Bathymetry Modelling from Altimeter-Based Gravity and Satellite Multispectral Images in the North Adriatic

Ljerka VRDOLJAK and Jelena KILIĆ PAMUKOVIĆ, Croatia

Key words: Digital Bathymetric Model, Satellite Altimetry, Satellite Derived Bathymetry

SUMMARY

Topography of the seafloor is an important parameter in almost all maritime related research. Traditional shipboard bathymetry methods are time and money consuming. Bathymetry LiDAR is optimal method for deriving depth of shallow sea areas but also quite expensive. Alternative methods for bathymetric mapping are low cost satellite remote sensing methods.

Satellite altimetry opened the possibility to map topography of the seafloor on the global scale. However, these data have a coarse resolution and their quality decay in coastal areas. Satellite Derived Bathymetry SDB refers to methods to estimate the depth from multispectral satellite images and are widely used in shallow coastal sea areas. SDB is limited by the extinction depth up to which it is possible to retrieve bathymetric data.

In this paper, digital bathymetry model of the study area in the North Adriatic is estimated combining data from altimeter-based gravity anomalies and satellite multispectral images. Depth is predicted using the Gravity Geologic Method and density contrast between seafloor and seawater is determined by control points composed of soundings from nautical chart. Bathymetry of shallow, coastal areas is enhanced by depth data derived from multispectral images using Satellite Derived Bathymetry methods. Model is validated against data from nautical charts. As compared to traditional survey methods, the model is time and cost-effective and has a high correlation with charted soundings.

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1. INTRODUCTION

Hydrography is the branch of applied sciences which deals with the measurement and description of the physical features of oceans, seas, coastal areas, lakes, and rivers, as well as with the prediction of their change over time (IHO, 2019). Bathymetry is a part of hydrography which deals with the depth and modeling of seafloor topography. Bathymetry underpins all maritime activities, from the primary purpose of safety of navigation to environmental protection and scientific research. Classical acoustic bathymetric methods or LiDAR are high-quality data able to meet the requirements set by IHO standards for hydrographic surveys (IHO, 2020); however, these methods are time and money consuming especially in shallow coastal areas.

As an alternative, depths can be estimated from remotely sensed satellite data. Satellite altimetry opened the possibility to model the topography of seafloor on a global scale. The first global bathymetric model estimated from satellite altimetry and sparse ship soundings was Smith and Sandwell model in 1997 (Sandwell and Smith, 1997). Methods to estimate bathymetry from altimetry derived gravity anomalies can cover all depth range. However, they have a coarse spatial resolution of 6 kilometers, and their quality decreases in coastal areas. Global bathymetric models are mostly based on bathymetry predicted from altimetry and augmented with direct measurements (Tozer et. al., 2014).

Satellite Derived Bathymetry SDB is a method of predicting the depth of shallow sea areas from multispectral satellite images. SDB dates to the 1970s when the correlation of water depths and pixels of a multispectral image was modeled (Lyzenga, 1978). Supporting a variety of maritime research: maps reconnaissance, tsunami modeling, habitat mapping, etc., Satellite Derived Bathymetry SDB is widely used to estimate the depths of sea areas shallower than 30 meters with up to submeter spatial resolution depending on a satellite sensor.

In this paper we explored the possibility to enhance the quality of bathymetry predicted from satellite - altimetry derived gravity anomalies with Satellite Derived Bathymetry SDB. A combined algorithm to estimate the bathymetry is tested in the coastal area of Medulin bay located on the eastern side of the Istrian peninsula in the North Adriatic Sea.

2. DATA AND METHODOLOGY

2.1 Study Area

In this paper, bathymetry is predicted by combining data from gravity model, multispectral satellite images, and data from the nautical chart over shallow waters of Medulin Bay and

