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Subaqueous geomorphology: options, tasks, needs

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Abstract. The purpose of the paper is to present the potentialities of current non-invasive methods for bottom surveys, including cartometric presentation of its relief and structure in both marine and inland reservoirs. The paper presents examples of results obtained in the Maritime Institute in Gdańsk during surveys carried out at the bottom of seas, lakes and rivers with the use of the same apparatus: primarily, a multibeam echosounder (MBES) to obtain a digital terrain model (DTM); a side-scan sonar (SSS) to obtain a general image of the nature of the bottom (its "roughness"); and seismic profiling (sub-bottom profiler, sediment echo sounder [SES]) to recognise the structure of the bottom. The obtained results constitute a necessary basis for carrying out further specialist surveys (non-invasive or invasive) when needed. Current bottom survey options that use MBES, SSS and SES may be treated as subaqueous equivalents of the subaerial potentialities of a land surface survey using LiDaR and GPR (Ground Penetration Radar).

Key words:
bottom relief,
bottom structure,
MBES,
SSS,
SES

Introduction

This paper is based on the experience gained during many years of bottom surveys carried out by the Maritime Institute in Gdańsk in open sea reservoirs (e.g. Rudowski and Gajewski 1998; Hac et al. 2011; Szefler et al. 2011; Wróblewskiet al. 2014), sea lagoons (e.g. Rudowski et al. 2009), lakes (e.g. Rudowski 2000; Rutkowski et al. 2005; Osadczuk 2017), in rivers and channels (e.g. Lisimenka et al. 2015; Wróblewski et al. 2016; Rudowski et al. 2017), basins and port canals (e.g. Dworniczak et al. 2017).

The obtained results have been illustrated with a few selected examples (Jarosławiec area, Oksywie area, Przekop Wisły area). They indicate that bottom survey options are currently of comparable accuracy to those obtained from respective surveys of land areas (Fig. 1).

Geomorphological surveys should constitute the basis of all kind of surveys of the bottom, both cognitive and utilitarian. Contemporary, modern research methods in fact enable a researcher to carry out accurate measurements of the bottom relief and its structure to even a decimetre level of accuracy. This ensures a proper reconnaissance, description and cartographic presentation of the bottom relief and structure carried out subaqueously, similarly to subaerial surveys carried out on the land surface.

The main tasks necessary to prepare a geomorphological map of the bottom, i.e. subaqueous geomorphology, are:

	SUBAERIAL SURVEYS	SUBAQUEOUS SURVEYS
AREAL		
DTM	LiDaR	MBES
SURFACE NATURE	AIR PHOTO	SSS
	LINEAR	
INTERNAL STRUCTURE	GPR	SES
MEASUREMENT LINES	MORPHOLOGICALLY AND ANTHROGENICALLY DEPENDENT	FREE
POINT		
SAMPLING/CORING	PROBES, EXCAVATIONS	GRAB SAMPLER, VIBROCORER
OTHER	VISUAL IDENTIFICATION	AUV, ROV

Fig. 1. A comparison of current methods of land (subaerial) and bottom (subaqueous) surveys (DTM – Digital Terrain Model, LiDaR – Light Detection and Ranging, GPR – Ground Penetration Radar, MBES – Multi-beam Echo Sounder, SSS – Side Scan Sonar, SES – Sediment Echo Sounder, AUV – Autonomous Underwater Vehicles, ROV – Remote Operated Vehicles)

- specifying and cartometric presentation of the bottom morphology that was obtained through multibeam echosounder, with the use of a 3D grid (not of lines or measurement points) – similar to a LiDaR image on the land surface (currently LiDaR bottom measurements are only possible in shallow waters and are significantly limited by water opacity (Nowak et al. 2015);
- specifying the bottom surface nature, associated with the morphology and the lithological variation in surface sediments, carried out on the basis of the backscatter pattern acquired with a side-scan sonar (Hac 2010);
- specifying the bottom internal structure, taking into account lithology and stratification, obtained through seismic profiling – having a penetration of a few metres (SES and/or sub-bottom profiler), a few dozen metres (boomer and sparker system), and even deeper (air-gun system) (Rudowski 2005);
- specifying the genesis and age of bottom forms, with differentiation of forms and/or recent zones, as well as their substratum, obtained as a result of assessment of vertical and lateral sequences of the collected data, which is supplemented with the results of additional non-invasive measurements, including magnetometric measurements (Kubacka et al. 2017), ROV images (Gajewski J. 2010; Gajewski L. 2010), the analysis of sediments from grab and core samples, CPT probes, etc.

