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COMPARATIVE ASSESSMENT OF TECHNIQUES FOR BATHYMETRY DERIVATION FROM MULTISPECTRAL SATELLITE IMAGERY IN THE NILE DELTA COAST-EGYPT

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Abstract Bathymetric mapping with frequent updating is an essential practice for marine monitoring, modeling, and management of active changes in coastal environment. While conventional field survey experience certain limitation in coverage, frequency beside operational difficulties, remote sensing-based bathymetry retrieval witnesses significant development. This research study investigates potential applicability, as well as optimal methodology, for bathymetry derivation from satellite imagery in Egyptian coast, through a case study application in the Nile delta coastal zone. The study presents application with three techniques for satellite - based water depth retrieval; Artificial Neural Network (ANN), Single Band Algorithm (SBA) and multi-band Ratio Transform Model, using LandSat8 imagery. Training alternative ANN networks showed moderate correlation of estimated water depths with ground truth datasets (RMSE of 1.54 and MAE of 1.22). Comparative application with one band versus multiband ratio proved favorable results with the later. Single Band Algorithm (SBA) resulted in considerably poor retrieval of satellite-based water depth, with coefficient of determination (R^2) = 51 %. On the other hand, Ratio Transform technique using two bands in the visible region of spectrum, namely blue and green, gave the optimum derivation of satellite-based water depth that agree with corresponding measured depths with (R^2) 80 % accuracy level. Results proved the advantageous use of satellite-based bathymetry in an important deltaic region with satisfactory performance. Evolving remote sensing technology offers a promise of better informative data with finer temporal, spectral and spatial resolution imageries. Future work is recommended to examine usage of imagery with finer resolution in critical region of challenging conditions.

Keywords Bathymetry, Remote Sensing, Nile Delta Coast, ANN

Introduction

Water depth mapping is an essential component for marine studies; modeling, planning and management. Bathymetry has a fundamental effect on energy conversion, wave propagation, current direction, safe navigation, spatial variability in surf zone circulation and sediment transportation in coastal zones [1-7]. With the dynamic nature of coastal zone, regular measurements for bathymetric map are required which are not always readily available or costly attained with gapping in frequency.

Surveys and field works for water depth measurements are challenged with limiting factors; qualified labor, expenses, time, and accessibility, that prevent full coverage with frequent data acquisition and updated knowledge as needed. Meanwhile, remote sensing technology is becoming a powerful tool in many fields of environmental and water resources management [8]. Various applications proved the effective role to add, enhance and expand data collection capability. Approaches addressed retrieving water depth using remote sensing acknowledged advantageous over the conventional hydrographic survey results in covering broad, more detailed areas with water depth up to 25 meters [9], while more potential are expected with the ever-advancing satellite resolution capacity [10].

Reviewed literature shows various approaches and applications that address processing of active/passive-based remote sensing reflectance to extract water optical properties and shallow-water bathymetry. Jupp [11] introduced an algorithm for derivation of bathymetry map by defining Depth of Penetration (DOP) zones, then interpolating gradual depths within each DOP zone. Early published empirical multispectral technique was used to retrieve bathymetry with certain limitation of assuming constant water clarity and homogenous substrate structure [12]. Later, similar yet inverse technique was used to map variability in bed cover features using algorithm with selective wavelength bands ratio that is suggested to have insignificant difference in overall water attenuation coefficient [3, 13]. Assuming that horizontal mixing would overcome variability in water optical properties was then modified to use remotely measured reflectance in mapping water depth while considering water column optical properties and bed type structure [4, 14-16]. Recently, Li *et al*. [17] presented another approach for wave-based bathymetry retrieval, while avoiding ground truth water depth measurements.

