime Office in Gdynia. Monitoring of Sea Shores Based on Data Obtained by LiDAR, Orthophotomap and Transverse Profiles of the Sea Shore. Available online: https://umgdy.ezamawiajacy.pl/pn/umgdy/demand/notice/public/15421/details (accessed on 8 August 2023). (In Polish)
28. Drążkiewicz, J.; Golan, M.; Kasprzak, A.; Kiejzik-Głowińska, M.; Klasa, D.; Kowalski, M.; Michniewicz, T.; Nadolny, A.; Pauś, P.; Żochowska, M. Construction of the Waterway Connecting the Vistula Lagoon with the Gdańsk Bay—The Waterway Concept according to the Solution of Consortium Mosty Gdańsk—Projmors (Part 3 B). *Mar. Eng. Geotech.* **2020**, *1*, 30–43. (In Polish)
29. Hydrographic Office of the Polish Navy. Notice to Mariners. Available online: https://bhmw.gov.pl/c/news/pdf/2022/9/WZ_37_2022.pdf (accessed on 8 August 2023). (In Polish)
30. IHO. *IHO Standards for Hydrographic Surveys*, 6th ed.; Special Publication No. 44; IHO: Monaco, Monaco, 2020.
31. Lane, S.N.; Richards, K.S.; Chandler, J.H. Developments in Monitoring and Modelling Small-scale River Bed Topography. *Earth Surf. Process. Landf.* **1994**, *19*, 349–368. [CrossRef]

32. Westaway, R.M.; Lane, S.N.; Hicks, D.M. Remote Sensing of Clear-water, Shallow, Gravel-bed Rivers Using Digital Photogrammetry. *Photogramm. Eng. Remote Sens.* **2001**, *67*, 1271–1282.
33. Koljonen, S.; Huusko, A.; Mäki-Petäys, A.; Louhi, P.; Muotka, T. Assessing Habitat Suitability for Juvenile Atlantic Salmon in Relation to In-stream Restoration and Discharge Variability. *Restor. Ecol.* **2012**, *21*, 344–352. [CrossRef]
34. Baptista, P.; Bastos, L.; Bernardes, C.; Cunha, T.; Dias, J. Monitoring Sandy Shores Morphologies by DGPS—A Practical Tool to Generate Digital Elevation Models. *J. Coast. Res.* **2008**, *24*, 1516–1528. [CrossRef]
35. Specht, M.; Stateczny, A.; Specht, C.; Widźgowski, S.; Lewicka, O.; Wiśniewska, M. Concept of an Innovative Autonomous Unmanned System for Bathymetric Monitoring of Shallow Waterbodies (INNOBAT System). *Energies* **2021**, *14*, 5370. [CrossRef]
36. Popielarczyk, D.; Templin, T. Application of Integrated GNSS/Hydroacoustic Measurements and GIS Geodatabase Models for Bottom Analysis of Lake Hancza: The Deepest Inland Reservoir in Poland. *Pure Appl. Geophys.* **2014**, *171*, 997–1011. [CrossRef]
37. Specht, C.; Weintrit, A.; Specht, M. Determination of the Territorial Sea Baseline—Aspect of Using Unmanned Hydrographic Vessels. *TransNav Int. J. Mar. Navig. Saf. Sea Transp.* **2016**, *10*, 649–654. [CrossRef]
38. Salameh, E.; Frappart, F.; Almar, R.; Baptista, P.; Heygster, G.; Lubac, B.; Raucoules, D.; Almeida, L.P.; Bergsma, E.W.J.; Capo, S.; et al. Monitoring Beach Topography and Nearshore Bathymetry Using Spaceborne Remote Sensing: A Review. *Remote Sens.* **2019**, *11*, 2212. [CrossRef]
39. Kasvi, A.; Salmela, J.; Lotsari, E.; Kumpula, T.; Lane, S.N. Comparison of Remote Sensing Based Approaches for Mapping Bathymetry of Shallow, Clear Water Rivers. *Geomorphology* **2019**, *33*, 180–197. [CrossRef]