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adjacent sea area located in the North Adriatic Subbasin along the eastern coast of the Istrian Peninsula with depths ranging up to 50 meters (Figure 1).
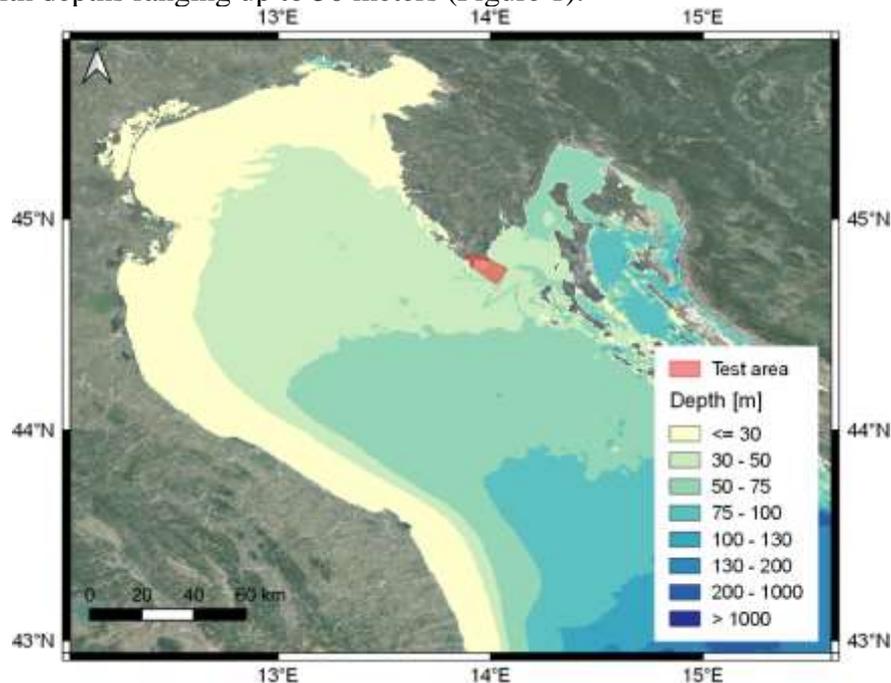
Figure 1. Study area around Medulin bay is highlighted in red. Bathymetry is derived from GEBCO 2020 digital bathymetric model (GEBCO, 2020).

2.2 Satellite Altimetry-Derived Gravity Anomalies

Satellite altimetry-derived gravity anomalies were obtained from Scripps Institute of Oceanography SIO model V 29.1. derived from altimetry data including data from CryoSat and Jason-1 missions. The model has a 1-minute resolution in WGS 84 coordinate system and accuracy of about 2 mGal (Sandwell et al., 2014).

2.3 Multispectral Satellite Images

The Landsat 8 Operational Land Imager and Thermal Infrared Sensor Collection 2 – Level 1 data collected on September 9, 2020, were downloaded from USGS EarthExplorer in GeoTIFF format in Universal Transverse Mercator (UTM) Zone 33 North projection (URL 1). The Landsat 8 satellite L8 orbits the Earth at an altitude of 705 kilometers in a sun-synchronous orbit with 16 days repeat cycle. L8 carries a two-sensor payload: The Operational Land Imager OLI and Thermal Infrared Sensor TIRS are collecting data in 11 spectral bands at nadir, with a 185 km large footprint, and an image resolution ranging from 15 m to 100 m depending on a particular waveband (USGS, 2019). The multispectral bands used for bathymetry prediction were blue band 2 (0.45 μm-0.51μm), green band 3 (0.53 μm -0.59 μm), and shortwave infrared (SWIR)-1 band 6 (1.57 μm – 1.65 μm), all with 30 meters resolution.

The Sentinel 2 Multi-Spectral Instrument MSI - Level 1C data collected on March 16, 2020, were downloaded from Copernicus Open Access Hub in JPEG2000 format in Universal

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Transverse Mercator (UTM) Zone 33 North projection (URL 2). Two identical SENTINEL-2 satellites phased at 180° to each other orbit the Earth in a sun-synchronous orbit at a mean altitude of 786 km with 5 days repeat cycle (ESA, 2015). MSI collects data at the nadir in 13 spectral bands, with a 290 km swath width, and an image resolution ranging from 10 m to 60 m depending on a waveband. The multispectral bands used for bathymetry prediction were blue band 2 (0.45 μm-0.52μm), green band 3 (0.54 μm -0.58 μm) with 10 meters resolution, and shortwave infrared (SWIR)-1 band 11 (1.57 μm – 1.66 μm) with 20 meters resolution.

