ENHANCING BATHYMETRIC MAPPING CAPABILITY USING MULTI-ZONE ENSEMBLE FITTING: FACILITATING EMERGING POST COVID-19 DEMANDS

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ABSTRACT: Determination of hydrospatial information across the marine environment has conventionally appeased by vessel-based acoustic surveys. For the first time in history, the unpredictability COVID-19 health crisis has shut down the entire social and economic sectors across the globe. The continuous nationwide lockdown has made it very difficult to mobilize vessels and survey crews for bathymetric mapping. With the emerging remote sensing technology, hydrospatial specialists today have too accustomed to live and work in the new normality. Apparently, hydrography is clearly undergoing dramatic change which an expanded role to serve an increasing number of stakeholders in the blue economy. In order to seek the maximum benefits from the adoption of forth industrial revolution (IR4.0) paradigms, utilization of high-technology sensors and various unmanned autonomous crafts for bathymetric data acquisition to generate actionable data and information to serve the hydrographic communities. In response to the COVID-19 outbreak, hydrographic communities have been forced to accelerate the adoption of emerging technologies to mitigate its impact. Indeed, satellite derived bathymetry (SDB) has become a recognized tool for acquisition to generate actionable hydrospatial data that can alleviate future economic upheavals. Stakeholders are able to extract the bathymetric depth information from the remotely sensed imagery in a split second without physical mobilization and on-site survey. In this paper a new proposed methodology using multi-zone ensemble fitting is introduced for bathymetric determination across the coastal region from high resolution satellite images. By segmentizing the training sets to fit into several designated depth zones, this sequential ensemble fitting approach demonstrates better performance if compares to the traditional single regression algorithm. Derived conclusion points out that newly proposed method can enhance the current bathymetric mapping capability and deliver precise and accurate actionable hydrospatial information in facilitating the emerging demands, in the post COVID-19 era.

1. INTRODUCTION

COVID-19 pandemic has become what may be the most troubling and complex health crisis that humanity has endured. The continuous nationwide lockdown across the globe on all social and economic sectors, has painfully damaging the developed markets since the coronavirus outbreak started in 2019. These changes and associated uncertainties have global ramifications, with significant impacts and implications to the entire global economy. Recently, the global economy has achieved fragile recovery from the depths of the COVID-19 pandemic, however many emerging economies are still suffering severe hardship. It is believed that vaccination will appease the end of pandemic recession and placing the world economy back to the pre-pandemic growth trajectories.

Traditionally, bathymetry depths are obtained via the submerged vessel-based acoustic gears (e.g. SBES & MBES). Thus far, this method is still the most popular despite being timely-consuming, labor-intensive and also requiring physical mobilization. The situation becomes tougher and complex when it requires regular repetitive surveys (e.g. monthly, quarterly, or annually) to measure the seasonal changes. Seafloor changes at the versatile and dynamic coastal zone can be related to natural morphological alteration as well as man-made activities which occur either gradually or happen out of the sudden. As a result, significant changes at those shallow and coastal regions are not practical to be attempted via the costly vessel-based sounding approach. Today, we have already grown accustomed to hearing that we live in a “new normal”, a transition towards reconfigured social and human-environment interactions.

In response to the pandemic, hydrospatial experts have to accelerate the adoption of emerging technologies to mitigate its impact in facilitating the emerging post COVID-19 demands. Actionable techniques and methodologies need to be formulated to build a resilient recovery trajectory. For instance, the adoption of various autonomous crafts (satellite, airborne, surface, underwater, etc.) and high-technology sensors (RADAR, LiDAR, multispectral, hyperspectral, etc.) for bathymetric data acquisition in this forth industrial revolution (IR4.0) paradigm. Thus, satellite bathymetry has been widely utilized as an alternative data acquisition technique in water level assessment (Hussaini *et al.*, 2019; Hussaini *et al.*, 2020) and bathymetric surveying to supply cost-effective hydrographic data (Zheng *et al.*, 2017;

Mavraeidopoulos *et al.*, 2017; Jégat *et al.*, 2016; Pe'eri *et al.*, 2013). Today, the satellite derived bathymetry (SDB) technologies can alleviate future hydrospatial data management upheavals and devoting to a hydro-spatially enable environment, which inspires inclusion beyond the traditional.