The subsequent step is to assess whether the study provides useful clues to achieve the indicated cognitive and utilitarian goals (Gajewski et al. 1999; Rudowski et al. 2009, 2011, 2017; Szefler et al. 2011, 2015; Hac et al. 2012; Kubacka et al. 2017).

Methods

Basic and advanced methods used in geomorphological surveys (along with apparatus data, measurement and interpretation methods) have been presented and discussed in detail at specialist symposia on marine geomorphology: “Research methods” in 2010, “Sea level, coastline” in 2014 and “Geomorphological Sea Floor Mapping” in 2017 (Dworniczak et al. 2018). Materials from symposia are available at the website of the Department of Operational Oceanography of the Maritime Institute in Gdańsk (1st Marine Geomorphology Symposium: http://zoo.im.gda.pl/dokumenty/I%20Sympozjum.pdf, 2nd Marine Geomorphology Symposium: http://zoo.im.gda.pl/dokumenty/II%20Sympozjum%20Morskiej%20Geomorfologii%20-%20Publikacja.pdf). The publication of Osadczuk (2017) discussing similar issues mainly related to investigations of the bottom sediments of inland basins also deserves attention.

Examples of selected geomorphological reports

The following three examples regarding the open sea bottom (Fig. 2), the nearshore bottom (Fig. 3) and river bottom (Fig. 4) were selected. These examples are a good representation of the options for the accurate non-invasive reconnaissance of the bottom that is required in order to obtain the detailed cartographic and geomorphological reports that are important in terms of achieving various cognitive and utilitarian purposes.

Jarosławiec area

The Jarosławiec area is located in Koszalin Bay, several kilometres north-west of Jarosławiec, on the open sea bottom, at a depth of 14–30 m (Szefler et al. 2011). The surveys were carried out in 2011 and were commissioned by Baltex Zatoka Ltd. in order to establish the potential occurrence of sand deposits. The choice of the survey area was identified based on information available at that time, mainly from analysis of the 1:200,000 Geological map of the Baltic Sea bottom (Michałowska and Pikies 1990) and of the 1:500,000 Geological atlas of the Southern Baltic (Masłowska and Michałowska 1995).

A detailed multibeam bathymetric map (Fig. 2A), a side-scan sonar map (Fig. 2B) and an interpreted geomorphological map (Fig. 2C) prepared with the use of seismic profiling are presented. A diversified bottom relief of complex genesis occurs here (Szefler et al. 2011), with relict moraine forms along with forms of marine accumulation and erosion.

