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RESEARCH ARTICLE

COMPUTATION OF DREDGED MATERIAL AND SELECTION OF THE BEST KRIGING METHOD

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ABSTRACT

In this study, it is demanded that a preparatory survey for an oil well location be carried out and the estimated number of dredged materials be calculated at various sections inside the perimeter of an oil mining lease (OML 38) located at Ovhor field, Niger Delta Region, Nigeria. Seven sub-sectional areas initially earmarked for dredging at predetermined depths were delineated for different purposes to accomplish the dredging task. The total sum of the seven sectional areas calculated was 89,321.31m^2. Of the seven sub-sectional areas, the volume of dredged material was calculated for only five by multiplying the obtained two-dimensional areas by the designed depth. The two sub-sections exempted from dredging were because depths are appropriate at these locations. The total volume of dredged material, therefore, calculated was 56,630.73m^3. Recording and monitoring of tidal observations and analysis complement bathymetry and dredging activities. Due to the rugged terrain, interpolation remains a viable option to predict spatial variability at unsampled dredged lines. To achieve this, different kriging methods were investigated before finally choosing the best. The model that made the most accurate predictions was "Indicator Kriging" with a mean error of 0.000364 and a root-mean-square-standardized error of 0.806. This result is geostatistically acceptable when predicting spatial variability at an un-sampled location. The indicator kriging approach was subsequently used to predict the spatial variability of the un-sampled locations encountered in the study area.

KEYWORDS

Bathymetry, Dredging, GNSS, Kriging, Oil well

1. INTRODUCTION

Dredging plays a vital role in the oil and gas industries and other marine applications on a global basis. The Niger Delta Region of Nigeria is the hub of oil and gas exploration and exploitation, hence dredging activities is mostly practiced. These industries have a strong demand for accurate spatial data. According to Walter, about 80% of the data used by the oil and gas industries is spatially derived but poorly referenced (Walter, 2011). This flaw has the potential to spell doom for a project's successful completion. Poor referencing leads to errors in positioning (X, Y, and Z), poor knowledge of the spatial relationships among different terrain elements, project failure, loss of lives, and waste of capital and resources (Walter, 2011). Andruszko pointed out that proper adjustment of the cutting elements to the characteristics of excavated material and quality positioning of the dredger will boost productivity while reducing geological condition complications occasionally encountered during dredging (Andruszko, 2021).

The National Oceanic and Administrative Agency, defined dredging as the removal of sediments, sand, and debris from the bottom of lakes, rivers, harbors, and other water bodies for various purposes (NOAA, 2021). Therefore, adoption of dredging has become an unavoidable necessity in waterway and reservoir maintenance due to global sedimentation challenge (NOAA, 2021). Pre-dredging investigation survey must be carried out before an advertisement for a contract bidding process is made public. Estimating the amount of material to be dredged from a specific body of water is critical for determining project costing and implementation, and so on (Wu et al., 2019; Althobiani and Shamji, 2019). Advancement in technology and equipment has revolutionised the way dredging is now done. To improve dredging accuracy and efficiency, some researchers suggested using contemporary GNSS technologies and geospatial information systems (GIS). Few articles are reviewd from related works in sub-section 1.1 (Mamunts et al., 2016).

1.1 Review of Related Literature

Aljiran and Alkandari adopted dredging method in Kuwait for the site preparation, soil reclamation, and remediation for refinery with fill materials excavated from some selected marine borrow areas, that was transported, and disposed via hydraulic transport system (Aljiran and Alkandari, 2019). According to dredging carried out on River Niger, Nigeria significantly improved the inland waterways transportation system by stimulating a cost-effective and convenient movement of people, goods, and services in Nigeria (Adejare et al., 2013; Burg, 2010). Dredging was adopted to provide and supply the 91Mm^3 of sand required for filling the reclaimed expanse of land of length 6,500m with an average width of 1,260m in Lagos State, Nigeria (Nwosu, 2010).