2. MATERIAL AND METHOD

2.1 Description of Study Area

The study was conducted in Forest City, Johor Bahru, Malaysia. It lies between 76,000mS to 80,000mS and 500mE to 5,500mE from the origin of Johor state and is strategically located adjacent to Singapore, along the Strait of Johor (see Figure 1). Basically, the chosen study area was formed by suspended sediment particles along its sea-fronted flat slopes. This research tailed the Forest City project since its early stage of development and monitoring the reclamation progression. In 2018, Forest City has completed its stage one earthwork project, one of its four artificial islands had been fully reclaimed and rose up from the waters at the Tanjung Kupang Bay.

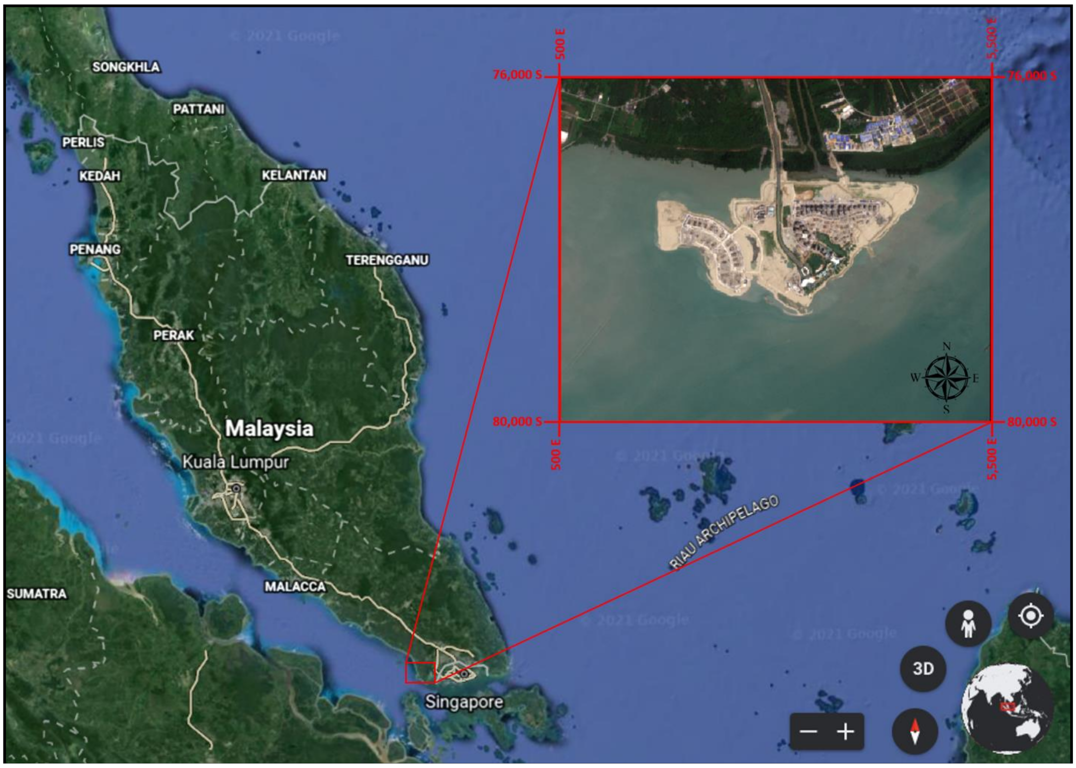

Figure 1: The study area of Forest City, Malaysia (Google Earth, 2021)

