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The Accuracy of Satellite Derived Bathymetry in Coastal and Shallow Water Zone

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ABSTRACT

Precise and accurate bathymetric measurements are conventionally acquired by means of ship-based acoustic equipment. Nevertheless, recent multispectral satellite imagery has been utilised as a substitute source to map the seabed topography which indicates new revolution in hydrographic surveying. This study assesses the satellite bathymetric depth's accuracy based on the vertical uncertainty as stated in the Standards for Hydrographic Surveys issued by the International Hydrographic Organization. Two empirical algorithms, namely, Dierssen's and Stumpf's approaches have been adopted to model the seafloor topography over the coastal and shallow water at Tanjung Kupang, Malaysia. The outcomes demonstrate a decent correlation between the derived water depths and the sounding values acquired from a ship-based acoustic survey. For instance, a total of 1,215 out of the 1,367 generated water depths by Stumpf's model have hit the minimum standard of survey in S-44. Similarly, out of the 1,367 samples from Diessen's model, 1,211 samples have met the minimum requirement listed in the survey standard. The results demonstrate both imageries derived bathymetry models convey promising results which can be ultilised for bathymetric mapping application. Therefore, this imagery derived bathymetry can be considered as an alternative bathymetric surveying technique to supply cost-effective solution and survey data to support the Blue Economy and Sustainable Development Goals 14.

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1. Introduction

The Coastal zone is an area of the encounter between land and sea, where the interaction of the sea and land progressions often occurs. In fact, excess of more than half of the world's population today is currently accommodating in this versatile coastal zone. These densely populated coastal and shallow water areas are getting extremely versatile and dynamic (Syvitski et al. 2005). Changes in these regions can be related to natural morphological alteration as well as human activities which occur either gradually or happen out of the sudden. The importance of this prominent feature on the Earth is widely recognized by the international community, and it is reflected in the one of the United Nation Sustainable Development Goals (SDG). Ocean and sea issues are reflected in SDG 14: Conserve and sustainably use the oceans, seas and marine resources for sustainable development. Thus, up-to-date survey data are essential for sustainable marine administration and development in the Blue Economy. More skilled staff and cost-effective solutions are required to offset and mitigate the threats to the aquatic environment.

Conventionally, bathymetric measurements are acquired via timely consuming ship-based acoustic systems like single beam echo sounding and multibeam system. Significant alterations over the seabed within a quick period may not be practically attempted via those acoustic methods. In short, some of the charts are outdated and may post potential hazards to the mariners. The prelude of remote detecting innovation has evolved new revolution in our hydrographic surveying industry since the previous decade. Today, the penetration capability of the electromagnetic spectrum into the water column has enabled human's capability to accomplish numerous missions including bathymetric derived from remotely sensed satellite images. Thus, the imagery derived bathymetry approach has wound up increasingly and been applied as a substitute approach to acquire new bathymetric data. The principle reason on the ground is that this inspiring method does not need extensive sum of money, time and energy when it comes to the nearshore and the coastal region.

Remote sensing using satellite technology has no doubt in delivering high resolution imagery for viewing purposes, likewise, it also allows us to reveal meaningful information out of the swift imagery collection. It has been applied as an effective supplemental approach to compromise the growing demands of up to date and comprehensive bathymetric depth data because of its tremendous spatial coverage and flexibility (Gao, 2009). Hence, this satellite bathymetry technique has substantiated itself as a beneficial reconnaissance instrument for nearshore imagery derived bathymetry mapping application (Mateo-Pérez *et al.*, 2020; Jégat *et al.*, 2016; Pe'eri *et al.*, 2013) as well as detecting the seafloor changes (Pacheco *et al.*, 2014; Darama *et al.*, 2019). In most of the earlier investigations, the majority of these depth retrieval algorithms are only practically work only across clear shallow ocean waters (Jawak *et al.*, 2015; Jégat *et al.*, 2016). Furthermore, some hydrographic offices from the European nations (e.g. UKHO, SHOM, etc.) have employed imagery derivation bathymetry extraction approach to update their nautical charts (Mavraeidopoulos *et al.*, 2017).