A popularly used method of water depth estimation by means of log-Linear algorism between detected multi-band reflectance and corresponding water depth were proposed to overcome bed cover and water column variability [3-4]. Stumpf *et al*. [16] presented an algorithm using reflectance ratio transform technique for mapping shallow-water bathymetry. Through application, benefits was demonstrated in retrieving depths of further deeper water (>25 m) unlike the linear transform algorithm presented earlier. It has been also argued the ratio transform method has fewer empirical coefficients required in tuning with ground truth data; also certain benthic stability over broader geographic areas is achieved. Through a case study area in china, Deng *et al*. [18] showed successful application for bathymetry mapping by applying the developed ratio transform model of Stumpf *et al*. [16]. The study also discussed the use of two different imagery sources, namely; DigitalGlobe Quick Bird and LandSat-7 ETM+ multispectral images, for overcoming technical problems with satellite remotely sensed imageries. In 2012, Doxani *et al*. [14] presented an application of linear bathymetric model in northern Greece coast, processing selective spectral bands of high spatial resolution (Worldview-2 image) with satisfactory results.

The nonlinear multidimensional nature of the relationship between water depths and remotely observed reflectance was addressed also with black box-based technique. Recent research studies [19-20] proposed Artificial Neural Networks (ANNs) algorithm to estimate shallow water depth. ANNs allow investigating different combinations of spectral bands so that targeted information about water depth are found without bed cover and water column properties. Similarly, other researchers applied ANNs, using various tempo-spatial/spectral remote sensing imageries in different study areas [21-23], and offered good bathymetric assessment retrieval, provided that an adequate field data is available. While proved successful, yet this method essentially require considerably large amounts of ground truth data.

In Egypt, Vanderstraete *et al* [24] presented an application for mapping bathymetry of coral reefs using ASTER infrared images through a case study in the Egyptian Red Sea Coast (Hurghada). Results, while considered preliminary with need to further investigations, showed general featuring of reef topography of the area. More recently, Moawad [25] also presented a study in Red Sea Coast, integrating data sets in a GIS environment; historical topographic map sheets, SRTM DTED, LandSat images, and shipboard depth soundings combined with satellite-based gravity data. Results found with coarse resolution enough for major characteristics of submarine land form structure (e.g. submerged deltas, valleys, shelves, canyons). Author expressed the need for higher resolution data to get smaller-scale features such as bathymetry estimates. Also, Abileah and Vignudelli [26] presented a study using remote sensing data in monitoring characteristics of the strategic Lake Nasser reservoir-Upper Egypt (south). LandSat and radar altimeter products were used to evaluate the lake surface area and water levels. In addition, approximate bathymetric data was assessed, as byproduct, based on fine tuned in-sit measurements, water level, surface area and reservoir capacity. Authors showed the beneficial use of remote sensing in regular monitoring of changes in reservoir capacity for lake Nasser. In north of Egypt, the importance of deltaic coastal lake of Burullus has also triggered studies addressing the use of multispectral imagery in retrieving shallow water bathymetry [27].

While remote sensing approach offers alternative solution than conventional measurement methods, the choice between airborne-based and satellite-based technique is mainly based on study purpose and available financial resources. Airborne-based technique provide high-resolution, finer scaled data, yet potentiality is compromised with excessive cost that usually faced with budget constraints as well as coverage limitation and deployment issues [16, 28-29]. Meanwhile, reviewed case studies proved that satellite-based technique successfully deriving general patterns of bathymetry within the top 25 meters of the water column. Therefore, this research study intent to present an application of remotely sensed bathymetry using LandSat data that is easily accessible and freely available.

Reviewed applications of remote sensing-based provide successful results, yet with empirical relationships that are generally site specific [16, 30], and no certain methodology or technique is considered optimal for all conditions and locations [31]. Therefore, this research study presents an application in the Egyptian Mediterranean coast to demonstrate potentiality of deriving bathymetry from satellite imagery; and evaluate feasibility versus reliability in filling gaps in sparse field data with more frequent updating. Three techniques for water depth retrieval are investigated; Single Band Algorithm (SBA), ratio transforms model and Artificial Neural Networks (ANNs). Results prove successful applicability of the ratio transform model in bathymetry retrieval with reasonable accuracy.