2.2 Material

The materials applied here are the multispectral imagery data and *in-situ* bathymetric depths acquired from the vessel-based acoustic surveys. The remotely-sensed multispectral data were derived from the Sentinel-2 imagery. Out of its thirteen spectral bands, three 10m resolution bands were utilized for the study, a pair of water-penetrating visible wavelength, blue (0.490µm) and green (0.560µm) in the bathymetric construction, while green band and near-infrared band (0.842µm) were applied to delicate land-water boundaries via Normalized Difference Water Index (NDWI). The satellite imagery data were captured on 21st January 2018 and the *in-situ* bathymetric depths were acquired in the middle of October 2017. Amongst the *in-situ* bathymetric data, basically there were divided into two sampling groups. The first cluster of training data sets was grouped for bathymetric model construction, whereas the second sample depths cluster was designated for data verification and assessment.

2.3 Bathymetric Derivation Models

Two bathymetric derivation modelling methods were applied in this study. The fundamental principle of SDB is measuring the intensity of electromagnetic wavelength which penetrating the water column and reflect back to the spectrometer sensor. Generally, the measured radiance is closely related to the incoming solar radiation, attenuation of radiation and reflection throughout the atmosphere and the water column. Henceforth, a linear inversion mathematical model could empirically express the relationship between the water-penetrating spectral. Over the years, there are numerous bathymetric derivation algorithms being developed for retrieving bathymetry data from satellite imagery (Gao, 2009; Jawak *et al.*, 2015). In most of the scenarios, the spectrally-based empirical models addressed by Stumpf *et al*. (2003), Dierssen *et al*. (2003) and Lyzenga *et al*. (2006) are believed to be working fine in the clear ocean waters.

2.3.1 Single Linear Regression

Dierssen *et al*. (2003) addressed a band-ratio idea to extract the water depth (Z). The water depth is estimated from two tuneable constant coefficients (m_0 & m_1) and the observed reflectance of two consecutive bands (Ri & Rj) mathematically. Equation 1 below illuminates the Dierssen's algorithm:

$$Z = m_0 * \ln\left[\frac{n\mathrm{R_w}(\lambda_\mathrm{i})}{n\mathrm{R_w}(\lambda_\mathrm{j}))}\right] + m_1 \qquad (1)$$

Where,

Z	= value from derived depth
R_w	= reflectance of bandi & band j
m_0	= tuneable constant
m_1	= offset of the depth
n	= a constant value

Least square regression is ordinarily being conducted to solve a solution where the equations happened to be more than the number of unknowns. Henceforth, it was applied to estimate the best fitted value to mathematically unravel the two unknown tuneable constants in the above mentioned designated Dierssen's equation. These diffuse attenuation coefficients were calculated using least square regression. Subsequently, the retrieved tuneable constants were then being applied back into the abovementioned Equation 1 to re-construct the bathymetric models for imagery derived bathymetric mapping.

2.3.2 Multi-Zone Ensemble Fitting

In contrast, this study has proposed a new methodology using multi-zone sequential ensemble fitting for bathymetric retrieval across the coastal region. It banded the normal linear regression model together with depth dependent on different depth of penetration (DOP) zones optimisation. It is primarily estimating the categorical dependent variable, with the aid of the independent variable. The computed output can only be between 0 to 1, in which the prefect linear regression is equal to 1. Theoretically, the entire data will be gone through an automatic computation exercise to compute gradient of the straight-line based on the function of the weighted sum of input (n) and subsequently determinate the zonal separation points as per required. Equation 2 and Equation 3 below are applied to determine the greatest gradient of a designated straight line, the computational is undergone as following:

$$Gradient_1\ (m_i) = \frac{y_{n-1+i} - y_i}{x_{n-1+i} - x_i} = \frac{Change\ in\ y_i}{Change\ in\ x_i} \qquad (2)$$

$$Gradient_2\ (m_{i+1}) = \frac{y_{2n-2+i} - y_{n-1+i}}{x_{2n-2+i} - x_{n-1+i}} = \frac{Change\ in\ y_{i+1}}{Change\ in\ x_{i+1}} \qquad (3)$$

By this sequential ensemble fitting approach and segmentizing the training sets to fit into several designated depth zones, it is believed that the newly proposed method can demonstrate better performance if compared to the traditional single regression algorithm. Thus, the synthetic multi-zone regression approach proposed here can be a more constructive solution to accomplish the seafloor topography with difference transparency conditions. Ideally, it is an automated data segmentation process developed based on the novel machine learning techniques to compute the threshold value for the segmented depth zones.