According to a synoptic review by Jawak *et al.* (2015), among the popular derivation models, Stumpf *et al.* (2003) and Lyzenga *et al.* (2006) are the widely used algorithms to deriving bathymetry information using remote sensing technologies. Nevertheless, most of the previous research works only focusing on statistical accuracy performance and examining the correlation (r^2) between derived depths and charted depths. In addition, this kind of research is less explored in the tropical environment setting and relatively new to a country like Malaysia (Najhan *et al.*, 2017). Consequently, this proposed paper attempts to evaluate the bathymetry derivation approach over the coastal and shallow water at Tanjung Kupang, Malaysia. This study is assessing the imagery derived bathymetry's accuracy derived by two empirical models. The allowable total vertical uncertainty (TVU) is referred to the Standards for Hydrographic Surveys that is published in the Special Publication No.44 (S-44) issued by IHO in 2020. Table 1 defines that the maximum allowable TVU for measuring water depths to be accomplished to achieve Special Order is limited to be within 0.25 metres, Order 1a and 1b are allowed to be 0.5 metres and roughly 1.0 metres for any bathymetric survey being conducted within a 10 metres water depth.

2.0 Area of Study

This study made an endeavour to estimate the bathymetric water depths at southwest of Johor Bahru, Malaysia, targeting the shallow and nearshore waters neighbouring to the Tanjung Kupang, Johor Bahru. Figure 1 illustrates the geographical location and coverage of the area of study which situated between 1° 18' N to 1° 21' N and 103° 34' E to 103° 38' E. Mostly, the aquatic circumscribing in this study area is highly turbid. It can represent and speak most of the seafloor conditions along the west coast districts in Peninsular Malaysia. By and large, the vast majority of the muddy shore face is bordered by level inclines with murky and turbid suspended dregs.

Table 1 Minimum allowable total vertical uncertainty (modified from IHO, 2020)

IHO Survey Order	$\mathbf{TVU} = \sqrt{a^2 + (b \times d)^2}$			
	Standards Assessment (Value d = 10 m)			
	Special	**1 a**	**1 b**	**2**
Maximum allowable TUV (95% Confidence level)	a = 0.25 m b = 0.0075 m	a = 0.25 m b = 0.0075 m	a = 0.25 m b = 0.0075 m	a = 0.25 m b = 0.0075 m
TVU	±0.261 m	±0.517 m	±0.517 m	±1.026 m
Feature Detection	Cubic features > 1 m	Cubic features >2 m, in depths up to 40 m; 10% of Depth beyond 40 m.	Not applicable	Not applicable

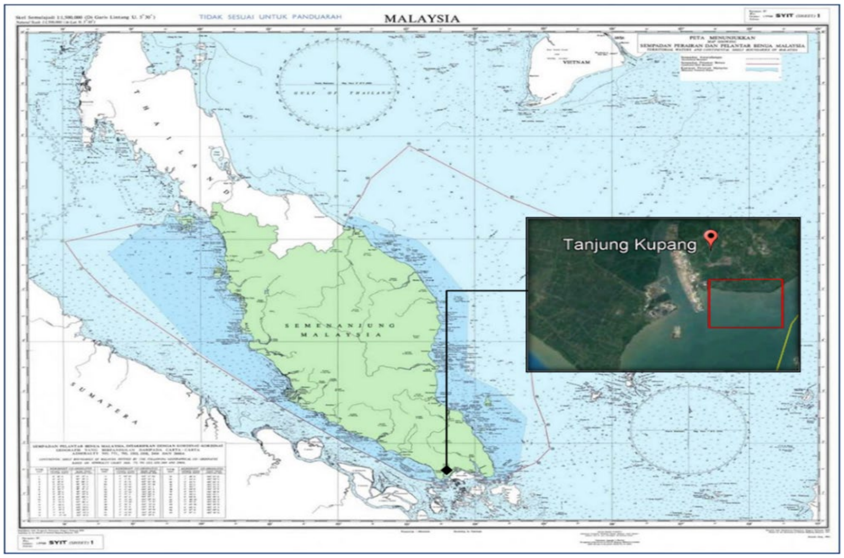

Figure 1 The geographical location of the study area

3.0 Data and Methodology

This section briefly reviews the satellite imagery derived bathymetry methods embraced here is to extract the water depths from multispectral imagery. It outlines the two bathymetry derivation models, physical characteristics of the multispectral satellite imagery, supplementary data as well as the imagery processing software applied in this paper.

