Statistical Modelling of Significant Wave Height: Inshore and Offshore Bonny River Estuary, Nigeria

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Abstract

The selection of best – fit probability distribution is of fundamental importance in the design, planning, and operability studies for harbours, coastal and offshore structures and exploitation of coastal resources. A wrong choice of probability distribution could lead to either under – or over – estimation of design loads, which may have detrimental impacts on safety and project economy. Consequently the Inshore and Offshore wave data of Bonny River estuary, Nigeria was studied by fitting Rayleigh, 2- parameter Lognormal, Fisher – Tippett Type 1(FT-1), 2-parameter and 3-parameter Weibull probability distributions using probability paper method. The probability distributions were subjected to five model evaluation metrics; coefficient of determination (R^2), demeaned RMSE, normalizedRMSE, Scatter index (SI) and Performance scores index(d_1) and a scoring scheme was adopted on the basis of which the best – fit probability distribution for either Inshore of Offshore was selected. The results show that 2-parameter Lognormal distribution is the best –fit probability distribution for the Inshore station, seconded closely by Fisher – Tippett Type 1 and 3- parameter Weibull distributions. The results also show that Fisher – Tippett Type 1 is the best – fit probability distribution for the offshore station seconded closely by 3 – parameter Weibull distribution. This study will contribute to the development of the coastal zone and also a recipe for Integrated Coastal Zone Management of the Nigerian Gulf of Guinea.

Key words: Bonny river estuary, goodness of fit tests, integrated coastal zone management, significant wave height, probability distribution models.

Introduction

Ocean waves may be generated by wind stresses from the atmosphere, earthquakes, gravity of the earth and celestial bodies, cosmic forces, and surface tensions. These forces can impose enormous impacts upon coastal and offshore structures (WMO – No. 72). The calculation of these forces in extreme is done statistically using the linear wave theory to predict the height and periods of the extreme waves. The most important wave design parameter and the most studied statistical parameter, is the significant wave height Hs(m), defined as the average height of the highest one-third of the waves, i.e. if all wave heights measured from the record are arranged in descending order. It has been shown that certain assumptions, the probability distribution of wave heights can be described completely in terms of the significant wave height (HMSO – 256). Consequently, the long-term behaviour of Hs should enable us to derive inference concerning the long-term statistics of individual wave heights. In practice, various probability distributions are fitted to the significant wave height data and the one giving the best visual fit is accepted. The distributions that have received particular application to coastal and offshore engineering are Rayleigh, 2- and 3- parameter log-normal, 2- and 3- parameter Weibull and Extreme value distribution (the Fisher Tippett Type 1.

The WMO-No. 702(1989) observed that 2-parameter Log-normal distribution is good fit, in the absence of seasonal cycle. It also observed that 3- parameter distribution gives better fit than the 2-parameter counterpart. Further, it asserted that Fisher-Tippett Type 1 distribution fits better to three-hourly data from the North Atlantic and North Sea.

The method of fitting the chosen distribution often involves the use of (i) probability paper (ii) Methods of Moments (MoM) and (iii) maximum likelihood estimates (ML).

The probability paper is a graph paper with non-linear scales on the probability and height axes. The probability distribution is fitted by putting a straight line through the plotted values, preferably using a spreadsheet. (e.g. Excel). The method is applicable to 2-parameter distributions. The probability paper method may be extended to fit, 3 – parameter distributions by plotting the data over a range of values of the third parameter to see which value gives the best fit to a straight-line by minimizing the residual variance or by maximizing the correlation coefficient.

The method of moments (MoMs) is an analytic method of estimating the parameters of a distribution. The MoMs is based on the simple idea, that since the moments of the distribution (mean, variance, skewness, etc.) depend upon the parameter values, estimate of these values can be obtained using estimates from the data of the mean, etc.

The method of maximum likelihood (MLE), consists of finding values for the distribution parameters,

which maximize the likelihood that the observed data come from this distribution (WMO – No.72. 1989). Ochi(1982) observed that there is no probability distribution function that universally fits all long – term wave height data. The usual approach is to investigate a number of commonly used distributions and then adopt the one giving the best – fit. Accordingly, the method of probability paper based on probability plots and least squared is adopted. The distributions being investigated are two-parameter Log-normal, two and three parameter Weibull, the Fisher-Tippett Type 1(FT-1) and Rayleigh. The modelling of significant wave height has not been studied in the Nigerian Gulf of Guinea. Therefore , the objective of this research is the selection of best – fit distribution on the basis of five goodness – of – fit tests using the probability paper method.   The modelling of long-term distribution of significant wave height is important for a wide range of activities including: exploitation of coastal resources , integrated coastal zone management (ICZM).