Materials &Methods

Study Area

The study area selected for applying the satellite-based bathymetry technique is the Nile delta coastal zone, extend over 110 km north of Egypt, that is located between 31˚ 26′ to 31˚ 43′ N latitude and 30˚ 29′ to 31˚ 34′ E longitude, figure 1.This deltaic coastal area is witnessing active developments and having importance for shoreline stability, sediment transport monitor, and ensured safe navigation and recreation activities. Therefore, the Coastal Research Institute (CoRI) of the Egyptian National Water Research Center carry out regular profile measurements, yet with certain limitation in extent coverage both along and in deep water.

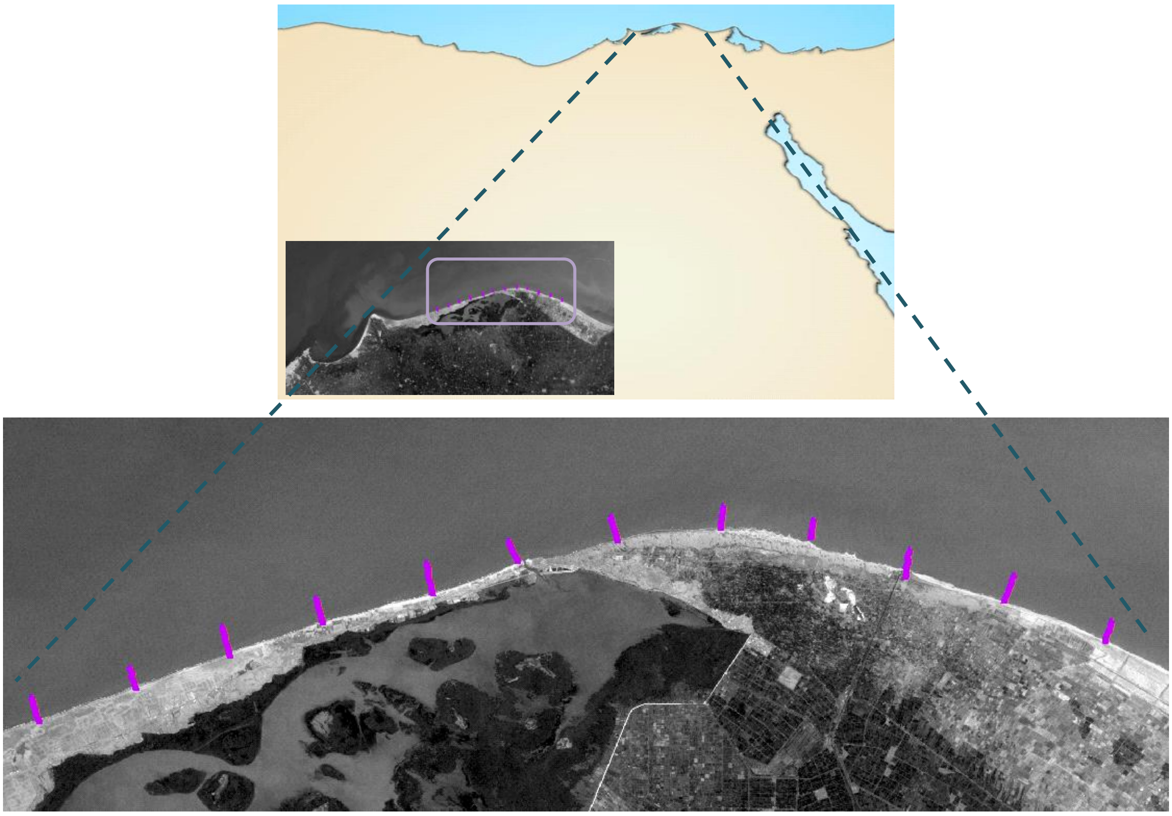


Figure 1: Study Area-Nile Delta Northern Coast& Ground-Truth Profiles

Principally, the algorithm used to translate remotely sensed light reflection into bathymetric information is based on attenuation mechanism. While travelling through the water column, light intensity decrease proportionally to distance, governed by the Beer's exponential law of energy transmission [9, 16], expressed as:

$I_d = I_0 \, e^{-Dk}$ Equation 1

Where, I_d is reflected light intensity, I_0= incident light intensity, *D is depth of water* and k = attenuation coefficient, which is a function of band wavelength, sea bed cover, and water column properties.