Table 1. Comparison of LANDSAT-8 and SENTINEL-2 satellite missions (ESA, 2015; USGS,2019)

	LANDSAT 8	SENTINEL-2
Mission Lifetime	2013 - present	2A 2015 – present 2B 2017 - present
Instrument principle	Pushbroom	Pushbroom
Repeat cycle [days]	16	5
Swath width [km]	185	290
Spectral bands	11	13
Spatial resolution [m]	15, 30, 100	10, 20, 60

2.4 Control and Check Points

Data from coastal nautical chart Pula-Kvarner 100-16 (HHI, 2016): chart soundings, contour data, and coastline were used to estimate, and check the quality of bathymetric data estimated from gravity data and multispectral satellite images. In Figure 2, black circles are control points used to estimate bathymetry, and green triangles are the check points used for the validation of the bathymetric model.
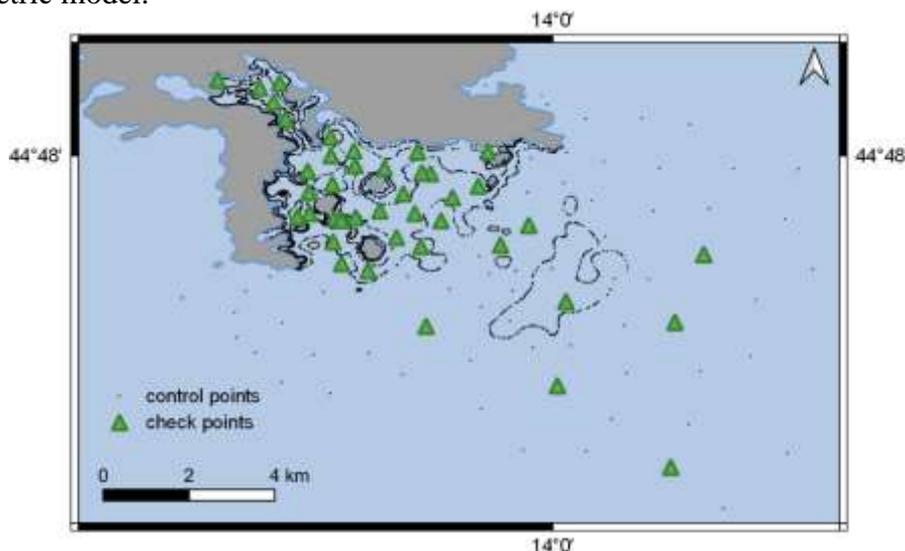
Figure 2. Control and check points collected from nautical chart

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A nautical chart is a compilation of bathymetric data acquired by the Croatian Hydrographic Institute in the years 1973-2015 by means of different multibeam and single-beam systems for hydrographic purposes. Quality of data corresponds to the Zone of confidence ZOC B defined by the International Hydrographic Organization IHO (IHO, 2020). Chart soundings refer to Chart vertical datum, Mean Low Lower Water MLLW. The satellite altimetry-derived gravity is based on the Mean Sea Level (MSL), so chart soundings were converted to MSL determined from tide gauge stations.

2.4 Gravity-Geologic Method GGM

The Gravity-Geologic Method was originally developed to estimate the depth of bedrock under a glacial drift deposit (Ibrahim and Hinze, 1972). Regarding the density contrast between the seawater and seabed, the method was adapted to estimate the depth of the seabed from gravity data (Kim et al., 2010, Xiang et al, 2017, Yeu et al., 2018). Figure 3 illustrates the principle of the GGM method.
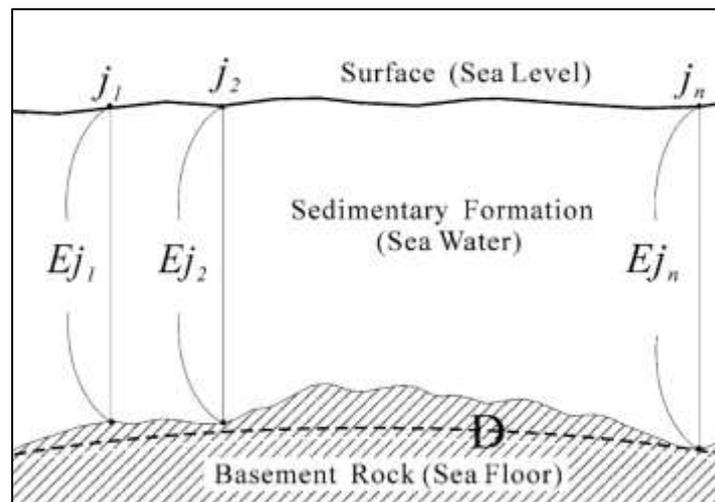
Figure 3. Geometry of Gravity-Geologic Method (GGM) (Kim et al., 2011)