2.4 Data Assessment and Analysis

There are many useful assessment tools and techniques available. However, it is significant to employ the right data analysis method to meet the goals set prior the experimental phase. Without a doubt, it includes an evaluation of a set of SDB derived depths against the sounding depths measured by the vessel-based sounding system. In conjunction with the objectives of this study, quantitative comparison was commenced to examine the accuracy between the derived depths and the actual surveyed soundings values. Statistical analysis and accuracy assessment based on the IHO S-44 Survey Standards (IHO, 2020) were conducted to examine the output of this study.

3. RESULTS AND FINDINGS

This section discusses on the preliminary results and findings from this designated imagery derived bathymetry study. The preliminary results show a potential to use SDB approach for bathymetric mapping of the study area. The following sub-sections henceforth will continue the exhaustive analysis focus on retrieving bathymetric depths via multi-zones sequential ensemble fitting.

3.1 Bathymetric Model

Figure 2 below illustrates an overview of the seabed topography relief formed by multi-zones sequential ensemble fitting approach surrounding Forest City Bay. Indeed, the bathymetric modelling map has shown a clear difference in intensity between areas located at different depths. Meanwhile, *in-situ* surveyed depths have been overlaid on the Sentinel-2 imagery (see Figure 3) and bathymetric model (see Figure 4). Based on the non-quantitative analysis, the generated Forest City Bay bathymetric terrain model has demonstrated realistic seabed terrain profiles in the general viewing perspective.

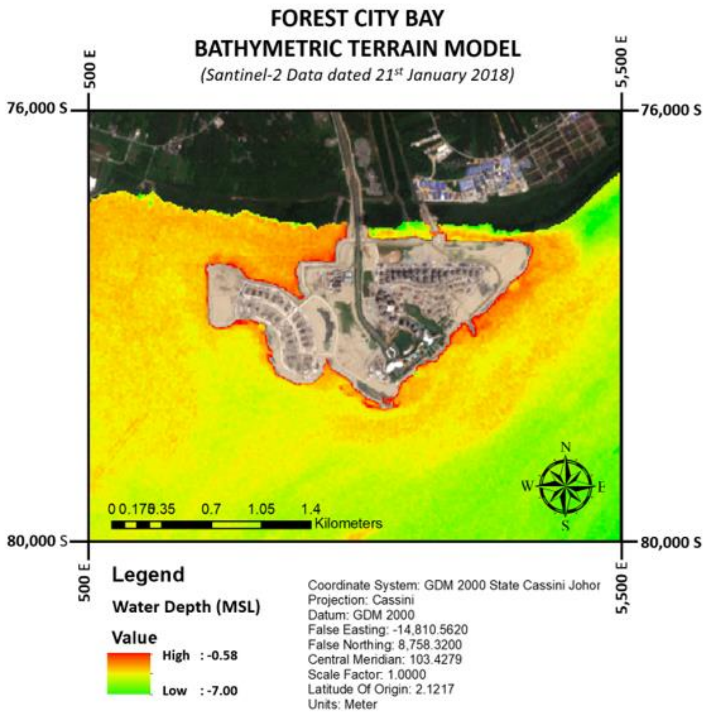

Figure 2: Bathymetric modelling map depicting the seabed terrain surrounding Forest City Bay

