ORIGINAL ARTICLE

Mapping bathymetry and shallow water benthic habitats in inland and coastal waters with Sentinel-2

Laura Argus,[1*] Tiit Kutser,[1] Birgot Paavel,[1] Martin Ligi,[1] Claudia Giardino,[2] Mariano Bresciani,[2] Tiia Möller[1]

[1]Estonian Marine Institute, University of Tartu, Mäealuse 14, 12618 Tallinn, Estonia; [2]National Research Council of Italy, Institute of Electromagnetic Sensing of the Environment (CNR-IREA), via Corti 12, 20133 Milan, Italy

ABSTRACT

Accurate determination of the water depth and benthic macroalgae composition in coastal and inland water bodies is important due to the high commercial and ecological value of these regions. Benthic habitat mapping by conventional methods provides good accuracy, but these methods are very expensive and limited by manpower and time factor, which is necessary for mapping large areas. Remote sensing methods significantly complement contact measurements and give additional information about the hard-to-reach areas. The usefulness of free Sentinel-2 data in bathymetry and habitat mapping has been demonstrated in clear oceanic waters. The aim of this study was to further test the suitability of Sentinel-2 imagery in creating maps of dominant benthic types, as well as in estimating bathymetry in optically complex marine and lake waters. Two study sites were selected to cover a representative range of optical variability - Lake Garda in northern Italy (an intermediate between clear ocean and optically very complex waters) and Viimsi peninsula on the Estonian side of the Gulf of Finland, in the Baltic Sea. The results show that Sentinel-2 imagery with 10 m spatial resolution is suitable for bathymetry and habitat mapping in optically complex inland and coastal waters. Our results show that bathymetry mapping is sufficiently accurate in waters less than 4 m deep in the case of the Baltic Sea and up to 7 m deep in Lake Garda. In such depths, the R^2 was above 0.93 in all four Sentinel-2 images used in the study. Bottom type mapping accuracy was in all cases over 73%, which is considered to be good, but due to the limited number of sampling points in both test sites, further studies are needed. The Sentinel-2 data quality and no cost of the imagery for users make it very useful for mapping bathymetry and shallow water habitats over large coastal areas or high number of lakes, especially in hard to reach by *in situ* methods areas. Moreover, the frequent revisit time allows moving from one-off maps to monitoring of temporal changes happening in dynamic shallow inland and coastal waters.

Corresponding author: laura.argus@ut.ee

Key words: bathymetry; benthic algal cover; coastal waters; inland waters.

Contributions: LA, TK, conceptualization, validation, manuscript review and editing; LA, TK, BP, ML, CG, MB, TM, data curation, manuscript original draft; LA, formal analysis; CG, MB, methodology; LA, CG, MB, visualization. All authors have read and agreed to the published version of the manuscript.

Conflict of interest: The authors declare no conflict of interest.

Citation: Argus L, Kutser T, Paavel B, Ligi M, Giardino C, Bresciani M, Möller T. Mapping bathymetry and shallow water benthic habitats in inland and coastal waters with Sentinel-2. *J. Limnol. 2023;82:2091.*

Edited by: Andrea Lami, *CNR-IRSA Verbania, Italy.*

Received: 9 August 2022.
Accepted: 20 February 2023.

J. Limnol., 2023; 82:2091
DOI: 10.4081/jlimnol.2023.2091

INTRODUCTION

Nearly three-quarters of the Earth's surface is covered by oceans, seas and smaller inland water bodies. Information about benthic communities alongside bathymetry is essential since many benthic communities and ecosystems of coastal zones, estuaries and inland water bodies have both commercial and ecological value, which makes these regions valuable in terms of biodiversity and marine resources (Werdell and Roesler, 2003). Therefore, it is necessary to carefully plan activities, which could affect the state of coastal waters and continuously monitor their conditions. Coastal zone receives all lands discharges, such as fresh-water, erosion products and sewage, and it is highly affected by different marine processes, including wave action, tidal currents, as well as storm surges (Halpern *et al.*, 2008). Taking this into account it can be concluded that coastline is a very valuable dynamical border area because of its morphological and ecological characteristics (Barale and Folving, 1996).

Benthic habitats are important components of coastal zone ecosystem, both marine and lacustrine. The vegetation contributes to the primary production in coastal areas, supporting grazing and detrital food webs. Aquatic vegetation is also providing food, spawning and nursery grounds for fishes and other invertebrate species (Francour, 1997; Hemminga and Duarte, 2000). Benthic vegetation helps to prevent coastal erosion by binding sediments and reduces nutrient loading and other forms of pollution (Fonseca, 1989).

The health of vegetation communities in coastal waters depends on suitable environmental conditions. Submerged aquatic habitat requires light for photosynthesis, growth, and survival (Dennison, 1987). The minimal requirement for light conditions of a particular species determines the maximal water depth at which it can survive (Dennison, 1993). The eutrophication and nutrient enrichment of coastal waters is a result of human activities and is widely recognized as a worldwide pollution threat (Halpern *et al.*, 2008; Schramm, 1996). Specific changes, such as decline or disappearance of certain plant communities, reduced diversity of the flora, blooms of short-lived annual forms and changes in depth distribution of benthic algae, have occurred in vegetation communities due to increasing eutrophication and decreasing light availability (Schramm, 1996).

In the context of ongoing climate change, high fluctuations in water levels are of fundamental importance, long periods without precipitation (snow and rain) are causing major problems in the management of water resources (Leira and Cantonati, 2008). Sustainable management of coastal environments requires the regular collection of accurate information on indicators of ecosystems health (Phinn *et al.*, 2005). Benthic habitat coverage and trends of the changes in it are indicators of water quality (Pearson, 1978). The purpose of monitoring is to track short-term and long-term changes in species distribution and structure. Benthic habitat mapping by conventional field-based methods (diving, underwater video, grab samples) provides good accuracy (Werdell and Roesler, 2003), but these are limited by manpower and the time factor, which is necessary for mapping large areas. Some areas are even hard to reach with conventional methods. Many coral reef lagoons, shallow reefs, tidal areas, and waterbodies, for example, are surrounded by wetlands or dense vegetation that makes it difficult to obtain information about benthic habitats. Remote sensing is the most useful tool in these situations.Remote sensing methods significantly complement field observations and give additional information about the hard-to-reach areas. Optical satellite data can be an efficient alternative for bathymetric derivation in shallow and clear coastal waters, providing temporal and spatial continuity (Phinn *et al.*, 2005; Dekker *et al.*, 2001; Fyfe, 2003). Time series of satellite imagery allow studying the long-term changes in benthic vegetation (Lõugas *et al.*, 2020). The potential of using remote sensing methods to retrieve bathymetry information and mapping the types of substrate cover has been used in very clear shallow waters (<30 m) worldwide (Mumby and Edwards, 2002; Kutser and Dekker, 2003; Kutser *et al.*, 2006; Knudby *et al.*, 2010; Dekker *et al.*, 2011; Hedley *et al.*, 2018) with only few examples found in more turbid optically complex waters (Lafon *et al.*, 2002; Vahtmäe *et al.*, 2006; Bramante *et al.*, 2013; Caballero *et al.*, 2019; Casal *et al.*, 2020; Kuhwald *et al.*, 2022).

