Journal of Urban and Environmental Engineering
E-ISSN: 1982-3932
celso@ct.ufpb.br
Universidade Federal da Paraíba
Brasil

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Journal of Urban and Environmental Engineering, vol. 6, núm. 2, 2012, pp. 86-93
Universidade Federal da Paraíba
Paraíba, Brasil

Journal of Urban and Environmental Engineering, v.6, n.2, p.86-93

ISSN 1982-3932
doi: 10.4090/juee.2012.v6n2.086093

Journal of Urban and Environmental Engineering

www.journal-uee.org

A STUDY ON THE EFFECTS OF TIDE ON SEDIMENTATION IN ESTUARIES OF THE NIGER DELTA, NIGERIA

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Received 15 July 2011; received in revised form 01 June 2012; accepted 10 November 2012

Abstract: Estuaries in the Niger Delta-Nigeria are influenced by tidal currents and wave actions due to their proximity to the Atlantic Ocean. Tidal current provides the energy required to move sediments in and out of the estuaries from the seashores, while wave actions curtails the deposition of sediments at the bottom of the estuaries as the bed get shallower, resulting in the modification and long-term regulation of siltation through erosion or accretion. The interaction between estuaries bathymetric shapes, tidal currents and wave actions can only be fully understood through analytical or mathematical relationships. Analytical methods are less accurate in predicting future tides, while none of the existing mathematical relationships can accurately predict tidal behavior in the Niger Delta region due to the fact that parameters governing tidal actions vary from region to region, hence the need for this study. This study shows the behavior of the estuaries in response to variation in tidal heights, currents and wave actions through mathematical modeling, a knowledge which is useful in planning and timing of marine activities that requires pre-knowledge of tidal levels, direction and current velocities. The models were formulated and calibrated using parameters generated from the hydrographic, hydraulics and geotechnical investigation, including local field observations and measurements conducted within the study area. Soil samples taken from the area are composed of peat, organic clays, silty clays and sand. Peat constitutes the dominant soil which is locally known as 'chikoko' with high compressibility and color ranging from dark brown to dark gray and texture from soft to firm. Typical bed material size (D_{50}) is approximately 0.2mm. Tides in the region are mostly semidiurnal with tidal prism ranging from 0.4 to 1.5m. The tidal strength is strongest at the inlets and decreases with distance inland. The depth of the estuaries is controlled by the strength of the tidal currents. Areas very close to the ocean with stronger tidal effect are very deep; while shallow canals and creeks predominates the hub of the estuaries. The results obtained using the present models compared favorably with the field measurements. Average correlation coefficients of 0.9 were obtained in some cases. The results showed that the estuaries erodes, accretes, or remain stable, depending on the rate at which sediment is supplied or removed from them.

Keywords: Sediments; tidal currents; mathematical models; bed level changes; tide predictions.

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INTRODUCTION

Estuaries and littoral zones form part of coastal formations, containing abundant natural resources that are beneficial to humanity. Estuaries are the meeting place for land drainage and the sea; they are greatly affected by storm surge, wave actions, geological changes, wind, sediment loads, tidal currents and other coastal phenomena. They are vulnerable to human interference and therefore require careful management to maintain them in good shape. Change in water level caused by 'tides' and 'surges' is a significant factor in sediment transport. The interaction between tidal currents, wave actions and sediment loads are essential conditions for coastal engineering planning, design, and construction, they are of great importance in the determination of state of estuaries (Longhurst, 1964).

Sedimentation process influences many situations that are important to humanity; silt deposition reduces the capacity of reservoirs, interferes with harbor operation and closes or modifies the path of watercourses, while in rivers and coastlines, sediment movement forms part of long-term pattern of geological processes. Estuaries and sea shores erode, accrete, or remain stable, depending on the rates at which sediment is supplied or removed from them (Bell *et al.,* 2000). Increased rate of siltation is noticed in areas of the estuaries where this interaction has been greatly altered or affected.