Figure 3: Hydrographic depths overlay on the Sentinel-2 imagery

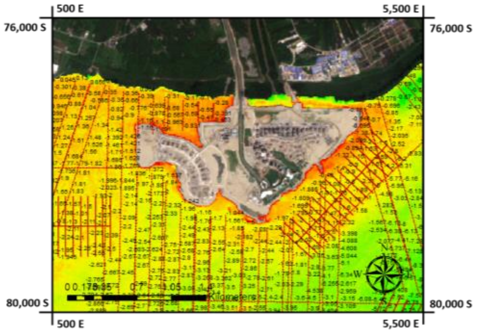

Figure 4: Hydrographic depths overlay on the bathymetric model

3.2 Statistical Analysis

Experimental results are computed based on the algorithm results and depth calibration sample acquired from vessel-based acoustic sounding survey. Through study done, the two different linear regression computation have been conducted to estimate the bathymetric depth values. The first approach is the commonly used single linear regression approach and the second one is the newly proposed multi-zones sequential ensemble fitting regression approach. The statistical behaviour of the computed results in the study is presented in Table 1 below. It presents the best correlation obtained in the first single linear regression equation as well as the three segmented seafloor zone respectively in the second approach.

Table 1. Statistical analysis of single linear regression and multi-zones sequential ensemble fitting regression

	Water Depth (m)	Linear Regression Equation	Coefficient of Determination (R^2)
Single Regression	0 to 7.00	y = 0.00521x + 0.08178	0.75
Multi-Zones Sequential Ensemble Fitting Regression	0 < 2.55	y = 0.01052x + 0.06831	0.80
	2.55 < 3.20	y = 0.00631x + 0.08130	0.40
	3.20 < 7.00	y = 0.00223x + 0.09636	0.55

Figure 5 and Figure 6 below illustrates the scatter plots of the algorithm results as a function of the surveyed water depth. The validation set compared 249 depths which were depicted from the *in-situ* surveyed data covering the study area, within the range from 0.00m to 7.00m. These depths were arbitrarily chosen, and for all seafloor classes contained some of the data used to configure the Dierssen's band ratio transformation.

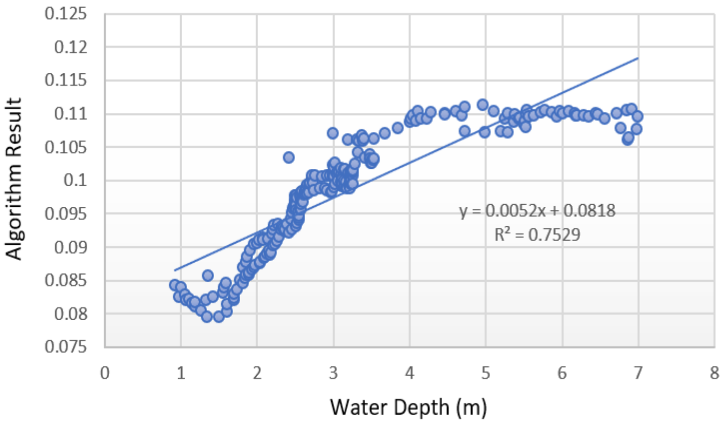

Figure 5: Statistical analysis using a single regression algorithm results as a function of the surveyed water depth.

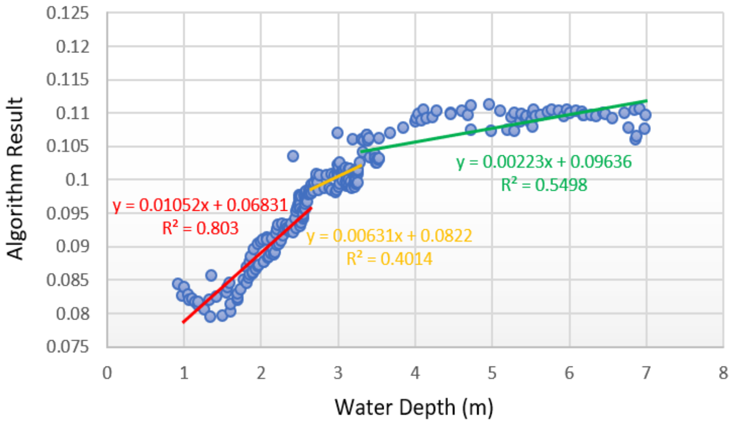

Figure 6: Statistical analysis using multi-zones sequential ensemble fitting regression algorithm results as a function of the surveyed water depth.