Literature shows increasing developments in bathymetry derivation process. Among most popular techniques, [3-4] used natural logarithm-transformation to linearize the relationship between water depth and spectral reflectance or radiance, as well as including multiple bands in the calculation process to overcome the effect of column property and sea floor cover heterogeneity. The Linear transform function is given as;

$D = a_0 + a_i\,[\mathrm{Ln}[R(L_i) - R_{deep}(L_i)]] + a_j\,[\mathrm{Ln}[R(L_j) - R_{deep}(L_j)]]$ Equation 2

Observed reflectance/radiance over optically deep water in band i&j ($R_{deep}(L_{i\&j})$) is subtracted from surface reflectance/radiance in corresponding band ($R(L_{i\&j})$) in order to to exclude the observed radiance from external reflection over water surface and atmospheric scattering. The empirical coefficients (a_0 , a_i, a_j) are then tunable with ground truth data to drive the water depth (D). Later, a rather simplified functional representation is introduced by stumpf *et al* [29] that relates water depth to the ratio of reflectance in two bands "ratio transform model" using less required empirical tuning with only two unknown coefficients. Rationale of this model was based on that within visible part of the spectrum, each band have different absorptions level. Therefore, received reflectance from band with higher absorption (e.g. red band) will decrease proportionally faster than the band with lower absorption (e.g. blue band). Consequently, the transformed ratio of these two bands (blue and red) will increase, which would implicitly compensate for variability in sea floor cover. Accordingly, the change in ratio with water depth is much pronounced than that caused by change in bed cover reflectance. Therefore, the suggested band ratio, tuned with ground truth measurements, would relate to depth independently from sea floor cover [16]. Similar concept is also supported in 2006 by Lyzenga *et al*. [15], showing confidence in developed multi-band algorithm for overcoming heterogeneity in sea floor cover as well as water column properties, while achieving fairly accurate water depth determination. The developed ratio transform model of Stumpf and *et al* [16] in 2003 is given as follows:

$D = C_1 \left(\frac{\ln R_i}{\ln R_j} \right) - C_0$ Equation 3

Where;

R_i and R_j = the received reflectance/radiance value for bands i and j

C_1= a tunable coefficient to scale band ratio to depth

C_0 = an offset value when water depth (D) = 0

This ratio transform model [16], with different combination of band pairs, was used in this study as one of the three techniques considered in investigating applicability as well as result quality. To compare results between using single band versus multispectral band combinations, Single Band Algorithm (SBA) was also examined using the most penetrating blue band natural logarithms, acknowledging the nonlinearity of water depth-reflectance relationship. The third technique was selected based on successful applications reviewed in other coastal regions of the Artificial Neural Network [19-23]. Potentiality in retrieving bathymetry of the Nile delta coast with satellite products was tested in the NeuroSolutions7 environment, multilayer perceptrons (MLPs) feed forward networks, while using different combinations of input bands and network structure. Data sets constructed with depths from available observed data and LandSat multispectral reflectance values and were divided for learning/training process, testing and cross-validation phase. Selection of best network structure and input bands was determined based on the least error.

The study considered four bands of LandSat imagery LC81770382013206, passed over the Nile delta region on 25th july, 2013, (table 1).

