Bathymetric mapping of shallow water using Landsat 8 and Sentinel 2A Satellite Data. Case Study: East Madura’s Waters

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Abstract. Bathymetric mapping was used to map the sea floor. The accurate and recent sea floor data are needed by many human activities such as for water transportation routes and off-shore infrastructure constructions. General in-situ mapping using multi/single beam echo-sounder is time consuming, high cost and difficult access to a remote area. Bathymetric mapping on shallow water near coastal area also facing a challenge when the in-situ mapping is difficult to be performed for the reason of the access of survey-ship. In this research, we proposed a new technique to map the shallow sea floor (less than 80 m of depth) using optical remote sensing satellite data by exploiting the Landsat 8 and Sentinel 2A imageries. The bathymetric data estimated from these satellites then validated with in-situ measurement data collected in April and October, 2015. The range of absolute depth was 8.724 – 12.056 meter for Landsat 8 and 9.220 -11.149 meter for Sentinel 2. A promising result was obtained for Landsat 8 data with NMAE of 21.288% and wider range of estimated depth compared with obtained depth by Sentinel 2. Both samples point of remote sensing images failed to deal with water depth shallower than 8 m and deeper than 13 meters.

1. Introduction

Indonesia is the world's largest archipelagic state. By the latest official count, the archipelago consists of 18,108 islands [1]. To manage the shallow waters between islands, bathymetric maps with sufficient accuracy are required. Bathymetric mapping in shallow water has an important role, especially in the shipping and construction sector. Bathymetric mapping certainly provides prospects as well as challenges for development in Indonesia, especially in coastal areas and marine sector. This technology can be used to reconnaissance survey in small island waters that has never been mapped.

To provide such data, a conventional measurement using an echo-sounder on board of ship is required. This method has limitations such as time-consuming, costly measurement and the difficulty of ship to approach shallow area. In addition to this conventional method, remote sensing technology provides an opportunity for shallow bathymetric mapping with the advantages especially for areas with rapid depth change and inaccessible areas with direct measurement.

In this study, we exploited the used of optical satellite images such as Landsat 8 and Sentinel-2A to map the depth of shallow water. The use of medium resolution satellite multispectral imagery is beneficial due to its open data, broad coverage area and sufficient spatial resolution[2], [3].
2. Method

2.1. Study area
This research was conducted in Poteran Island (PPP) and Gili Iyang (PGI) waters which are administratively located in Sumenep Regency. PPP is located between the coordinates of 113.94 °E to 114.06 °E and 7.07 °S to 7.10 °S with the UTM zone of 49S and 50S. While PGI is located between 114.16 °E to 114.19 °E and 6.96 °S to 7.01 °S with UTM zone of 50S.

Figure 1. Study area: Poteran Island and Gili Iyang waters.

2.2. Data and software
Primary data used in this research was the in-situ data of water depth in PPP (collected in April 2015) and PGI (collected in October 2015) waters. While the secondary data used was Landsat 8 terrain corrected level (L1T) at path/row of 117/65 with acquisition time of April 22, 2015 and October 31, 2015 as well as Sentinel-2A Level 1C with data acquisition time of October 24, 2015. All of data processing was performed by using ESA SNAP 5.0 and ArcGIS 10.3 software.

2.3. Data processing
The first step of data processing was radiometric calibration. In this step, the Landsat data stored in DN (Digital Number) format was converted into Top of Atmosphere (TOA) radiance format by using the following algorithm:

\[ L_\lambda = M_\lambda \times Q_{cal} + A_\lambda \]  \hspace{1cm} (1)

\( L_\lambda \) is TOA spectral radiance, \( M_\lambda \) is Band-specific multiplicative rescaling factor, \( A_\lambda \) is Band-specific additive rescaling factor, dan \( Q_{cal} \) is Quantized and calibrated standard product pixel values (DN) [4].