At higher water levels, waves can attack and erode a greater range of elevations on the estuaries bank profile (Allen, 1964). Tidal currents determine estuaries bathymetric shapes by modifying the existing morphology through erosion or sedimentation along the course. Tidal currents are very important factors in sediment transportation along the Nigerian coastline and Niger Delta estuarine waters. The tides, off-shore Nigeria generally approached from the southwest and is of the semi-diurnal type (Allen, 1964). There are two tidal circles per day with approximately six hours return period. The tidal prism varies between 1 to -1.5 m and in some cases, can be more than 2 m above lowest water level. Tidal current are strongest at the inlets and could vary from about 2.0 m/sec to 5.0m/sec (Dublin-Green *et al.*, 2006) and decreases with distance inland. The ability to predict variation in tidal level, velocities and direction assists in timing and planning of tidal driven projects e.g. positioning of swamp rig or lay barges in oil drilling operation. Knowledge of variation in tidal level, heights and tidal direction also assist in timing and planning certain works that requires the prior knowledge of tidal conditions. Knowledge of tidal heights variation is also very important; since many Estuary Rivers and harbors have shallow bars which will prevent boats with significant draft from entering at certain states of the tide.

The aim of this study is to develop a more accurate method of tide prediction in the Niger Delta region Nigeria. Arthur Doodson was the first to devise mathematical methods to analyze tidal motions in shallow waters, oceans and lakes. This is an extension of study of tide height by harmonic analysis initiated by Laplace, William Thomson and George Darwin. His analysis is based on periodic function in terms of Fourier series, over a period of observation covering a time interval (Doodson, 1921). Due to the complexity and time involved in generating tide heights and current tables by navigators, his analysis became the international standard for the study of tides and the production of tide tables through the method of determination of Harmonic Elements by least-square fitting to data observed at each place of interest.

Doodson method is based on association of the astronomical phases-using observations made at one time with different astronomical phases, to predict happenings decades away.

The principle is based on the following mathematical relationships:

$$A(t)=A\left[1+A_a cos\left(W_a t+P_a\right)\right] \quad (1)$$

where H = tidal height relative to a known datum (m), A = amplitude, A_a = size of the variation around the average value of A, Wa = angular speed of this variation, P_a = phase with regard to the time t = 0.

In the case of tidal current, analysis of the situation is more complex. The frequency (or period) and phase of the forcing cycle is known from astronomical observations, and, there is not just one of such frequency. Relevant periods are the time of the earth's revolution, the completion of the moon's orbit around the earth, and the earth's orbit around the sun.

Nigerian Institute for Oceanography and Marine Research (NIOMR) and the department of Geo-informatics and surveying, University of Nigeria, Enugu campus use analogue and acoustic tide gauges in monitoring and recording tidal data in the region, in order to generate tide heights and current tables for navigational uses with stations at three different locations in the Niger delta region namely: Bonny, Escravos and Akaso, located within latitudes 4° 27′, 5° 34′ and 4° 19′ North and Longitudes 7° 11′, 5° 11′ and 6° 02′ East respectively (Ojinnaka, 2005). This method is less accurate in predicting future tide levels when compared with mathematical models

Many other methods and mathematical relationships exist for tide prediction, but none of these relationships can accurately predict tidal behavior in the Niger delta region due to the fact that parameters governing tidal behavior vary from region to region. Hence the need to develop a mathematical relationship that can accurately predict tidal behavior in Niger delta region based on prevailing parameters.

MATERIALS AND METHOD

The study area – Ekulama, falls within the mangrove swamp environment of the Niger Delta (**Fig. 1**); it is underlain by recent deltaic sediments and covered by medium dense to dense halophytic mangrove vegetation. It lies within coordinates, 460290 mE 479970 mE and 55246.734 mN – 69750.484 mN of the oil rich Niger Delta coastal formation and covers approximately 285.43 km² (**Fig. 2**). It is bathed by San Bartolomeo River and Sego creek, with majority of the landscape mostly under water. The bulk of the sediments that enter the estuary are supplied by flood waters from upland via the Niger and Benue rivers, in addition to the huge amount of organic materials generated by the mangrove forest. River Niger with a total drainage area of about 1,100 km² transports approximately 25 mg/l of sediment into Niger delta estuaries (Gibbs *et al.*, 1987). Increasing human activities in the area through oil and gas exploration and exploitation also accounts for a great percentage of sediment sources to the estuary. The soils in the area are in essence, composed of peat, organic clays, silty clays and sand. Peat constitutes the dominant soil which is locally known as 'chikoko' with high compressibility and color ranging from dark brownish to dark grayish and texture from soft to firm. Typical bed material size (D_{50}) is approximately 0.2 mm (SPDC, 2005). This paper considered the effects of tides and sediment loads on estuaries, with Ekulama 19 access canal, as a case study.

Part of the data obtained by Shell Petroleum Development Company of Nigeria SPDC, through elaborate field studies of the estuary canals and it's environ were used in this report. The field data collections were designed to ascertain the behavior of hydrographic, hydraulic and geologic processes occurring in the estuaries and to recover bank and riverbed sediments for laboratory analyses.

