*Rev. Ivoir. Sci. Technol., 24(2014) 1 - 11*
*ISSN 1813-3290, http://www.revist.ci*


# VALIDATION OF A TIDAL PREDICTION MODEL FOR IVORIAN COASTALINE: APPLICATION FOR COASTAL VULNERABILITY STUDY

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## ABSTRACT

Seven years of tidal gauge record have been analyzed by tidal analysis and prediction model Utide. This study has showed that the tide predicted by the model and that observed are the closed. It has been also showed that ocean tide increase over the 1982-2014 period in this area. Model output could help filling data gaps which are regularly observed in tidal record and assessing exceptional tidal height which constitutes a threat of coastal area.

**Keywords :** *tide, prediction, coastal vulnerability, ivorian shoreline.*

## RÉSUMÉ

**Validation d'un modèle de prédiction de la marée pour la côte ivoirienne: application à l'étude de la vulnérabilité côtière**

Sept années d'enregistrements marégraphiques ont été analysées au moyen d'un modèle d'analyse et de prédiction de la marée Utide. L'étude a montré que la marée prédite par le modèle se superpose bien à la marée observée par les marégraphes le long du littoral ivoirien (Abidjan). Elle a montré également une tendance à la hausse de la hauteur d'eau sur la période 1982-2014. Les sorties de ce modèle peuvent désormais combler le déficit de données constaté au niveau des enregistrements marégraphiques qui souffrent de beaucoup d'irrégularités et peuvent aussi mettre en évidence les marées exceptionnelles qui constituent une menace pour la zone côtière.

**Mots-clés :** *marées, prédiction, vulnérabilité côtière, littoral ivoirien.*

## I - INTRODUCTION

West African coasts are being degraded and become vulnerable due to human activities including industrialization, population growth, expanding social and economic activities both on land and water and climate change. The Implementation Plan of the World Summit on Sustainable Development places great emphasis on the need to obtain information about the environment as the basis for monitoring its behavior and forecasting the effects of environmental change, so as to provide decision makers with the tools they need to improve and sustain development and to mitigate or reverse undesirable trends or effects. Living by the sea has many benefits. It offers possibilities of trade and travel, and increasingly of water-based recreation. But there are risks. Sometimes high tides and storms combine to flood low-lying coastal region causing local damage. As our cities and our patterns of coastal region development become intricate, we become more and more vulnerable to disaster. In extremes cases the delicate infrastructure of coastal cities may be destroyed. In November 1966, St Mark's Square in Venice was covered by more than 1 meter of water [1].

To predict future changes and the impacts of human activities, it is necessary to have a complete understanding of sea level variation. The first step is to make a measurement of sea level. The measurements of sea level are particularly important because sea level is always changing, for many reasons [1]. Some changes are rapid while others take place very slowly. The main causes of sea level changes are regular and periodic oscillations movements caused by the gravitational forces of the moon and sun. Sea level records are usually dominated by twice-daily oscillations due to the tides, although there are seiches, tsunamis, weather effects and seasonal cycles. The measurements represent also a great challenge because they have a wide range of applications:

*(i) Scientific applications* include research into ocean tides and the space and time-scales of variability in the ocean circulation; studies of the sea level changes which occur as a consequence of climate change; and investigations of geological processes which result in sea level changes. *(ii) Practical applications* include coastal engineering, in which sea level data are needed as instantaneous levels, as well as statistics of extreme levels over long periods; most benefits is using tide energy to produce energy. Short-term measurements, often with real-time data transmission, are needed for ship movements in harbors and ports, for issuing storm surge and tsunami warnings, and for the operation of sluices and barrages. Although these benefits, sea level data in West African coastal countries is limited in size and quality [2]. Most of tide gauges in this region have records spanning a few years while many of them are not operational because it is difficult to maintain them over several years.

