WIOMSA – IOC (of UNESCO)

REPORT ON

TIDAL ANALYSIS & PREDICTION

KENYA.

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PREFACE

The Intergovernmental Oceanographic Commission (IOC) of UNESCO developed a Global Sea Level Observing System (GLOSS) program in 1985 to address the growing concern about the rise in mean sea level around the globe. Through GLOSS, a network consisting of about 300 tide gauges have been installed throughout the globe. The regional component of GLOSS in the Western Indian Ocean (WIO) Region is through IOC's Regional Committee for the Co-operative Investigations in the North and Central Western Indian Ocean (IOCINCWIO), which was established in 1979 by resolution XI-9 of the eleventh session of the IOC Assembly.

IOCINCWIO coordinates development and implementation of regional oceanographic research activities in the member states in the region (Comoros, French Indian Ocean islands, Kenya, Madagascar, Mauritius, Mozambique, Seychelles, South Africa and Tanzania).

Sea level observations, analysis and interpretation of data has been one of the areas of concern to IOCINCWIO. Several sessions of IOCINCWIO have been held in the region and among the recommendations is the establishment of a regional tide gauge network and enhancement of scientific and technical capacity in tide gauge installation and maintenance, sea level data analysis and interpretation as well as products preparation.

Although there is plenty of sea level data available in the WIO region, it has not been subjected to thorough analysis despite the fact that there is sufficient scientific capacity for analysis and interpretation of data. Tide predictions in particular are only generated in a few countries in the region by local scientists while other countries rely on services from outside to produce tide tables.

In a deliberate effort to encourage the use of sea level data in the region, a project was proposed for tidal analysis and prediction in the WIO region with the support of Western Indian Ocean Marine Science Association (WIOMSA) and IOC of UNESCO through its Division of Ocean Data and Information Network for Africa (ODINAFRICA).

The objective of the project is to provide an insight on the status of sea level monitoring in some selected locations in the WIO region through preparation of comprehensive national reports. This involved collection and analysis of sea level data from selected tide gauge stations and production of tidal predictions for those stations for the period 1 January 2008 – 31 December 2009.

The project also aims to avail the tidal predictions in an appropriate format on the ODINAFRICA and WIOMSA websites. The national and regional reports shall also be posted on both websites.

Experts from Kenya, Tanzania, Mauritius, Mozambique and Seychelles were identified to prepare National Reports on Tidal Analysis and Prediction for their respective countries.

The project kicked-off with a regional workshop for the experts that was held in Mombasa on 1-5 April 2008 to harmonise the methods to be applied in the analysis of available sea level data and identification of suitable softwares to be used for carrying out tide predictions. The experts also drafted the guidelines to be used in preparing the national reports.

The first part of this report is a description of the historical and current status of the sea level network in Kenya, availability of data from stations, as well as scientific and technical capacity available in the country. The second part is a presentation of the results of harmonic analysis of time series of sea level data and tide predictions for Mombasa and Lamu.

CONTENTS

1.0 Introduction

1.1 Country Status on Sea level observations and related activities/network

The Intergovernmental Oceanographic Commission (IOC) of UNESCO developed a Global Sea Level Observing System (GLOSS) program in 1985 to address the growing concern about the rise in mean sea level around the globe. The objective of GLOSS was to provide high quality standardized data from which valuable sea level products can be produced for international oceanographic such as World Ocean Circulation Experiment (WOCE), Tropical Oceans Global Atmosphere (TOGA) and regional research programmes as well as for practical application on a national level. Kenya is one of the countries participating in GLOSS and has already received support and assistance in terms of training of our specialists and provision of equipment through IOC.

1.2 Kenya's Participation in Sea Level Monitoring Program

Kenya lies along the equator on the east coast of Africa in the Western Indian Ocean (WIO) region. It has a land surface area of 590,000 km^2 and a coastline of about 600 km. The coastline extends from Shimoni on the south near the border with Tanzania to Kiunga on the north near the border with Somalia (Figure 1).

In Kenya, the first gauge was installed in 1933 in Kilindini harbour, Mombasa by the former East Africa Railways and Harbours Corporation (EARHC) and was in operation until 1956. Another gauge (Munro gauge) was installed in the 1960's at the Kipevu pilot jetty at the present Kenya Ports Authority Headquarters and operated intermittently upto1976. However, little data is available from this gauge. In 1975/6, a team from the Permanent Service for Mean Sea Level (PSMSL) collected one-year continuous data.

In the late 1980's, the University of Hawaii in collaboration with the TOGA Sea Level Centre established a network of sea-level stations, which continue to provide useful information. Realising the importance of sea level data for navigation and harbour planning, beach protection and development and overall marine research, Kenya Marine & Fisheries Research Institute (KMFRI) requested for a tide gauge through IOC-UNESCO from the University of Hawaii (UH) in June, 1986 to start its tide gauge network. Following that request, the University of Hawaii donated a tide gauge, which was installed at Liwatoni jetty in Kilindini harbour, Mombasa. A second tide gauge was installed by UH in Lamu in 1996. KMFRI is responsible for maintaining both the Mombasa and Lamu tide gauge stations. Two KMFRI Technicians are attached to each station.

1.3 Status of GLOSS Stations in Kenya

1.3.1 Mombasa Tide Gauge (Latitude: 04^o 04´S Longitude: 039^o 039’E)

A Leopold Stevens gauge was installed in Mombasa in 1986 with technical assistance from University of Hawaii Sea Level Centre (UHSLC). This was later changed to a Fisher and Porter float gauge in 1991. The station continues to operate well and data is available. Some of the benchmarks were removed during construction work at the harbour where the gauge is located. The Mombasa gauge is float type installed on a stilling well. The station is equipped with modern data logger, measuring sea level every minute and storing on diskette at 15 minutes interval.

In August 2006, a major upgrading of the Mombasa tide gauge was carried out with the assistance of field technicians from UHSLC. This involved a thorough overhaul of the existing equipment, installation of additional sensors (pressure and radar sensor). The station was also equipped with satellite data transmition facilities to enable near real-time data access. Mombasa tide gauge is a Principal station on the GLOSS network and also a dedicated component of the proposed Indian Ocean Tsunami Warning System (IOTWS).

1.3.2 Lamu Tide Gauge (Latitude: 02^o 17´ S; Longitude: 040^o 54’ E)

The Lamu gauge is a float type installed on a stilling well. It was installed in 1996 by the University of Hawaii Sea Level Centre (UHSLC). The station is equipped with modern data loggers, measuring sea level every minute and storing on diskette at 15 minutes interval. In addition, the Lamu tide gauge is equipped with a satellite data transfer device to enable real time access to data. Earlier, there was a Valeport BTH 700 gauge was installed at the end of 1988 but was not operational since 1992. This was due to a problem with electrical connection on the jetty where it was installed. During the time the gauge was out of operation, data was collected manually at half hour interval during day time (0900 to 1600 HRS).

In August 2006, the Lamu tide gauge station underwent a major overhaul of equipment. The station was also fitted with additional sensors (pressure and radar sensor). Lamu is also a principal station on the GLOSS network and a dedicated component of IOTWS. Data from this station (and others like it in the region) can be used to confirm or cancel a tsunami warning throughout the region.

Both stations Mombasa and Lamu stations continue to operate well and data is available. Kenya is also coordinating the regional component of GLOSS. The profiles of both historical and operational stations in Kenya are presented in Tables 1 and 2.