A group researcher used data from the Multi-Beam Echo Sounder to calculate dredging volume and then used Hypack and AutoCAD Civil 3D software to determine the best dredging strategy (Khomsin et al., 2018). Both software packages were found to be suitable for dredging the

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Tanjung Perak port via the Surabaya West Access Channel, according to the findings. Some researchers in Nigeria like and from other countries such as were opposed to dredging, citing its negative effects on the environment, human health, and marine ecosystems (Adebimpe et al., 2012; Adekunbi et al., 2018; Okoyen et al., 2020; Wilber and Clark, 2001; Seiyaboh et al., 2013; Shao et al., 2015). The emphasis of this paper, however, differs by examining the value of dredging to the socioeconomic growth of Nigeria's primary source of foreign revenue earning.

According to geostatistics is a branch of mathematics that uses statistics to analyse spatial data, including their attributes at a particular location in time and space (Santos et al., 2017; ESRI, 2010). In the 1980s, this aspect of statistics was first applied in the mining industry and earth sciences specializations like geology (Wu et al., 2019). Without geostatistical techniques, it is difficult to evaluate uncertainties in fields where spatial relationships between measured and unmeasured quantities are crucial to predictive decision-making (Varouchakis, 2019). Many scientists and engineers leveraging the capacity of geostatistic interpolation have encountered difficulties accessing areas of interest one way or the other during data collection at some point in their research endeavours. Adopting spatial interpolation principles is, therefore, necessary as an option to overcome this challenge.

Kriging is a spatial interpolator named after Dr. D.G. Krige, a mining engineer from South Africa. Kriging can be either precise or smoothed, depending on the measurement error model (Matheron, 1963b). It is very flexible and allows researchers to investigate the graphs of spatial autocorrelation and cross-correlation (Chilès and Desassis, 2018; Matheron, 1963b). Kriging uses statistical models to generate a variety of output surfaces, including predictions, prediction standard errors, probability, and quantile (Krige, 1951; Krige, 1952; ESRI, 2007). The flexibility of kriging requires data understanding, experience, and decision-making efforts. Kriging is based on the assumption that the data is generated by a stationary stochastic process (Chilès and Desassis, 2018). Asante and Kwadwo adopted Ordinary Kriging method to estimate flotation, bank height and gravel depth at Dunkwa Goldfields Limited site to produce a contour map that enabled the depiction of the possible non-dredgeable areas while Indicator Kriging (IK) was used to remove outlier (Asante and Kwadwo, 1993).

A proposed an alternative method of sediment transport dynamics analysis that employs two-dimensional interpolation with vectorial kriging spatial characterisation of a directional stochastic process in the interpolation of the vector azimuth (Lucio et al., 2006). The Schelde River, which divides Belgium and Holland, and the Itanhém River estuary, located in the southern Brazilian state of Bahia, provided the two sets of granulometric data that were used. The kriging method has proven to be effective in reducing prediction errors and controlling the sediment transport direction when compared to the in-situ energetic conditions observed. A group researchers applied kriging algorithms to predict uncertainties in the fate of contaminants and the volume of dredged sediment by describing the shape and size of measurement and prediction supports and the generation of simulated models as an alternative to smooth kriging models for propagating the uncertainty associated with various dredging scenarios (Goovaerts et al., 2009). They recommended cross-validation as a key factor in selecting the most accurate predictive model.