The launch of Sentinel-2 on June 23rd in 2015, with 10-60 m spatial resolution, multi-spectral instrument (MSI) with 13 spectral channels in the visible/near infrared (VNIR) and short wave infrared spectral range (SWIR) and 3-5 days (depending on the latitude) revisit time, opened new possibilities in mapping changes that happen in shallow water coastal environments. The usefulness of Sentinel-2 for such purposes has been demonstrated for oceanic, marine and inland waters (Hedley *et al.*, 2018; Casal *et al.*, 2020; Traganos and Reinartz, 2018; Fritz *et al.*, 2019; Ghirardi *et al.*, 2019; Caballero and Stumpf, 2019; Yunus *et al.*, 2019; Wilson *et al.*, 2020; Dörnhöfer *et al.*, 2016). However, majority of the studies have been carried out in clear waters of Pacific and Atlantic Oceans and in relatively clear lakes. The aim of this study was to further demonstrate the suitability of Sentinel-2 in creating maps of dominant benthic types, as well as in estimating bathymetry in optically complex shallow marine and lacustrine waters.

METHODS

Study sites

Two study sites were selected to cover a representative range of optical variability and aquatic ecosystems. The first site was Lake Garda in northern Italy (Figs. 1 and 2) and the second test site was Viimsi peninsula in Estonian side of the Gulf of Finland, in the Baltic Sea (Fig. 3). Lake Garda is a subalpine lake with a surface area of 368 km^2, a water volume of 49 km^3 and a mean depth 133.3 m (max 350 m). Lake Garda is an important resource for recreation and tourism and an essential water supply for drinking, agriculture, industry and fishing for the region. Water conditions range from oligotrophic to mesotrophic and shallow coastal areas are inhabited by a variety of macrophytes, whose value is very relevant in preserving the oligotrophic status of the Lake Garda waters (Salmaso *et al.*, 2018). Prairies of rooted macrophytes comprise many different species (*Lagarosiphon*, *Vallisneria*, *Potamogeton*, *Najas* and *Chara*) and with well recognized ecological functions. The largest areas of bottoms colonized by macrophytes are situated in the southern part of the lake. Another relevant shallow area is located in the pelagic waters of the south-eastern basin, where native macrophytes species can grow, as they are less disturbed by anthropogenic factors. Of great importance in the lake are the public and private navigations, for a total of 27 harbours in the whole basin. A recent report from 2016 from NaviGarda shipping company, whose fleet is made up of 21 units, documented over 2.5 million people transported in 2016.

The Estonian site was in the Gulf of Finland area close to Tallinn (Fig. 3). Viimsi peninsula and Aegna Island surroundings are under great anthropogenic stress. Tallinn city with many ports and frequent ship traffic is located at the west side of the peninsula and the Port of Muuga (the largest port in the area) is located on the eastern part of the peninsula. The peninsula itself is under heavy construction since it is a fast-growing area for housing and industry. The substrate in the study area is mainly sand, gravel and large rocks transported to the area from Scandinavian mountains during the ice age. The latter makes conventional sampling quite dangerous. Dominating flora is brown macroalgae *Fucus vesiculosus* (the main habitat forming species in the Baltic Sea) and green filamentous algae like *Cladophora glomerata* (Fig. 4). For the Baltic Sea benthic habitats and substrate types we have a spectral library collected over many years (Vahtmäe *et al.*, 2006; Kutser *et al.*, 2006a; Kutser *et al.*, 2006b; Vahtmäe and Kutser, 2013; Kotta *et al.*, 2014). Therefore, there was no need in collecting extra reflectance [Rrs (λ)] spectra of macroalgae and plants.

In situ data

In Lake Garda, a field campaign was carried out on June 6-8, 2017. The locations of sampling stations are shown in Fig. 1. Both water column parameters and benthic habitats were characterized in optically shallow waters while only water column properties were measured in the deep stations. Remote sensing reflectance of the water was measured with Ramses (TriOS) spectrophotometers. The measurements were carried out with having an upwelling radiance sensor just below the water surface to avoid glint. Optical water properties were measured with WetLabs instrument set, which consists of a hyperspectral absorption and attenuation meter AC-S, backscattering sensor ECO-BB3 that measures backscattering coefficients at three wavelengths and a volume scattering sensor ECO-VSF3 measuring scattering at three wavelengths and three angles. The WetLabs instrument package included also a CTD for temperature, salinity and depth measurements according to instructions described by Uusõue *et al.* (2022). The frame was slowly lowered through the water column and instruments were measured continuously.

Water samples were collected from the surface layer (between the surface and 0.5 m depth) and taken for determining concentrations of chlorophyll-a (Jeffrey and Humphrey, 1975), CDOM (Davis-Colley and Vant, 1987) and total suspended matter (EPA, 1993). Total and CDOM absorption coefficients were measured in laboratory using an a-sphere (HobiLabs) integrating cavity absorption meter. Optical water properties were characterized in different environments – deep water stations (blue squares in Fig. 1), macrophyte dominated shallow water areas (red square), sandy shores (yellow square) and macroalgae dominated areas (green square). The total number of bio-optical sampling stations was 16 while bottom was mapped with drop video in 22 stations. The videos were later analysed in laboratory using the methodology by Möller *et al.* (2009) to estimate species composition and the percentage of benthic habitat cover. Specimen of

Fig. 1. The location map of Lake Garda test site.

Fig. 2. Sampling stations of Lake Garda test site. Shown with blue square were optically deep and only the water column was characterized. The region indicated with the red square was dominated by macrophytes, the region shown with yellow square was dominated by sandy bottom and the region indicated with green square indicates the area dominated by macroalgae. The stations indicated with X where optically shallow waters with mixed (bare substrate, macrophytes and macroalgae) bottom type.

macrophytes and macroalgae were taken to the boat where reflectance spectra were measured with Ramses spectrometers and photos were taken to help video interpreters who are not familiar with the Lake Garda flora. Fieldwork was planned during a Sentinel-2A overpass. However, there were thunderstorms in the Lake Garda area during the Sentinel-2 data acquisition. Therefore, images from June 26 and July 8, 2017, were used.

In Viimsi test site, field campaign was more challenging due to wind and waves. It did not allow to carry out all fieldwork in 1-2 days as in Lake Garda. Therefore, the fieldwork was performed in several stages: “deep” water sampling with the WetLabs instrumentation package and water sampling was carried out on September 2, 2017 (four stations), benthic habitat mapping with drop video (fragments shown in Fig. 4) was carried out on September 15 (35 samples) and very shallow water depth and benthic habitat registration was carried out on September 13 by walking in shallow water (26 sampling points). The best Sentinel-2 images closest to the *in situ* sampling dates were available from June 4 and July 7, 2017 and they were Sentinel-2A images.