Due to the lack of consistent systematic data and the uncertainties in future projections, the West African coastal countries are vulnerable. According to [3], a vulnerable coastline is characterized by low coastal relief, subsidence, extensive shoreline retreat, and high wave/tide energy. Using population criteria of one million people in 2005, [4] identified 19 port cities in Africa which are exposed to coastal flooding due to storm surge. Taking high-end scenarios of social and economic, climate change and non-climate trends, two cities (Lagos and Abidjan) in West Africa contain the bulk of exposure. Given the low wealth and poor development of flood management in West Africa, this existing exposure is of concern as Lagos and Abidjan have growing cities with high population density.

Among these forcing, the tidal futures have a periodic oscillation, measured as the height between successive high and low levels. However, the spring tides could appear as an exceptional phenomenon which could exacerbate the coastal vulnerability. Unfortunately, very few studies are dedicated to tidal analysis and prediction along the Ivorian coast. In addition, sea level time series records are very short and contain many gaps. Float tide gauges are installed at San Pedro and Abidjan harbors since a long time however most of the data are in analogic format or are not accessible. The data used in this study (from 1982 to 1988) are those of the harbor of Abidjan (Figure 1) and provided by the Research Quality Data Set (RQDS) of the University of Hawaii Sea Level Center [5]. In order to fill this gap, it becomes useful to develop model in order to predict the tide based on the available records. The aim of this paper is to validate a prediction model of tidal using coastal in situ data for a coastal vulnerability study in Cote d'Ivoire.


**Figure 1 :** *Location of the tide gauge stations along the Ivorian coast (high panel). Location of the Abidjan – Appontement (in Vridi canal) tide gauge station*

## II - MATERIAL AND METHODS

### II-1. Description of Utide model

The Utide model (Unified Tidal Analysis) package has been developed to make tidal analysis over years up to 2 and also the Matlab analysis function accepts records with times that are uniformly or irregularly distributed and can provide accurate nodal correction results for records with durations of up to 18.6 years [6]. It integrates the method of analysis of prior tidal package (e.g. t-tide [7] and r_t-tide [8]). Another particularity of this model is its capability to analyze two-dimensional data such tidal current, which couldn't make other past tidal model. Utide model can be used to treat one or two-dimensional input data. The model equation in complex form [9] is defined by ***Equation 1.***

$$x^{mod}(t_i) = \sum_{q=1}^{n_{allc}} \left(E_{iq} a_q^+ + E_{iq}^* a_q^-\right) + \bar{x} + \dot{x} \times \left(t_i - t_{ref}\right) \qquad (1)$$

Where:

- $\bar{x} = \bar{u} + i\bar{v}$ represents the respective means of the two perpendicular raw real components of current;
- $\dot{x} = \dot{u} + i\dot{v}$ represents the trend two parameters, which have been defined above, if is included in the model as coefficient;
- $t_{ref} = \left(t_1 + t_{n_t}\right)/2$ is a time central among the raw input times, and here it is defined as the average of the first and last raw input times;
- The complex conjugate $a_q^+$ and $a_q^-$ represent the constant complex amplitudes for each component q that rotates counter-clockwise and clockwise in time;
- The counter-clockwise and clockwise rotating elements those the complex coefficients multiply, take exponential forms $E_{iq}$ and $E_{iq}^*$ respectively and where $E_{iq} = P_{iq} \times F_{iq} \times expi(U_{iq+}V_{iq})$, $P_{iq}$, $F_{iq}$, $U_{iq}$ and $V_{iq}$ represent the correction factor for pre-filtering, the nodal/satellite correction amplitude factor, phase offset at time $i$, the astronomical argument in radians, which is relative to the equilibrium tide at Greenwich.

The above summation is over all $q = 1 \ldots n_{allc}$ constituents (non-reference, reference, and inferred). In the two-dimensional case, the amplitude and phase information for each constituent is conventionally reported as four current ellipse parameters.