Razali computed dredge volume from excavated sand using bathymetry datasets and deployed five spatial interpolation methods including ordinary kriging for prediction prior the computations of dredge volume (Razali, 2017). The standard deviation obtained revealed that using the allowable level of different limits, between ± 0.5 to ± 1% of dredge volume was generated. A group researchers compared different spatial interpolation methods including (OK) and Universal Kriging (UK) for historical hydrographic data of the lowermost Mississippi River (Wu et al., 2019). The results showed that such interpolation is necessary for predicting depth morphological investigation and channel change detection needed for dredging and other engineering works. Henrico, applied an optimal interpolation method to derive a conclusion between Inverse distance weighting (IDW) and Ordinary Kriging (OK) while engaging in the prediction of the bathymetry of Saldanha Bay (Henrico, 2021). IDW performed better than OK for the study area based on the separation of data into components of 100% original, 66%, and 33% subsets. This research aimed to determine the volume of dredged material, tidal behaviour, and prediction of spatial variability at un-sampled dredged lines. Integrated RTK-GNSS bathymetric surveys, pre- and post-dredged bathymetric surveys, and tidal observations are remarkable methods deployed for successful execution.

2. Materials and Methods

2.1 Study Area

The study area is located at Ovhor Field Oil Mining Lease (OML) 38 in Sapele Local Government Area, Delta State, Nigeria. It falls within zone 31 North of the Universal Transverse Mercator. Geographically defined by the following coordinates: (5.2310E, 6.2120N and 6.3370E, 5.3360N). The area is dominated by a thick rainforest on a tidal swamp. The geological formation of the area is classified as possessing peat and soft mud from field investigations. Figure 1 depicts a map of Nigeria showing the study's location.

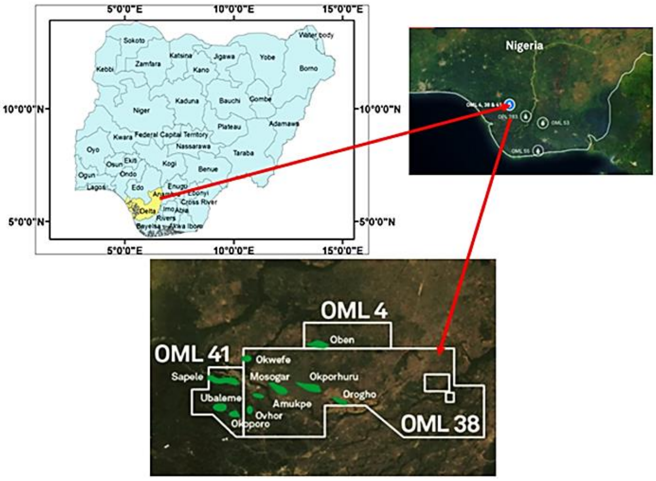

Figure 1: Map of Nigeria Showing The Study Location

2.2 The Role of Bathymetric Surveys

Bathymetric surveys were conducted for a variety of reasons, including determining the access route, pre and post-dredge depth determinations, dredging to flotation and full dredging, clearing of navigable waterway, and calculating the volume of excavated material, among others. Different methods are available to compute the volume of material dredged after performing bathymetric surveys. Some of them are: DTM, Contour, TIN, Grid, Profile, Simpson's rule, Trapezoidal rule, etc. Since we know the area of each section, we can multiply each by the required dredging elevation (depth). The Trapezoidal rule was used to calculate the volume of dredged material, as shown in equation 1 (Ghilani and Wolf, 2004). Figure 2 depicts the bathymetric survey and ongoing dredging work.

$$V = \frac{d}{2}[A_1 + A_n + 2(A_2 + A_3 + A_4 + \cdots + A_{n-1})] \quad (1)$$

Where: V is the volume dredged, d is the depth of excavation, A_1-A_n are the beginning and last areas, n is the number of cross-sectional area involved.