After the calibration process, the second step was atmospheric correction. The main idea of this step is to correct the effect of atmosphere that exists on the data measured by sensor which was strongly affect the accuracy of satellite data [5]–[7]. Atmospheric correction for Landsat 8 data was performed by using Second Simulation of a Satellite Signal in the Solar Spectrum-Vector (6SV) web-based software to produce parameter coefficient of \( x_a \), \( x_b \) and \( x_c \) [8]–[11]:

\[ y = x_a \times L_\lambda - x_b \]  \hspace{1cm} (2)

\[ ACR = y(1 + x_c \times y) \]  \hspace{1cm} (3)

\[ Rrs(\lambda) = ACR/\pi \]  \hspace{1cm} (4)
ACR is atmospheric correction reflectance, $L_A$ is ToA radiance, $R_{rs}(\lambda)$ is remote sensing reflectance, and $x_a$, $x_b$, $x_c$ are parameter coefficient for atmospheric correction (was retrieved from http://6s.ltdri.org/).

Atmospheric correction for Sentinel-2A was performed by using Sen2Cor plugin on ESA SNAP 5 software. This plugin converted Level-1C Top of Atmosphere Reflectance data into Level-2A Bottom of Atmosphere Reflectance[12]. To achieve the same remote sensing reflectance unit (sr-1) all converted reflectance for Landsat 8 and Sentinel 2A data then divided by $\pi$.

The next was called masking. This step was needed to separate the pixel of waters and the land. To perform this process, NDWI (Normalized Difference Water Index) method was implemented. NDWI values less than zero are land pixel and set to be zero. This stage was performed to make sure that land pixel did not affect water pixel during implementing of bathymetric algorithm[13].

\[
NDWI = \frac{(R_{rs}(\text{Red}) - R_{rs}(\text{NIR}))}{(R_{rs}(\text{Red}) + R_{rs}(\text{NIR}))} \tag{5}
\]

$R_{rs}(\lambda)$ is remote sensing reflectance at Red and Near Infrared band from Landsat 8 and Sentinel-2A imageries.

The final result of pre-processing steps is remote sensing reflectance for all bands. These $R_{rs}(\lambda)$ then processed using Van Hengel and Spitzer algorithm. This algorithm transforms satellite data to relative depth of shallow water[14]. In this step, $R_{rs}(\lambda)$ at band red, green and blue were input into Van Hengel and Spitzer algorithm as follow:

\[
r = \arctan (U_r + \sqrt{(U_r^2 + 1)}) \tag{6}
\]
\[
s = \arctan (U_s + \sqrt{(U_s^2 + 1)}) \tag{7}
\]
\[
U_r = \frac{(Var \times 3 + Var \times 2)}{(2 \times Cov \times 2 \times 3)} \tag{8}
\]
\[
U_s = \frac{(Var \times 4 + Var \times 2)}{(2 \times Cov \times 2 \times 4)} \tag{9}
\]
\[
Y = [\cos (r) \cdot \sin (s) \cdot X2] + [\sin (r) \cdot \cos (s) \cdot X3] + [\sin (s) \cdot X4] \tag{10}
\]

$X2$, $X3$, and $X4$ are remote sensing reflectance at band 2, 3 and 4 respectively. $Var \times 2$, $x3$, and $x4$ are a variance of remote sensing reflectance at band 2, 3 and 4 respectively. $Cov \times 2 \times 3$ and $Cov \times 2 \times 4$ are covariances of remote sensing reflectance at band 2-3 and band 2-4 respectively. $r$ and $s$ are the rotation angle parameter for calculating the relative depth index. $Y$ is relative depth value.