All the tests were carried out in accordance with BS1377 methods of test for soil for civil engineering purposes. The soil investigation is in accordance with accepted geotechnical engineering practices; the conclusions and recommendations reached in this report is based on the data obtained from soil borings and tests performed. In addition, information gathered from previous pre and post dredging surveys was analyzed in other to reach the conclusions made in this report.

Fig. 1 Map of Niger Delta (Southern Nigeria) showing Ekulama.

Fig. 2 Map of Ekulama showing Well -19 Access canal - Study area.

The following operations were carried out during the field investigation: travers, bathymetric and hydrographic surveys, current velocity and tidal gauge measurement, water column and riverbed sediment sampling, soil borings and sampling.

Bathymetric Survey

Bathymetric data were generated to determine the riverbed topography and bank slope angles using Raytheon Echo sounder. The echo sounder operates by sending acoustic signal to the riverbed through a transducer, which also receives a return signal from the riverbed. The time interval between these two actions is converted electronically to give the depth of the riverbed with reference to the water surface after corrections.

Traverse survey

Travers survey was carried out in order to establish geometry of the canals. The survey was carried out on existing survey points to provide controls along the access of the canal. These controls were used to detail the canal and all existing features within the area to be surveyed. Horizontal angles were measured using Wild

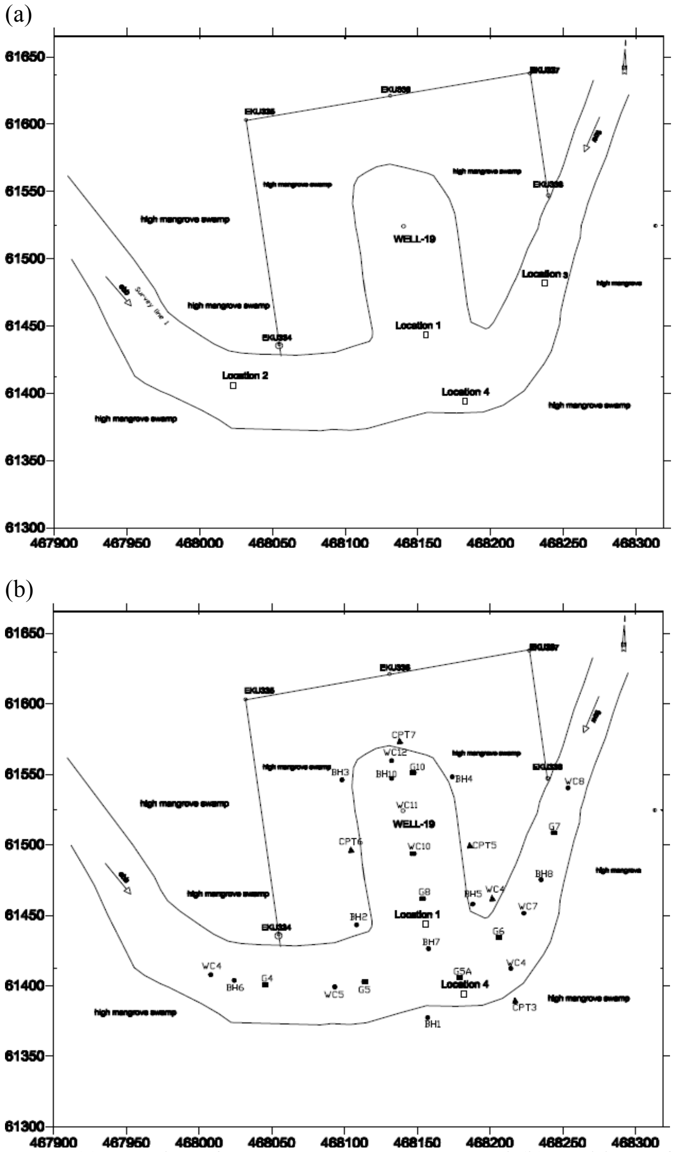

Fig. 3 (a) Locations for current measurements, and (b) Positions of the boreholes, cone penetration test,water column test, and bottom sediment collection.

T2 while distance was measured using Wild d11660 electromagnetic distance measurement (EDM).

Current measurement

Andrea recording current meter (RCM 9) with Acoustic Doppler current sensor 3620 was used in water current measurements. The current meter is self-recording and intended to be moored to measure and record the vector-averaged velocity and direction of the tidal current. The instrument features a newly developed RCM Doppler current sensors as well as sensor for conductivity, turbidity, pressure and oxygen measurements. The data obtained are stored inside a removable and reusable solid stage data storage unit DSU 2990 and read in a computer with DSU reader 2995.