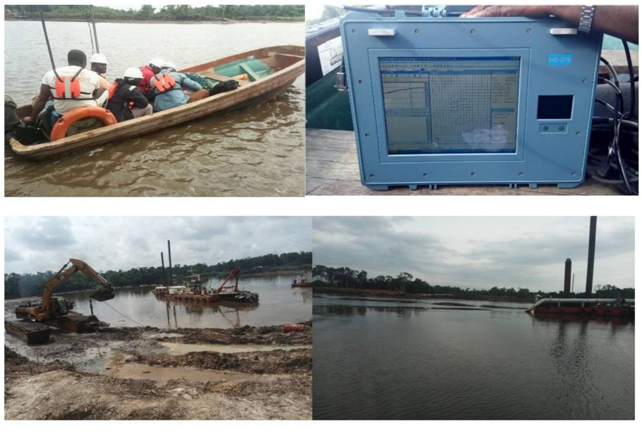

Figure 2: Bathymetric survey and dredging work in progress

2.3 Preliminary Geostatistical Investigation

It is good practice to check the normality or pattern of behaviour of spatial data through a histogram plot before proceeding with the geostatistical analysis, especially when using the ArcGIS 10.3 geostatistic analyst tool. The probability and statistic book of contains a table that summarizes the effectiveness of histograms in preliminary data investigation analysis

(Saporta, 1978). It specifies that a set of *n* values in the histogram must not be exceeded. From the table, values are given for risks in terms of 1% and 5% for *n* starting from 7 to 5000. The sample size for this study was 3,736 points, which is close to 4,000. The coefficient for a 5% error risk, verified at this level, is about ±0.064. This confirmed that the distribution of data is indeed symmetrical. Figure 3 shows the skewness which is acceptable as specified by (Saporta, 1978). Figure 3 shows the output of data normality investigation.

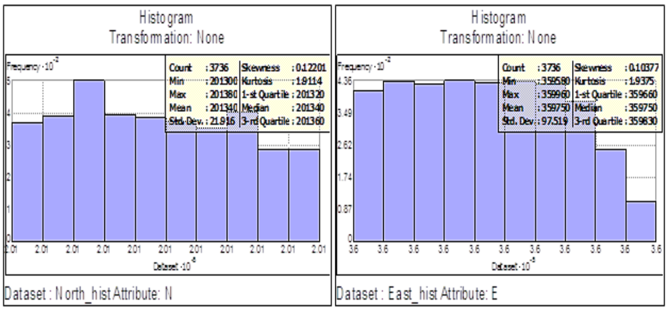

Figure 3: Histogram Plot of The 2D Dredger's Navigation Data

2.4 Selection of Appropriate Interpolation Methods

After we successfully verified the data with a histogram plot, it is then possible to use the geostatistical analysis wizard to select the desired interpolation methods, which are divided into three categories: (i) Deterministic, which includes (inverse distance weighting, global polynomial interpolation, radial basis function, and local polynomial interpolation); (ii) Geostatistics, which includes (kriging, co-kriging, areal interpolation, and empirical Bayesian kriging); and (iii) Interpolation with barriers, comprising mainly of (kernel smoothing and diffusion kernel). However, the interpolation method considered in this work is limited only to the geostatistics method of Kriging and its types.

2.5 The Kriging Methods

Kriging is a very flexible geostatistics method used for predicting the value in a geographic location provided a set of measurements is available. The prediction can either be exact or smoothed based on the measurement error model. It derives output surfaces such as predictions, prediction standard errors, probability, and quantile from statistical models. It is applied mainly in dredging, mining, agriculture, structural engineering, soil science, geology, and environmental sciences. Table 1 shows six different Kriging models (Hengl, 2009; ESRI, 2021; Goovaerts, 1997).