40. Li, J.; Knapp, D.E.; Schill, S.R.; Roelfsema, C.; Phinn, S.; Silman, M.; Mascaro, J.; Asner, G.P. Adaptive Bathymetry Estimation for Shallow Coastal Waters Using Planet Dove satellites. *Remote Sens. Environ.* **2019**, *232*, 111302. [CrossRef]
41. Szafarczyk, A.; Toś, C. The Use of Green Laser in LiDAR Bathymetry: State of the Art and Recent Advancements. *Sensors* **2023**, *23*, 292. [CrossRef]
42. Guo, K.; Li, Q.; Wang, C.; Mao, Q.; Liu, Y.; Zhu, J.; Wu, A. Development of a Single-wavelength Airborne Bathymetric LiDAR: System Design and Data Processing. *ISPRS J. Photogramm. Remote Sens.* **2022**, *185*, 62–84. [CrossRef]
43. Su, D.; Yang, F.; Ma, Y.; Wang, X.H.; Yang, A.; Qi, C. Propagated Uncertainty Models Arising from Device, Environment, and Target for a Small Laser Spot Airborne LiDAR Bathymetry and its Verification in the South China Sea. *IEEE Trans. Geosci. Remote Sens.* **2020**, *58*, 3213–3231. [CrossRef]
44. Gupta, S.G.; Ghonge, M.M.; Jawandhiya, P.M. Review of Unmanned Aircraft System (UAS). *Int. J. Adv. Res. Comput. Sci. Eng. Inf. Technol.* **2013**, *2*, 1646–1658. [CrossRef]
45. Lewicka, O.; Specht, M.; Specht, C. Assessment of the Steering Precision of a UAV along the Flight Profiles Using a GNSS RTK Receiver. *Remote Sens.* **2022**, *14*, 6127. [CrossRef]
46. Burdziakowski, P. Increasing the Geometrical and Interpretation Quality of Unmanned Aerial Vehicle Photogrammetry Products Using Super-resolution Algorithms. *Remote Sens.* **2020**, *12*, 810. [CrossRef]
47. Gonçalves, J.A.; Henriques, R. UAV Photogrammetry for Topographic Monitoring of Coastal Areas. *ISPRS J. Photogramm. Remote Sens.* **2015**, *104*, 101–111. [CrossRef]
48. Hu, Q.; Li, L.; Duan, J.; Gao, M.; Liu, G.; Wang, Z.; Huang, D. Object Detection Algorithm of UAV Aerial Photography Image Based on Anchor-free Algorithms. *Electronics* **2023**, *12*, 1339. [CrossRef]
49. Koukiou, G.; Anastassopoulos, V. UAV Sensors Autonomous Integrity Monitoring—SAIM. *Electronics* **2023**, *12*, 746. [CrossRef]
50. Nex, F.; Remondino, F. UAV for 3D Mapping Applications: A Review. *Appl. Geomat.* **2014**, *6*, 1–15. [CrossRef]
51. Lewicka, O.; Specht, M.; Stateczny, A.; Specht, C.; Dardanelli, G.; Brčić, D.; Szostak, B.; Halicki, A.; Stateczny, M.; Widźgowski, S. Integration Data Model of the Bathymetric Monitoring System for Shallow Waterbodies Using UAV and USV Platforms. *Remote Sens.* **2022**, *14*, 4075. [CrossRef]
52. Specht, M.; Szostak, B.; Lewicka, O.; Stateczny, A.; Specht, C. Method for Determining of Shallow Water Depths Based on Data Recorded by UAV/USV Vehicles and Processed Using the SVR Algorithm. *Measurement* **2023**, *221*, 113437. [CrossRef]
53. Giordano, F.; Mattei, G.; Parente, C.; Peluso, F.; Santamaria, R. MicroVEGA (Micro Vessel for Geodetics Application): A Marine Drone for the Acquisition of Bathymetric Data for GIS Applications. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2015**, *40*, 123–130. [CrossRef]
54. Kurowski, M.; Thal, J.; Damerius, R.; Korte, H.; Jeinsch, T. Automated Survey in Very Shallow Water Using an Unmanned Surface Vehicle. *IFAC Pap.* **2019**, *52*, 146–151. [CrossRef]