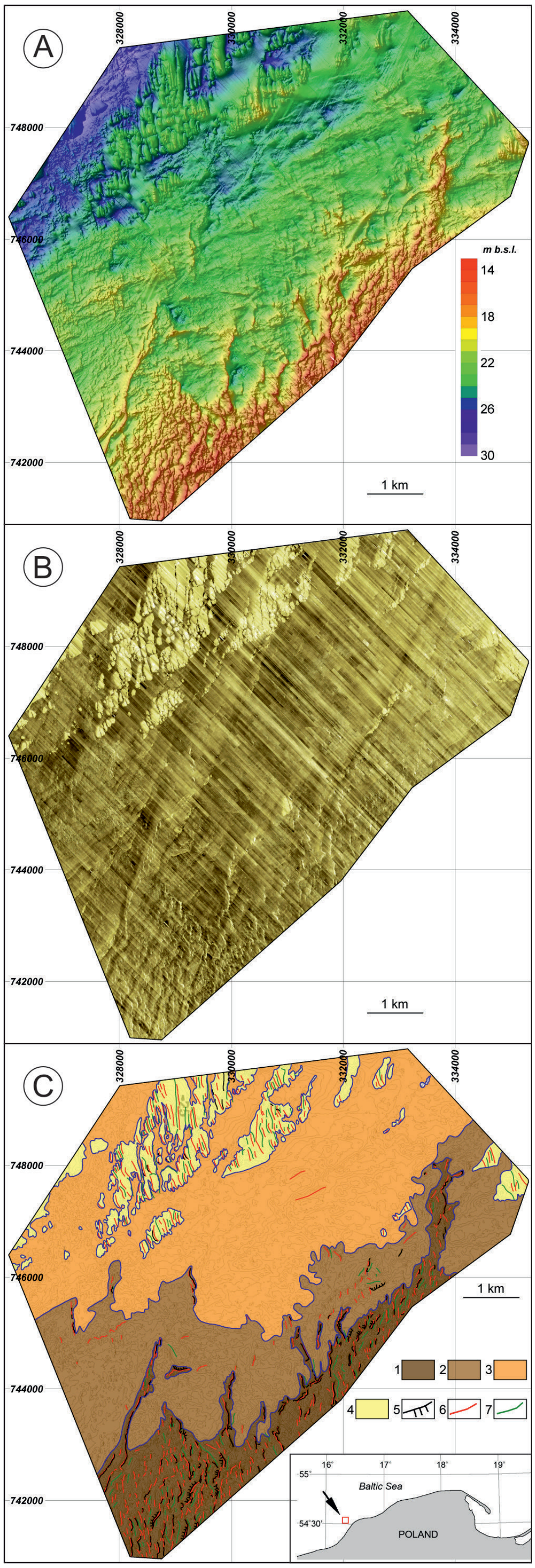

Fig. 2. Nearshore bottom in the vicinity of Jarosławiec: A – bathymetric map; B – side-scan sonar map; C – geomorphological map: 1 – morainic relief, 2 – morainic relief with marine sediment accumulation, 3 – polygenetic relief, glacial and marine origin, 4 – subaqueous dunes, 5 – short scarps, 6 – ridge and bulge axis, 7 – gully, furrow and cut axis

The obtained results indicate that on most of the bottom surface only a thin (a few centimetres thick), spatially variable cover of sand of recent marine sedimentation occurs (due to its nature this cover has not been marked on the geomorphological map; Fig. 2C). Only in the north of the area does a small field of subaqueous dunes occur; the dunes are of distinct variable shapes, thickness and location, and cannot be a sufficient basis for profitable sand extraction (Szefler et al. 2011).

Oksywie area

The Oksywie area constitutes part of the coastal seabed of the Kępa Oksywska, surveyed in order to determine the occurrence of anthropogenic objects, particularly military ones, which are numerous in this area. The wreck of the ship Stuttgart is among them (Fig. 3).

A detailed bathymetric map (Fig. 3A) and a geomorphological map (Fig. 3B) and a block diagram (Fig. 3C) created as a combination of bathymetric and side-scan sonar image are presented. The bot-