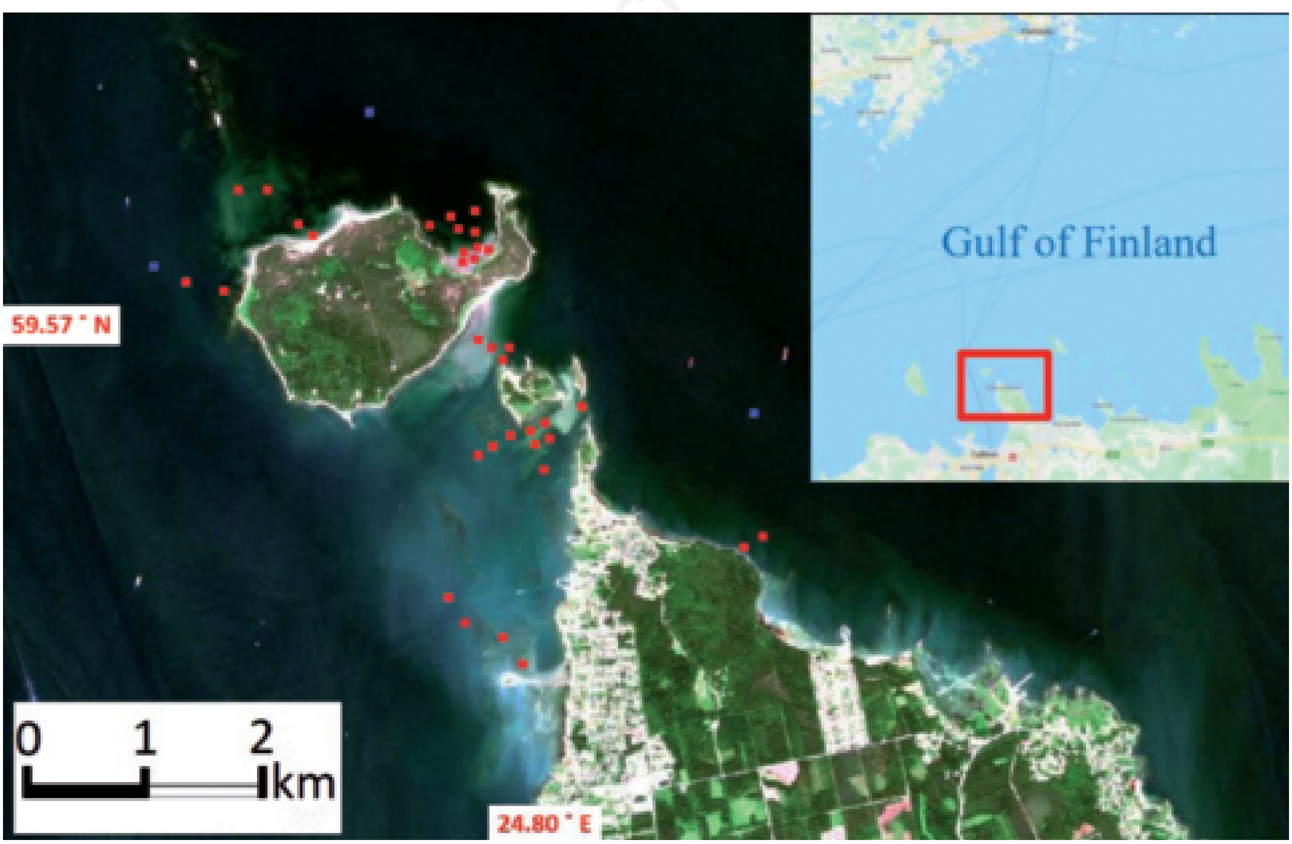

Fig. 3. Study site in the Gulf of Finland – Aegna Island and the tip of Viimsi Peninsula. The fragment of Sentinel-2 image with the study area is shown in the red box on the map. Sampling stations are shown with red and blue dots. The stations indicated with blue represent points where optical water properties were measured.

Remote sensing methods

Image Data Analysis (IDA by Numerical Optics, https://www.numopt.com/) software package was used for image processing and visualization (Hedley *et al.*, 2018). IDA allows to perform several image pre-processing steps (atmospheric correction, glint removal) and allows to retrieve water depth, benthic habitats and optical water properties using the adaptive lookup table (ALUT) approach (Hedley *et al.*, 2009, 2012, 2018).

The first step in the image pre-processing was sun glint removal. The deglint tool in IDA applies an image-based water surface sun-glint correction according to the methods described in Hedley *et al.* (2005) and Kay *et al.* (2009). The basis of the method is that an image band in the near infrared (NIR) or short wave infra-red (SWIR) is used to quantify the glint proportion in each pixel, which can then be removed from the bands in other wavelengths. The tool provides various options that can apply to the different variants of the methods described in Kay *et al.* (2009). The glint removal method in IDA is entirely image-based and does not require metadata on the sea state or solar-view geometry.

Bathymetry mapping along with benthic habitat estimations is the next step in image processing. The required input for estimating bathymetry is an image of the bottom of atmosphere (BOA) remote sensing reflectance, being the ratio of water-leaving radiance to the irradiance on top of the water surface. The Bathy tool in IDA estimates bathymetry from image data using a model inversion method. The methods implemented are very similar to those published by Hedley *et al.* (2009, 2012, 2018). The basis of the optimization method is a forward model of above-water spectral remote sensing reflectance) based on parameters of the water column and bottom substrates reflectance. Since model inversion methods work with water-leaving reflectance as a radiometric quantity, accurate atmospheric correction is essential and has a significant impact on the bathymetry results (Goodman *et al.*, 2008). IDA software package uses deep water calibration (DWC) approach (Hedley *et al.*, 2018). DWC atmospheric correction is based on a set of look-up-tables for atmospheric reflectance and transmission, including a maritime 99% relative humidity aerosol model as described in (Antoine and Morel, 1999). The look-up-tables are generated by libRadtran (Emde *et al.*, 2015) and are parameterized on solar-view geometry, with the only two free parameters being aerosol optical thickness, τ (550) ranging between 0 and 0.3, and wind speed, u10, ranging between 0 ms^{-1} and 10 ms^{-1} (conditions of the sea surface state). The main effect of these two parameters is to notionally contribute to a spatially homogenous component of the atmosphere and indirect sea-surface reflectance, *i.e.*, sky reflectance (Hedley *et al.*, 2018). Atmospheric correction estimates a value for the aerosol optical thickness and a value for wind speed to be applied over the whole image area. This estimation is based on a set of deep-water areas selected by the user. The required input for estimating bathymetry is an image of the bottom of atmosphere (BOA) remote sensing reflectance, being the ratio of water-leaving radiance to the irradiance on top of the water surface. The assumption of the underlying models is that the input data must have been atmospherically corrected and any component of reflected light (sun or sky glint) from the upper side of the air-water interface has been removed.

To estimate the bathymetry and water optical properties, model needs to know the range of possible bottom reflectance. In general, the bottom reflectance would not be expected to be the same over the whole area to be analysed, dark patches of macroalgae (seaweeds) or corals surrounded by brighter sand are clear examples of this. Within a remote sensing image pixel (10 m x 10 m), there may be a mixture of bottom types in any proportion. The main method for handling bottom reflectance in the Bathy tool