The complex coefficients have associated positive, real magnitudes $A_q^+$, $A_q^-$, and associated phases $\varepsilon_q^+$, $\epsilon_q^-$, $A_q^+ = \left|a_q^+\right|$,

$$A_q^- = \left|a_q^-\right|,\ \varepsilon_q^+ = \arctan\left(\frac{Im(\varepsilon_q^+)}{Re(\varepsilon_q^+)}\right) \textbf{ and } \varepsilon_q^- = \arctan\left(\frac{Im(\varepsilon_q^-)}{Re(\varepsilon_q^-)}\right). \qquad \textbf{(2)}$$

In one-dimensional case, model equation (the raw input is the real-value $h^{raw}(t_i)$) representing any one-dimensional quantity, for example sea level. In the above equations, substituting $h$ everywhere by $u$, and taking all $v$ parameters is identically to zero. Utide model consists of a pair of Matlab functions designed to be easy to understand and implement: *ut_solv()* for analysis and *ut_reconstr()* to use the analysis results for reconstruction of a time sequence for a hind-cast or forecast/prediction if needed [9]. Utide tidal model is used in this study to analyze one-dimensional data such as tidal gauge record, which is described below.

### II-2. Description of data

The tide gauge data used in this work have been recorded by hydrographic services of harbor of Abidjan-Vridi (Côte d'Ivoire) located in the Gulf of Guinea ***(Figure 1).*** They are 7 years (January 1st 1982 to December 31st 1988) hourly datasets recorded by A.OTT tide gauge. The A.OTT is a mechanic tide gauge or float tide gauge [10]. It uses mechanic system that records the variation of sea level through an up and down movement of a float at the surface of sea. The advantageous of this tide gauge is that it records directly the profile of the variation of sea level on a paper [11].

## III - RESULTS AND DISCUSSION

### III-1. Time variability of the statistics of the in situ tide data

***Figure 2*** shows hourly variability of tide recorded at the harbor of Abidjan. The tide is characterized by periodic variability with value comprised between 0.3m and 1.7m. These tide experienced strong seasonal variability with maximum values in spring and fall, and minimum values in summer showing the signature of the coastal upwelling [12,13]. We observe some peaks in spring and at the end of fall with important values higher than 1.6 m. Previous work in that area [14-16] characterized these tide of micro tidal with values less than 1.4 m. But these values higher than 1.6 m are observed in that area. This could be explained by the fact that these works are old or may be due to the quality of the data used. The statistics of these data we used are characterized by a mean of 1m, a 1st quartile and 3rd quartile with respective values 0.84 and 1.17 and a median of 1.02.

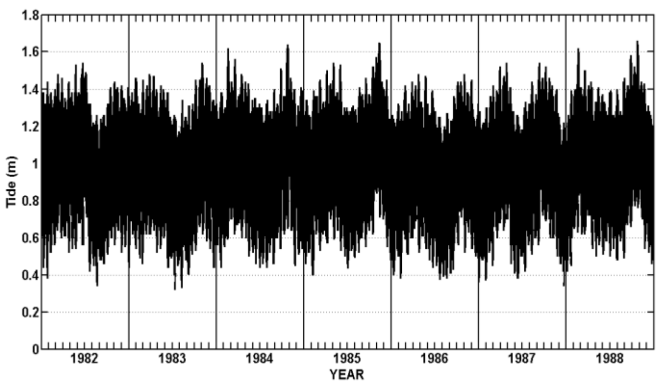


**Figure 2 :** *Hourly variability of the tide (in m) at the Harbor of Abidjan. The data cover the period 1st January 1982 at 01.AM to 31st December 1982 at 00PM*

***Figure 3*** shows the decomposition of the tide time series at the harbor of Abidjan. The trend is characterized by strong interannual variability of the maximum and minimum values. Maximum trends are observed in with a period around two years. The random characterizes the periodic variability of the tide effect.