55. Lemieszewski, Ł.; Radomska-Zalas, A.; Perec, A.; Dobryakova, L.; Ochin, E. GNSS and LNSS Positioning of Unmanned Transport Systems: The Brief Classification of Terrorist Attacks on USVs and UUVs. *Electronics* **2021**, *10*, 401. [CrossRef]
56. Liang, J.; Zhang, J.; Ma, Y.; Zhang, C.-Y. Derivation of Bathymetry from High-resolution Optical Satellite Imagery and USV Sounding Data. *Mar. Geod.* **2017**, *40*, 466–479. [CrossRef]
57. Makar, A. Limitations of Multi-GNSS Positioning of USV in Area with High Harbour Infrastructure. *Electronics* **2023**, *12*, 697. [CrossRef]
58. Stateczny, A.; Gronska-Sledz, D.; Motyl, W. Precise Bathymetry as a Step Towards Producing Bathymetric Electronic Navigational Charts for Comparative (Terrain Reference) Navigation. *J. Navig.* **2019**, *72*, 1623–1632. [CrossRef]
59. Stateczny, A.; Kazimierski, W.; Burdziakowski, P.; Motyl, W.; Wisniewska, M. Shore Construction Detection by Automotive Radar for the Needs of Autonomous Surface Vehicle Navigation. *ISPRS Int. J. Geo-Inf.* **2019**, *8*, 80. [CrossRef]

60. Stateczny, A.; Grońska, D.; Motyl, W. Hydrodron—New Step for Professional Hydrography for Restricted Waters. In Proceedings of the 2018 Baltic Geodetic Congress (BGC Geomatics 2018), Olsztyn, Poland, 21–23 June 2018.
61. Specht, M.; Specht, C.; Wąż, M.; Naus, K.; Grządziel, A.; Iwen, D. Methodology for Performing Territorial Sea Baseline Measurements in Selected Waterbodies of Poland. *Appl. Sci.* **2019**, *9*, 3053. [CrossRef]
62. Agrafiotis, P.; Skarlatos, D.; Georgopoulos, A.; Karantzalos, K. Shallow Water Bathymetry Mapping from UAV Imagery Based on Machine Learning. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2019**, *XLII-2/W10*, 9–16. [CrossRef]
63. Specht, M.; Wiśniewska, M.; Stateczny, A.; Specht, C.; Szostak, B.; Lewicka, O.; Stateczny, M.; Widźgowski, S.; Halicki, A. Analysis of Methods for Determining Shallow Waterbody Depths Based on Images Taken by Unmanned Aerial Vehicles. *Sensors* **2022**, *22*, 1844. [CrossRef]
64. Bertin, S.; Floc'h, F.; Le Dantec, N.; Jaud, M.; Cancouët, R.; Franzetti, M.; Cuq, V.; Prunier, C.; Ammann, J.; Augereau, E.; et al. A Long-term Dataset of Topography and Nearshore Bathymetry at the Macrotidal Pocket Beach of Porsmilin, France. *Sci. Data* **2022**, *9*, 79. [CrossRef] [PubMed]
65. de MF Rocha, R.; Höskuldsson, Á.; Jónsdóttir, I.; Martinez, F.; Hey, R. Bathymetry and Changes on Seafloor Topography of the Southern Reykjanes Ridge (2013 Multibeam Survey—SOEST/HÍ). In Proceedings of the 2017 IEEE/OES Acoustics in Underwater Geosciences Symposium (RIO Acoustics), Rio de Janeiro, Brazil, 25–27 July 2017.
66. Reins, N.J. Long Term Bathymetry Changes in the Lower Mississippi River due to Variability in Hydrograph and Variable Diversion Schemes. Ph.D. Thesis, University of New Orleans, New Orleans, LA, USA, 2018.
67. Sakhaee, F.; Khalili, F. Sediment Pattern & Rate of Bathymetric Changes due to Construction of Breakwater Extension at Nowshahr Port. *J. Ocean Eng. Sci.* **2021**, *6*, 70–84.