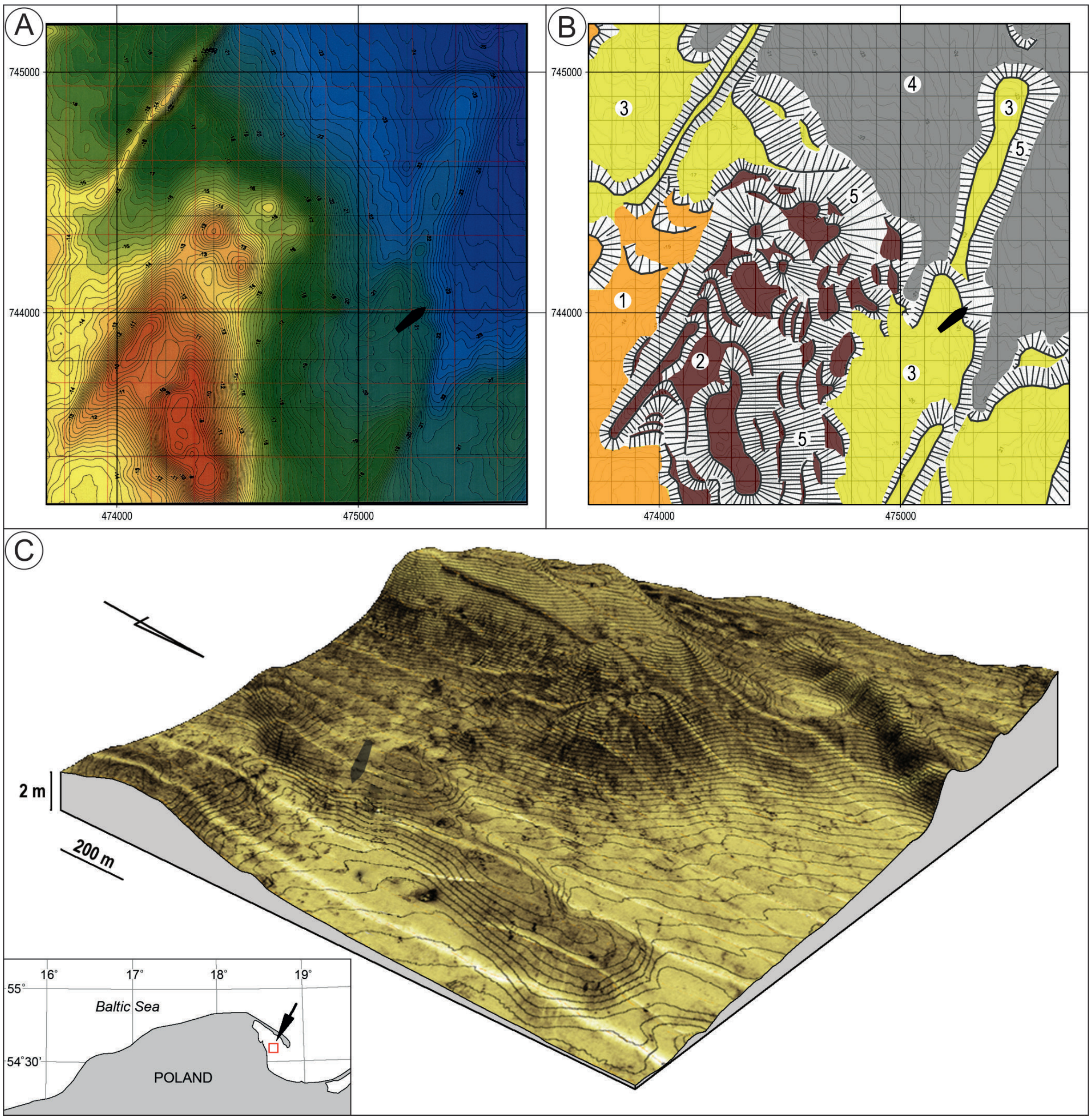

Fig. 3. Oksywie area: A – bathymetric map; B – geomorphological map: 1 – morainic plain, 2 – morainic plain with a surface heavily anthropogenically modified – mainly anthropogenic dump of sediments and materials from the construction of the port, 3 – beaches, sandbars, 4 – marine accumulation plain, 5 – slopes; C – block diagram of the side-scan sonar bottom image along with the shaded bottom relief. In figures A, B, and C the location of the wreck of the ship Stuttgart is marked with a black symbol

tom relief clearly shows a preserved fragment of the former coast formed at sea level ca. 20 m, with a steep “palaeocliff” of morainic plateau. At the cliff-foot there are coastal palaeoforms like sandy barriers (spits) with sandy palaeobeach between them. Figure 3B does not indicate a thin (less than 20-cm-thick), variable layer of contemporary sandy muds (Kudłak et al. 2012; Wróblewski et al. 2014).

The presented state of the bottom in the Oksywie area from 2009 is the basis for subsequent monitoring surveys of the changes in the fuel leak from the wreck of the ship Stuttgart, as well as the effects of the progressive ecosystem contamination (Wróblewski et al. 2014; Święch and Hac 2016).

Przekop Wisły area

The Przekop Wisły is a canal excavated in 1895 to enable unconstrained flow of waters in order to prevent floods associated with the impeded run-off of river waters flowing on a significant stretch along the shore (Wróblewski et al. 2015; Rudowski et al. 2017). The length of the canal (from Świbno to its mouth) is 3.4 km, its width is 420–450 m, and its depth is up to 7 m. It is a characteristic model of a rectilinear river with stable banks, a variable flow with a usual speed of around 1 m/s (depending on the state of the Vistula river and the sea conditions).

A part of the surveys carried out in order to assess the possibility of occurrence of an unconstrained flow of spate waters (precipitation waters, ice blockages) and to prevent flood hazards in the Żuławy area was presented by Lisimenka et al. (2015) and Rudowski et al. (2017).

The bottom relief of the Przekop Wisły by multibeam bathymetry is presented in Figure 4A. The bottom of the canal is asymmetrical, with areas lying at different depths and with numerous subaqueous dunes with varied size, shape (ripples, megaripples, sandy dunes *sensu* Ashley 1990). Different morphological units can be recognised (I–IV in Fig. 4A) (Wróblewski et al. 2016). For part of the bottom area, a shaded-relief image of the surface (Fig. 4B), a bathymetric profile (Fig. 4C) and a seismic cross-section (Fig. 4D) are presented. A block diagram is also presented in Figure 4E, being a compilation of all those elements and enabling spatial assessment of the bottom relief and sub-bottom structure. According to the authors this is the first presentation of the bottom relief together with bottom structure in a flowing river.