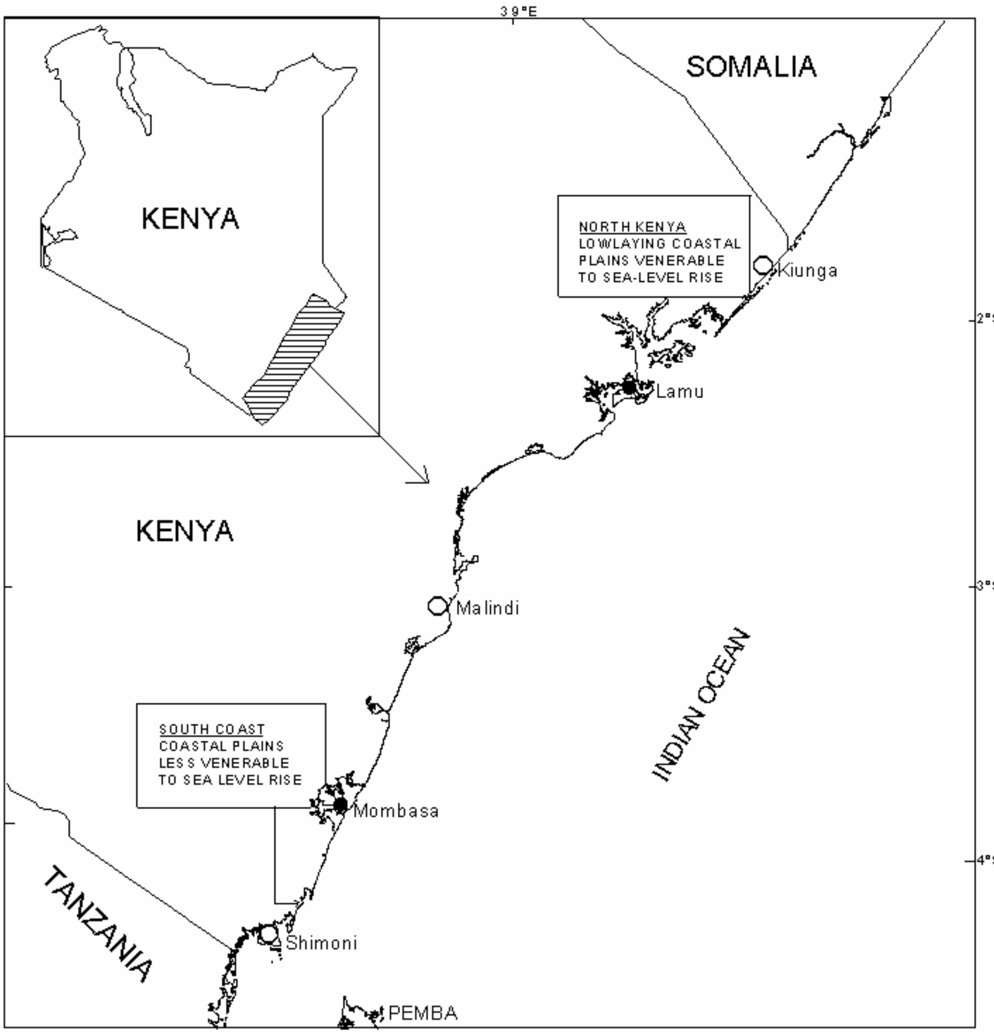

Fig 1: Map of Kenya Coastline showing location of installed tide gauge stations (●) and planned stations (o).

Fig 2: Photo of upgraded Mombasa tide gauge station

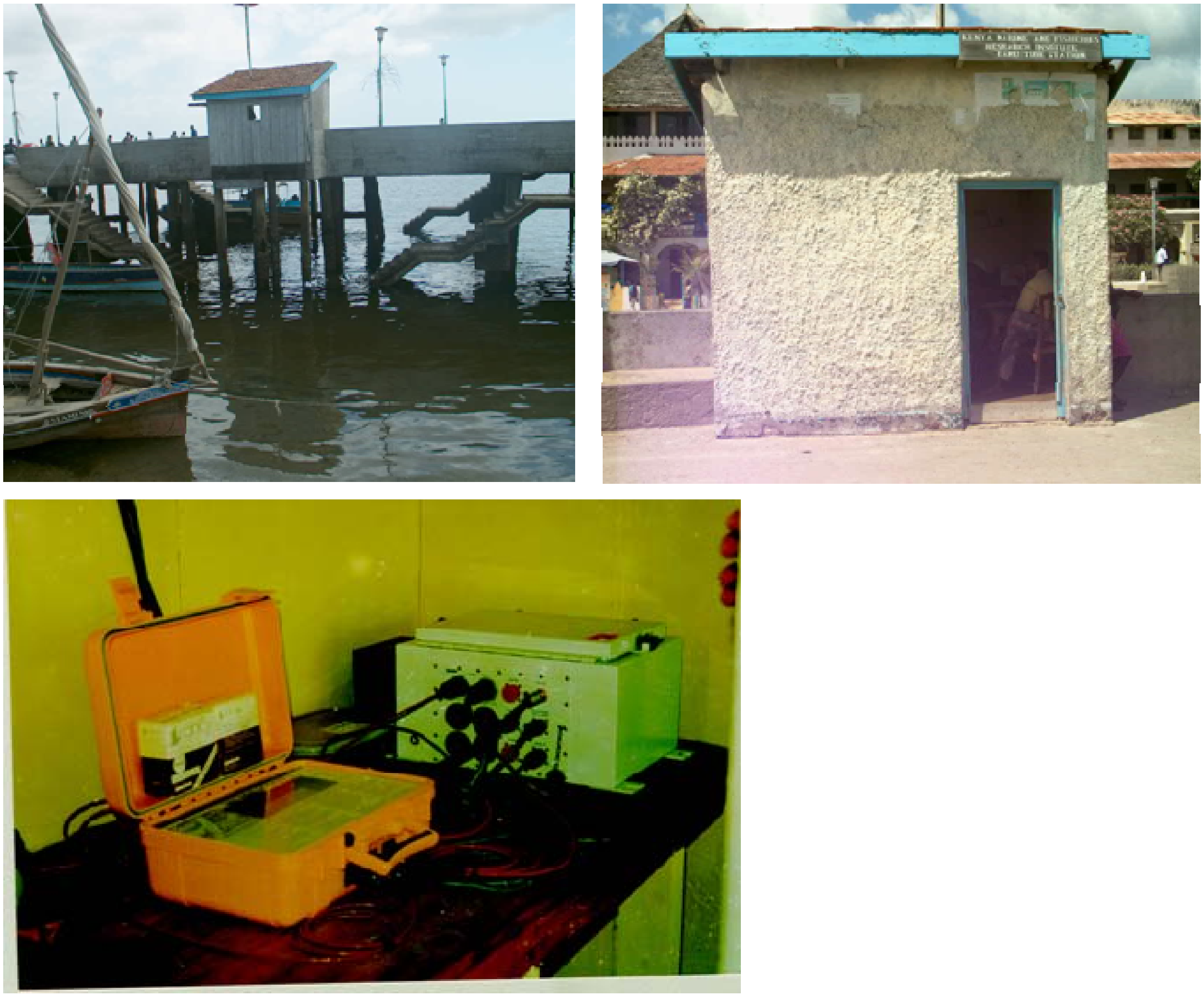

Fig 3: Photo of Lamu tide gauge station

1.3.3 Additional Stations by KMD

The Kenya Meteorological Department (KMD) is in the process of installing and testing three additional stations along the Kenyan coastline. These are at: Shimoni (4^o 39´ S, 39^o 23´E), Malindi (3^o 15´S, 40^o 08´E) and Lamu (02^o 17´ S, 040^o 54’ E) . Photos of the 3 new stations is shown in Figs 4, 5 and 6. Once the stations are fully operational, there shall be five stations covering the Kenyan coast. The gauges are also equipped with additional sensors and transmiting data in real-time (Table 1). However, data access from those stations is restricted. Additional information can be obtained by contacting the director of KMD (director@meteo.go.ke).