3.1 Methodology

This dedicated paper fused both the remote sensing and geographical information system (RS & GIS) techniques to estimate the bathymetric depth values from the multispectral satellite imagery. The entire methodology, data processing workflow as well as the data assessment process is illustrated in Figure 2 below.

Selection of dedicated satellite imagery was determined based on the quality of the sensed imageries, area of the spectral coverage, ground pixel resolution as well as its spectrum range. Prior commencing the bathymetry derivation development, image pre-processing progression was conducted to abolish the unwanted path radiance, atmospheric effects and also filter out all the annoying sea surface reflectance. Subsequently, it was trailed with the geometric correction to get rid of the distortion errors. Next, a set of precise surveyed depths was discrete into two separate data sets. The first training dataset was adopted to construct the linear regression models, resolve the most fitting tuneable constant coefficient in bathymetry derivation algorithms. While, the second testing data was arranged for the data accuracy and assessment analysis.

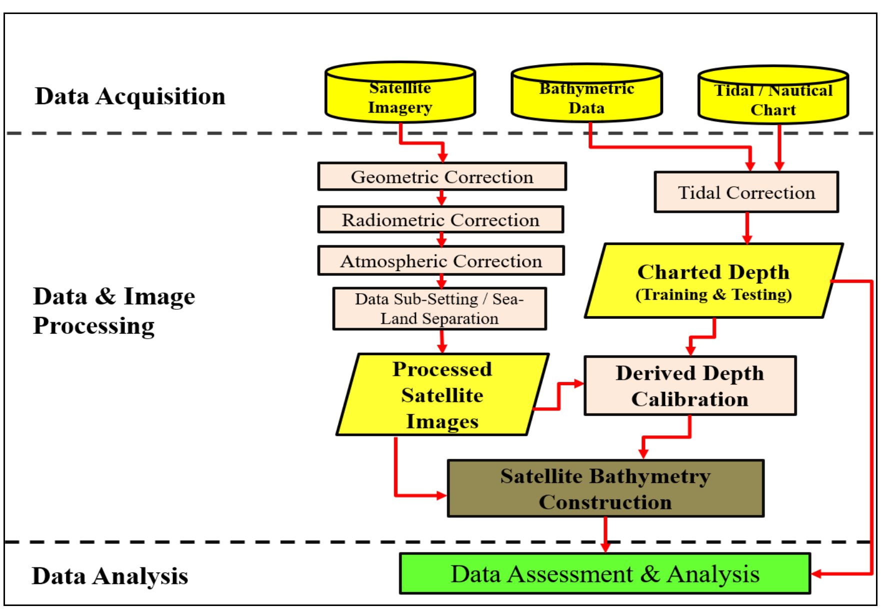

Figure 2 The flowchart of the entire methodology and processing stages

3.2 Multispectral Spectral Images

Landsat-8 multispectral satellite images acquired in June 27, 2013 were utilised in this feasibility study. Theoretically, short wavelength spectrum in the visible region is more desirable in imagery derived bathymetric mapping because these spectrums have a greater penetration into the aquatic environment. For instance, electromagnetic radiation of blue spectrum (0.45-0.52μm) and green spectrum (0.53-0.59μm) were chosen because of its low attenuation when passing through the water column if compared to other visible spectral.

Radiometric, atmospheric and geometric correction were conducted on to these images to remove unnecessary sea surface reflectance, unwanted path radiance and annoyed atmospheric effects as well as geometrically remove the distortion effect. Subsequently, those huge multispectral satellite images were cropped into smaller samples, comparatively small frame to optimise the satellite imagery processing.

3.3 In-situ Bathymetry Measurement

A designated *in-situ* bathymetric survey had been conducted throughout the entire study area in August 2013. These precise bathymetric depths were acquired via single beam echo sounder fitted on a fully equipped survey boat, synchronized with precise positioning obtained from a differential global navigation satellite system. The bathymetric depths were collected across the planned 25 metres line spacing and 5 metres point interval apart survey lines in the study area. All the measured data were tidally correlated to become the reduced depths. Subsequently, the surveyed bathymetric depths were adopted in constructing the depth-retrieval algorithm and being utilised in data assessment processing later.