In general, observed gravity anomalies g_{obs} consists of short wavelength gravity g_{short} caused by local variations in seabed and long wavelength gravity g_{long} caused by deeper masses expressed by following equation:

$$g_{obs} = g_{short} + g_{long} \tag{1}$$

Short wavelength gravity field is estimated by using a simple Bouguer slab formula at control points j with known depth D_j:

$$g_{short}(j) = 2\pi G(\Delta\rho)(D_j - D) \tag{2}$$

where:
G is the gravitational constant (G=6.672x10^{-8}cm^3/gs^2),
$\Delta\rho$ is density contrast in g/cm^3,

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D_j is measured depth at control points (j), and

D is the deepest depth of the control points.

Long wavelength gravity is calculated at control points g_{long} (j) by subtracting the short wavelength gravity from observed gravity:

$$g_{long}(j) = g_{obs}(j) - g_{short}(j) \tag{3}$$

Long wavelength gravity at unknown points $g_{long}(i)$ can be interpolated from long wavelength gravity at control points g_{long} (j) and short wavelength gravity at unknown points $g_{short}(i)$ can be determined from observed gravity field:

$$g_{short}(i) = g_{obs}(i) - g_{long}(i) \tag{4}$$

By rearranging the equation 2, depths at unknown points D(i) can be estimated from short wavelength gravity at unknown points $g_{short}(i)$ as follows:

$$D(i) = \frac{g_{short}(i)}{2\pi G \Delta \rho} + D \tag{5}$$

2.5. Satellite Derived Bathymetry SDB

Empirical band ratio Satellite Derived Bathymetry (SDB) techniques are widely used for their simplicity although the model must be calibrated using control points with known depth. The concept underlying the log-ratio algorithm is that the bottom radiance of one band will decay with depth faster than of another band. Bathymetry was estimated using the empirical band ratio technique and Stumpf (2003) formula:

$$D = m_1 \left(\frac{\ln (L_{obs}(\lambda_i))}{\ln (L_{obs}(\lambda_j))} \right) - m_0 \tag{6}$$

Where:

D is depth estimation,

m_1 and m_0 are empirically determined gain and offset,

$L_{obs}(\lambda i)$ is the observed radiance of blue band, and

$L_{obs}(\lambda j)$ is the observed radiance of green band.

2.6. Combined Bathymetric Algorithm

Due to altimetry limitations, the quality of bathymetric data predicted from gravity anomalies will decay in coastal areas. Satellite Derived Bathymetry based on multispectral images is limited by the extinction depth of about 30 meters. In this paper we explore the possibility to enhance the quality of the topography of the seabed estimated from altimeter-derived gravity anomalies in coastal areas with Satellite Derived Bathymetry based on multispectral satellite images.

Figure 4 shows the combined algorithm for bathymetry estimation. A combined digital bathymetry model with 100 meters resolution is estimated from altimeter derived-gravity anomalies and multispectral satellite imagery. Soundings, points with known depth, are used as control data to calibrate the model.