3.3 Accuracy Performance

The International Hydrographic Organization (IHO) has developed a means of determining the accuracy standards of bathymetric surveys in its Special Publication No.44 (S-44) issued in 2020. Generally, it sub-divides the minimum standards into four different survey types. The allowable total vertical uncertainty (TVU) in Special Order is limited to be within 0.25-meter, Order 1a and 1b are allowed to be 0.5-meter and coarsely 1.0-meter for Order 2 bathymetric survey being conducted within a 10 meters water depth. Table 2 below demonstrates the quantitative analysis results based on the TVU Survey Standards. Overall, the multi-zones sequential ensemble fitting regression analysis results are in a better performance compared to the traditional single linear regression within the study area.

Table 2. Overall quantitative analysis

	Single Linear Regression	Multi-Zones Sequential Ensemble Fitting Regression
Total Sample	294	294
Special Order	52	135
Order 1a & 1b	62	54
Order 2	82	21
Total Pass	196	210
Total Fail	98	84

4. DISCUSSION

In most of the scenarios, the spectrally-based empirical models are believed to be working fine in the clear ocean waters. However, as mentioned in previous works by Bramante *et al.* (2013), Sánchez-Carnero *et al.* (2014), Tang & Biswajeet (2015) and Tang & Mahmud (2018), water clarity apparently plays an important factor restricting the penetration of visible wavelengths into the water column. Water clarity and turbidity may affect the linear relationship between spectral reflectance and water depth. Indeed, dark submerged mud in the tropical region will result in a false shoal in most satellite bathymetry derivation algorithms when estimating the coastal and shallow water regions.

Without a doubt, this newly proposed multi-zones sequential ensemble fitting approach is capable to perform better than the conventional empirical methods which focusing on a single linear approach. Based on the results, although the total passing rate did not upsurge drastically, however the number of training data which accomplished the IHO's S-44 Special Order had tripled and improved by nearly 28%. In contrast, it surged from 52 in the single linear regression to 135 in multi-zone regression trajectory. Nonetheless, there was only little upward trend on the total passing rate, increased about 5%, reaching 210 from 196. On the other hand, the total failing amount dropped from 98 to 84 respectively. By segmentizing the study area into three designated water depth zones, the estimated bathymetric data seems to be more accurate with more data are achieving better accuracy and subsequently boost up the total number of data which passing through the minimum allowable TVU survey orders.

SDB modelling enable the collection of high-resolution bathymetric data to be integrated with terrestrial information in order to develop coastal terrain models and shoreline model. Thus, the preface of SDB also allows us to quantify and interpret the seabed topography as well as monitoring the changes via multi-temporal satellite images. With proper calibration and precise bathymetry inversion model, accurate and reliable bathymetric depths can be estimated via the high-resolution multispectral imagery. Hence, SDB approach here can be an efficient and repeatable way to derive the seabed topography along huge segments of coastline. The study suggests that the segmentation transformation approach can be an alternative source of hydrospatial data during the COVID-19 lockdown period. This non-contact method is possible to produce a reliable seabed topographical modelling in a comparatively less costly and labour-intensive manner.

5. CONCLUSION

The current COVID-19 outbreak has created a wide scope of socio-economic interruption, which causes obliterating in various perspectives. Our insight of the true fitness of the hydrographic industry under the ravage of COVID-19 flare-up is largely based on very limited data and great extent dependent on exceptionally restricted information. Therefore, SDB technology enables hydrographers to derive depths from remotely sensed satellite imagery data in a split second without physical mobilization and on-site survey. From the above findings, this study has shown a convincing outcome that the proposed method is capable to estimate decent bathymetric depths from the remotely sensed satellite imagery. The newly proposed multi-zones sequential ensemble fitting approach has performed slightly better than the single linear regression transformation method. The completeness of this study indeed will benefit to the hydrography industry. Hence, it is possible to produce hydrospatial information for safety maritime navigation in a less costly and labor-intensive manner.