Fig 4a: Stilling well of the tide gauge at the Old Jetty of Kilifi Mnarani club.

Fig 4b: Tide gauge at Kilifi Mnarani Club.

Fig5a: Wasini Island Tidal and Automatic Weather Station installed at the Old Navy Jetty

Fig 5b: The stilling well of the tide gauge at Wasini Island.


Fig 6a: Lamu Island Automatic Weather Station, at the New Fisheries Jetty of Ministry of Fisheries Development.


Fig 6b: Stilling Well of tide gauge at New Fisheries Jetty in Lamu Island.

1.4 Capacity (Technical and Scientific)

There is still limited capacity for repair and maitenance of the our tide gauges. Lack of spare parts and tools has been a major hindrance to carrying out minor repair jobs and levelling. We rely on services of technicians from UH Sea Level Centre for installation and maintenance of the two tide gauges. Regular maintenance of both gauges is supervised by KMFRI's Principal Laboratory Technologist (Mr. Jimmy Onyango) and the National Sea Level contact (Dr. Charles Magori).

Two KMFRI Technicians are attached to both stations. None of the Technicians on site has received training at PSMSL, UHLC, etc. However, a few of them have received in-service training and some additional hints during the visits to Kenya by field technicians from UHSLC. This has contributed fairly well in improving the accuracy and quality of the data.

Several Scientists at KMFRI have received post graduate training in Physical Oceanography. There is sufficient capacity on analysis and interpretation of sea level data. In addition four Kenyan scientists have received training sponsored by IOC on Sea Level Data Analysis and Interpretation. They are Mika Odido at PSMSL, UK in 1992, Charles Magori at Dehra Dun, India in 1995, Clive Angwenyi in Cape Town, South Africa in 1998 and Antony Kibue in Oostende, Belgium in 2006.

2.0 Objectives

The objectives of this exercise were:

- Collect and analyse sea level data from Mombasa and Lamu sea level stations in Kenya and prepare tidal predictions for the stations for the period 1 January 2008 to 31 December 2009,

- Compare predictions and actual observations for the period January – June 2008 and submit a graph of the tidal residuals for this period.

- Avail the tidal predictions in an appropriate format on the ODINAFRICA and WIOMSA websites.

- Prepare a comprehensive report which should include: (a) the listing of high and low waters (height against local time and GMT) as well as hourly heights for January 2008 – December 2009, (b) graphs of the tidal variations, as well as tidal residuals for the period for the period January – June 2008.

3.0 Data from Mombasa and Lamu Stations

The sea level data (hourly, daily and monthly means) for the Kenyan stations are available at KMFRI in JASL format. Because of our close collaboration with UHSLC, both Mombasa and Lamu stations are now transmitting data on near real-time time basis to UHSLC database. Quality Control of data is performed at UHSLC. Monthly means are also available at the Permanent Service to Mean Sea Level (PSMSL). It should be noted that the available data has some unprecedented data gaps resulting from occassional breakdown of equipment.

For Mombasa station, available data is from 1975/6 and 1986-2008.
The data available from Lamu station is in digital form and analogue charts. The digital data is from 1989, and 1996–2008 and the analogue chart is from 1990 to 1992. All the digital data from both stations are available in International data centres namely PSMSL and UHSLC. The archived data can be downloaded for free from the following web sites.

- http://www.soest.hawaii.edu/UHSLC
- http://www.pol.ac.uk/psmsl/gloss.info.html

Real-time data from both stations can be accessed via the World Meteorological Organization (WMO) Global Telecommunication System (GTS) on the UHSLC and ODINAFRICA websites using the liks below:

- http://ilikai.soest.hawaii.edu/RSL

- http://www.vliz.be/vmdcdata/iode

3.1 Data Selection for Tidal Analysis

Data used in this study was downloaded from the ”Research Quality” database on the UHSLC website that archives data in hourly, daily and monthly means. For Mombasa station, hourly time series data for year 1999 was selected as the base period to be used for the analysis with 2007 as the validating period. For Lamu station year 2002 was selected as the analysis period and 2007 as the validating period. This was based on the consideration that there are few data gaps (or no gaps) in the available hourly data sets for the selected years.

4.0 Methodology

The selected data was subjected to manipulation in Textpad environment in order to fit the required format that is compatible with the tidal analysis softwares mentioned below. The base period data was then subjected to harmonic analysis procedure and finally the prediction of high and low and hourly values for the specified period. Plots of hourly data and quality checks were carried out before producing tide table for years 2008 and 2009.

Harmonic analysis is a mathematical method of extracting sinusoidal components of specific frequencies from for example time series of water levels (hourly intervals). It is based on the methods of least squares. Instead of fitting a straight line to the data by varying its slope and intercept, a set of cosine (or sine) curves with given frequencies w are fitted by varying amplitudes and phases, minimizing the sum of deviation from the original curve. In classical harmonic analysis, the tidal signal is modelled as a sum of a finite set of sinusoids at specific frequencies related to astronomical parameters.

Three tidal analysis softwares that were utilized in this study are (a) SLPR2, (b) T_TIDE and (c) Task-2000.

SLPR2 software is a FORTRAN based programme that operates under the DOS environment. It performs harmonic analysis of hourly time series observations of sea levels to extract tidal constituents, predict hourly and also the High and Low listings of sea levels. The software includes the Foreman's tidal analysis and prediction routines. Further details regarding the software can be obtained by refering to Caldwell, 1998.

T_TIDE is a set of programs that has been written in MATLAB to:

- i) perform classical harmonic analysis for time series data for periods of about one year of data (or shorter)
- ii) use nodal corrections to account for some unresolved tidal constituents, and
- iii) compute confidence intervals for the analysed components

T_Tide comprises a translation of the Foreman Tide analysis mark the theory. Further details of the theory can be found in "Classical Tidal Harmonic Analysis Including Error Estimates in MATLAB using T_TIDE", (Pawlowicz *et. al*., 2002).

TASK-2000 software is a FORTRAN based and uses the Microsoft Excel environment. The software performs harmonic analysis and tidal predictions in form of high and low listings as well as hourly values. The software package is derived from the TIRA tidal analysis programs. For further details, please refer to Bell *et. al*., 2000.