Water column samples

Hanna model H 1001300 multi parameter and data logger was used to determine in-situ, salinity, water temperature, pH value, conductivity and total dissolved solids (TDS) at three depths; surface, mid-depth and bottom levels. This involves the dipping of the probe of the meter directly into the sample in a 2-litre container. The reading for the parameter measured is displayed on the screen of the equipment and recorded.

Hydro graphic surveys

Result of pre and post dredged surveys of the canals in the region from 1992 to 1996 were obtained from SPDC dredging department, from which canal centre profiles, entrance, middle and end cross-sections and bar charts showing sediment distribution along the canal profiles were studied.

Tidal Gauge Measurement

Tide gauges were installed close to the point of observation to measure the water surface elevations, and at the same time record the time of observation. The gauge was a 4m staff, painted and marked in a manner to cover the lowest and highest known depths of water within the study area. Readings was taken at intervals of 10 minutes.

Soil sampling methods

Disturbed and undisturbed soil samples were collected from the bank and bed of the Ekulama well 19 access canal (study area), through boring at a depth of 3 m to 4 m using hand auger at intervals of 0.5 m and when necessary. The samples were fixed on to an adapter, which was screwed either on to the handle or onto extension rod of the auger. The large undisturbed samples were adequately protected against change of moisture content and damage in transit. The samples were placed in tins, tightly packed with sand dust to prevent damage, with the lid of the tins sealed with adhesive tape. A careful record of all the samples taken were kept, indicated on the lids were location position, depth and other relevant data.

Laboratory tests

Detailed laboratory investigations were carried out on representative disturbed samples obtained from the open boreholes for the classification tests and other tests by SPDC consultants, of which some of the results are used in this report. The samples from the boreholes were described visually with respect to color and texture.

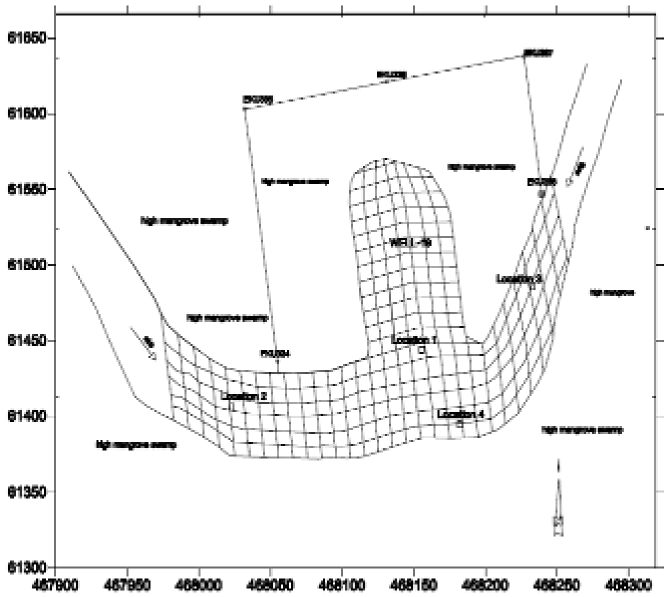

Fig. 4 Geometry/mesh at surface level.

In addition, information gathered from previous dredging, physical examination of the soil within the study reach/depth, geotechnical, tidal gauge recordings and topographical Situation/position of the study area in the Niger Delta coastal flood plain was considered.

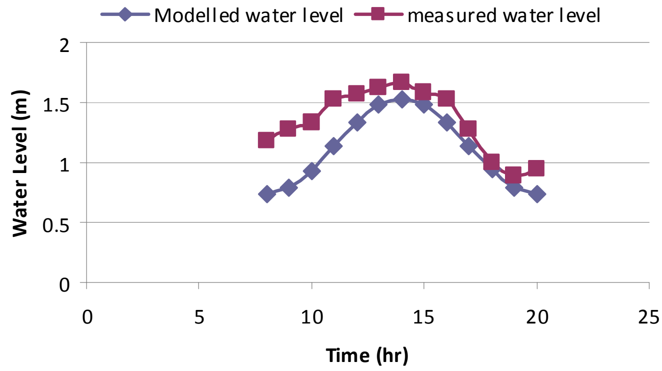

Fig. 5 Comparison of modeled and measured water level at location 1 (day 1).