REFERENCE

Bramante, J. F., Raju, D. K. & Sin, T. M. (2013). Multispectral Derivation of Bathymetry In Singapore's Shallow, Turbid Waters. *International Journal of Remote Sensing*, 34(6), 2070-2088.

Dierssen, H. M., Zimmerman, R. C., Leathers, R. A., Downes, T. V., & Davis, C. O. (2003). Ocean Color Remote Sensing of Seagrass and Bathymetry in The Bahamas Banks By High-Resolution Airborne Imagery. *Limnology and Oceanography*, 48(1part2), 444-455.

Gao, J. (2009). Bathymetric Mapping by Means of Remote Sensing: Methods, Accuracy and Limitations. *Physical Geography*, 33(1), 103-116.

Hussaini, A., Mahmud, M. R., Tang, K. K. W., & Abubakar, A. G. (2019). Water Level Fluctuation Assessment of Lake Chad For Environmental Sustainability Using Remote Sensing And Geographic Information System Technique. *International Archives of the Photogrammetry, Remote Sensing & Spatial Information Sciences*.

Hussaini, A., Mahmud, M. R., & Tang, K. K. W. (2020). Change Detection for the Past Three Decades Using Geospatial Approach in Lake Chad, Central Africa. In *IOP Conference Series: Earth and Environmental Science* (Vol. 540, No. 1, p. 012001). IOP Publishing.

Jawak, S. D., Vadlamani, S. S., & Luis, A. J. (2015). A Synoptic Review on Deriving Bathymetry Information Using Remote Sensing Technologies: Models, Methods and Comparisons. *Advances in Remote Sensing*, 4(02), 147.

Jégat, V., Pe'eri, S., Freire, R., Klemm, A., & Nyberg, J. (2016). Satellite-Derived Bathymetry: Performance and Production. In *Canadian Hydrographic Conference, May* (pp. 16-19).

Lyzenga, D. R., Malinas, N. R., & Tanis, F. J. (2006). Multispectral bathymetry using a simple physically based algorithm. *IEEE Transactions on Geoscience and Remote Sensing*, 44(8), 2251-2259. doi:10.1109/Tgrs.2006.872909

Mavraeidopoulos, A. K., Pallikaris, A., & Oikonomou, E. (2017). Satellite derived bathymetry (SDB) and safety of navigation. *The International Hydrographic Review*.

Pe'eri, S., Azuike, C., & Parrish, C. (2013). Satellite-derived bathymetry a reconnaissance tool for hydrography. *Hydro International*.

Sánchez-Carnero, N., Ojeda-Zujar, J., Rodríguez-Pérez, D., & Marquez-Perez, J. (2014). Assessment of different models for bathymetry calculation using SPOT multispectral images in a high-turbidity area: the mouth of the Guadiana Estuary. *International Journal of Remote Sensing*, 35(2), 493-514.

Stumpf, R. P., Holderied, K., & Sinclair, M. (2003). Determination of water depth with high-resolution satellite imagery over variable bottom types. *Limnology and Oceanography*, 48(1), 547-556.

Tang, K., & Pradhan, B. (2015). Converting digital number into bathymetric depth: a case study over coastal and shallow Water of Langkawi Island, Malaysia. In *FIG Working Week 2015*.

Tang, K. K. W., & Mahmud, M. R. (2018). Imagery-Derived Bathymetry in Strait of Johor's Turbid Waters Using Multispectral Images. *ISPRS-International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *4249*, 139-145.

Zheng, G., Chen, F., & Shen, Y. (2017). Detecting the water depth of the South China Sea reef area from WorldView-2 satellite imagery. *Earth Science Informatics*, *10*(3), 331-337.