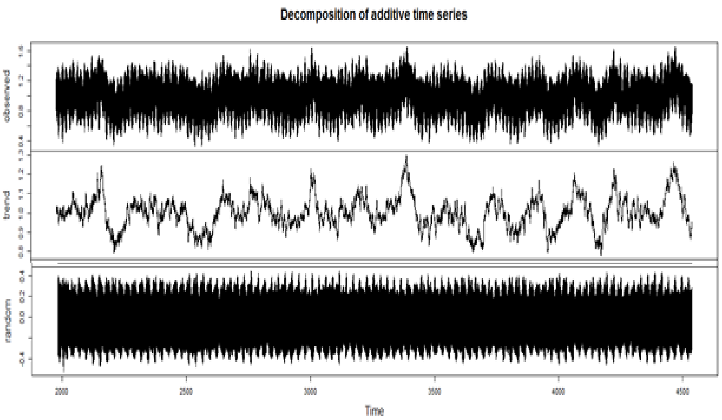


**Figure 3 :** *Decomposition of the tide data time series into the trend and the random (tide values in m)*

One important characteristics of the tide is the high and low time and heights. When an important tide height coincides with a storm surge or a depression, the conditions at the coast are exacerbated and the vulnerability is high. Besides important high tide values could lead to flooding if the slope of the coast is not important as for many of Western African coasts. ***Figure 4*** shows daily variability of the maximum height tide observed along the Ivorian coast. The tide along the Ivorian coast is semi-diurnal so, we represent the maximum value of the two daily peaks. We observe seasonal variability of the high tide modulated by strong interannual variability of the maximum values. Maximum values are generally observed after summer when the coast is vulnerable after washed by strong waves coming from Southern Ocean [17]. That increases the impact of these tides on coastal erosion and degradation of the coast. In 1982, 1983, 1986 and 1987, the peaks are less than 1.5 m while for the other years, the peaks are higher than 1.6 m.

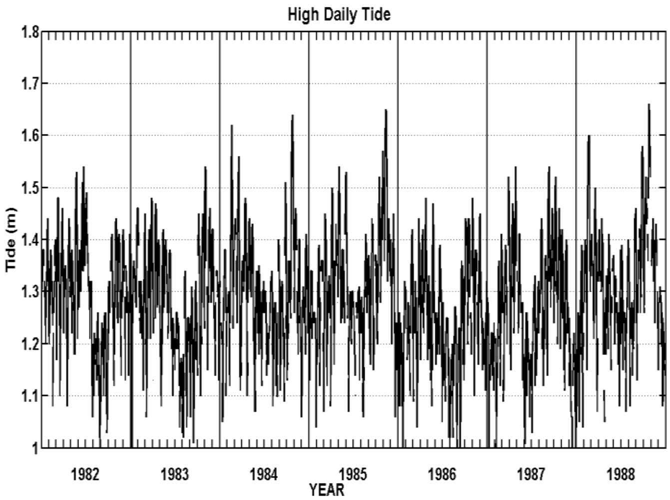


**Figure 4 :** *Daily variability of the maximum value of the high tide (in m). The maximum value between the two consecutive daily high tide values is chosen*

## III-2. Using a prediction model to study the vulnerability of the coast

For the coastal engineering and human protection, it is important to predict the occurrence of high tide and exceptional tide. Some exceptional tides, spring tides leading to flooding by example, along the US coast, have occurred these years in the Atlantic Ocean [18]. These tides have also induced coastal erosion along Brazilian coast [19]. Predicting these tides is of great importance along the African coast where people agglomeration is important. The objective of this part is to analyze if the tide model could help in understanding the coastal vulnerability along the Ivorian coast. ***Figure 5*** shows the raw tide data, the reconstructed data and the different tide constituents extracted by harmonic analysis performed on the raw data. The predicted tide has the same shape as the raw data, characterized by periodicity and seasonal variability both modulated by interannual variability. The residuals are approximately 0 showing that the reconstructed tide is close to the raw data. The dominant tide constituents are M2 (Principal lunar semidiurnal constituent), S2 (principal solar semidiurnal constituent), K1 (Luni-solar declinational diurnal constituent) and SSA (Semiannual Solar constituent). Meanwhile, the other constituents are not neglected. Utide uses more than four constituents to perform the prediction justifying the quality of the prediction.