3.4 Derivation Algorithms

This study attempts to determine the bathymetric depths over the shallow and coastal zone through two different empirical approaches. The derivation models by Stumpf *et al.* (2003) and Dierssen *et al.* (2003) adopted the fundamental principle of the Beer-Lambert Law, expressed the intensity of light decreases exponentially with the increasing of depth, primarily the observed reflectance from the optical sensor to the water depth. Henceforth, a linear inversion mathematical model could empirically express the relationship between the water-penetrating spectral.

3.4.1 Stumpf's Model

Stumpf *et al.* (2003) invented a band-ratio algorithm to estimate the water depth (Z) through two tuneable constant coefficients (m_0 & m_1) and of two consecutive water-penetrating spectral bands (R_i & R_j). It uses the division between detected reflectance log values to calculate depth of water and the ratio will estimate a simultaneous change when the depth change. Equation 1 shows the Stumpf's algorithm.

$$Z = m_0 * \frac{\ln(R_w(\lambda_i))}{\ln(R_w(\lambda_j))} - m_1 \qquad (1)$$

Where,
Z = value from derived depth
R_w = reflectance of band$_i$ & band$_j$
m_0 = tuneable constant
m_1 = offset of the depth
n = a constant value

3.4.2 Dierssen's Model

Dierssen *et al.* (2003) addressed alike band-ratio idea to extract the water depth (Z). However, it is modelled slightly differently by presenting the log-difference between two detected reflectance values. Similarly, the water depth is estimated from two tuneable constant coefficients (m_0 & m_1) and the observed reflectance of two consecutive bands (R_i & R_j) mathematically. Equation 2 below illuminates the Dierssen's algorithm:

$$Z = m_0 * \ln\left[\frac{nR_w(\lambda_i)}{nR_w(\lambda_j))}\right] + m_1 \qquad (2)$$

Where,
Z = value from derived depth
R_w = reflectance of band$_i$ & band$_j$
m_0 = tuneable constant
m_1 = offset of the depth
n = a constant value

3.4.3 Least Square Regression

Least square regression is ordinarily being conducted to solve a solution where the equations happened to be more than the number of unknowns. This mathematical technique is decent for financing the most well-fitted line to a certain arrangement of focus by diminishing the total of the residuals' squares ended with the results of each single mathematical equation. Basically, it minimises the entirety of squared residuals or offsets between detected values against the close-fitting qualities conceded by a derivation model.

Henceforth, it was applied to estimate the best fitted value to mathematically unravel the two unknown tuneable constants in the two above mentioned designated equations. These diffuse attenuation coefficients were calculated using least square regression via Equation 3 and Equation 4 below. Consequently, the retrieved tuneable constants were then being applied back into the previous Equation 1 and Equation 2 to re-construct the bathymetric models for imagery derived bathymetric mapping.

$$\hat{x} = \left(A^T A\right)^{-1} A^T \hat{y} \qquad (3)$$

$$\begin{bmatrix} m \\ c \end{bmatrix} = \left(\begin{bmatrix} x_1 & 1 \\ x_2 & 1 \\ \vdots & \vdots \\ x_n & 1 \end{bmatrix}^T \begin{bmatrix} x_1 & 1 \\ x_2 & 1 \\ \vdots & \vdots \\ x_n & 1 \end{bmatrix} \right)^{-1} \begin{bmatrix} x_1 & 1 \\ x_2 & 1 \\ \vdots & \vdots \\ x_n & 1 \end{bmatrix}^T \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{bmatrix} \qquad (4)$$

3.5 Accuracy Assessment

Assessment of data is a vital step in the defining the applicability of the derived bathymetric data which is usually referred as the data quality assurance too. Without a doubt, it includes an evaluation of a set of imagery derived bathymetric depths against the sounding depths measured by the ship-based acoustic system. Quantitative comparison was commenced to examine the accuracy between the derived depths and the actual surveyed soundings values. Assessment of data accuracy was featured based on several statistical approaches, correlation coefficient (r), correlation of determination (r^2), mean absolute error (MAE) as well as the root mean square error (RMSE) between both datasets.