Table 1: Profile of Operational Stations in Kenya

Station Name	Location Lat	Lon	Responsible Organisation	Collaborating Institution(s)	Type of guage/ Manufacturer	Data Span	Mode of Transmision	Data Sources	Others Sensors	Remarks
Mombasa	*04°4' S*	*39° 39'E*	*KMFRI*	*UHSLC*	*Fisher & Porter Float gauge on stilling well*	*1986-2008*	*Near Real-time*	*-UHSLC -ODIN-AFRICA -PSMSL*	*-Radar -Pressure*	*-Significant gaps -digital data*
Lamu	*02°17'S*	040° 54'E	*KMFRI*	*UHSLC*	*-Float gauge on stilling well -UH Ref. level switch*	*1996-2008*	*Near Real-time*	*-UHSLC -ODIN-AFRICA -PSMSL*	*-Radar -Pressure*	*-Few gaps - digital data*
Shimoni	4° 39´ S	39° 22´ E	*Kenya Met Dept. (KMD)*	-	*Acoustic gauge with automatic weather station (AWT) – Sutron Corporation, USA.*	*July 2007 - 2008*	*Real-Time*	*KMD*	*-pressure -wind -temp. -atmsp. pressure -humidity*	*-Restricted data access*
Kilifi	3° 38´ S	39° 51´E	*KMD*	-	*Acoustic gauge with AWT – Sutron Corporation, USA.*	*July 2007 - 2008*	*Real-Time*	*KMD*	*-pressure -wind -temp. -atmsp. pressure -humidity*	*-Restricted data access*
Lamu	2° 17´S	40° 54´E	*KMD*	-	*Acoustic gauge with AWT – Sutron Corporation, USA.*	*July 2007 - 2008*	*Real-Time*	*KMD*	*-pressure -wind -temp. -atmsp. pressure -humidity*	*-Restricted data access*

Table 2: Profile of Historical Stations in Kenya

Station Name	Location Lat	Lon	Responsible Organisation	Collaborating Institution(s)	Type of guage/ Manufacturer	Data Span	Data Sensors	Remarks
Lamu	*02°17' S*	040° 54' E	*KMFRI*	*KPA*	*Valeport BTH 700 gauge*	*1988-1992*	-	*data in analogue charts*
Kilindini harbour - Mombasa	-	-	*EARHC*	*KPA*	-	*1933-1956*	-	*-scant info on gauge and data*
Kipevu Pilot Jetty - Mombasa	-	-	*KPA*	-	*Munro gauge*	*1960 - 1976*	-	*-scant info on gauge and data*
Kilindini harbour - Mombasa	-	-	*PSMSL*	*KPA*	-	*1975-1976*	-	*- data available at PSMSL*

4.1 Analysis and Interpretation

Table 3a:- Main tidal constituents from harmonic analysis results
Station Name: Mombasa

Constituent	Constituent name	Amplitude (cm)	Phase (deg)
M_2	Principal Lunar semi diurnal	104.57	66.72
S_2	Principal Solar semi diurnal	51.29	66.59
O_1	Lunar declinational diurnal	11.45	242.62
K_1	Luni-solar declinational diurnal	19.28	156.03
K_2	Luni-solar declinational semi diurnal	13.93	203.83
N_2	Larger Lunar elliptic semidiurnal	19.23	27.50

Table 3b:- Main tidal constituents from harmonic analysis results
Station Name: Lamu

Constituent	Constituent name	Amplitude (cm)	Phase (deg)
M_2	Principal Lunar semi diurnal	97.90	227.36
S_2	Principal Solar semi diurnal	48.60	72.80
O_1	Lunar declinational diurnal	12.51	34.64
K_1	Luni-solar declinational diurnal	20.79	160.92
K_2	Luni-solar declinational semi diurnal	14.09	215.06
N_2	Larger Lunar elliptic semidiurnal	18.01	233.28

Table 4: Tidal statistics, amplitudes and phases based on harmonic analysis.

Parameter	Formula	Mombasa station	Lamu station
Form number	$(K_1+O_1)/(M_2+S_2)$	0.20	0.23
Spring Range	$2.0(M_2+S_2)$	3.12 m	2.93 m
Neap Range	$2.0(M_2-S_2)$	1.07 m	0.99 m
Mean Range	$2.2(M_2)$	2.08 m	1.96 m

From harmonic analysis performed by SLPR2 software, the tidal characteristics for both Mombasa and Lamu stations are very similar as shown in Tables 3 and 4 above.

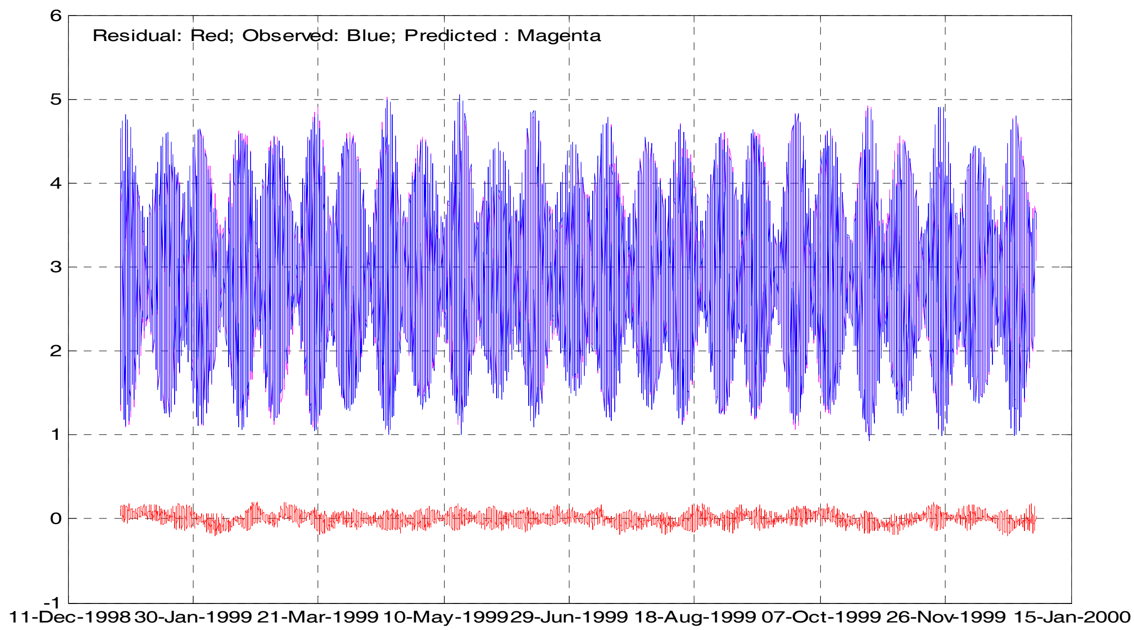

Fig 7: Graphs of observed, predicted and residual using 1999 hourly sea level data for Mombasa by T_TIDE.