Table 1: Investigated Kriging Model Types

S/No:	Kriging Type	Model	Remark
1	Ordinary	$Z(\mathbf{s}) = \mu + \varepsilon(\mathbf{s})$	Where: μ is regarded as an unknown constant
2	Simple	$Z(\mathbf{s}) = \mu + \varepsilon(\mathbf{s})$	Where: μ is a known constant
3	Universal	$Z(\mathbf{s}) = \mu(\mathbf{s}) + \varepsilon(\mathbf{s})$	Where: $\mu(\mathbf{s})$ is some deterministic function
4	Indicator	$I(\mathbf{s}) = \mu + \varepsilon(\mathbf{s})$	Where: μ is an unknown constant and $I(\mathbf{s})$ is a binary variable
5	Probability	$I(\mathbf{s}) = I(Z(\mathbf{s}) > c_t) = \mu_1 + \varepsilon_1(\mathbf{s})$ $Z(\mathbf{s}) = \mu_2 + \varepsilon_2(\mathbf{s})$	Where: μ_1 and μ_2 are unknown constants and $I(\mathbf{s})$ is a binary variable created by using a threshold indicator, $I(Z(\mathbf{s}) > c_t)$
6	Disjunctive	$f(Z(\mathbf{s})) = \mu_1 + \varepsilon(\mathbf{s})$	Where: μ_1 is an unknown constant and $f(Z(\mathbf{s}))$ is an arbitrary function of $Z(\mathbf{s})$. Notice that you can write $f(Z(\mathbf{s})) = I(Z(\mathbf{s}) > c_t)$

2.6 Variogram Or Semi variogram Modelling

In some cases, the terms "variogram" and "semivariogram" are used interchangeably. However, the semivariogram is half of a variogram function when measuring the dissimilarity between pairs of data points separated by a specified lag distance, according to (Matheron, 1963b; ESRI, 2021). There are many different semivariogram models to choose from in ArcGIS 10.3. When modeling the semivariogram, the autocorrelation can be examined and quantified. Equation 2 shows a typical semivariogram model.

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [z(u_i) - z(u_i + h)]^2 \qquad (2)$$

Where: $\Upsilon(h)$ is the semivariance which is a function of the lag distance *h*, (m²); *h* refers to the lag spacing vector in (m); $z(\boldsymbol{u}_i)$ is the the depth of excavation in (m) at the spatial location $\boldsymbol{u}_i$; $\boldsymbol{u}_i$ signifies the vector of the spatial coordinates (x, y) for the sample locations of each measured depth.

2.7 Cross-Validation

Cross-validation is a technique that offers a platform for evaluating and comparing the performance of the different interpolation methods (Bhunia et al., 2016; ESRI, 2007). For cross-validation, the following error prediction techniques were statistically examined. Table 2 shows the different statistical models.

Table 2: Cross-Validation Process

S/No:	Cross-Validation	Model	Remark
1	ME	$\frac{\sum_{i=1}^{n}(\hat{Z}(s_i) - z(s_i))}{n}$	The mean error helps calculate the averaged difference between the measured and the predicted values.
2	RMSE	$\sqrt{\frac{\sum_{i=1}^{n}(\hat{Z}(s_i) - z(s_i))^2}{n}}$	This model indicates how closely a model predicts the measured values. The smaller the value of error obtained, the better the prediction result.
3	MSE	$\frac{\sum_{i=1}^{n} (\hat{Z}(s_i) - z(s_i)) / \hat{\sigma}(s_i)}{n}$	This model makes use of the average of the standardized errors to predict the outcome. The acceptable value for this error should be as close to 0 as possible.
4	RMSSE	$\sqrt{\frac{\sum_{i=1}^{n} \left[(\hat{Z}(s_i) - z(s_i)) / \hat{\sigma}(s_i) \right]^2}{n}}$	This should be very close to 1 if the prediction standard errors are valid. Otherwise overestimation or underestimation could occur.
5	ASE	$\sqrt{\frac{\sum_{i=1}^{n} \hat{\sigma}^2(s_i)}{n}}$	This is achieved by taking to the average of the prediction standard errors

Note: ME = Mean Error, RMS = Root-Mean-Square Error, MS = Mean Standardized, RMSSE = Root-Mean-Square Standardized Error, ASE = Average Standard Error

3. Results and Discussions

3.1 Determination of Dredged Area

The sequence of dredging activities was monitored by creating a base map showing the Digital Bed Model (DBM). When overlaid on the base map previously loaded into the dredging mater software, the area covered for a specific day/night, as the case may be, can be easily viewed. The calculated sectional areas are depicted in Figure 4.