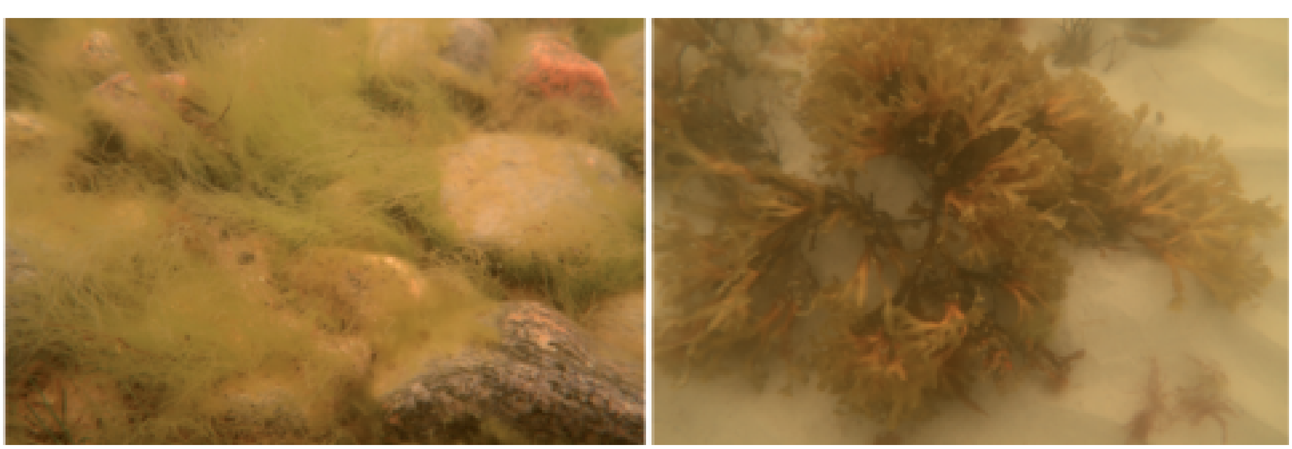

Fig. 4. Frames from videos made during fieldwork in Viimsi test site on 15 September 2017. Green filamentous algae *Cladophora glomerata* on the left and brown macroalgae *Fucus vesiculosus* on the right image.

is to specify a set of bottom types, each with a specific spectral reflectance, referred to as 'endmembers'. In this study, we used our own spectral library that consists of average spectra of every possible bottom type (red-, green-, brown macro-algae, seagrasses and other higher plants, bare substrate, deep water) present in both study areas. The bottom reflectance in the model can then take the value of a 'linear mix' of any pair of endmembers in the set; this specifies the range of possible reflectance encompassed by the model. For bathymetry assessment, methodology, where a 3 by 3 pixels window was used to assess the water depth has been chosen; 3 by 3 pixels represent that the average value of 9 surrounding pixels has been calculated and extrapolated to all 9 pixels in question.

A confusion matrix was prepared to assess the results of classification, comparing the results on a class-by-class basis A confusion matrix is a table that allows visualizing the performance of classification by comparing the predicted value of the target variable, in our case pixels, with its actual value and gives out standard accuracy indicators (User's accuracy, Producer's accuracy and overall accuracy). User's accuracy is computed by dividing the number of correctly classified pixels in each category by the total number of pixels that were classified in that category (the row total) and it represents the probability that a pixel classified into a given category actually represents that category on the ground. Producer's accuracy is a result of dividing the number of correctly classified pixels in each category (on the major diagonal) by the number of reference pixels "known" to be of that category (the column total) and the value represents how well reference pixels of the ground cover type are classified. Overall accuracy is computed by dividing the total number of correctly classified pixels (*i.e.,* the sum of the elements along the major diagonal) by the total number of reference pixels (Congalton, 1991). Also, the coefficient of determination (R^2) was stated.

RESULTS AND DISCUSSION

Optical water properties

Concentrations of optically active substances measured in both test sites are given in the Tab. 1. It is seen that the CDOM, TSM and Chlorophyll-a concentrations in all sampling stations were low or very low compared to Viimsi test site and higher than those measured in the oceanic waters (Morel *et al.*, 2010; Dutkiewicz *et al.*, 2019). Low absorption and backscattering coefficients (Fig. 5) also confirm that from optical point of view, Lake Garda is an intermediate waterbody between the open ocean and the Baltic Sea. CDOM concentration in the Viimsi study area was typical to open parts of the Baltic Sea as there are no major rivers near the study site that would contribute large amount of CDOM. On the other hand, TSM concentrations were relatively high. This is probably due to sediments re-suspension, as the shallow water areas in the Viimsi study site are relatively exposed to winds from different directions. Chlorophyll-a concentrations were typical for cyanobacteria season and exceeded the national monitoring threshold of a bloom in the Baltic Sea (5 mg m-3)" (Estonian Legislation, Water Act; https://www.riigiteataja.ee/en/eli/512012017001/consolide). Reflectance spectra were measured in each sampling station in order to be able to check performance of atmospheric correction of Sentinel-2 imagery. Average reflectances are shown in Fig. 6. Reflectance spectra of the macroalgae and plant specimens were measured with Ramses on board the boat. Examples are shown in Fig. 7.

Image processing can be done with and without glint removal. Whether to apply the deglint procedure depends on the image quality. Quite often an image that seems to be nearly perfect at the first glance is actually badly glint contaminated after a more detailed inspection. It was clear from visual inspection that large parts of the Lake Garda Sentinel-2 image were contaminated with glint, a condition that is rather frequent during summer for the lake. Therefore, the glint removal procedure available in the IDA software was used to improve the image quality. The images before and after glint correction are shown in Fig. 8.

Bathymetry mapping

Altogether, 53 *in situ* measured depth points from a depth range of 0 to 7 meters were collected from the two study areas – 12 from Lake Garda and 41 from Viimsi. Retrieved bathymetry maps are shown in Fig. 9 and in the

Tab. 1. Concentrations of optically active substances measured in Lake Garda and Viimsi during the field campaigns.

Water quality (all stations)	aCDOM (440) (m^{-1})	TSM ($g\ m^{-3}$)	Chl-a ($mg\ m^{-3}$)
Average (Lake Garda)	0.05	0.99	1.11
Average (Viimsi)	0.56	9.1	6.82
Max (Lake Garda)	0.11	1.73	1.91
Max (Viimsi)	0.59	10.7	8.63
Min (Lake Garda)	0.02	0.45	0.46
Min (Viimsi)	0.53	8.3	5.14

case of the Viimsi test site the depths measured in the field work varied from 0.5 m to 4.9 m and retrieved values from remote sensing images varied from 0.47 m to 4.75 m, while the coefficient of determination (R^2) was 0.95. In Lake Garda, measured water depth values from fieldwork varied from 1.2 m to 7 m and image-derived water depth was from 1.4 m to 6.6 m, while R^2 was 0.95.

Sentinel-2 has high revisit time. Therefore, it should be reasonable to process several images and use their average as a final product, especially if the images are acquired with small time interval during which the benthic habitats and bathymetry should remain the same. However, in our case cloud-free images with minimal glint effect were two weeks apart in Lake Garda and more than