The final step in implementing the bathymetric algorithm is calculation of linear correlation between relative and absolute in situ depth. Absolute depth then can be calculated from a regression formula with independent variable of any relative depth. The estimated absolute depth was validated using in situ data to assess the accuracy of depth retrieval algorithm. For this purpose, the Normalized Mean Absolute Error (NMAE) was used with an acceptance threshold of $\leq 30\%$ [15]

\[
NMAE (\%) = \frac{1}{N} \sum \left| \frac{X_{\text{estimated}, i} - X_{\text{measured}, i}}{X_{\text{measured}, i}} \right| \cdot 100 \tag{11}
\]

$X_{\text{estimated}}$ is estimated depth from remote sensing data following Van Hengel and Spitzer technique, $X_{\text{measured}}$ is in-situ measured depth and $N$ the number of sampling data.

Following the research of Jaelani [5]. The estimated depth is accepted if NMAE value is equal or less than 30%. Then an Inverse Distance Weight (IDW) method was implemented for spatial interpolation to extract the depth data for all pixels and contour [16].
3. Result and Discussion

Atmospheric corrected $Rrs(\lambda)$ of Landsat 8 and Sentinel 2 by 6SV and Sen2Cor algorithm, respectively were inputted into Van Hengel and Spitzer algorithm using 60 virtual stations to extract reflectance remote sensing in the satellite image and produce a relative depth data.

Table 1. Rotation angle parameter.

| Parameter | Landsat 8       | Sentinel-2A      |
|-----------|-----------------|------------------|
| $Ur$      | 1.667618479     | 1.519722616      |
| $r$       | 74.52533655     | 73.327245570     |
| $Us$      | 1.692036372     | 1.553073192      |
| $s$       | 74.70837469     | 73.611568150     |

Figure 2. Sample point in PPP.  
Figure 3. Sample point in PGI.  
Figure 4. Estimated relative depth by Landsat 8.  
Figure 5. Estimated relative depth by Sentinel-2A.
From Table 1, the main parameter of rotation angle ($r$ and $s$) for two different satellite images have been calculated. These data then were used to calculate the relative depth from each satellite image. The relative depth was presented in Figure 4 and 5 for Landsat 8 and Sentinel 2A, respectively. As presented at two figures above, the relative estimated depth value from Landsat 8 was 0 - 0.322 meter and Sentinel-2A is 0 - 0.266 meter.

A relative depth is used to calculate the absolute estimated depth from each satellite image. A regression model was used to make a relationship between relative and absolute depth using in-situ measured depth and estimated relative depth from 60 field stations collected on Poteran and Gili Iyang waters.

As presented in Figure 6 and 7, a regression model between relative and absolute data was made for Landsat 8 and Sentinel 2A satellite images. It was clearly seen that correlation coefficient ($R^2$) was low, indicated by $R^2$ of 0.102 (Landsat 8) and 0.008 (Sentinel-2A). The relationship equation as follows:

\[
y = -6519.726 (\text{RD}_{\text{Landsat}})^2 + 2660.196 (\text{RD}_{\text{Landsat}}) - 93.633 \tag{12}
\]

\[
y = -8808.089 (\text{RD}_{\text{Sentinel}})^2 + 1114.769 (\text{RD}_{\text{Sentinel}}) - 24.122 \tag{13}
\]

$\text{RD}_{\text{Landsat}}$ is relative depth value from Landsat 8 satellite image, $\text{RD}_{\text{Sentinel}}$ is relative depth value from Sentinel-2A satellite image, and $y$ is the absolute estimated depth. By using this regression model, an estimated absolute depth was calculated for the entire satellite image.

![Figure 6. Regression model of estimated relative depth by Landsat 8 and in-situ measured depth.](image6)

![Figure 7. Regression model of estimated relative depth by Sentinel 2 and in-situ measured depth.](image7)

![Figure 8. Accuracy of estimated depth by Landsat 8.](image8)

![Figure 9. Accuracy of estimated depth by Sentinel 2A.](image9)
Figure 10. Bathymetric map obtained from Landsat 8 satellite image.

Figure 11. Bathymetric map obtained from Sentinel-2A satellite image.