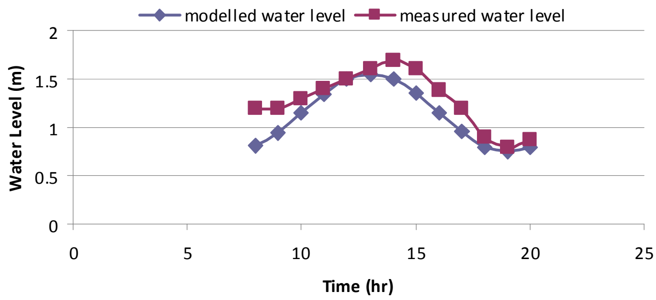

Fig. 6 Comparison of modeled and measured water level at location 1 (day 2).

Ekulama Well-19 access canal geometry /mesh

The study reach is about 500 m long, between 50 to 70 m wide. The main channel depth varies between 2 to 6 m. The domain was made up of square mesh, with h and k units in x and y directions and cross sections taken at every 10m interval while the vertical plane was divided into layers of 0.62 m represented by *L*.

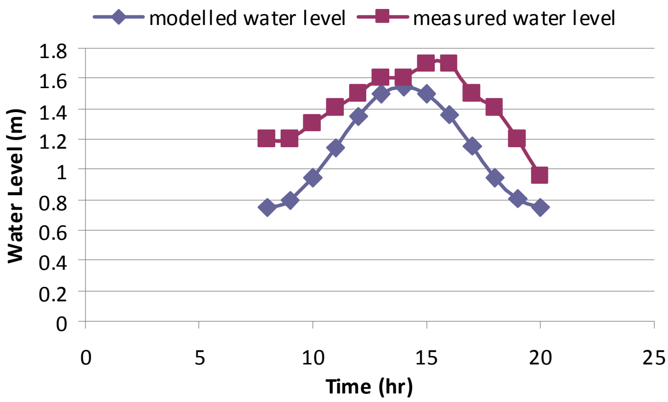

Fig. 7 Comparison of modeled and measured water level at location 1 (day 3).

RESULTS AND DISCUSSION

Variation of water level with time

The following equation formulated by the authors based on local tidal information from Ekulama was used to predict water level at hourly time interval in the Niger delta estuarine Rivers.

$$H_t = H + \frac{\Lambda}{2}\sin\left(\frac{\pi t}{6}\right) \qquad (2)$$

where H_t = water depth (m), H = lowest- low water depth (m), Λ = tidal prism (m), t = time (hours), and $\sin\left(\frac{\pi t}{6}\right)$, represents tidal effects **Eq. (2)** above predicts semidiurnal tides and are valid for regions with approximately 6 hours return period (two tidal circles in a day). It can give accurately a one week prediction and it subject to re-calibration when there is a major change in weather condition, taking into account the rise in global sea level. The results as indicated in **Figs 5−12**, showed a sinusoidal variation of water height with time, with maximum and minimum water levels representing high and lower low water levels.

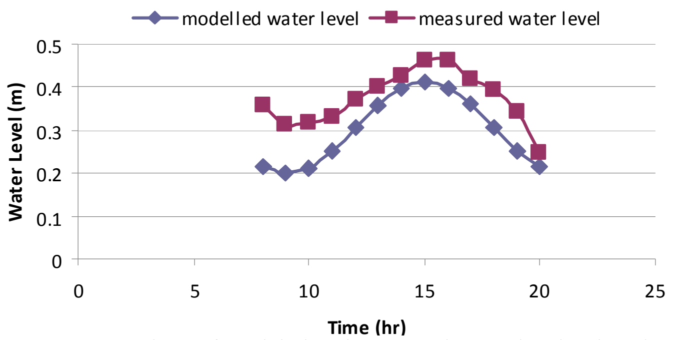

Fig. 8 Comparison of modeled and measured water level at location 2 (day 1).

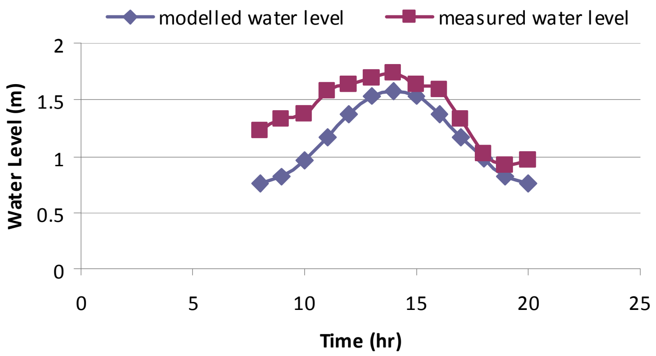

Fig. 9 Comparison of modeled and measured water level at location 2 (day 2).