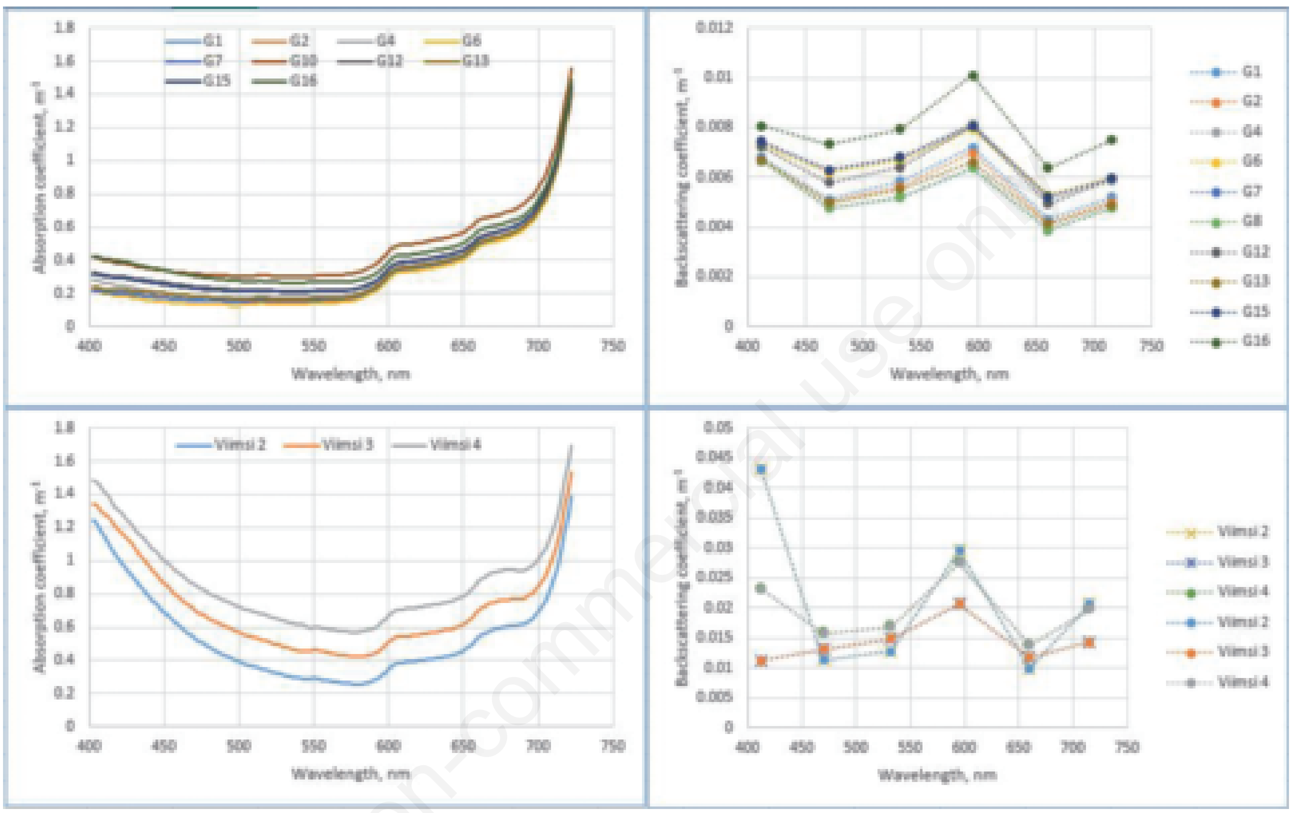

Fig. 5. Total absorption (left) and backscattering coefficients (right) measured in Lake Garda (top) and Viimsi (bottom).

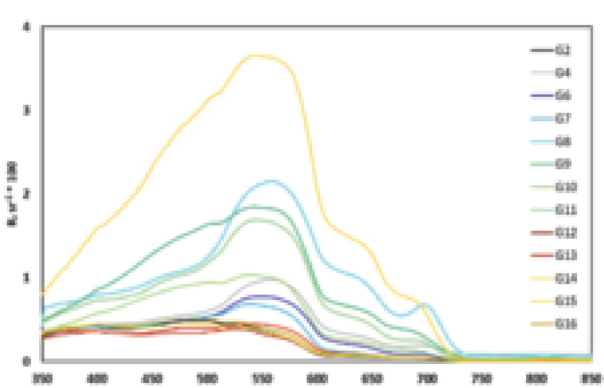

Fig. 6. Reflectance spectra measured in different sampling stations in Lake Garda.

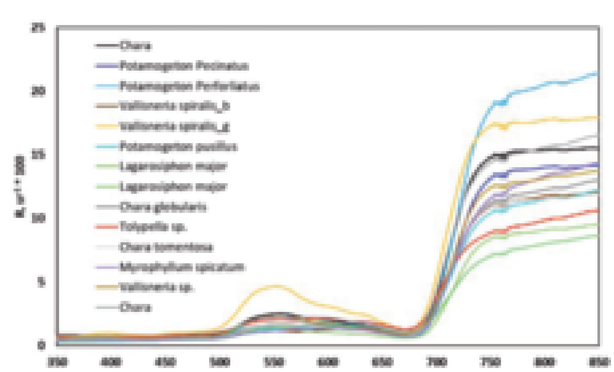

Fig. 7. Reflectance spectra of different macrophytes and macroalgae taken out from Lake Garda.

a month apart in Viimsi. Therefore, it was decided to retrieve bathymetry and habitat information from each image separately (Fig. 10).

The chosen study methodology, where 3 by 3 pixels window was used to assess the water depth, enabled us to produce reliable bathymetry maps with IDA in optically complex Baltic Sea and a subalpine lake. In both test sites the R^2 was 0.95 which shows excellent concurrence between image derived water depth and measured water depth.

Benthic habitat mapping

Altogether, 42 *in situ* points with bottom habitat data were collected from the two study areas –10 from Lake Garda and 32 from Viimsi.

We have shown in our previous studies (Kutser *et al.*, 2006, 2006a, 2006b; Vahtmäe *et al.*, 2006) that separating brown and red macroalgae from each other is possible only with hyperspectral sensors and in very shallow (less than 3 m) water. However, it can be seen in Tab. 2, that there are no red algae in the study sites (they usually grow in deeper areas). The classification results did not show presence of red algae either. The same studies show that it is very difficult or nearly impossible to separate green macroalgae, seagrasses and other higher-order plants from each other, based on their optical signatures (especially when multispectral sensors are used). In the Garda test sites there were two points and in Viimsi test site there were three points where higher order vegetation (HOV) was found, but user accuracy was 0% from both Lake Garda images and from 04.06.2017 Sentinel-2 image and 25% from 07.07.2017 Viimsi image and in every case, HOV was classified wrong. It was classified as green

Fig. 8. The effect of applying glint removal procedure in IDA software on the Lake Garda image from 23.06.2017 (A, original; B, deglinted).

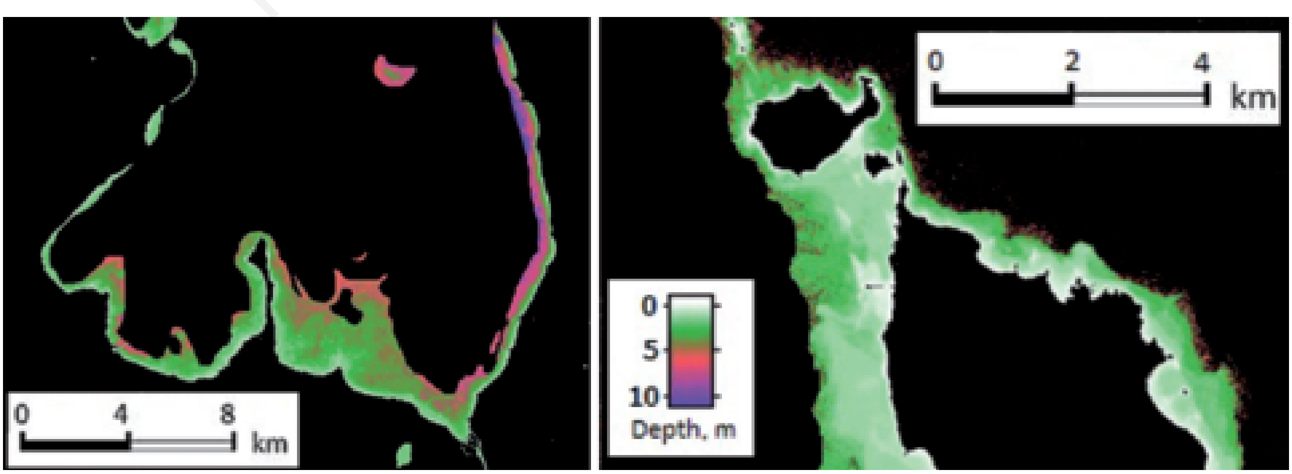

Fig. 9. Retrieved bathymetry maps from Lake Garda test site on the left and Viimsi test site on the right. Land and deeper depths have been masked out by visual inspection and shown in black.

algae, so it was decided to combine HOV and green algae classes. In Lake Garda, no brown algae were detected during the *in situ* campaign nor it was presented in the classification result, so this class has been removed from the classifying accuracy table.