Table 1: Spectral Bands for LandSat-8 OLI

Spectral Region		Spectral Bands (μm)
Blue	band 2	0.452–0.512
Green	band 3	0.533–0.590
Red	band 4	0.636–0.673
NIR	band 5	0.851–0.879

Generally field measurements are not acquired simultaneously in the exact satellite overpass timing and observations are selected to the nearest corresponding time. While LandSat satellite visiting intervals are 16-day, yet not all imageries are readily usable due to haziness and other operational constraints [26]. The ground truth datasets used were obtained from the Coastal Research Institute (CoRI) regular profiling during seasonal surveys in (September-November) 2013, using 12 profiles ground truth measurements of water depth. The depths were corrected for recorded tide at that particular time. The remotely sensed spectral reflectance data and ground survey data (ground truth) were then used in the investigated algorithms.

ERDAS IMAGINE and ArcGIS Software were used to perform satellite imagery pre-processing; atmospheric correction, sun glint removal, dark pixel subtraction, multispectral technique analysis as well as result demonstration purposes. Land was masked out from the satellite imagery to distinguish between land and water for analysis of reflectance within the water area. Accuracy level of predicted water depth from the considered techniques, with reference to corresponding observed data, was assessed using root-mean-square error (RMSE), mean absolute error (MAE) and/or correlation coefficient (r).

Results

Artificial Neural Network (ANN)

Various input band-combinations and network structures have been tested to compare results and decide best representation with fitness degree between predicted water depth versus available datasets. In each trial, 80% of data was used in the learning process and the rest 20% was used for validation/testing process. Using three-band inputs from the visible spectrum to one hidden layer neural network gave worst results, with Root Mean Squared Error (RMSE) of 1.86 and Mean Absolute Error (MAE) of 1.63.The best results, yet still fairly poor in accuracy, were achieved by training ratio of band 2 (blue) and band 3 (green) natural logarithms; giving RMSE of 1.54 and MAE of 1.22 (figure 2). Notably, the black-box non-linearity nature of the ANN technique showed no significant effect on prediction accuracy (RMSE 1.53 and MAE1.21) when using the blue to green band ratio without logarithmic transform. While the ANN results was not satisfactory enough, yet gave indication of possible band combination best related to water depth representation.

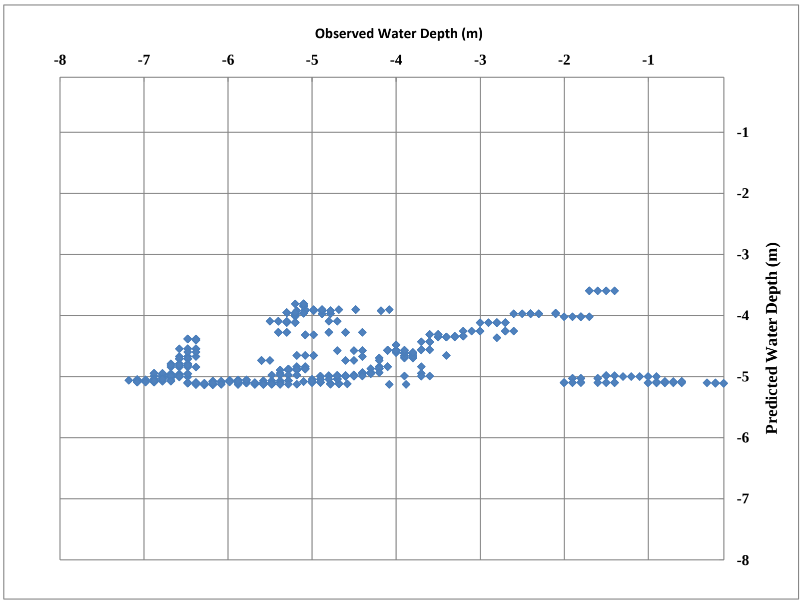


Figure 2: Example results of ANN estimated versus observed water depths

Single Band Algorithm (SBA)

The Single Band Algorithm (SBA) was applied using the blue band, band (2) of the LandSat-8 Spectrum, with wavelength range of 0.452–0.512 µm. The blue band was selected on basis of being considered the most penetrating into water column. Overall accuracy of derived water depth, in comparison to ground truth, was considered insufficient with coefficient of determination (R^2)=51%. The algorithm results showed misrepresentation, with amplified discrepancy in the very shallow part of the Nile delta coastal region under investigation, figure 3. This could be resulted from near shore benthic activities; sea floor and/or water quality heterogeneity effect that is pronounced when using single band in bathymetry retrieval process.