The proposed examples clearly indicate that there are great opportunities regarding measurements and surveys carried out at small depths *in vivo*, including in rivers. This applies to the flow survey potentialities in terms of hydrology and hydraulics, as well as geomorphology and geology, which is important both for contemporary river environments (including in ecosystem surveys) and for the appropriate recognition of the nature of river palaeoenvironments.

Discussion

The purpose of the paper was to present potentialities of current non-invasive methods of bottom surveys, including cartometric presentation of its relief and structure in both marine and inland reservoirs. The purpose was achieved by presenting selected examples from works carried out at the Maritime Institute in Gdańsk, which clearly illustrate the present-day possibilities of recognising the bottom relief and bottom structure of sea and river basins using modern research methods. Unpublished works for commercial purposes carried out in lakes, canals and port basins, etc., were also used.

It is currently possible to carry out cartographic studies with an accuracy of better than 20 cm. This requires appropriate equipment and time to adapt to individual needs. However, it is always possible to use the same equipment, regardless of the water basin. The authors are of the opinion that the proposed term “subaqueous geomorphology” well reflects the possibility of conducting research of the bottom of any water basins using the same equipment, without the need for specialised adjustments (of dimensions, power, etc.) to local environmental conditions. The currently used terms “marine geomorphology” or “subsea geomorphology” (Rudowski et al. 2014; Micallef et al. 2018) should be, in the authors’ opinion, related only to seabed surveys.