In situ data was classified into three main classes – sand, areas dominated by green algae cover, and areas covered by brown algae. It has to be kept in mind that the "bare" substrate, in this case, sand, is actually not a clean substrate. First of all, every object in sea or lake water is always overgrown with some marine organisms. Even a single sand particle is always covered with a film of microscopic algae. Moreover, the *in situ* data was classified as sand if vegetation cover was less than 40%. On the other hand, 30% vegetation cover on the substrate may spectrally look like vegetation not as bare substrate. This explains the misclassifications between the sand and green algae classes.

In both test sites, classification accuracy shows the best results in classifying green algae. In both cases, there was one measuring point where green algae were classified as sand. Measured water depths in these measuring points were 4.1 m in Viimsi and 2.7 m in Lake Garda. Also, there are a few points where sand is classified as green algae. In Viimsi test site it can be explained by the fact that at the image acquisition time (07.07.2017) there was visible cyanobacteria bloom and due to that, water was green and sand appeared through the water column like green algae. It has been shown in our earlier studies (Vahtmäe *et al.*, 2006), that algal blooms in the water column and benthic vegetations may look spectrally nearly identical. As mentioned before, there was two months gap between field campaign and usable Sentinel-2 image in Viimsi test area due to the cloud coverage, so there was no other option but to use this image with visible bloom in the benthic mapping process. In Lake Garda same mix ups with green algae and sand happened. Lake Garda is an intermediate waterbody and if there is large concentration of phytoplankton, water may seem greenish and sand through the water column may seem more like green algae reflectance than to bare sand reflectance.

It has been shown in earlier studies (Kutser *et al.*, 2002, 2006, 2020), that the physics-based model inversion methods are very sensitive to the quality of input data. Consequently, atmospheric correction and other pre-processing steps must ensure that the reflectance is perfect before analytical methods are applied to process the imagery. Otherwise, the physics-based methods tend to fail.

Despite of very different water quality conditions of the two chosen test sites, high-accuracy bathymetry maps were obtained with IDA software from Sentinel 2 imagery, upon removal of glint and corrections of atmospheric effects. It has to be noted, that the *in situ* data is based on dominant algae/plant cover within a 1 m^2 area. Sentinel-2 pixel is 100 m^2 and vegetation is very patchy

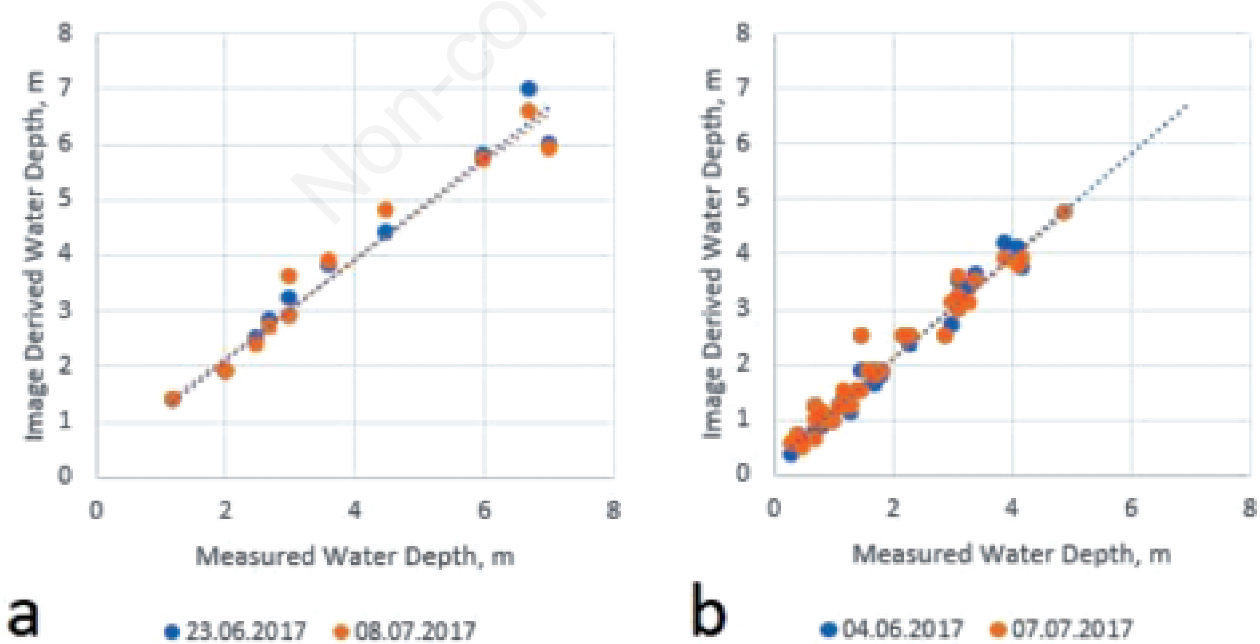

Fig. 10. Scatterplot of satellite derived depth vs in situ depth in Lake Garda (a) and Viimsi (b) test sites. Coefficient of determination of Lake Garda test site was R^2= 0.97 (23.06.2017), R^2=0.96 (08.07.2017) and of Viimsi test site R^2= 0.95 (04.06.2017), R^2=0.96 (07.07.2017).

in both test sites. There are no extensive seagrass beds or kelp forests that have "monospecies" cover within 10x10 m pixels. Thus, the spatial heterogeneity also impacts the bottom classification results. We planned to study these effects by flying our airborne imaging spectrometer HySpex simultaneously with Sentinel-2 overflight in the Viimsi test site. However, as mentioned before, weather conditions were not favourable for airborne campaigns (strong wind, variable cloud cover). From water management point of view, it is desirable to map benthic habitats during the maximum cover. However, due to the cloud cover, there was a significant gap between Sentinel-2 image acquisitions in the Viimsi test site and we may have not captured the absolute maximum cover. This does not diminish the value of the results in terms of demonstrating remote sensing capabilities.

In the Baltic Sea, sand is often darker than the bright white coral sand. Therefore, it is harder to distinguish sandy areas from vegetated areas or deep water than it is in tropical oceanic waters. Thus, not only the higher complexity of water column properties but also the higher similarity of benthic types make shallow water remote sensing in the studied waterbodies harder than in clear oceanic waters. This is also a reason why it is necessary to use regional endmember spectra rather than the bottom spectra that are included in the IDA.

Tab. 2. Classification accuracy from Sentinel-2 images. Bold values indicate the number of correctly classified pixels.