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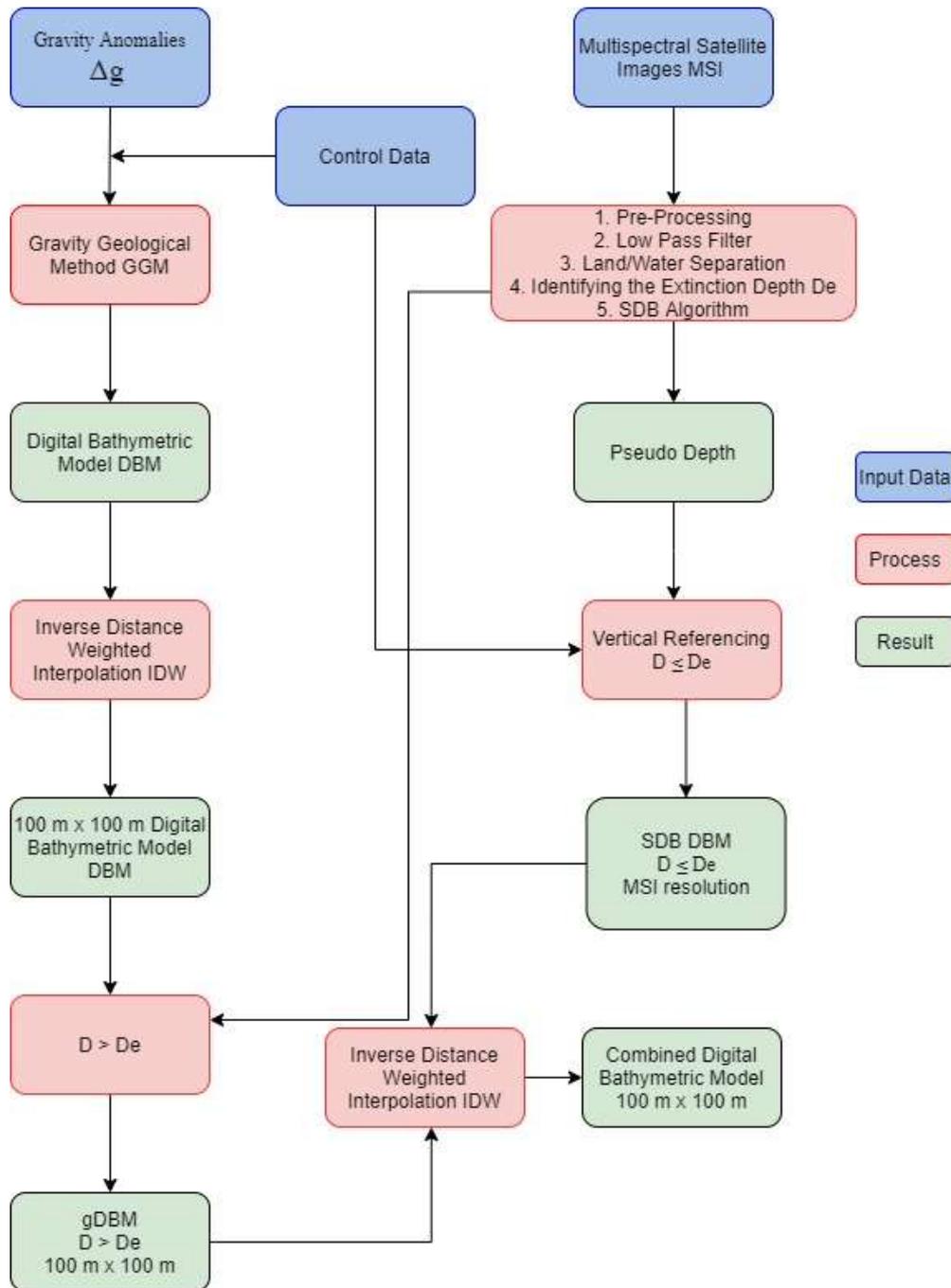
Figure 4. Combined algorithm for bathymetry prediction

Firstly, the digital bathymetric model DBM is estimated from altimeter derived-gravity data using the Gravity Geologic Method GGM described in section 2.4. and interpolated to 100 meters grid.

The procedure to derive bathymetric data from multispectral satellite images includes the following steps (Pe'eri et al., 2014; IHO and IOC, 2018): 1. Pre-Processing of the satellite imagery that includes corrections for environmental conditions; 2. Low Pass Filtering of the satellite images to remove the "Spackle noise"; 3. Land/Water separation; 4. Identifying the Extinction Depth (De) up to which it is possible to retrieve bathymetric information; 5. Applying SDB Algorithm. SDB algorithm is Stumpf's (2003) log ratio algorithm applied to the blue and green band. The result is Pseudo depth that needs to be vertically referenced using the control points. Vertically referenced satellite derived digital bathymetric model (SDB DBM) has a resolution of input satellite multispectral images.