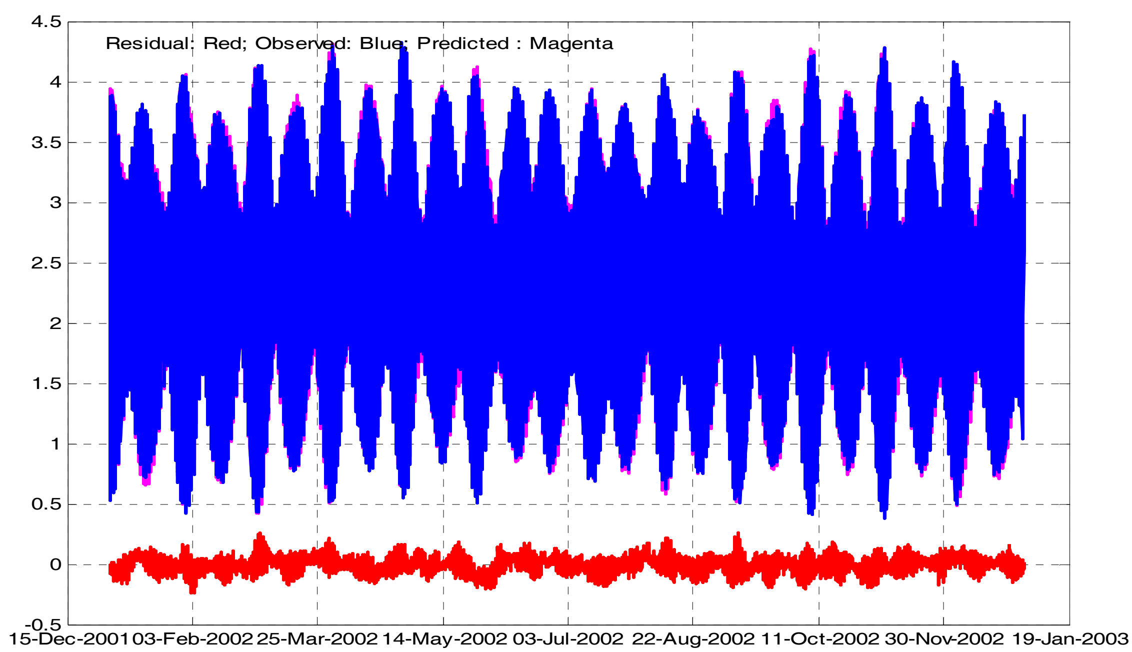

Fig 8: Graphs of observed, predicted and residual using 2002 hourly sea level data for Lamu by T_TIDE.

In general, the selected datasets were subjected to the data management procedures, extraction of tidal constituents through harmonic analysis and finally the generation of tide predictions in form of high and low listings and hourly values for the specified period. Since the results may be affected by validation based on the output and known variations, the residuals were computed from a year whose data is outside the period used in the harmonic analysis phase.

A form number, F, has been defined as the ratio of the sum of amplitudes of diurnal tidal species over semi diurnal species. According to Defant (1958), a simplified definition for F, $F = (k_1+O_1)/(M_2+S_2)$, can be used to characterize tidal types. If F is less than 0.25, the tide is referred to as semi-diurnal, and if F is greater than 3.0, the tide is diurnal. Value of F between 0.25 and 3.0 are considered as mixed tides. From results of harmonic analysis, the form numbers for Mombasa and Lamu stations are 0.20 and 0.23 respectively, indicating that the tides are typically semi-diurnal. The spring tidal range for Mombasa and Lamu are 3.12 m and 2.93 m respectively while the corresponding neap range is 1.07 m and 0.99 m respectively (Table 4).

The residuals are small (~20 cm) for both stations as can be seen in Figures 7 and 8. They could be due to local forcing by wind stress and air pressure fluctuations. This indicates that meteorological forcing plays a minor role in the water level variations at both stations. It also further indicates that water level variations are exclusively driven by tidal forcing.

SLPR2 and T_TIDE softwares that were used have given fairly similar results of the harmonic constituents for each station (See Annex I). The tides can be characterised as being strongly semidiurnal, with the major constituents having similar amplitudes, phase lags and consequently similar tidal ranges for the two stations.

From observed data, water level variations at Mombasa and Lamu tide stations are sinusoidal with two unequal peaks daily. In addition, high water occurs in Mombasa roughly 5 minutes earlier than in Lamu. This phenomenon is also reproduced in high low listings and hourly values on the tide tables for both stations (Annex II).

Both tidal analysis softwares were able to resolve tidal constituents with higher periods. A total of 68 harmonics were generated with corresponding amplitudes and phase lags (Annex I). This is attributed to the one-year continuous hourly data set (with few gaps) that was used as input data in harmonic analysis.

Validation results for Mombasa and Lamu for the period of 1 January to 30 June 2008 are shown in Figures 9 and 10. These are based on comparison between tide predictions (produced by constituents generated by harmonic analysis using 1999 sea level data for Mombasa and 2002 data for Lamu) and actual observations. For both stations, the residuals are less than 20 cm indicating that the observed sea levels compare well with the predicted values.

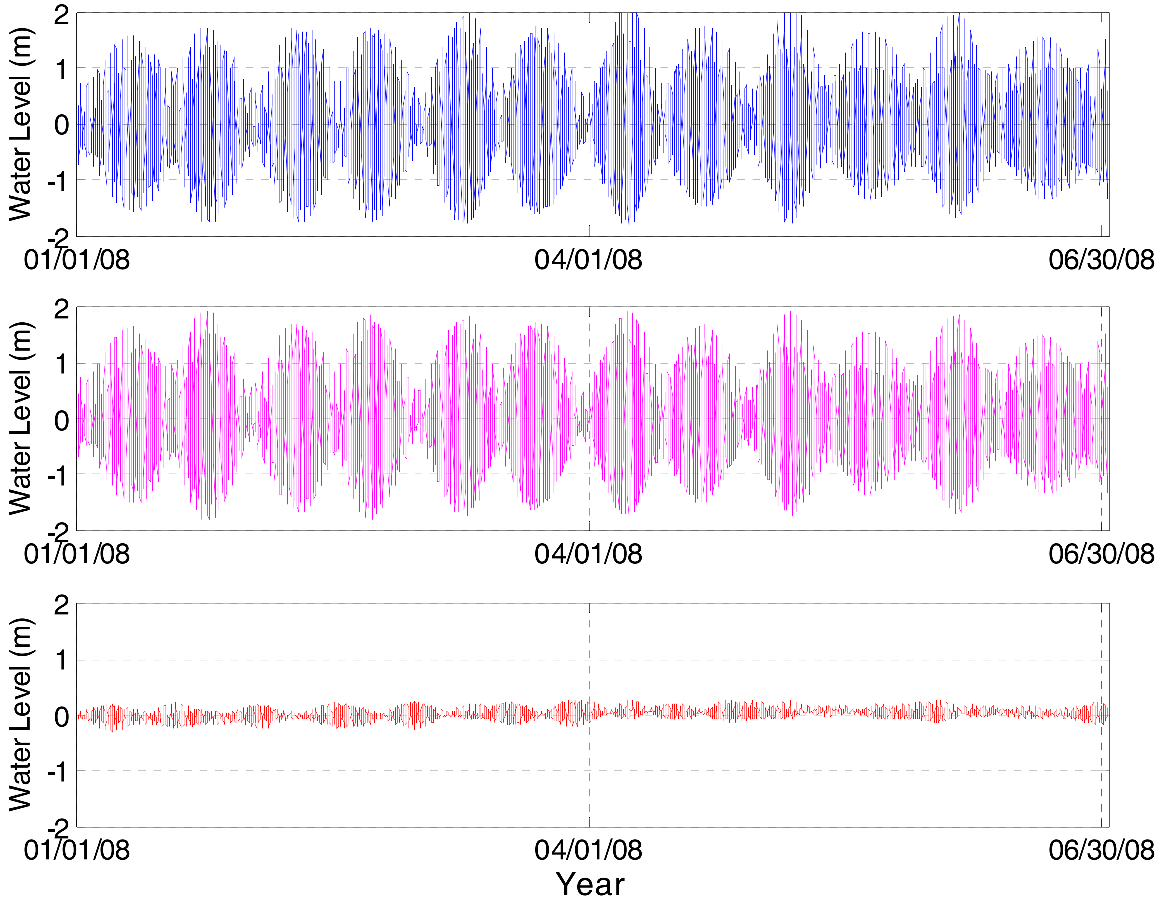

Fig 9: Validation results – Observed (blue), computed (magenta) and residual (red) sea levels for Mombasa station (1 January – 30 June 2008)