4.0 Result and Discussion

This section discusses on the preliminary results and findings from this designated imagery derived bathymetry study. Serenely, Figure 3 illustrates various images representing the southwest of Johor, Malaysia, which include (a) Landsat-8 (RGB); (b) Nautical Chart; (c) Stumpf's model; and (d) Dierssen's model. Particularly, the seabed topography relief through their digital elevation models (DEM) is demonstrated in the following Figure 4 to Figure 5. Meanwhile, the descriptive statistical analysis and quantitative analysis of both models are shown in Table 2 and Table 3.

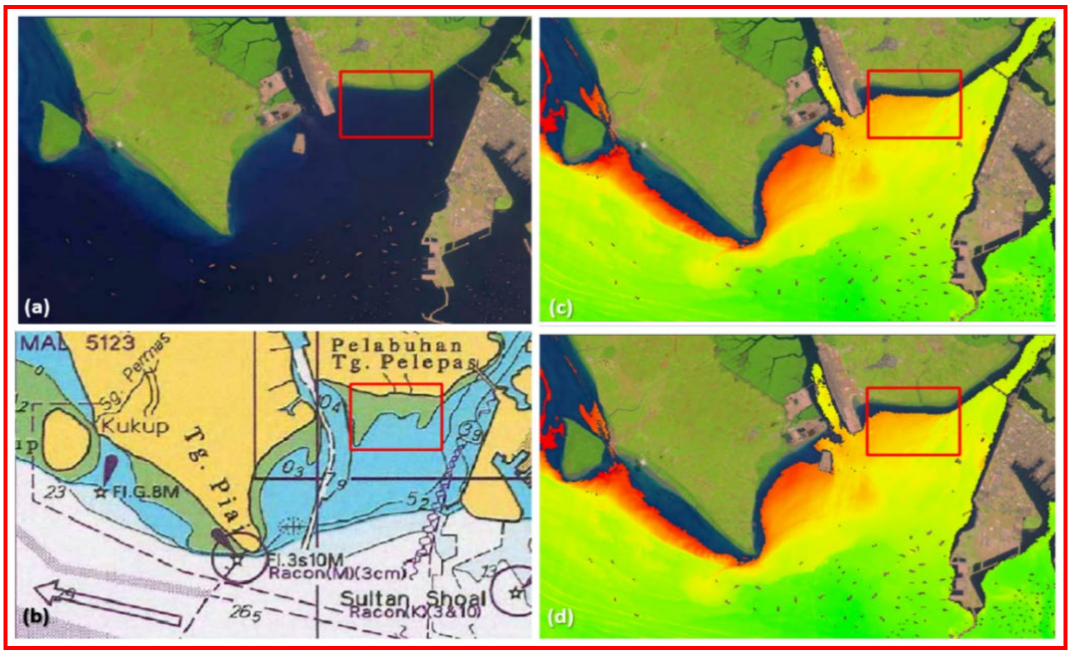

Figure 3 Images showing the area of study. Image (a) Landsat-8 (RGB) (b) Nautical Chart (c) Stumpf's model & (d) Dierssen's model