Depth data in marine areas deeper than the depth limit of the Satellite Derived Bathymetry or Extinction depth (De) are retrieved from digital bathymetric model estimated from gravity data (gDBM), then augmented with satellite derived bathymetry model SDB DBM, and interpolated to Combined Digital Bathymetric Model with 100 meters resolution.

2.7. Quality Control

To estimate the quality of the digital bathymetric models, bathymetric data is commonly compared to check points with known depth. Root Mean Square Error RMSE and Pearson coefficient which determines the correlation between of the model's depth and control data set, were calculated to validate the model.

3. RESULTS

The bathymetric model of the coastal marine area around the Medulin bay located in the North Adriatic along the eastern coast of the Istrian peninsula was estimated using the combined algorithm for bathymetry estimation. A combined bathymetric model was calculated using altimetry derived gravity anomalies, multispectral satellite images, and nautical chart data. A set of check points from coastal chart 100 -16, were used to determine the quality of calculated bathymetric models.

Figures 5-7 show the results of the combined algorithm for bathymetry prediction.

A density contrast of 10 000 kg/m^3 was chosen to estimate the bathymetry from SIO altimeter based-gravity anomaly model V.29.1. using the Gravity Geologic Method. 1 arc minute bathymetric model (Figure 5) in WGS 84 coordinate system with depths referring to the Mean Sea Level MSL was projected to Universal Transverse Mercator 33N (UTM 33 N) and interpolated to 100 meters grid (gDBM). The correlation of the gDBM with check points was 0.92 and RMSE was 6.64 meters.

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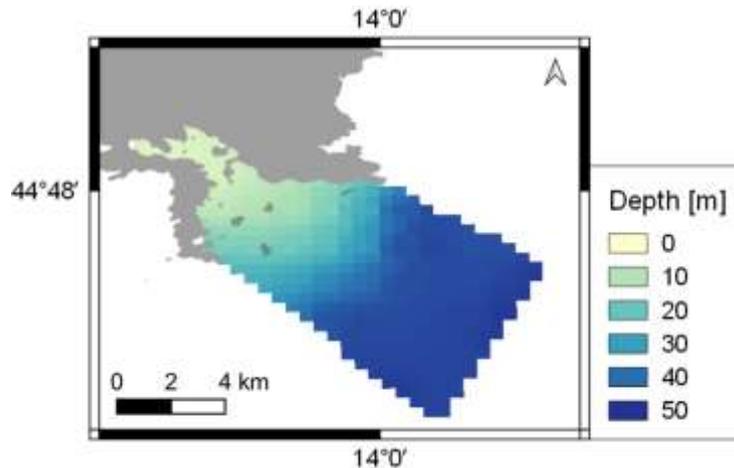
Figure 5. Bathymetric model (1') estimated from SIO gravity anomalies and chart data