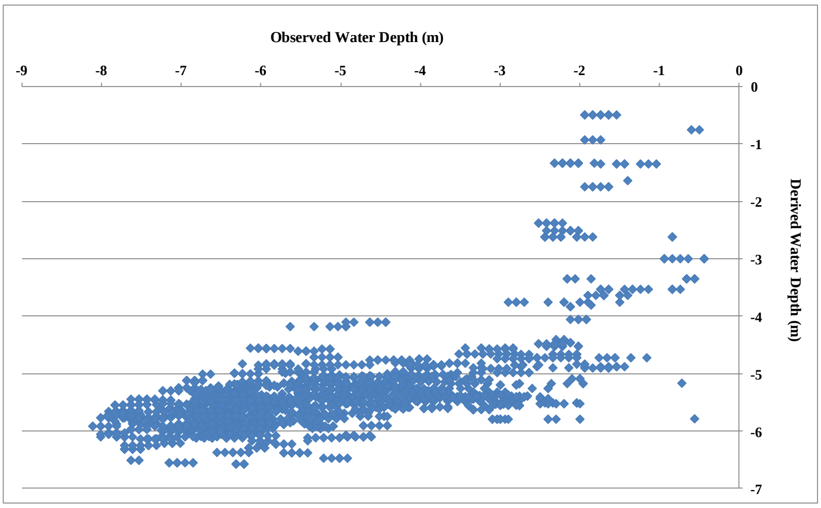


Figure 3: Retrieved water depths using blue Single Band Algorithm (SBA) versus Measured water depths

Ratio Transform Model

The technique of retrieving water depth with transformed ratio of two bands of the LandSat imagery spectrum was applied, while considering different pairs. Results obtained with reflectance logarithmic ratio of band 2(blue) and band 3(green), give best agreement of satellite-based derived water depth with measured bathymetry profiles. Figure (4) presents scatter plot of ground truth bathymetry versus blue-green band ratio model results, with satisfactory fitting (R^2 = 80%). Further statistical analysis of results showed that absolute difference between ground measured and remotely sensed-bathymetry does not exceeding 1 meter for 73% of the time, figure (5). LandSat -based retrieved bathymetry is illustrated in figure 6a, while detailed isobaths in focus area of interest is shown in figure 6b.

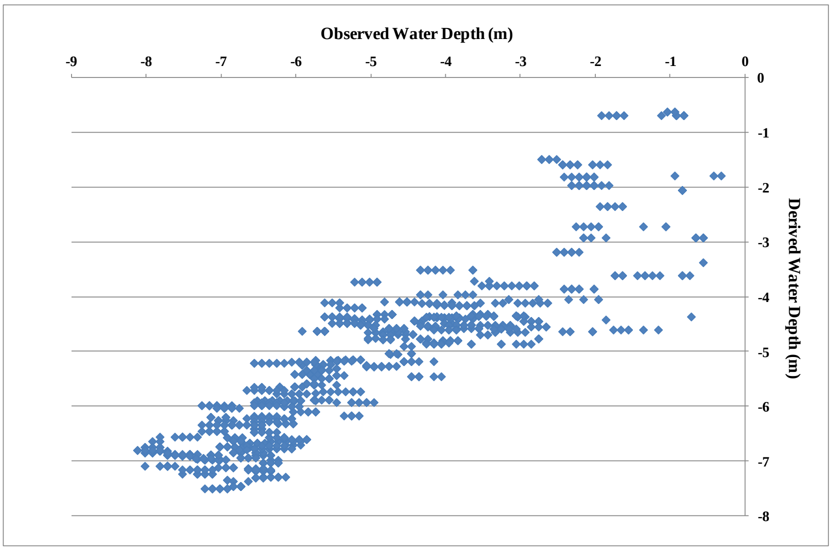


Figure 4: Observed dataset versus satellite-based water depth using Blue-Green transformed ratio