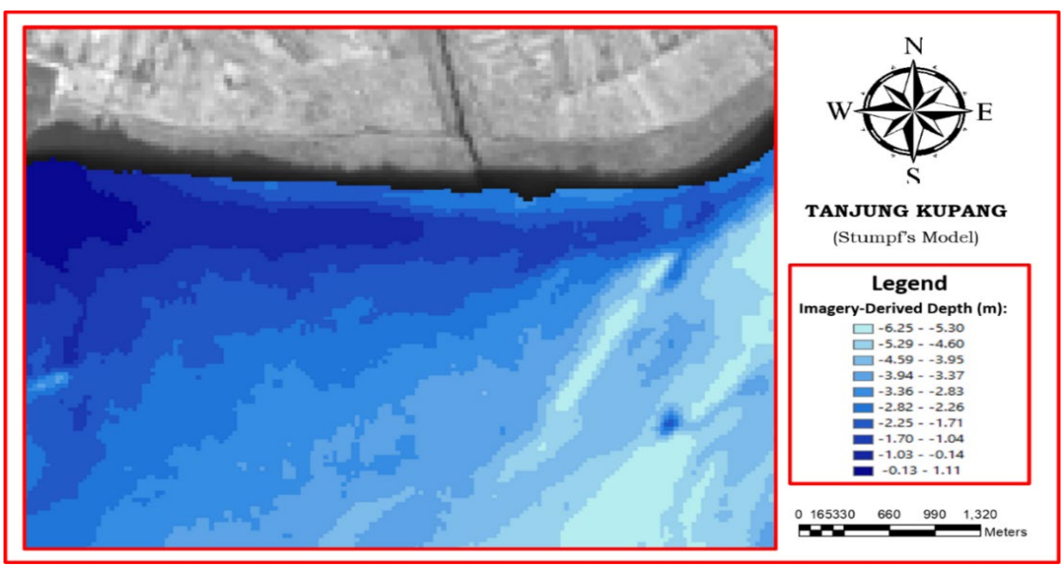

Figure 4 Bathymetric model across the study area from Stumpf's model

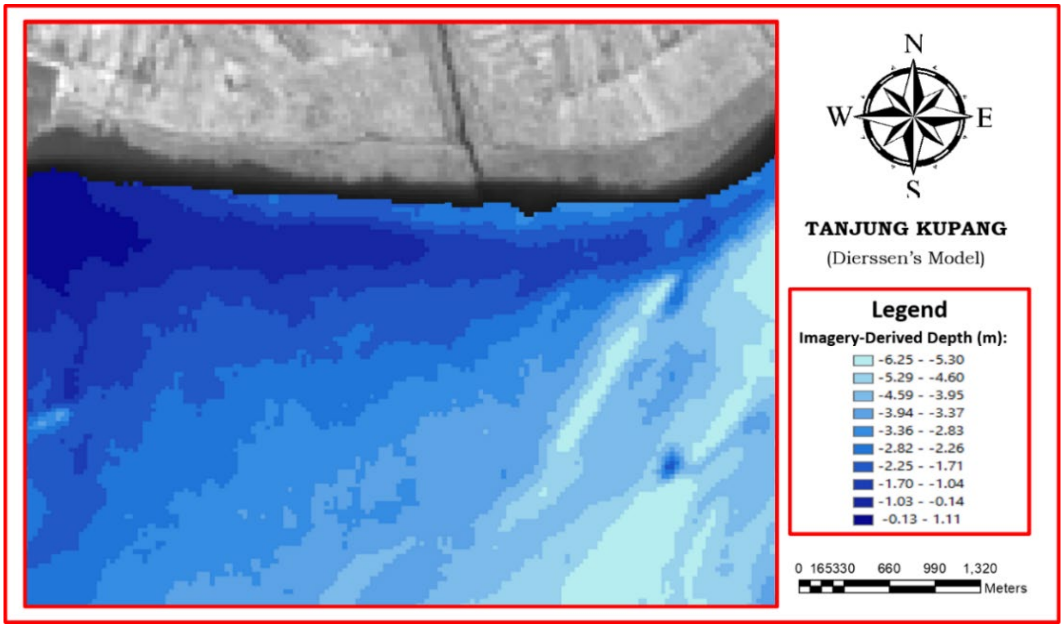

Figure 5 Bathymetric model across the study area from Dierssen's model

So as to numerically access the accuracy of the imagery derived bathymetry depths, assessment of data was commenced using 1,367 check points, randomly extracted from the surveyed SBES dataset. In general, the statistical analysis indicates that Dierssen's model obtains 0.878 metres in term of its RMSE while Stumpf's model yields 0.885 metres for its RMSE. The MAE performs by Dierssen's model is equivalents to 0.629 metres, whereas Stumpf's model gets 0.631 metres for its MAE. Meanwhile, the r^2 value of Stumpf's approach is 0.5828 and Dierssen's approach is 0.5834. Overall, both models have shown a similar correlation coefficient, 0.76. The statistical analysis indicates that both derivation bathymetry models have delivered satisfying outcomes in this shallow and turbid aquatic environment.