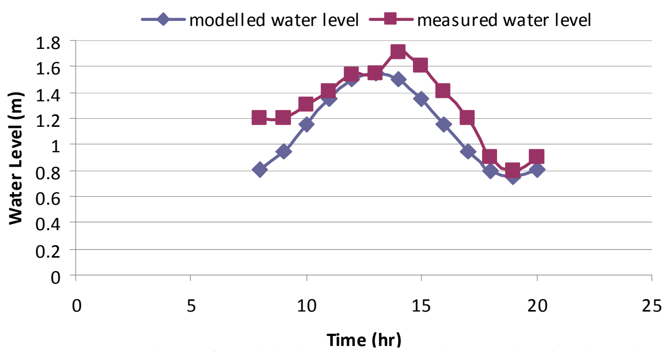

Fig. 10 Comparison of modeled and measured water level at location 2 (day 3)

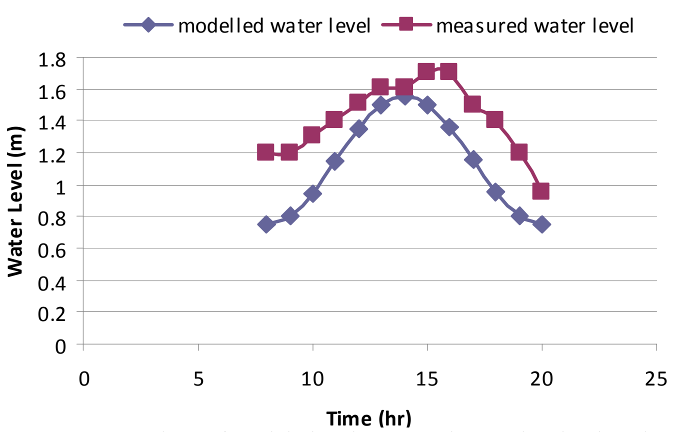

Fig. 11 Comparison of modeled and measured water level at location 3 (day 1).

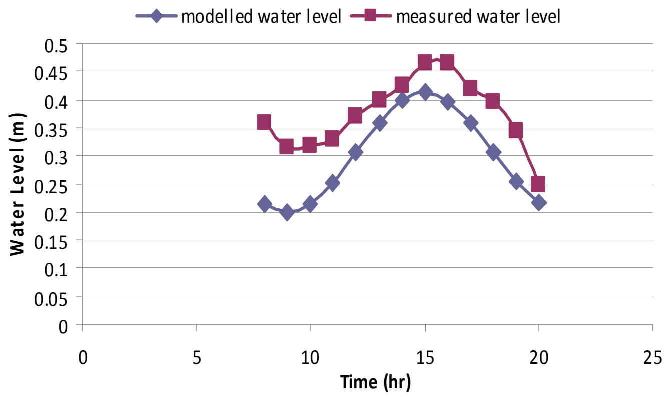

Fig. 12 Comparison of modeled and measured water level at location 3 (day 2).

Variation of tidal velocity with time

The following equations formulated based on the information recorded from current measurement was used to predict the variation of velocity with time:

$$u = u_{min} + u_{ave}\cos\left(\frac{2\pi t}{12}\right) = u_{min} + u_{ave}\sin\left(\frac{\pi t}{6}\right) \quad (3)$$

where u = instantaneous velocity (m/s), u_{min} = minimum recorded velocity (m/s), u_{ave} = amplitude (average velocity) in m/s, and $\sin(\pi t/6)$ represents tidal effects, this is valid for regions with approximately 6 hours return period (two tidal circles in a day). **Equation (3)** above was used to predict the variation of velocity with time at different locations and water depth. The equation is subject to re-calibration within one week or when there is a major change in weather condition, or rise in global sea level. The results after calibration were superimposed with measured velocities at the same locations to give average correlation coefficient of 0.85. The velocity fluctuates in a sinusoidal manner; highest velocities were recorded during ebbing due to the combined effect of high water volume and gravitational pull as shown in **Figs 13** and **14**.

During flow conditions, the velocity is the resultant of gravitational pull/slope and ebb (the effect of the harmonic motions of the earth, moon and sun in relation to each other against the force of gravity). Minimum velocities (slack tide) were recorded during each transition period.