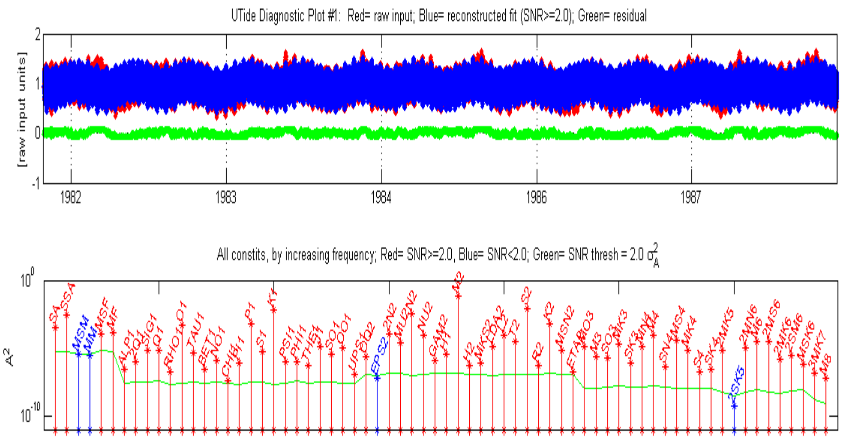


**Figure 5 :** *Temporal variability of the raw data (red) and reconstituted data (blue). The residual (difference between raw and reconstituted data) are superimposed in green. The different constituents extracted from harmonic analysis and used to reconstruct the data are presented in figure of low panel*

***Figure 6*** shows the temporal variability of the daily high tide height of the prediction of tide over the 1982-2014 period at the harbor of Abidjan. We observe strong seasonal and interannual variability of the tide height. Maximum peaks appear yearly in spring and after summer. The maximum peaks after summer appears during a period when the coast is vulnerable. The long-term trend shows an increase of the tide height over the years from a range of 1.2 m and 1.3 m during respectively the 1982-1990 and 2010-2014 periods.

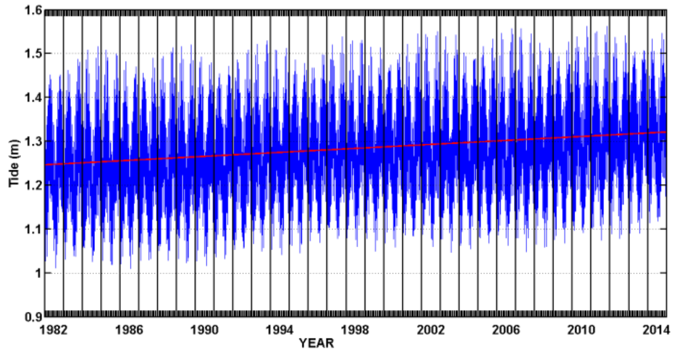


**Figure 6 :** *Temporal variability of the daily high tide height (in m) from the prediction of the tide over the 1982-2014 period using in situ tide gauge data and Utide model. The model is stable after 1 year of analysis. In red, is superimposed the trend*

## IV - CONCLUSION

This study has showed that the tide predicted by the assimilation data model Utide and that observed by tidal gauge at Abidjan harbor are close because residual is approximately zero. The Tidal heights are characterized by periodic and seasonal variability, which are also modulated by interannual variability. Maximum values are generally observed after summer and maximum trend has two years periodicity. Ocean tide has been increased over the 1982-2014 period and it was probably one main cause of coastal flooding observed along Ivorian coast during these last years. The capacity of the data assimilation model Utide to reconstruct tidal signal along Ivorian coast is a major result because it would help to predict exceptional tides, which are one of main threat on coastal population and infrastructure. It can also help to produce high and low heights data for marine's activities. Assimilation of recent tidal records in Utide model to assess tidal characteristics is necessary to improve these main results.