Figure 8 and 9 presented the accuracy of estimated data compared with in-situ measured one with NMAE of 25.777% and 26.887% for Landsat 8 and Sentinel 2 images, respectively. These NMAE indicated that the estimated depth accuracy from Landsat 8 was better than Sentinel-2A and both estimated depth accuracy was acceptable for both data sources.

The range of absolute depth was 8.724 – 12.056 meter for Landsat 8 and 9.220 – 11.149 meters for Sentinel 2, as presented in Table 1 and Figure 6. The estimated depth of Landsat was wider than of Sentinel 2 data (3.332 m and 1.929 m). Both of sample point data failed to retrieved depth data deeper than 13 m as measured in the waters of Poteran (about 25 meters).

Table 2. Absolute Estimated Depth data obtained from Landsat 8 and Sentinel-2A.

| Satellite Image | Average Absolute Depth (Meter) | Maximum Absolute Depth (Meter) | Minimum Absolute Depth (Meter) | Correlation Between In-situ Depth ($R^2$) | NMAE (%) |
|----------------|--------------------------------|--------------------------------|--------------------------------|------------------------------------------|----------|
| Landsat 8      | 11.016                         | 12.056                         | 8.714                          | 0.102                                    | 25.777   |
| Sentinel-2A    | 10.477                         | 11.149                         | 9.220                          | 0.008                                    | 26.887   |

4. Conclusion
We have processed remotely sensed data acquired by Landsat 8 and Sentinel 2 data for estimating seafloor depth, especially at shallow water. A promising result was obtained for Landsat 8 data with NMAE of 25.777% and wider range of estimated depth compare with obtained depth by Sentinel 2. Both of remote sensing images failed to deal with water depth shallower lower than 8 meters and deeper than 13 meters.