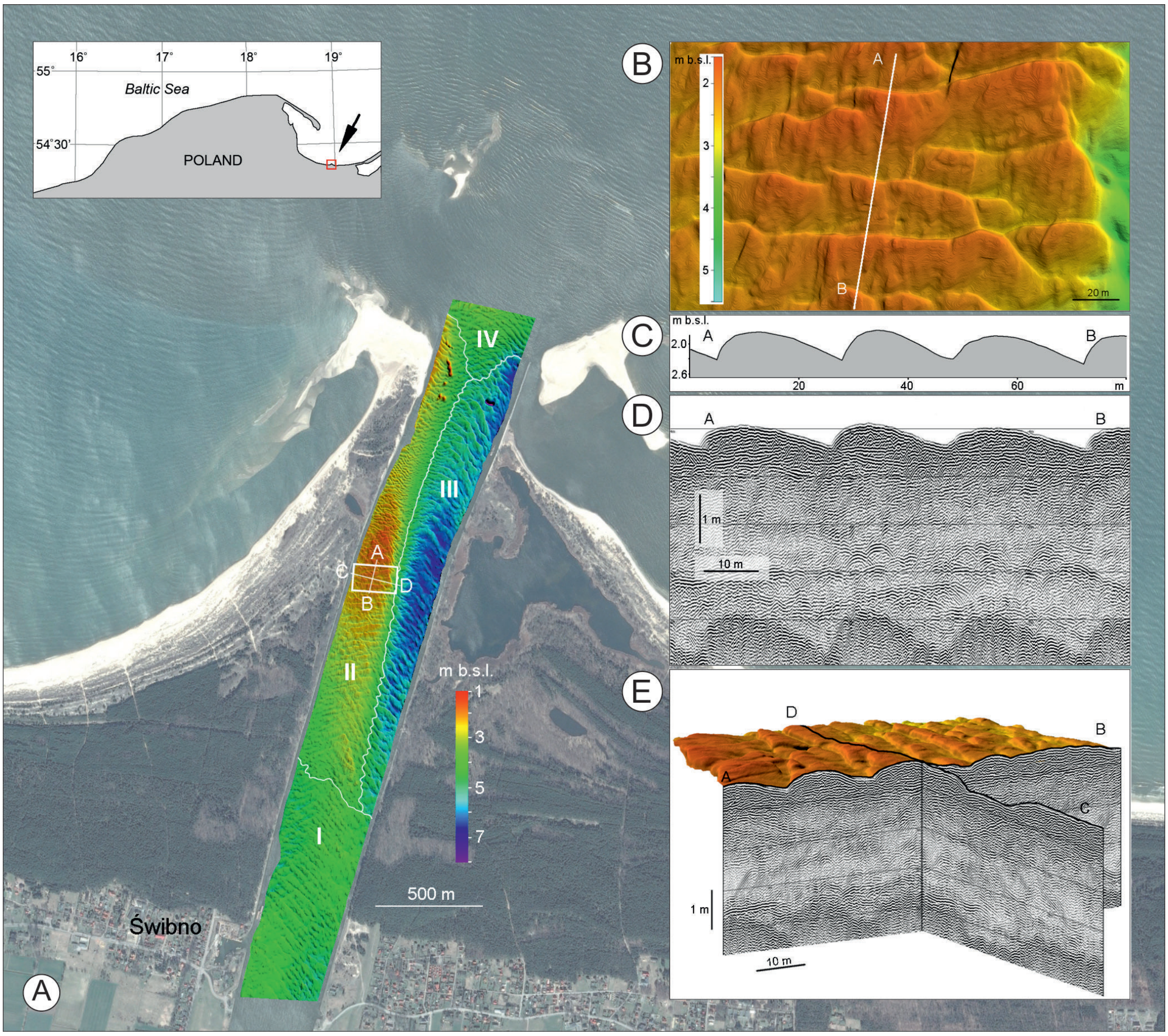

Fig. 4. Przekop Wisły area: A – bottom relief image with morphological units marked: I – rapid, II – side bar, III – pool, IV – front bar (*acc. to* Wróblewski et al. 2016); B – image of an enlarged fragment of the bottom surface with its bathymetric profile (C); seismic cross-section (D) and fence diagram of the geological structure (E), Background: satellite image (by CNES / Airbus, April 5, 2014)

Summary and conclusions

A digital model of the bottom surface accompanied by a sonar image allows the elaboration of a bottom relief image. Mapping of the appropriate geomorphological units is supported by information from other measurements regarding: the internal structure, the analysis of the sediments from grab and core samples, magnetometry, bottom photography and other methods.

Geomorphological data of the bottom (especially cartographic data) provide the basic indicators of environmental conditions, their state and changes (this is best done on the basis of detailed monitoring results). These data are essential for all purposes regarding reconnaissance and specifying the nature of the bottom for cognitive and utilitarian purposes, including shore protection and coastal zone management, habitat assessment, exploitation and natural resources extraction, usefulness in technological infrastructure assessment, geohazard assessment and other specialist purposes.

Nowadays, due to the dynamics of the processes occurring at the bottom (mainly in seas and rivers), 4D-type (x, y, z, t) surveys, which include the temporal aspect, and even 5D-type (4D + r) surveys, which include the issue of a specific geomorphological unit, are necessary. It is also important to specify the current state of the bottom and of the forms in relation to their development *in vivo* and *in situ*.

Weather conditions are the main factor limiting both the possibility to use the subaqueous geomorphology method and its ultimate quality. In the case of sea surveys, measurements are not possible with a wind force greater than 2 on the Beaufort scale. In the future this difficulty may be largely overcome by the use of unmanned submarine vehicles mapping the bottom, following the example of drones imaging the land from the air.

In efficiency and effectiveness of bottom mapping for geomorphological purposes (and not only that), it is hugely important to ensure the correct procedure for carrying out the measurements and reporting the mapping results. The basic norm is to start bathymetric mapping and the analysis of the obtained image of the bottom relief, which ensures the accurate and economic planning of further, detailed works (e.g. places of sediment sample collection). A specialist, digital, initial processing of the data (collected in the form of a point cloud) requires appropriate servers, operators and time, and is a time-consuming activity that usually limits the efficiency of works.

The final results depend to a large degree on an appropriate synchronisation of particular types of bottom measurements, including inevitable gaps in the measurements.

Preparation of a complete set of issues may require the work of a large team of specialists in measurement, data processing, data interpretation, and final elaboration. The copyright should apply to all contractors, including measurement and data processing managers.

The pioneering presentation of the possibility to carry out *in vivo* reconnaissance of the internal structure of bottom forms in a flowing river deserves separate emphasis. Until now it has only been possible in specialist experimental works carried out in laboratories. This is necessary for measuring e.g. displacements of forms and/or their components.

The results of the investigations currently being carried out in various academic and research institutions, government authorities and industries using the new potentialities of bottom surveys indicate the sense in identifying a new branch of geomorphology, to be described as "subaqueous geomorphology" and encompassing the bottom areas of all reservoirs.

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No potential conflict of interest was reported by the authors.

Author Contributions

Study design: S.R., R.W., J.D.; data collection S.R., R.W., J.D., K.S., B.H., Ł.G.; statistical analysis: S.R., R.W., J.D., K.S., B.H., Ł.G.; result interpretation S.R., R.W., J.D., K.S., B.H., Ł.G.; manuscript preparation S.R., R.W., J.D., K.S., B.H., Ł.G.; literature review: S.R., R.W., J.D., K.S., B.H., Ł.G.

Disclosure statement

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