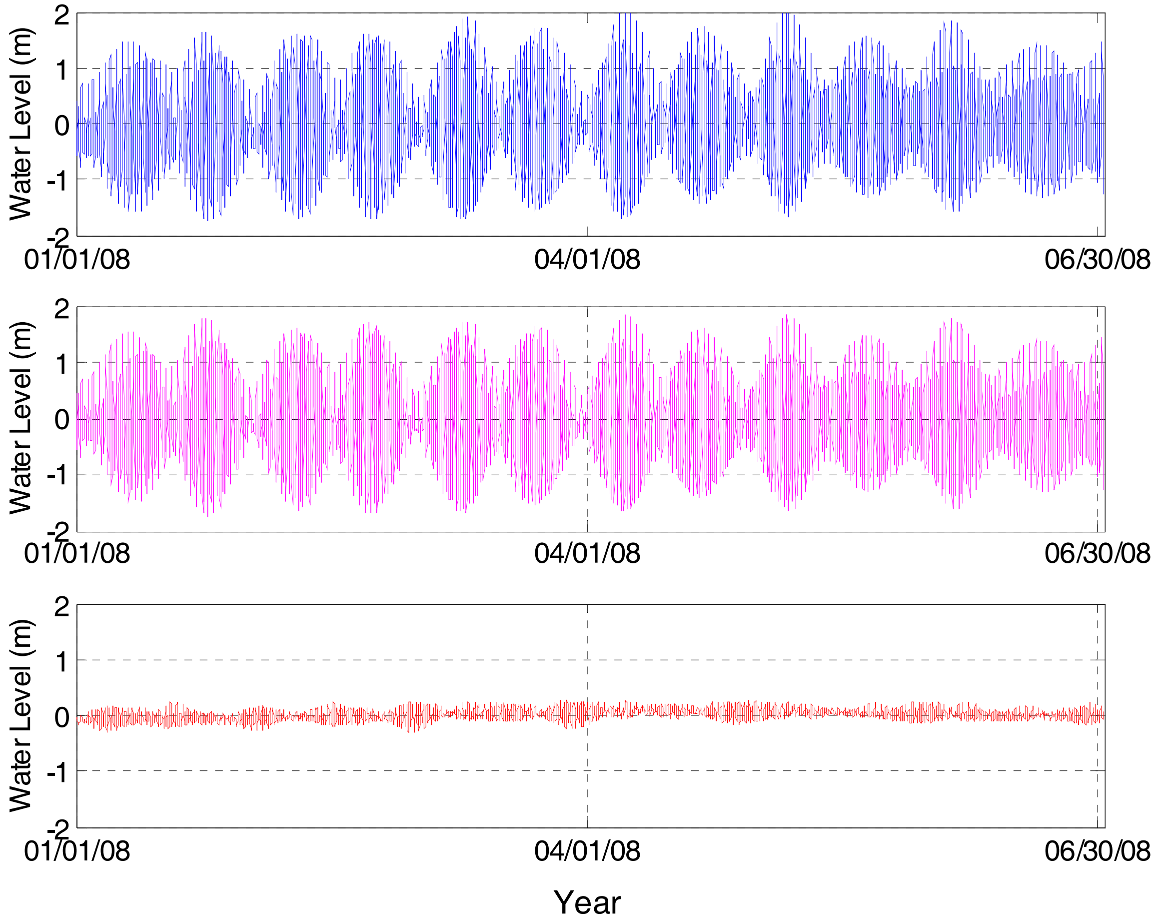

Fig 10: Validation results – Observed (blue), computed (magenta) and residual (red) sea levels for Lamu station (1 January – 30 June 2008)

5.0 Conclusion and Recommendation

Water level variations in Mombasa station are typically semi-diurnal with spring tide range of 3.12 m and neap tide range of 1.07 m. The corresponding values for Lamu are 2.93 m and 0.99 m respectively. As indicated by the residuals, meteorological forcing due to wind stress or fluctuations in air pressure plays a minor role in the water level variations. At both stations, astronomical tides account for more than 90% of the water level variations.

SLPR2 and T_TIDE run on the same routine but operate on different environments. The two softwares generate exactly the same number of tidal constituents. Tide tables from both packages compare fairly well.

Both Mombasa and Lamu are principal stations on GLOSS network and are also dedicated components of the IOTWS. In order to enable Kenya to generate high quality sea level data and products for local scientists and international oceanographic programmes and data centres and also IOTWS, there is an urgent need to develop technical capacity for installation and maitenance of tide gauges and also for analysis and quality control of sea level data.

There is sufficient scientific capacity for analyis and interpretation of sea level data in Kenya. Although a few of out tide gauge technicians have received in-service training and some additional hints during the visits to Kenya by field technicians from UHSLC, there is still limited capacity for repair and maitenance of the our tide gauges. WIOMSA could contribute to capacity building by providing Marine Research Grants (MARG II) for tide gauge technical staff.

The IOTWS fellowship programme on Sea Level Sciences and Applications programme should consider providing grants for our local technicians to visit specialised sea level data centres e.g UHSLC, PSMSL for internship. The topics to be covered during the internship should include review of sea level equipments, types, installation, levelling and maintenance as well as processing and quality control of data.

References

Bell C., J.M.Vassie, and P.L.Woodworth (1998): POL/PSMSL Tidal Analysis Software Kit 2000, CCMS Proudman Oceanographic Laboratory.

Caldwell P. (1998): Sea level Data processing On IBM-PC Compatible Computers version 3.0, University of Hawaii Sea Level Centre (UHSLC).

Defant, A. (1958): Ebb and Flow. Ann Arbor Science Paperbacks, Ann Arbor. 121p.

Pawlowisz R., Beardsley B. and Lentz S. (2002): Classical Tidal Harmonic Analysis Including Error Estimates in MATLAB using T_TIDE. *Computers and Geosciences*, Vol. 28, pp 921-937.

Acknowledgement

I would like to thank WIOMSA and IOC/UNESCO through ODINAFRICA for supporting this exercise. I also wish to thank members of the tidal analysis team in the region for their cooperation and sharing of knowledge and experiences on the use of the three tidal analysis and prediction softwares. Special thanks to Patrick Caldwell of UHSLC for the assistance he provided. Many thanks to KMFRI for supporting the sea level monitoring programme in Kenya and colleague Sam Ngete for his assistance on posting the tide predictions for Mombasa and Lamu on the WIOMSA and ODINAFRICA websites.