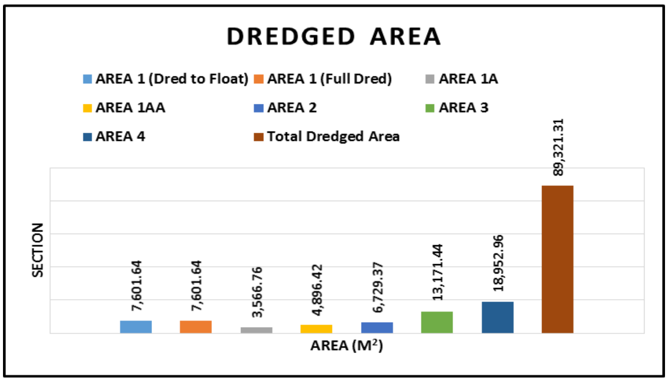

Figure 4: Sectional Areas Covered During Dredging

Figure 4 depicts the sectional areas where dredging is or is not to take place. The AREA 1 "Dred to Float" section represents the first capital dredging completed to allow the dredger proper access to work. The area covered in this section amounted to 7,601.637m^2. The AREA 1 "Full Dred" section is the second dredging, reaching the expected depth according to the design specification. This section has the same area coverage of 7,601.637m^2 as well. The "AREA 1A" section is the smallest, covering 3,566.76m^2. The section tagged “AREA 1AA” covers 4,896.42m^2. The “AREA 2” section covers 6,729.37m^2. The "AREA 3" covers a total area of 13,171.44m^2. The "AREA 4" section, which is the largest, covers 18,952.96m^2. The total of all the areas covered gave 89,321.31m^2.

3.2 Depth Differencing

Pre-and post-dredged bathymetric surveys are carried out according to project specifications. Bathymetric surveys were conducted in only five of the seven sections involved because dredging was not required in the other two. Figure 5 summarises the findings of the analysis conducted to determine the differences between pre-and post-dredged surveys, which are required for calculating the quantities of material dredged from each section.

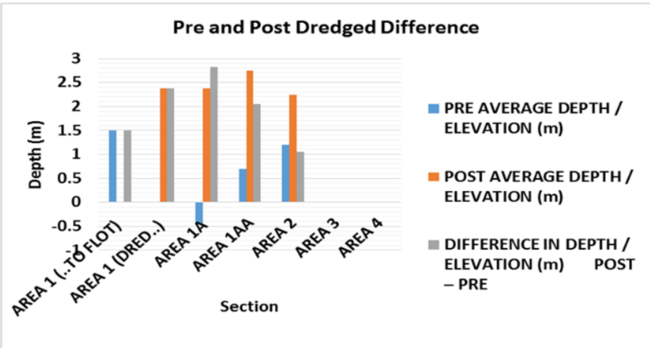

Figure 5: Pre And Post Dredged Sectional Elevation Differences

The difference between the pre-dredged and post-dredged bathymetric surveys is depicted in Figure 5. Because no post-dredge depth elevation was observed during the pre-dredge bathymetric survey of AREA 1, also termed (dredging to floatation), the pre-dredge depth elevation was retained as 1.5m. Therefore, the difference in elevation at this section remains at 1.5 m. This implies that an area shallower than the 1.5m conforming to the project design specification was dredged uniformly by the RTK-GNSS enabled dredger. Similarly, at AREA 1 (Full depth dredging), the post-dredge average depth elevation achieved at this section was 2.38m, resulting in a 2.38m difference.

At AREA 1A, the average depth for the pre-dredge bathymetric survey was -0.45m while the post-dredge average elevation was 2.37m. The difference of 2.28m was dredged at this section. AREA 1AA had a pre-dredge average depth of 0.7m and a post-dredge average depth of 2.75m, indicating a 2.05m difference in uniform dredging at this section. AREA 2 has a pre-dredge average depth elevation of 1.2 meters and a post-dredge average depth elevation of 2.25 meters, with a difference of 1.05 meters dredged at this section. Dredging was not required in AREAs 3 and 4, as these sections were unaffected. The differences derived for each section were instrumental during the derivation of the volume of dredged material.