Landsat 8 and Sentinel-2 multispectral imagery MSI were used to estimate the bathymetry of the shallow coastal area using the log-ratio method. Both satellites have passive optical sensors that collect solar radiation reflected from the Earth, in this case from the seafloor. Satellite Derived Bathymetry is limited by extinction depth up to which bathymetric data can be estimated. In the study area, the extinction depth was estimated to be 20 meters. The result of the Stumpf (2003) formula applied to blue and green spectral was the Pseudo depth (Figure 6a) which needed to be vertically referenced using the set of control points. In this paper, chart data were used as control points. Gain m_1 and offset m_0 were determined using the linear regression; for Landsat 8 data $m_1=1498.1$ and $m_0=-1489.8$ and for Sentinel 2 $m_1=303.53$ and $m_0=-315.01$. Results of the SDB algorithm were two models of a coastal marine area with depths shallower than 20 meters: Landsat 8 with 30 meters resolution and Sentinel 2 (Figure 6b) with 10 meters resolution. Landsat 8 had an RMSE of 4.45 m and correlation of 0.75 while Sentinel 2 had an RMSE of 2.58 and a correlation of 0.91. As compared to check data from coastal nautical chart 100-16 Sentinel 2 data had higher quality, so these data were the input parameter for the calculation of a Combined Digital Bathymetric Model (CDBM).
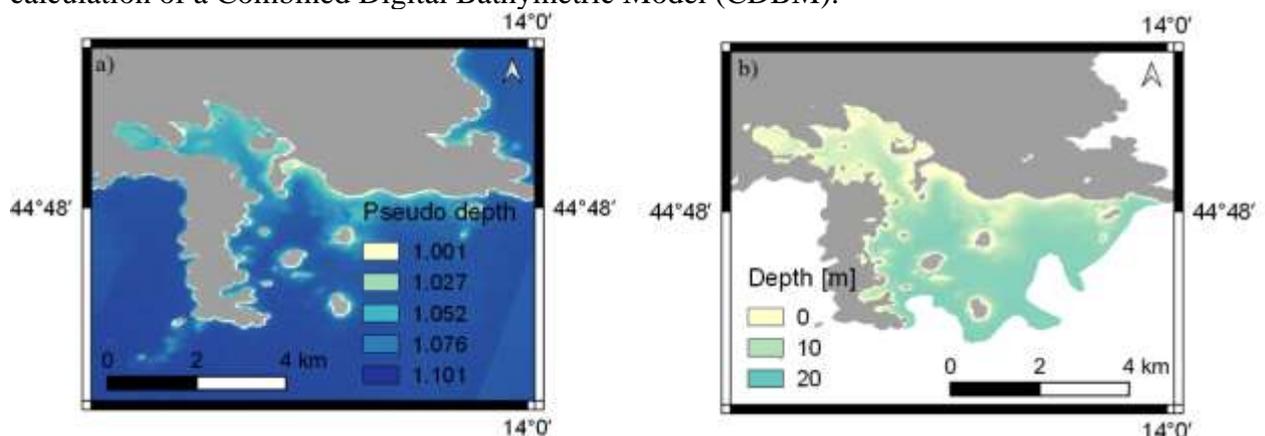
Figure 6. Satellite Derived Bathymetry using Sentinel 2 images: a) Pseudo depth, b) 10 meters bathymetric model

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Depth deeper than 20 meters from bathymetric estimated from gravity gDBM were augmented with data from Sentinel-2 and interpolated to Combined Digital Bathymetric Model (CDBM) that runs from the coast up to 50 meters depth.

The combined model has a resolution of 100 meters in Universal Transverse Mercator UTM 33 coordinate system with depths refer to the Mean Sea Level MSL. (Figure 7).
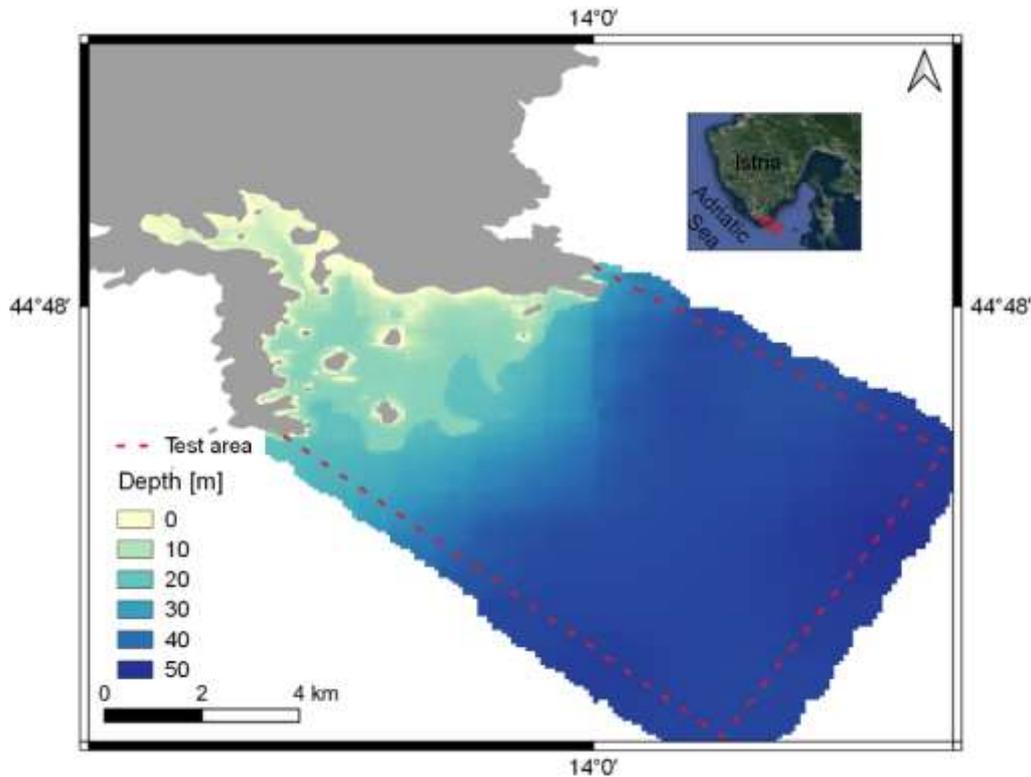
Figure 7. Combined digital bathymetric model of Medulin bay with 100 meters resolution