Table 2 Descriptive statistical analysis for Stumpf's and Dierssen's derivation models

Statistical Analysis	Imagery Derived Bathymetry model	
	Stumpf's Model	Dierssen's Model
Root mean square error (RMSE)	0.885	0.878
Mean absolute error (MAE)	0.631	0.628
Correlation of determination (r^2)	0.5828	0.5834
Correlation coefficient (r)	0.76	0.76

Table 3 The quantitative analysis of Stumpf's and Dierssen's derivation models

Details	Stumpf's derivation model		Dierssen's derivation model	
	Samples	Percentage (%)	Sample	Percentage (%)
Total samples	1367	100	1367	100
IHO Passed	1215	88.9	1211	88.6
IHO Failed	152	11.1	156	11.4
Special order	474	34.7	513	37.5
Order 1a & 1b	395	28.9	370	27.1
Order 2	346	25.3	328	24.0

In general, both models have demonstrated adequate results. In terms of total vertical uncertainty (TVU) accomplishment rate, 88.9% and 88.6% out of the 1,367 samples generated from Stumpf's and Dierssen's derivation models are able accomplished the minimum IHO survey standards based on the IHO's guidelines; meanwhile, the result also shows that there are 152 samples (11.1%) generated from Stumpf's model and 156 samples (11.4%) by Dierssen's model yet to go along the base necessity set up established in IHO's survey standard, respectively.

Undeniably, 474 samples (34.7%) out of the total 1,367 samples from Stumpf's model and 513 samples (37.5%) out of the total 1,367 samples from Dierssen's model have fruitfully meet the class of Special Order; another 395 samples (28.9%) by Stumpf's model and 370 samples (27.1%) by Dierssen's model successfully fall under class Order 1a & 1b, while 346 points (25.3%) generated from Stumpf's model and 328 points (24.0%) generated from Dierssen's model successfully passed the minimum accuracy specification at least class Order 2 as per stipulated in IHO's S-44.

Dominant part of the previous investigations just focusing on benthic survey over the clear shallow water areas and the tropical coastal region is less examined. Also, most of the suggested bathymetric derivation studies neglected the accuracy perspective. To summarize, the above-mentioned derivation algorithms had successfully formed linear inversion mathematical models which could empirically express the relationship between the water-penetrating spectral through a relatively turbid water zone across the study area. Thus far, the correlation and minimum IHO survey standards performance analysis results obtained in this study indicated that band-ratio derivation algorithms may also work over the muddy and turbid water regions in the tropical environment setting. Based on the finding outcomes, this analysis showed that in the future, satellite remote sensing data can be utilised in determining the depth of water. This remote sensing and GIS technique could be recognized as a new survey technique to map the broad seabed topography along the coastlines.

5.0 Conclusion

In the culmination of examination, the objectives and goals are effectively achieved. It analyses the practicality of the imagery derived bathymetric mapping in relatively shallow and profoundly turbid aquatic environment in Tanjung Kupang, Malaysia. The comparative analysis between Stumpf's and Dierssen's empirical models against the precise single beam survey training dataset has been evaluated. In the course of an experiment, there is no overwhelming difference between the results from Stumpf's and Dierssen's derivation models. Additionally, it is capable to achieve the minimum TVU specification stipulated in the IHO's S-44 document.

However, when looking into a more comprehensive point of view, the RMSE and MAE are showing greater values than the allowed TVUs as per specified in Order Special and Order 1a & 1b. The water clarity and turbidity has always been the key factor that determines the level of penetration level for visible wavelengths in the water column for bathymetry derivation. The absorption and scattering of spectrum triggered by the dissolved organics and suspended particles as well as dregs in water column do influent the maximum depth of penetration in the turbid region. In short, it will lead to an incorrect shoaling in bathymetric depth retrieval. Like most other scientific researches, this preliminary findings and outcomes indicate that there are needs for further extensive study, probably in unravelling the testing site into few different depth zones and apply extra ground-truthing points to redefine the most appropriate linear regression analysis on each designated depth zone. Perhaps, such tactic can formulate multi-linear regression models to define the most suitable constant diffuse attenuation coefficients based on each designated water depth in a more ideal algorithm.

In short, this satellite bathymetry technique does not require any equipment mobilisation necessities, offers a quick and effective solution to unveil seafloor relief over a broader area of study. The encouraging preliminary results can be an alternative source of bathymetric data when mapping the coastal and shallow water in tropical region. Conversely, this imagery derived bathymetry can be considered as cost-effective bathymetric surveying solutions to supply more up-to-date survey data to governing the marine administration and development in the Blue Economy and to support the initiative of SDG 14.

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