Effects of tidal velocity on siltation

The effect of tidal velocity on siltation was examined by plotting the changes in bed level at a fixed point with time, with the initial bed level as a control datum. Using a modification of equation previously used in formulating the 3-D modeling of sediment transport and

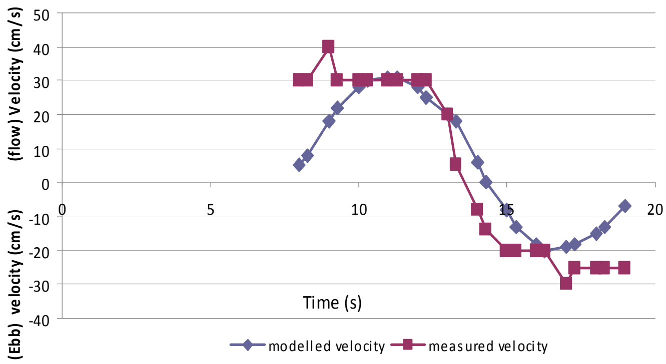

Fig. 13 Comparison of measured and modelled velocity at Location 1 (Surface depth).

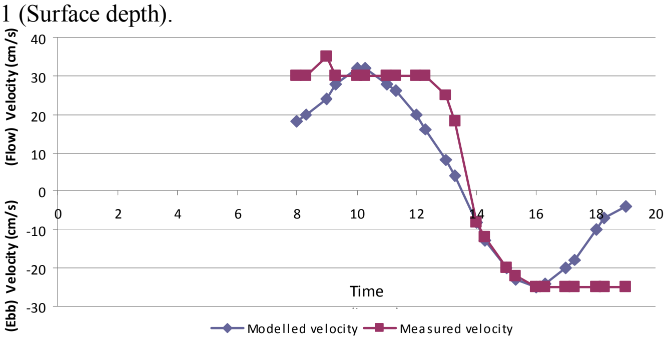

Fig. 14 Comparison of modelled and measured velocity at location 1 (Mid depth).

the effects of dredging in the Haihe Estuary (Wang *et al.*, 2002). The model formulated using was calibrated with field measurements and subsequently used to predict bed level form for Ekulama Well 19 access canal, as shown in **Fig. 15** below.

Bed Level Prediction

The equation of bed level form is:

$$\frac{\partial Z_b}{\partial t} + \frac{C_d}{\gamma_b^1}\left[\frac{\partial c\psi u}{\partial x} + \frac{\partial q_{bx}}{\partial x}\right] f = 0 \qquad (4)$$

where z_b= bed elevation; ψ = 1/h = coordinate transformation; h= water depth below low-low water; u = near zero velocity; c = depth averaged sediment concentration; γ_b^1 = dry weight of deposit per volume $q_{bx} = \frac{S_*}{8} C_d \delta_u$ = rate of transportation of fluid mud layer in x direction $S_* = 0.033 d_{50}^{-0.605}$ = is a coefficient and is empirically given as a function of the median diameter, u = average velocity component in x direction:

$$\delta = H \times 10 - \frac{1}{2.3}\left(\frac{K}{2}\frac{E}{E_*} + 1\right) \qquad (5)$$

in which E is the Composite average velocity, given as:

$$E = \sqrt{\bar{U}^2 + \bar{V}^2} \qquad (6)$$

where E_* is the composite shear velocity given as:

$$E_* = \sqrt{\bar{U}_*^2 + \bar{V}_*^2} \qquad (7)$$

where K is Von Karman constant = 0.41 (Wang *et al.*, 2002), V = user defined dimensionless constant which is location specific (Dike *et al.*, 2010), and C_d = 0.2 for turbulent flows (Rajpot, 2007)

Interaction between bed level and tide actions

The results as shown below indicates that tidal currents provides the steady supply of energy needed to regulate bed elevation and movement of sediments in and out of the estuaries. This is shown by the sinusoidal variation