Annex I: Harmonic Constituents for Mombasa and Lamu Stations

Harmonic Analysis Results *(by SLPR2 Software)*

Mombasa Station

No.	Name	Frequency	Amplitude (cm)	Phase (degrees)
1	Z0	0.00000000	287.0746	0.00
2	SA	0.00011407	3.8323	326.23
3	SSA	0.00022816	2.1805	232.47
4	MSM	0.00130978	1.4136	29.54
5	MM	0.00151215	0.2188	115.52
6	MSF	0.00282193	0.2738	140.39
7	MF	0.00305009	1.6251	103.98
8	ALP1	0.03439657	0.0800	213.26
9	2Q1	0.03570635	0.3967	176.17
10	SIG1	0.03590872	0.4672	271.81
11	Q1	0.03721850	2.6461	213.45
12	RHO1	0.03742087	0.5031	296.55
13	O1	0.03873065	11.4497	242.62
14	TAU1	0.03895881	0.1305	236.92
15	BET1	0.04004043	0.0583	113.34
16	NO1	0.04026859	1.0655	153.90
17	CHI1	0.04047097	0.2373	196.61
18	PI1	0.04143851	0.2014	299.53
19	P1	0.04155259	5.5090	184.45
20	S1	0.04166667	1.9509	279.65
21	K1	0.04178075	19.2839	156.03
22	PSI1	0.04189482	0.0718	85.21
23	PHI1	0.04200891	0.1274	286.33
24	THE1	0.04309053	0.2631	72.55
25	J1	0.04329290	1.1462	181.55
26	SO1	0.04460268	0.1232	126.61
27	OO1	0.04483084	0.9538	266.86
28	UPS1	0.04634299	0.2098	313.12
29	OQ2	0.07597494	0.2907	353.66
30	EPS2	0.07617731	0.5773	79.69
31	2N2	0.07748710	2.1209	341.66
32	MU2	0.07768947	1.7164	100.72
33	N2	0.07899925	19.2309	27.50
34	NU2	0.07920162	3.9776	103.80
35	H1	0.08039733	1.4055	44.13
36	M2	0.08051140	104.5691	66.72
37	H2	0.08062547	0.4180	322.95
38	MKS2	0.08073957	1.3933	342.71
39	LDA2	0.08182118	1.0684	201.69
40	L2	0.08202355	3.5585	269.57
41	T2	0.08321926	3.2980	235.37
42	S2	0.08333334	51.2899	66.59

Harmonic Analysis Results *(by SLPR2 Software)*

Mombasa Station

No.	Name	Frequency	Amplitude (cm)	Phase (degrees)
43	R2	0.08344740	1.0329	26.72
44	K2	0.08356149	13.9268	203.83
45	MSN2	0.08484548	0.0786	208.79
46	ETA2	0.08507364	0.6838	221.30
47	MO3	0.11924210	0.2441	55.59
48	M3	0.12076710	0.2360	17.66
49	SO3	0.12206400	0.0241	192.79
50	MK3	0.12229210	0.1648	228.35
51	SK3	0.12511410	0.1239	171.81
52	MN4	0.15951060	0.5044	163.48
53	M4	0.16102280	1.2621	216.99
54	SN4	0.16233260	0.1900	185.74
55	MS4	0.16384470	0.7113	211.80
56	MK4	0.16407290	0.2040	358.41
57	S4	0.16666670	0.2954	196.22
58	SK4	0.16689480	0.1803	340.19
59	2MK5	0.20280360	0.0407	10.38
60	2SK5	0.20844740	0.0823	83.12
61	2MN6	0.24002200	0.0127	296.60
62	M6	0.24153420	0.0888	233.14
63	2MS6	0.24435610	0.2856	232.84
64	2MK6	0.24458430	0.0694	328.24
65	2SM6	0.24717810	0.1102	237.79
66	MSK6	0.24740620	0.0854	29.52
67	3MK7	0.28331490	0.0365	164.15
68	M8	0.32204560	0.0890	115.57

Harmonic Analysis Results *(by SLPR2 Software)*

Lamu Station

No.	Name	Frequency	Amplitude (cm)	Phase (degrees)
1	Z0	0.00000000	226.8187	0.00
2	SA	0.00011407	3.0283	313.27
3	SSA	0.00022816	4.2109	173.24
4	MSM	0.00130978	1.0775	345.23
5	MM	0.00151215	1.3954	347.27
6	MSF	0.00282193	0.8059	171.35
7	MF	0.00305009	1.7470	334.94
8	ALP1	0.03439657	0.2656	262.21
9	2Q1	0.03570635	0.4477	77.60
10	SIG1	0.03590872	0.6134	229.68
11	Q1	0.03721850	2.8312	48.88
12	RHO1	0.03742087	0.4264	196.34
13	O1	0.03873065	12.5106	34.64
14	TAU1	0.03895881	0.5272	33.85
15	BET1	0.04004043	0.1686	3.08
16	NO1	0.04026859	1.2200	221.21
17	CHI1	0.04047097	0.2610	338.10
18	PI1	0.04143851	0.3412	31.02
19	P1	0.04155259	5.5317	206.35
20	S1	0.04166667	2.0385	288.56
21	K1	0.04178075	20.7877	160.92
22	PSI1	0.04189482	0.1643	348.54
23	PHI1	0.04200891	0.3315	266.69
24	THE1	0.04309053	0.3407	337.53
25	J1	0.04329290	1.3453	163.19
26	SO1	0.04460268	0.5794	65.55
27	OO1	0.04483084	1.4206	153.17
28	UPS1	0.04634299	0.2533	154.50
29	OQ2	0.07597494	0.1731	352.66
30	EPS2	0.07617731	1.0488	115.12
31	2N2	0.07748710	1.6268	252.12
32	MU2	0.07768947	2.6589	92.39
33	N2	0.07899925	18.0132	233.28
34	NU2	0.07920162	3.7702	18.47
35	H1	0.08039733	0.8558	257.32
36	M2	0.08051140	97.9024	227.36
37	H2	0.08062547	0.4774	99.92
38	MKS2	0.08073957	0.3500	131.18
39	LDA2	0.08182118	1.4018	228.09
40	L2	0.08202355	3.3389	26.97
41	T2	0.08321926	3.4597	267.92
42	S2	0.08333334	48.5989	72.80

Harmonic Analysis Results *(by SLPR2 Software)*

Lamu Station

No.	Name	Frequency	Amplitude (cm)	Phase (degrees)
43	R2	0.08344740	0.5820	59.06
44	K2	0.08356149	14.0940	215.06
45	MSN2	0.08484548	0.3193	159.39
46	ETA2	0.08507364	0.6877	209.84
47	MO3	0.11924210	0.8960	39.59
48	M3	0.12076710	0.2601	211.79
49	SO3	0.12206400	0.6765	251.41
50	MK3	0.12229210	0.7041	151.69
51	SK3	0.12511410	0.5326	19.04
52	MN4	0.15951060	0.9179	215.39
53	M4	0.16102280	2.3698	211.13
54	SN4	0.16233260	0.4169	95.07
55	MS4	0.16384470	1.9457	62.18
56	MK4	0.16407290	0.5481	218.35
57	S4	0.16666670	0.6311	281.98
58	SK4	0.16689480	0.3324	67.39
59	2MK5	0.20280360	0.2319	184.26
60	2SK5	0.20844740	0.1166	172.00
61	2MN6	0.24002200	0.3343	298.99
62	M6	0.24153420	0.5930	293.58
63	2MS6	0.24435610	1.1048	155.54
64	2MK6	0.24458430	0.2677	289.98
65	2SM6	0.24717810	0.3953	354.95
66	MSK6	0.24740620	0.2259	137.61
67	3MK7	0.28331490	0.0744	151.30
68	M8	0.32204560	0.2102	290.67