		Ground reference Classification accuracy			
Viimsi 04.06.2017	**Sand**	**Green algae**	**Brown algae**	**Total**	**User accuracy(%)**
Sand	**3**	2	0	5	60
Green algae	0	**10**	0	10	100
Brown algae	1	3	**7**	11	63.64
Total	4	15	7	26	
Producer accuracy (%)	75	66.67	100		
		Overall accuracy (%) 76.92			

		Ground reference Classification accuracy			
Viimsi 07.07.2017	**Sand**	**Green algae**	**Brown algae**	**Total**	**User accuracy (%)**
Sand	**2**	3	0	5	40
Green algae	1	**9**	0	10	90
Brown algae	1	2	**8**	11	72.73
Total	4	14	8	26	
Producer accuracy (%)	50	64.29	100		
		Overall accuracy (%) 73.08			

		Ground reference Classification accuracy		
Lake Garda 23.06.2017	**Sand**	**Green algae**	**Total**	**User accuracy (%)**
Sand	**2**	1	3	66.67
Green algae	0	**7**	7	100
Total	2	8	10	
Producer accuracy (%)	100	87.50		
		Overall accuracy (%) 90.00		

		Ground reference Classification accuracy		
Lake Garda 08.07.2017	**Sand**	**Green algae**	**Total**	**User accuracy (%)**
Sand	**1**	2	3	33.33
Green algae	0	**7**	7	100
Total	1	9	10	
Producer accuracy (%)	100	77.78		
		Overall accuracy (%) 80.00		

CONCLUSIONS

Sentinel-2 data quality and availability have increased the opportunities to monitor hard to reach coastal areas that have both ecological and commercial value. Sentinel-2 mission, with Sentinel-2A and Sentinel-2B registering data at 10 m of spatial resolution and a nominal revisit time of 5 days may not guarantee that cloud-free images can be received in less than a week, particularly in Baltic Sea area, where a high percentage of cloud coverage has often compromised the results obtained.

It may be concluded that Sentinel-2 is suitable for bathymetry and habitat mapping on optically complex inland and coastal waters. The depths at which this can be done are shallower than in clear oceanic water, but the results are still very valuable for coastal managers, monitoring agencies, researchers and in other fields.

Bathymetry mapping in waters less than 4 m in the Baltic Sea and less than 7 m in Lake Garda gave accurate results with R^2 being above 0.93 in all four Sentinel-2 images from where water depth was estimated. Bottom type mapping accuracy was in all cases over 73%, which is considered to be good, but due to the limited number of sampling points in both test sites, further studies are worthwhile.

In the context of climate change and with a scarcity of the quantity of water in the river and lakes, the bathymetry information associated with the water level is of great importance not only for an ecological point of view but for navigation management, the indication of the areas that may, in the event of a decrease in levels, be a potential danger for navigation is of fundamental importance, as well as information relating to the bathymetry and the coverage of the seabed in the areas in front of the ports.

ACKNOWLEDGMENTS

This research was funded by European Space Agency project number 4000118692/16/I/SBo, Estonian Research Council, grant number PUT PRG302, and H2020 project Water-ForCE.

REFERENCES

Antoine D, Morel A, 1999. A multiple scattering algorithm for atmospheric correction of remotely sensed ocean colour (MERIS instrument): principle and implementation for atmospheres carrying various aerosols including absorbing ones. Int. J. Remote Sens. 20:1875-1916.

Barale V, Folving S, 1996. Remote sensing of coastal interactions in the Mediterranean region. Ocean Coast Manag. 30:217-233.

Bramante JF, Raju DK, Sin TM, 2013. Multispectral derivation of bathymetry in Singapore's shallow, turbid waters. Int. J. Remote Sens. 34:2070-2088.

Caballero I, Stumpf RP, Meredith A, 2019. Preliminary assessment of turbidity and chlorophyll impact on bathymetry derived from Sentinel-2A and Sentinel-3A satellites in South Florida. Remote Sens. 11:645.

Caballero I, Stumpf RP, 2019. Retrieval of nearshore bathymetry from Sentinel-2A and 2B satellites in South Florida coastal waters. Estuar. Coast. Shelf Sci. 226:106277.

Casal G, Hedley JD, Monteys X, Harris P, Cahalane C, McCarthy T, 2020. Satellite-derived bathymetry in optically complex waters using a model inversion approach and Sentinel-2 data. Estuar. Coast. Shelf Sci. 241:106814.

Congalton RG, 1991. A review of assessing the accuracy of classifications of remotely sensed data. Remote Sens. Environ. 37:35-46.

Davies-Colley RJ, Vant WN, 1987. Absorption of light by yellow substance in freshwater lakes. Limnol Oceanogr. 32:416-425.

Dekker AG, Brando VE, Anstee JM, Pinnel N, Kutser T, Hoogenboom J, *et al.*, 2001. Imaging spectrometry of water, p. 307-359. In: FD van der Meer and SM De Jong (eds.), Imaging spectrometry: Basic principles and prospective applications. Springer, Dordrecht.

Dekker AG, Phinn SR, Anstee J, Bissett P, Brando VE, Casey B, *et al.*, 2011. Intercomparison of shallow water bathymetry, hydro-optics, and benthos mapping techniques in Australian and Caribbean coastal environments. Limnol. Oceanogr-Meth. 9:396-425.

Dennison WC, 1987. Effects of light on seagrass photosynthesis, growth and depth distribution. Aquat. Bot. 27:15-26.

Dennison WC, Orth RJ, Moore KA, Stevenson JC, Carter V, Kollar S, *et al.*, 1993. Assessing water quality with submersed aquatic vegetation. BioScience 43:86-94.

Dörnhöfer, K, Göritz, A, Gege, P, Pflug, B, Oppelt, N, 2016. Water constituents and water depth retrieval from Sentinel-2A - A first evaluation in an oligotrophic lake. Remote Sens. 8:941.

Dutkiewicz S, Hickman AE, Jahn O, Henson S, Beaulieu C, Monier E, 2019. Ocean colour signature of climate change. Nat. Commun. 10:1-13.

Emde C, Barlakas V, Cornet C, Evans F, Korkin S, Ota Y, *et al.*, 2015. IPRT polarized radiative transfer model intercomparison project - Phase A. J. Quant. Spectrosc. Radiat. Transf. 164:8-36.

EPA (Environmental Protection Agency), 1993. ESS Method 340.2: Total suspended solids, mass balance (dried at 103-105ºC) volatile suspended solids (ignited at 550ºC). Environmental Sciences Section, Wisconsin State Lab of Hygiene, Madison.

Fonseca MS, 1989. Sediment stabilization by *Halophila decipiens* in comparison to other seagrasses. Estuar. Coast. Shelf Sci. 29:501-507.

Francour P, 1997. Fish assemblages of *Posidonia oceanica* beds at Port-Cros (France, NW Mediterranean): assessment of composition and long-term fluctuations by visual census. Mar. Ecol. 18:157-173.

Fritz C, Kuhwald K, Schneider T, Geist J, Oppelt N, 2019. Sentinel-2 for mapping the spatio-temporal development of submerged aquatic vegetation at Lake Starnberg (Germany). J. Limnol. 78:1824.

Fyfe SK, 2003. Spatial and temporal variation in spectral reflectance: Are seagrass species spectrally distinct? Limnol. Oceanogr. 48:464-479.

Lõugas L, Kutser T, Kotta J, Vahtmäe E, 2020. Detecting long time changes in benthic macroalgal cover using landsat image archive. Remote Sens. 12:1901.

Ghirardi N, Bolpagni R, Bresciani M, Valerio G, Pilotti M, Giardino C, 2019.Spatiotemporal dynamics of submerged aquatic vegetation in a deep lake from Sentinel-2 data. Water 11:563.

Goodman JA, Lee Z, Ustin SL, 2008. Influence of atmospheric and sea-surface corrections on retrieval of bottom depth and reflectance using a semi-analytical model: a case study in Kaneohe Bay, Hawaii. Appl. Opt. 47:F1-F11.