5. References
[1] J. W. Lillesand, Thomas; Kiefer, Ralph W.; Chipman 1999, Remote Sensing and Image Interpretation, 4th Edition. United States: John Willey & Sons.
[2] J. Price 1994, “How unique are spectral signatures?,” Remote Sens. Environ., vol. 49 IS-3 SP.
[3] J. Flusser, F. Sroubek, and B. Zitov 2007, Image Fusion: Principles, Methods, and Applications.
[4] P. J. Carper, W., M. Lillesand, T., W. Kiefer 1990, “The use of intensity-hue-saturation transformations for merging SPOT panchromatic and multispectral image data,” PHOTOGRAMMETRIC Eng. Remote Sens., vol. 56, pp. 459–467.
[5] V. K. Shettsigara 1992, “A generalized component substitution technique for spatial enhancement of multispectral images using a higher resolution data,” Photogramm. Eng. Remote Sens., vol. 58, pp. 561–567.
[6] D. A. Yocky 1996, “Multiresolution wavelet decomposition image merger of Landsat Thematic Mapper and SPOT panchromatic data,” Photogramm. Eng. Remote Sens., vol. 62, pp. 1067–1074.
[7] C. Pohl and J. L. Van Genderen 1998, “International Journal of Remote Sensing Multisensor image fusion in remote sensing: concepts, methods and applications,” Int. J. Remote Sens. int. j. Remote Sens., vol. 19, no. 5, pp. 823–854 1998.
[8] Feng Gao, J. Masek, M. Schwaller, and F. Hall 2006, “On the blending of the Landsat and MODIS surface reflectance: predicting daily Landsat surface reflectance,” IEEE Trans. Geosci. Remote Sens., vol. 44, no. 8, pp. 2207–2218.
[9] E. Chuvieco 2009, Fundamentals of Satellite Remote Sensing 1st Edition. CRC Press.
[10] B. Murti 2009, “Validitas dan Reliabilitas Pengukuran,” 2011. [1] R. Cribb, M. Ford, R. Cribb, and M. Ford, “Indonesia as an archipelago: managing islands, managing the seas,” Indones. beyond Water’s Edge Manag. an Arch. State, pp. 1–27.
[11] D. R. Lyzenga 1978, “Passive remote sensing techniques for mapping water depth and bottom features,” Appl. Opt., vol. 17, no. 3, pp. 379–83.
[12] D. R. Lyzenga 1981, “Remote sensing of bottom reflectance and water attenuation parameters in shallow water using aircraft and Landsat data,” Int. J. Remote Sens., vol. 2, no. 1, pp. 71–82.
[13] United States Geological Survey, “Using the USGS Landsat 8 Product | Landsat Missions,” 2013. [Online]. Available: https://landsat.usgs.gov/using-landsat-8-product. [Accessed: 10-Nov-2016].
[14] L. M. Jaelani, B. Matsushita, W. Yang, and T. Fukushima 2013, “Evaluation of four MERIS atmospheric correction algorithms in Lake Kasumigaura, Japan,” Int. J. Remote Sens., vol. 34, no. 24, pp. 8967–8985.
[15] L. M. Jaelani et al. 2015, “An improved atmospheric correction algorithm for applying MERIS data to very turbid inland waters,” Int. J. Appl. Earth Obs. Geoinf., vol. 39, pp. 128–141.
[16] R. Limehuwey and L. M. Jaelani 2016, “Development of Algorithm Model for Estimating Chlophyll-a Concentration Using In-Situ Data and Atmospherically Corrected Landsat-8 Image by 6S, Case Study: Gili Iyang’s Waters,” in Internasional Seminar of Basic Science, no. May, pp. 1–7.
[17] S. Y. Kotchenova, E. F. Vermote, R. Matarrese, and F. J. Klemm 2006, “Validation of a vector version of the 6S radiative transfer code for atmospheric correction of satellite data. Part I: path radiance,” Appl. Opt., vol. 45, no. 26, pp. 6762–74.
[18] F. Wang, S. Wang, and Y. Zhou 2011, “A study of 6S model used for atmospheric correction of MODIS image over Taihu Lake,” in 2011 International Conference on Multimedia Technology, no. 3, pp. 116–119.
[19] E. F. Vermote, D. Tanre, J. L. Deuze, M. Herman, and J.-J. Morcette 1997, “Second Simulation of the Satellite Signal in the Solar Spectrum, 6S: an overview,” IEEE Trans. Geosci. Remote Sens., vol. 35, no. 3, pp. 675–686.
[20] L. M. Jaelani, F. Setiawan, H. Wibowo, and Apip 2015, “Pemetaan Distribusi Spasial Konsentrasi Klorofil-A dengan Landsat 8 di Danau Matano dan Danau Towuti, Sulawesi Selatan,” in Pertemuan Ilmiah Tahunan Masyarakat Penginderaan Jauh Indonesia, pp. 1–8.
[21] European Space Agency, “Sentinel-2 User Handbook,” 2015. [Online]. Available: https://earth.esa.int/documents/247904/685211/Sentinel-2_User_Handbook. [Accessed: 10-May-2017].
[13] B. Gao 1996, “NDWI—A normalized difference water index for remote sensing of vegetation liquid water from space,” Remote Sens. Environ., vol. 58, no. 3, pp. 257–266.

[14] W. VAN HENGEL and D. SPITZER 1991, “Multi-temporal water depth mapping by means of Landsat TM,” Int. J. Remote Sens., vol. 12, no. 4, pp. 703–712.

[15] L. M. Jaelani, F. Setiawan, and B. Matsushita 2015, “Uji Akurasi Produk Reflektan-Permukaan Landsat Menggunakan Data In situ di Danau Kasumigaura , Jepang,” in Pertemuan Ilmiah Tahunan Masyarakat Ahli Penginderaan Jauh Indonesia, no. XX, pp. 464–470.

[16] G. H. Pramono 2008, “Akurasi Metode IDW dan Kriging untuk Interpolasi Sebaran Sedimen Tersuspensi di Maros, Sulawesi Selatan,” Forum Geogr., vol. 22, no. 1, pp. 145–158.

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