Harmonic Analysis Results *(by T_TIDE Software)*

Mombasa Station

No.	**Name**	**Frequency**	**Amplitude (cm)**	**Phase (degrees)**
1	Xo	0.0000000	287.00	0.00
2	SA	0.0001141	2.51	162.78
3	SSA	0.0002282	1.12	27.05
4	MSM	0.0013098	0.66	23.00
5	MM	0.0015122	0.14	321.83
6	MSF	0.0028219	0.45	351.48
7	MF	0.0030501	1.35	27.42
8	ALP1	0.0343966	0.07	309.05
9	2Q1	0.0357064	0.3	332.54
10	SIG1	0.0359087	0.44	344.54
11	Q1	0.0372185	2.21	1.63
12	RHO1	0.0374209	0.5	358.06
13	O1	0.0387307	11.49	0.89
14	TAU1	0.0389588	0.13	335.65
15	BET1	0.0400404	0.18	351.41
16	NO1	0.0402686	1.6	273.83
17	CHI1	0.0404710	0.17	46.15
18	PI1	0.0414385	0.14	87.40
19	P1	0.0415526	5.43	354.12
20	S1	0.0416667	2.42	311.99
21	K1	0.0417807	18.97	354.56
22	PSI1	0.0418948	0.17	327.35
23	PHI1	0.0420089	0.34	324.02
24	THE1	0.0430905	0.32	346.94
25	J1	0.0432929	1.07	345.98
26	SO1	0.0446027	0.13	56.28
27	OO1	0.0448308	1.11	7.49
28	UPS1	0.0463430	0.23	41.05
29	OQ2	0.0759749	0.17	210.21
30	EPS2	0.0761773	0.2	44.68
31	2N2	0.0774871	1.67	318.22
32	MU2	0.0776895	1.53	23.99
33	N2	0.0789992	18.78	4.49
34	NU2	0.0792016	3.99	2.95
35	H1	0.0803973	1.1	2.07
36	M2	0.0805114	103.85	25.27
37	H2	0.0806255	0.64	84.10
38	MKS2	0.0807396	0.52	356.10
39	LDA2	0.0818212	1.16	46.57
40	L2	0.0820236	3.07	36.12
41	T2	0.0832193	3.02	55.74
42	S2	0.0833333	51.49	64.31

Harmonic Analysis Results *(by T_TIDE Software)*

Mombasa Station

No.	Name	Frequency	Amplitude (cm)	Phase (degrees)
43	R2	0.0834474	0.58	75.55
44	K2	0.0835615	14.38	62.33
45	MSN2	0.0848455	0.29	289.02
46	ETA2	0.0850736	0.55	64.64
47	MO3	0.1192421	0.32	147.61
48	M3	0.1207671	0.33	131.49
49	SO3	0.1220640	0.11	154.16
50	MK3	0.1222921	0.19	32.82
51	SK3	0.1251141	0.17	334.81
52	MN4	0.1595106	0.66	100.54
53	M4	0.1610228	1.13	136.53
54	SN4	0.1623326	0.03	195.61
55	MS4	0.1638447	0.59	172.55
56	MK4	0.1640729	0.17	179.76
57	S4	0.1666667	0.26	195.64
58	SK4	0.1668948	0.12	190.03
59	2MK5	0.2028035	0.01	32.77
60	2SK5	0.2084474	0.08	294.32
61	2MN6	0.2400221	0.03	203.77
62	M6	0.2415342	0.04	125.51
63	2MS6	0.2443561	0.24	139.13
64	2MK6	0.2445843	0.06	166.25
65	2SM6	0.2471781	0.14	201.60
66	MSK6	0.2474062	0.08	186.26
67	3MK7	0.2833149	0.04	244.35
68	M8	0.3220456	0.05	315.56

Harmonic Analysis Results *(by T_TIDE Software)*

Lamu Station

No.	Name	Frequency	Amplitude (cm)	Phase (degrees)
1	Xo	0.0000000	227.00	0.00
2	SA	0.0001141	3.03	145.93
3	SSA	0.0002282	4.21	44.51
4	MSM	0.0013098	1.08	153.40
5	MM	0.0015122	1.39	13.12
6	MSF	0.0028219	0.8	5.22
7	MF	0.0030501	1.75	40.15
8	ALP1	0.0343966	0.26	5.47
9	2Q1	0.0357064	0.4	341.17
10	SIG1	0.0359087	0.59	3.99
11	Q1	0.0372185	2.61	345.69
12	RHO1	0.0374209	0.42	354.37
13	O1	0.0387307	11.81	4.31
14	TAU1	0.0389588	0.49	64.62
15	BET1	0.0400404	0.16	323.74
16	NO1	0.0402686	0.74	61.43
17	CHI1	0.0404710	0.24	2.99
18	PI1	0.0414385	0.34	352.23
19	P1	0.0415526	5.56	0.02
20	S1	0.0416667	2.91	316.47
21	K1	0.0417807	19.95	358.53
22	PSI1	0.0418948	0.16	25.98
23	PHI1	0.0420089	0.32	345.62
24	THE1	0.0430905	0.32	343.51
25	J1	0.0432929	1.18	42.35
26	SO1	0.0446027	0.55	96.11
27	OO1	0.0448308	1.03	36.28
28	UPS1	0.0463430	0.2	66.16
29	OQ2	0.0759749	0.17	80.50
30	EPS2	0.0761773	1.06	60.00
31	2N2	0.0774871	1.63	5.16
32	MU2	0.0776895	2.68	62.60
33	N2	0.0789992	18.12	11.38
34	NU2	0.0792016	3.79	14.55
35	H1	0.0803973	0.86	51.91
36	M2	0.0805114	98.71	31.34
37	H2	0.0806255	0.48	97.82
38	MKS2	0.0807396	0.32	149.39
39	LDA2	0.0818212	1.42	19.78
40	L2	0.0820236	4.71	40.33
41	T2	0.0832193	3.46	75.28
42	S2	0.0833333	48.57	72.92

Harmonic Analysis Results *(by T_TIDE Software)*

Lamu Station

No.	Name	Frequency	Amplitude (cm)	Phase (degrees)
43	R2	0.0834474	0.48	77.35
44	K2	0.0835615	12.95	69.38
45	MSN2	0.0848455	0.32	185.25
46	ETA2	0.0850736	0.6	82.01
47	MO3	0.1192421	0.85	173.15
48	M3	0.1207671	0.26	97.76
49	SO3	0.1220640	0.64	221.09
50	MK3	0.1222921	0.68	153.24
51	SK3	0.1251141	0.51	216.69
52	MN4	0.1595106	0.93	157.42
53	M4	0.1610228	2.41	179.06
54	SN4	0.1623326	0.42	233.15
55	MS4	0.1638447	1.96	226.25
56	MK4	0.1640729	0.51	236.78
57	S4	0.1666667	0.63	282.12
58	SK4	0.1668948	0.31	282.04
59	2MK5	0.2028035	0.23	350.12
60	2SK5	0.2084474	0.11	9.96
61	2MN6	0.2400221	0.34	45.15
62	M6	0.2415342	0.61	65.47
63	2MS6	0.2443561	1.12	123.59
64	2MK6	0.2445843	0.25	112.36
65	2SM6	0.2471781	0.4	159.09
66	MSK6	0.2474062	0.21	156.15
67	3MK7	0.2833149	0.07	119.97
68	M8	0.3220456	0.22	226.86

Annex II: High – Low Tide Predictions for Mombasa and Lamu Stations

Annex III: Hourly Tide Predictions for Mombasa and Lamu Stations