Model data were interpolated to the location of check points resulting in two sets of depth in check points: Chart depth and Model depth. The correlation coefficient between these two sets is 0.97 and the RMSE of the model calculated from the residuals is 4.73 meters (Table 2).

Table 2. Quality of the bathymetric models

	RMSE [m]	Correlation Coefficient
LANDSAT 8*	4.45	0.75
SENTINEL 2*	2.58	0.91
gDBM (GGM)	6.64	0.92
CDBM (GGM_SDB)	4.73	0.97

*Area shallower than 20 meters

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4. CONCLUSION

As compared to classic bathymetric methods, satellite remote sensing methods are cost and time effective.

Satellite altimetry opened the possibility to globally map the topography of the seafloor. However, due to altimeter limitations, the quality of the bathymetric data decreases in the coastal areas. Satellite Derived Bathymetry SDB is a method of estimating the depth from multispectral images in shallow sea areas. SDB methods are limited by an extinction depth of about 30 meters.

In this paper, a combined bathymetric algorithm was presented. Bathymetry that was estimated from altimeter derived-gravity anomalies has been augmented with satellite derived bathymetry SDB data to improve the quality of the model in the shallow coastal areas.

The model was tested and validated in the study area in North Adriatic. The topography of the seafloor in the Medulin bay and adjacent sea area with depths up to 50 meters was modeled using the combined algorithm for bathymetry prediction. The model was validated using the chart soundings.

The correlation coefficient of the bathymetric model estimated from SIO gravity anomalies V.29.1 using the Gravity Geologic Method with density contrast of 10 000 kg/m^3 was 0.75 and Root Mean Square Error (RMSE) was 6.64 meters.

In sea areas shallower than 20 meters, depths were derived from Landsat 8 and Sentinel-2 imagery using the log-ratio method. Landsat bathymetric model had 30 meters resolution and a correlation with chart soundings was 0.75. The Sentinel-2 bathymetric model had 10 meters resolution, and a correlation with chart soundings was 0.91.

Bathymetry derived from gravity was augmented with Sentinel data in areas shallower than 20 meters in a Combined Digital Bathymetric Model with 100 meters resolution in UTM 33N coordinate system with depth referring to Mean Sea Level MSL. Correlation of the Combined Bathymetric Model was 0.97 and RMSE was 4.73 meters. Quality of the bathymetric model was improved by augmenting the model estimated from gravity with Satellite Derived Bathymetry.

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URL 2: https://scihub.copernicus.eu/dhus/#/home

BIOGRAPHICAL NOTES

Ljerka Vrdoljak has been a hydrographic surveyor at Hydrographic Institute of the Republic of Croatia since 2014. She has a masters degree in Geodesy and Geoinformatics from Faculty of Geodesy, University of Zagreb and is a PhD candidate with research interest in bathymetry mapping by remote sensing.

Jelena Kilić Pamuković is an assistant professor. She has been employed at the Faculty of Civil Engineering, Architecture and Geodesy of the University of Split, Croatia since 2013 and in the same year has enrolled in PhD in Geodesy and Geoinformatics at the Faculty of Geodesy, University of Zagreb. In 2019 she got her PhD in the field of Land Menagement. As an author and co-author, she published more than 20 publications.

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