**_ACKNOWLEDGMENT_**

*We thank the authors of the University of Hawaii Sea Level Center (UHSLC) and Global Sea Level System (GLOSS) which provided us with good quality of sea level data.*

## REFERENCES

[1] – D. PUGH, *Changing Sea Levels: Effects of Tides & Weather and Climate, Cambridge University Press*, (2004), www.cambridge.org, 265 pp

[2] – P. L. WOODWORTH, A. AMAN and T. AARUP, *African Journal of Marine Science* 29 (3), (2007), 321–330.

[3] - V. M. GORNITZ, T. W. WHITE and R. M. CUSHMAN, *In Proceedings of Seventh Symposium on Coastal and Ocean Management. Long Beach, CA (USA)*, (1991), 2354-2368.

[4] - R. J. NICHOLLS, S. HANSON, C. HERWEIJER, N. PATMORE, S. HALLEGATTE, J. CORFEE-MORLOT, J. CHATEAU and R. MUIR-WOOD, *OECD Environment Working Papers, No.1, OECD publishing*, (2008) , doi: 10.1787/011766488208.

[5] - P. CALDWELL, *Joint archive for sea level. University of Hawaii, School of Ocean and Earth Science and Technology Annual Data Rep, 2000*, SOEST-00-07, 52 pp.

[6] - D. L. CODIGA, *Graduate School of Oceanography, University of Rhode Island, Narragansett, RI*., (2007), 14.
[7] - R. PAWLOWICZ, B. BEARDSLEY and S. LENTZ, *Computers and geosciences*, (2002), 929–937.
[8] - K. E. LEFFLER and D. A. JAY, *Continental Shelf, Research*, (2008), doi:10.1016/j.csr.2008.04.011
[9] - D. L. CODIGA, *Graduate School of Oceanography, University of Rhode Island, Narragansett*, (2011), 59 *ftp://www.po.gso.uri.edu/pub/downloads/codiga/pubs/2011Codiga-UTide-Report.pdf*
[10] - F. LEFEVRE, *Université Toulouse III-Paul Sabatier, Thèse de doctorat (France),* (2000), 281 pp.
[11] - I.O.C. (Intergovernmental Oceanographic Commission), (2006). (*www.pol.ac.uk/.../manuals/manual_14_final_21_09_06.pdf*)
[12] - A. BAKUN, C. ROY and S. LLUCH-COTA *Blackwell Science Inc. Malden, Massachusetts* (1998), 103-141.
[13] - E. TOUALY, G. STANOJEVIC, K. Y. KOUADIO and A. AMAN, *Asian Journal of Applied Science* (2012) doi: 10.3923/ajaps.
[14] - F. VARLEJT, Etudes Eburnéennes. vol.VII (1958), l0l-220.
[15] - L. LEMASSON et J. P. REBERT, *Cah. Orstom, série Océanogr.,* Vol. 9, n°1, (1973)67-95.
[16] - J.M. VERSTRAETE and J. PICAUT, *Deep-Sea Research Gate Supplement II to Volume 26*, (1979).
[17] - E. TOUALY, A. AMAN, P. KOFFI, T.E. WANGO and F. MARIN, *Submitted to African Journal of Marines Sciences*, (2014).
[18] - E. SPANGER-SIEGFRIED, M. F. FITZPATRICK and K. DAHL. Cambridge, MA: Union of Concerned Scientists, (2014), www.ucsusa.org/encroachingtides/,76 pp.
[19] - D. L. B. MALLMANN and P .S. PEREIRA, *Journal of Coastal Research, Special Issue,* No. 71 (2014) 24–29.