Halpern BS, Walbridge S, Selkoe KA, Kappel CV, Micheli F, D'Agrosa C, Watson R, 2008. A global map of human impact on marine ecosystems. Science 319:948-952.

Hedley JD, Harborne AR, Mumby PJ, 2005. Simple and robust removal of sun glint for mapping shallow-water benthos. Int. J. Remote Sens. 26:2107-2112.

Hedley JD, Roelfsema C, Brando V, Giardino C, Kutser T, Phinn S, *et al.*, 2018. Coral reef applications of Sentinel-2: Coverage, characteristics, bathymetry and benthic mapping with comparison to Landsat 8. Remote Sens. Environ. 216:598-614.

Hedley JD, Roelfsema C, Koetz B, Phinn S, 2012. Capability of the Sentinel 2 mission for tropical coral reef mapping and coral bleaching detection. Remote Sens. Environ. 120:145-155.

Hedley JD, Roelfsema C, Phinn SR, 2009. Efficient radiative transfer model inversion for remote sensing applications. Remote Sens. Environ. 113:2527-2532.

Hemminga MA, Duarte CM, 2000. Seagrass ecology. Cambridge University Press, Cambridge: 298 pp.

Jeffrey ST, Humphrey GF, 1975 New spectrophotometric equations for determining chlorophylls a, b, c1 and c2 in higher plants, algae and natural phytoplankton. Biochem. Physiol. Pflanz. 167:191-194.

Kay S, Hedley JD, Lavender S, 2009. Sun glint correction of high and low spatial resolution images of aquatic scenes: a review of methods for visible and near-infrared wavelengths. Remote Sens. 1:697-730.

Knudby A, Newman C, Shaghude Y, Muhando C, 2010.Simple and effective monitoring of historic changes in nearshore environments using the free archive of Landsat imagery. Int. J. Appl. Earth Obs. Geoinf. 12:116-S122.

Kotta J, Remm K, Vahtmäe E, Kutser T, Orav-Kotta H, 2014. In-air spectral signatures of the Baltic Sea macrophytes and their statistical separability. J. Appl. Remote Sens. 8:083634.

Kuhwald K, Schneider von Deimling J, Schubert P, Oppelt N, 2022. How can Sentinel-2 contribute to seagrass mapping in shallow, turbid Baltic Sea waters? Remote Sens. Ecol. Conserv. 8:263-425.

Kutser T, Dekker AG, Skirving W, 2003. Modelling spectral discrimination of Great Barrier Reef benthic communities by remote sensing instruments. Limnol. Oceanogr. 48:497-510.

Kutser T, Hedley JD, Giardino C, Roelfsema C, Brando VE, 2020. Remote sensing of shallow waters–A 50-year retrospective and future directions. Remote Sens. Environ. 240:111619.

Kutser T, Jupp DLB, 2002. Mapping coral reef benthic habitat with a hyperspectral space borne sensor, p. 18-22. Proceedings Ocean Optics Conference XVI.

Kutser T, Miller I, Jupp DL, 2006. Mapping coral reef benthic substrates using hyperspectral space-borne images and spectral libraries. Estuar. Coast. Shelf Sci. 70:449-460.

Kutser T, Vahtmäe E, Martin G, 2006a. Assessing suitability of multispectral satellites for mapping benthic macroalgal cover in turbid coastal waters by means of model simulations. Estuar. Coast. Shelf Sci. 67:521-529.

Kutser T, Vahtmäe E, Metsamaa L, 2006b. Spectral library of macroalgae and benthic substrates in Estonian coastal waters. Proc. Estonian Acad. Sci. Biol. Ecol. 55:329-340.

Lafon V, Froidefond JM, Lahet F, Castaing P, 2002. SPOT shallow water bathymetry of a moderately turbid tidal inlet based on field measurements. Remote Sens. Environ. 81:136-148.

Lee Z, Carder KL, Chen RF, Peacock TG, 2001. Properties of the water column and bottom derived from airborne visible infrared imaging spectrometer (AVIRIS) data. J. Geophys. Res. Oceans. 106:11639-11651.

Lee Z, Carder KL, Mobley CD, Steward RG, Patch JS, 1998. Hyperspectral remote sensing for shallow waters. I. A semi-analytical model. Appl. Opt. 37:6329-6338.

Lee Z, Carder KL, Mobley CD, Steward RG, Patch JS, 1999. Hyperspectral remote sensing for shallow waters: 2. Deriving bottom depths and water properties by optimization. Appl. Opt. 38:3831-3843.

Leira M, Cantonati M, 2008. Effects of water-level fluctuations on lakes: an annotated bibliography. Hydrobiologia 613:171-184.

Möller T, Kotta J, Martin G, 2009. Effect of observation method on the perception of community structure and water quality in a brackish water ecosystem. Mar. Ecol. 30:105-112.

Morel A, Claustre H, Gentili B, 2010. The most oligotrophic subtropical zones of the global ocean: similarities and differences in terms of chlorophyll and yellow substance. Biogeosciences 7:3139-3151.

Mumby PJ, Edward, AJ, 2002. Mapping marine environments with IKONOS imagery: enhanced spatial resolution can deliver greater thematic accuracy. Remote Sens. Environ. 82:248-257.

Pearson TA, 1978. Macrobenthic succession in relation to organic enrichment and pollution of the marine environment. Oceanogr. Mar. Biol. Ann. Rev. 16:229-311.

Phinn SR, Dekker AG, Brando VE, Roelfsema CM, 2005. Mapping water quality and substrate cover in optically complex coastal and reef waters: an integrated approach. Mar. Pollut. Bull. 51:459-469.

Salmaso N, Boscaini A, Capelli C, Cerasino L, 2018. Ongoing ecological shifts in a large lake are driven by climate change and eutrophication: evidences from a three-decade study in Lake Garda. Hydrobiologia 824:177-195.

Schramm W, 1996. Marine benthic vegetation: recent changes and the effects of eutrophication. Springer, Dordrecht: 473 pp.

Traganos D, Reinartz P, 2018. Mapping Mediterranean seagrasses with Sentinel-2 imagery. Mar. Pollut. Bull. 134:197-209.

Uusõue M, Ligi M, Kutser T, Bourrin F, Uudeberg K, Kangro K, Paavel B, 2022. Effects of weather conditions on particle dynamics and properties in West-Estonian coastal areas. Oceanologia 64:694-716.

Vahtmäe E, Kutser T, 2013. Classifying the Baltic Sea shallow water habitats using image-based and spectral library methods. Remote Sens. 5:2451-2474.

Vahtmäe E, Kutser T, Martin G, Kotta J, 2006. Feasibility of hyperspectral remote sensing for mapping benthic macroalgal cover in turbid coastal waters - a Baltic Sea case study. Remote Sens. Environ. 101:342-351.

Werdell PJ, Roesler CS, 2003 Remote assessment of benthic substrate composition in shallow waters using multispectral reflectance. Limnol. Oceanogr. 48:557-567.

Wilson KL, Wong MC, Devred E, 2020. Branching algorithm to identify bottom habitat in the optically complex coastal waters of Atlantic Canada using Sentinel-2 satellite imagery. Front. Environ. Sci. 8:579856.

Yunus AP, Dou J, Song X, Avta, R, 2019. Improved bathymetric mapping of coastal and lake environments using Sentinel-2 and Landsat-8 images. Sensors 19:2788.