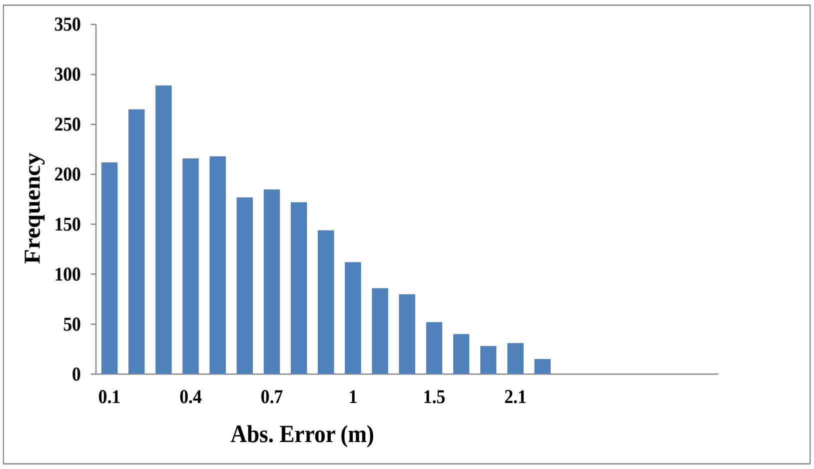
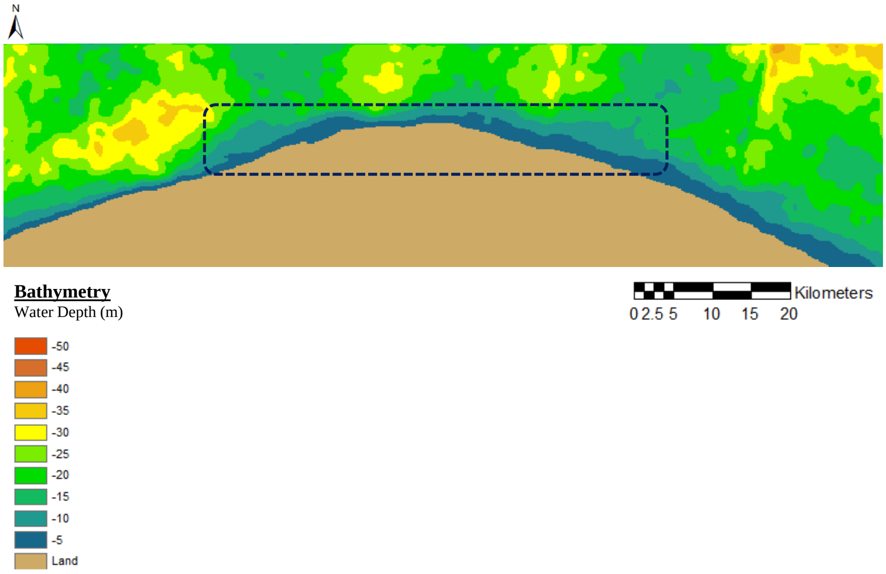


Figure 5: Histogram of absolute difference between satellite-based versus observed water depths

(a)



(b)