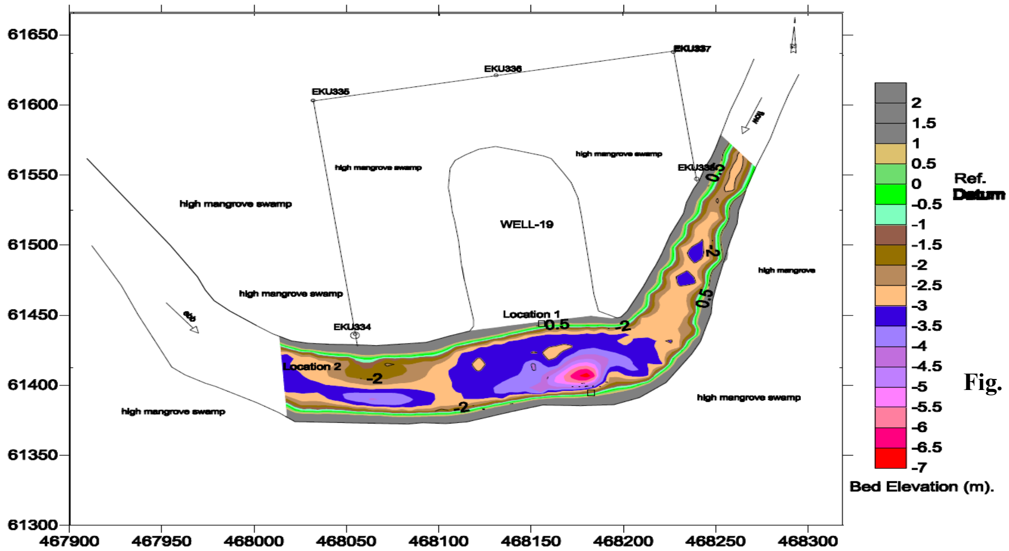

Fig. 15 Predicted Bed Level form of Ekulama Canal 19 (Open river) (Below low water Level - Ref. Datum).

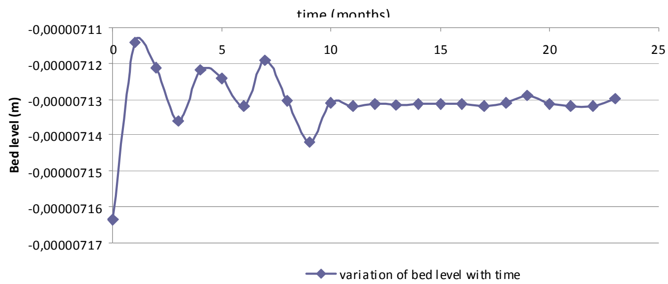

Fig. 16 Variation of bed level with time (up stream station -canal center line).

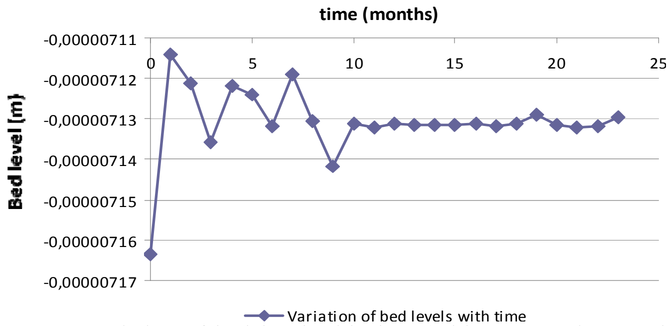

Fig. 17 Variation of bed level with time (midstream station-canal center line).

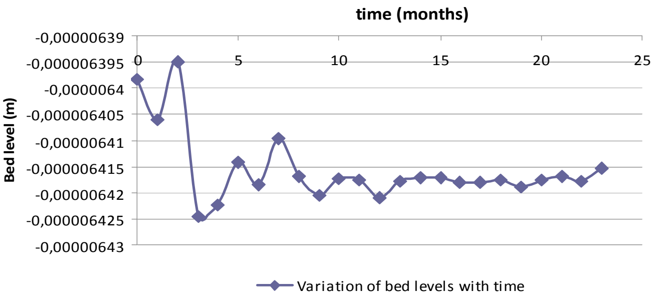

Fig. 18 Variation of bed level with time (down stream station-canal center line).

of bed level with time due to the changes in tidal strength and direction. In the long term, a dynamic balance between the effects of tides, wave actions and estuaries bathymetric shape on sediments input and output regulates sediment build-up as well as maintain the estuaries in a good shape.

CONCLUSION

The Niger Delta Estuaries were found to be controlled by the interaction between tidal currents and sediment loads using a mathematical model. The model showed that the Estuaries erode, accrete, or remain stable, depending on the rate of this interaction. This phenomenon was found to have contributed immensely in the formation, preservation and alteration of the estuarine environment by regulating long-term sedimentation in the region, causing the Estuaries to remain as open-water bodies, even after many thousand years despite all the sediments coming in through the Rivers and the Seas.

Acknowledgment We acknowledge the supports of Shell Petroleum Development Company of Nigeria limited (SPDC), Port Harcourt Nigeria, during the course of this study.

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