68. Schweiger, C.; Koldrack, N.; Kaehler, C.; Schuettrumpf, H. Influence of Nearshore Bathymetry Changes on the Numerical Modelling of Dune Erosion. *J. Coast. Res.* **2020**, *36*, 545–558. [CrossRef]
69. Sawczyński, S.; Kaczmarek, L.M. Modeling Bathymetry Changes in the Coastal Zone—State of Knowledge Analysis. *Tech. Sci.* **2014**, *17*, 219–233.
70. Toodesh, R.; Verhagen, S.; Dagla, A. Prediction of Changes in Seafloor Depths Based on Time Series of Bathymetry Observations: Dutch North Sea Case. *J. Mar. Sci. Eng.* **2021**, *9*, 931. [CrossRef]
71. Zagadański, A.; Suchwałko, A. Time Series Analysis and Forecasting. In *Practical Introduction Based on the R Environment*; Polish Scientific Publishers PWN: Warsaw, Poland, 2016.
72. Alqahtani, A.; Ali, M.; Xie, X.; Jones, M.W. Deep Time-series Clustering: A Review. *Electronics* **2021**, *10*, 3001. [CrossRef]
73. de Sousa, L.S.; Raude, J.M.; Wambua, R.M.; Mutua, B.M. Bathymetry Changes Caused by Sedimentation in an Unlined Canal of the Chókwè Irrigation Scheme, Mozambique. *Irrig. Drain.* **2022**, *71*, 783–803. [CrossRef]
74. Kim, M.; Lee, S.; Jeong, T. Time Series Prediction Methodology and Ensemble Model Using Real-world Data. *Electronics* **2023**, *12*, 2811. [CrossRef]
75. Monteys, X.; Harris, P.; Caloca, S.; Cahalane, C. Spatial Prediction of Coastal Bathymetry Based on Multispectral Satellite Imagery and Multibeam Data. *Remote Sens.* **2015**, *7*, 13782–13806. [CrossRef]
76. Xu, S.; Ye, N.; Xu, S. A New Method for Shoreline Extraction from Airborne LiDAR Point Clouds. *Remote Sens. Lett.* **2019**, *10*, 496–505. [CrossRef]
77. Farris, A.S.; Weber, K.M.; Doran, K.S.; List, J.H. Comparing Methods Used by the U.S. Geological Survey Coastal and Marine Geology Program for Deriving Shoreline Position from Lidar Data. Available online: https://pubs.usgs.gov/of/2018/1121/ofr20181121.pdf (accessed on 8 August 2023).
78. Dąbrowski, P.S.; Specht, C.; Specht, M.; Burdziakowski, P.; Makar, A.; Lewicka, O. Integration of Multi-source Geospatial Data from GNSS Receivers, Terrestrial Laser Scanners, and Unmanned Aerial Vehicles. *Can. J. Remote. Sens.* **2021**, *47*, 621–634. [CrossRef]
79. DHI. MIKE 21/3. Available online: https://www.mikepoweredbydhi.com/products/mike-21-3 (accessed on 8 August 2023).
80. Azhary, W.A.H.W.; Awang, N.A.; Hamid, M.R.A. The Assessment of Rip Current at Kerachut Beach Using Hydrodynamic Modelling. *IOP Conf. Ser. Mater. Sci. Eng.* **2016**, *136*, 012087. [CrossRef]
81. Parsapour-moghaddam, P.; Rennie, C.D.; Slaney, J. Hydrodynamic Simulation of an Irregularly Meandering Gravel-bed River: Comparison of MIKE 21 FM and Delft3D Flow models. *E3S Web Conf.* **2021**, *16*, 12–24. [CrossRef]
82. Yan, J.; Chen, M.; Xu, L.; Liu, Q.; Shi, H.; He, N. Mike 21 Model Based Numerical Simulation of the Operation Optimization Scheme of Sedimentation Basin. *Coatings* **2018**, *40*, 02004. [CrossRef]