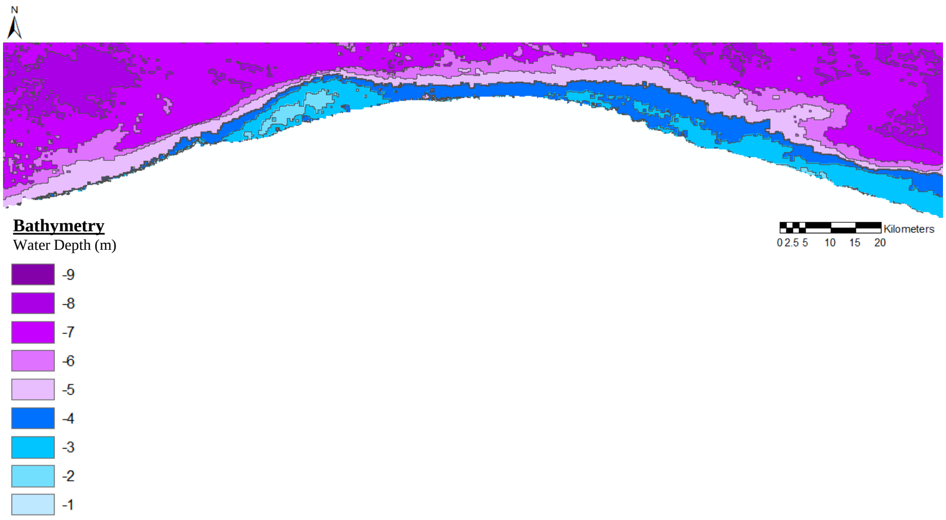


Figure 6: LandSat -based retrieved bathymetry for the study area with ratio transform model

(a) Water depths up to -50 meter

(b) Detailed isobaths in focused coastal strip, 1 meter interval

Conclusions & Recommendation

Mapping bathymetry is a defining factor in studying, monitoring and managing active changes in coastal environment. In Nile delta coastal zone, bathymetric information is a basic requirement for inter-related researches on hydrodynamic processes, benthic environment, water quality...etc. Meanwhile, conventional field surveys are customarily faced with certain limitations with finance, time and operational constraints, as well as occasional difficulty in accessibility, which create wide gabs in measurement processes. In recent decades, remote sensing-based techniques have witnessed remarkable development in the field of submarine applications, in general, and bathymetric mapping in particular. Approaches of remotely sensed bathymetry algorithm are principally based on imperial relationship link radiance in multispectral imagery with ground truth, and are acknowledged to be site specific and non-transferable to other region.

This research study investigated, through a study area in the Nile delta coastline with the Mediterranean Sea, potentiality and reliability level of retrieving water depth using freely available LandSat satellite imageries. Three techniques of deriving bathymetry have been applied using processed imagery in correspondence with ground truth data offered by the Coastal Research Institute (CORI); Artificial Neural Network (ANN), Single Band Algorithm (SBA) and multi-band Ratio Transform Model. Results obtained from various ANN network structures and band combinations indicated best depth retrieval by training logarithmic ratio of band2 (blue) and band3 (green); with RMSE of 1.54 and MAE of 1.22. While the ANN results were considered with moderate accuracy in water depth derivation, yet implied best band combination influence water depth representation.

Comparative application with one band versus transformed multiband ratio was presented to highlight difference in remotely derived depths. Single Band Algorithm resulted in considerably poor retrieval of satellite-based water depth, with coefficient of determination (R^2) = 51 %. Results showed pronounced discrepancy that is mostly justified by near shore benthic activities; sea floor and/or water quality heterogeneity impact. A deficiency that is overcome by using multi-band ratio. Ratio transform technique using two bands in the visible region of LandSat 8 spectrum, namely blue and green, gave the optimum derivation of satellite-based water depth. The results show that the proposed method has high performance, and the derived water depth agree with corresponding measured depths with (R^2) 80 % accuracy level.

Results proved the advantageous capability of deriving satellite imagery-based bathymetry in an important deltaic region of Egyptian Mediterranean coastal zone with satisfactory performance, using fraction of conventional field survey requirements. Potentially, remote sensing applications can be employed in creating long-term database, frequently updating bathymetric estimations, monitoring changes with expended coverage and frequency of data acquisition, while decreasing field survey trips.

With the continuously evolving remote sensing technology and imaging platforms, in a remarkable pace, it is expected to get better informative data with higher temporal, spectral and spatial resolution imageries. Future research work is recommended to compare other types of multispectral/ hyperspectral imagery with finer spatial/temporal resolution to examine potentiality in more sensitive regions with certain challenging condition.

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