3.3 Determination of Volume of Dredged Material

The estimation of the quantity (volume) of material dredged is useful for various purposes, such as: calculating the expected (size and depth) of dredging coverage, project bidding cost analysis, determination of land reclamation, stockpiling earth amount, navigation, canalisation, channelization, sediment sample characterization analysis, etc. The volume of material computed for each section is presented in Figure 6.

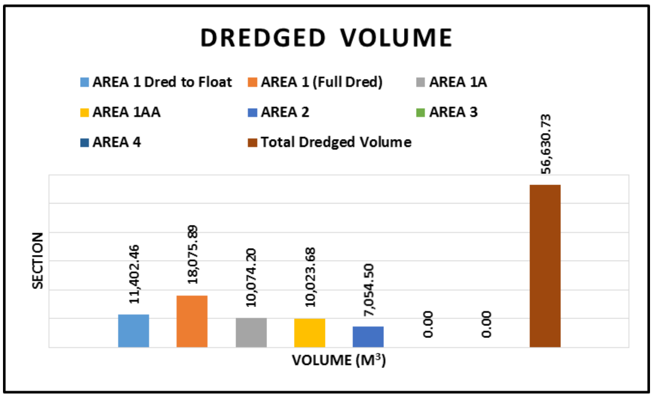

Figure 6: Sectional Areas Dredge Volume

Figure 6 depicts the sectional volumes of dredged material removed during the dredging exercise. The AREA 1 "Dred to Float" section represents the first capital dredging project to allow the dredger access to all parts of the study area. In this section, the volume of material calculated was 11,402.46m^3. Similarly, the section identified as “AREA 1 (Full Dred)” is the second dredging work to the actual depth according to the design specification and project proposal. This section yielded 18,075.89m^3 of volume dredged. The difference in volume obtained from dredging to full depth versus dredging to flotation was 6,673.44 m^3. The volume of dredged material in the section labelled "AREA 1" is 10,074.20m^3. The quantity of material removed from the section tagged “AREA 1AA” was 10,023.68m^3. Again, the material removed from the “AREA 2” section amounted to 7,054.50m^3. The “AREA 3” does not need dredging, so it was 0.00m3. Finally, dredging did not apply to the final section tagged “AREA 4” so it was 0.00m^3. The total of all the volumes of material dredged at the project site gave 56,630.73m^3.

3.4 Tidal Study

The duration and interval of available data are important factors in determining tidal behaviour at a specific location. Tides must be monitored in a specific area for hydrographic surveys and other related activities such as dredging. The results of such studies will provide crucial information about high and low water levels, which are critical for the safe navigation of vessels, dredgers, and barges, among other things. Figure 7 shows the result of tidal monitoring which tool about five months of consistent tide observations at the project site.

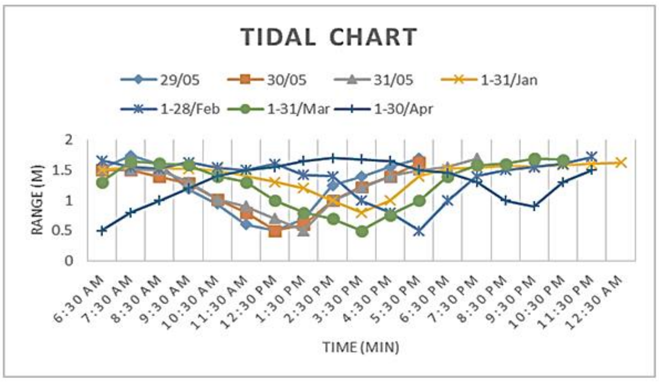

Figure 7: Observed tidal plot for the study area

Figure 7 depicts the observed tidal plot at the study site, which corresponds to variations in water level measured every 30 minutes for five months. On the 29th of May 2019, the lowest and highest tide ranges were 0.5m and 1.7m, respectively, as shown in the graph. On the 30th of May, the lowest and highest tide ranges were 0.5m and 1.6m, respectively. On May 31st, the lowest and highest tide ranges were 0.5m and 1.69m, respectively. The lowest and highest tidal ranges were 0.8m and 1.60m, respectively, in April. The lowest and highest tide ranges recorded for March were 0.5m and 1.69m, respectively. In February, the lowest and highest tide ranges were 0.5m and 1.72m, respectively. The lowest and highest tide ranges were 0.8m and 1.60m, respectively, for January.

3.5 Inspection of Interpolation Output

The output of the investigation of various interpolation methods under kriging is presented in Table 3. If the root-mean-squared standardized errors are greater than 1, underestimating the variability in the predictions is unavoidable; however, if the root-mean-squared standardized errors are less than 1, overestimating the variability in the predictions is possible (ESRI, 2007). However, RMSE approaching unity (1) is most desirable. Therefore, the indicator kriging method superseded other kriging methods with a RMSE of 0.8060 and a mean error of 0.000364. Figure 8 depicts the last stage of the kriging interpolation procedure followed in ArcGIS 10.3 software.

Table 3: Cross-Validation Statistics

	Cross-Validation Statistics					
Kriging Methods	Samples size	ME	RMSE	MSE	RMSSE	ASE
Ordinary	3736	0.000191	0.0139	0.000212	0.0157	0.85900
Simple	3736	0.070600	0.5510	0.005420	0.0654	11.2790
Universal	3736	0.000191	0.0139	0.000212	0.0157	0.85900
Indicator	3736	0.000364	0.1050	0.001330	0.8060	0.13100
Probability	3736	0.002810	0.0959	0.143000	4.5620	0.02120
Disjunctive	3736	0.174000	10.098	0.000192	0.0123	821.911

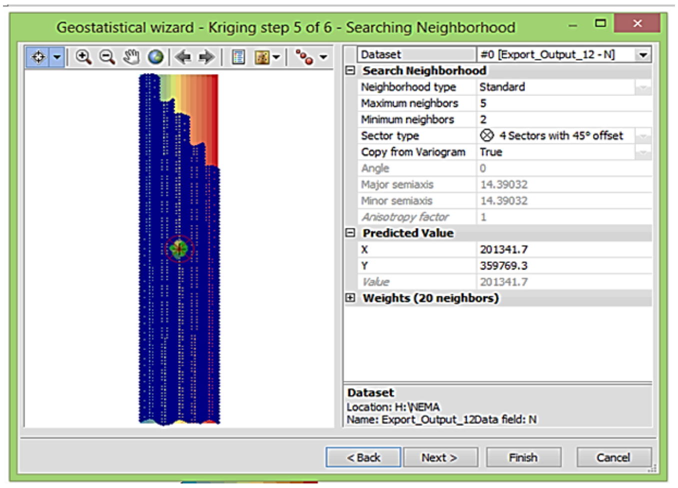

Figure 8: Prediction output for the un-sample dredging lines

Figure 8 shows information such as the maximum value of the horizontal coordinates, the maximum and minimum nearest neighbors' participants, and the sector type and offset, among other things. This projected the dredger's heading adequately.

4. Conclusion

According to the findings of this study, the sectional areas and the volume of dredged material were calculated. Tidal monitoring was carried out to ensure that the water level did not become a source of hindrance for the successful completion of the project. We found the most appropriate predictive interpolation model as "indicator kriging" for the un-sampled location using the geostatistical analyst tool in ArcGIS version 10.3. Finally, the robustness of the GNSS positioning technique has made it much easier to locate the blue peg and provision of navigation guide to the dredger and bathymetry surveys properly.

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