2.0 Materials and Methods.
2.1 Data and Study Area
The Inshore wave measurement station is situated near Bonny Island while the Offshore station is located near the Bonny Offshore Oil Production Platform at approximately $4^o16'$N and $7^o19'$E. The coordinates of the Inshore station is at approximately $4^o25.5'$N and $7^o8.6'$E or at Nigerian National Grid co-ordinates 520200E, 47250N. The water depths at inshore station and offshore station are 13m and 20m respectively. The astronomical tide is semi-diurnal. The maximum tidal range observed is 2.5 meters. Figure 1 shows the locations of the inshore and offshore wave measurement stations.
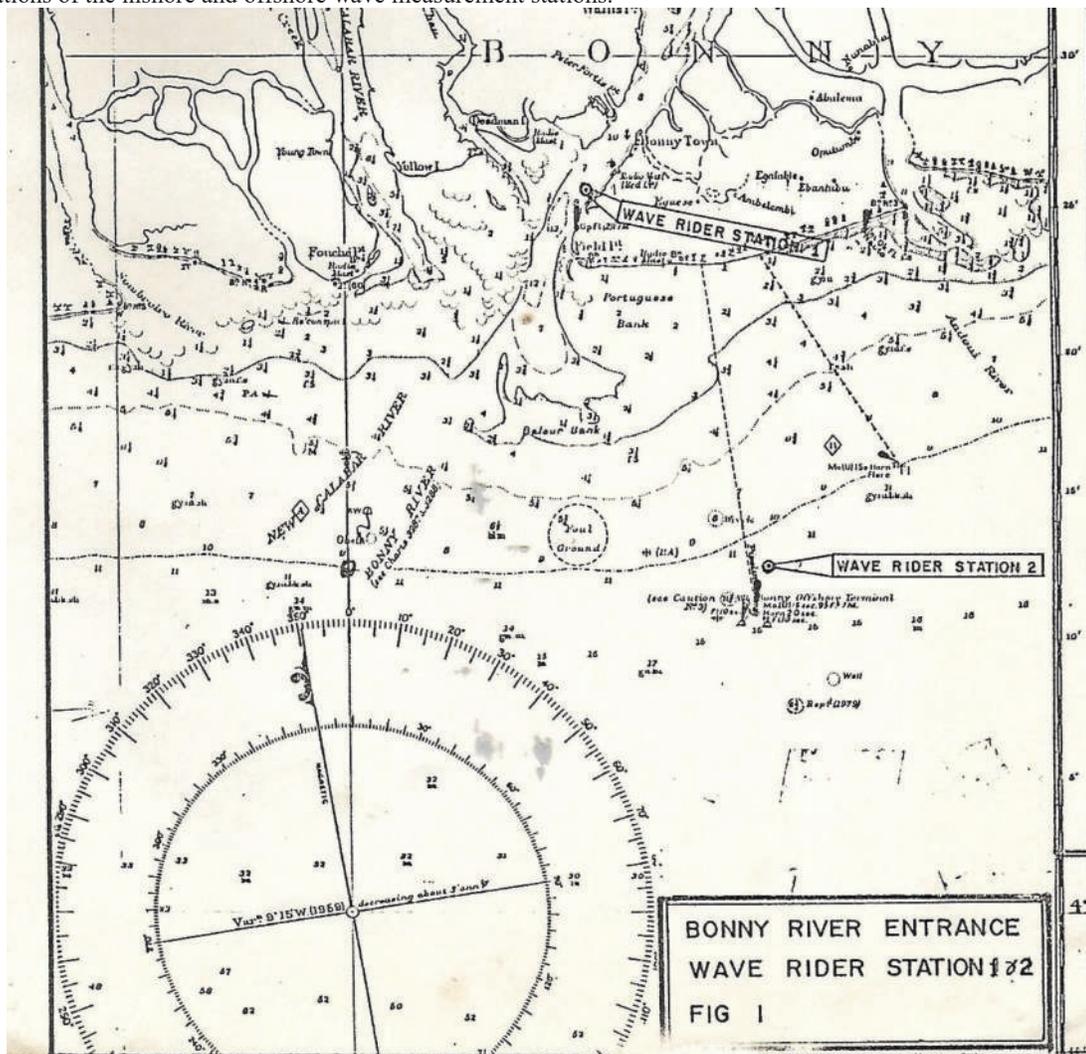
The wave height measuring system consist of a datawell waverider buoy with radio transmitter and a DIWAR (Digital Wave Receiver). The DIWAR is designed for the reception of the wave height measurement, transmitted by the waverider and direct communication with the Hp Vectra is via RS232 transmit and receive

module. The unit consists of a radio receiver, phaselock for demodulator, anti- aliasing filter, A-D converter and RS232 communication port. The various onshore wave logging components are shown in Figure 2(Nigerian LNG - Annual Report, 1990).
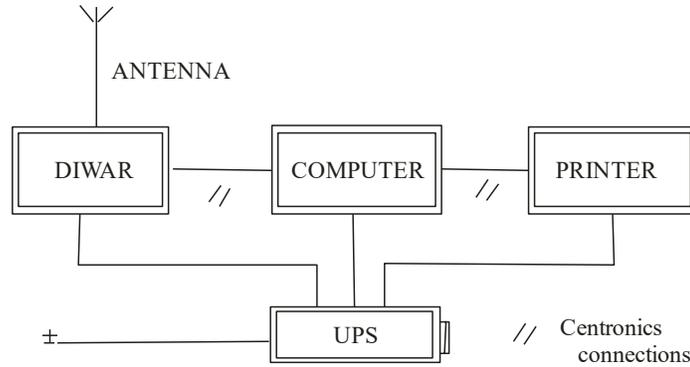
Figure 2: Onshore Wave Logging System

2.2 Probability Distribution

The probability distributions, Cumulative density functions, and probability plotting axes of the selected probability models are shown in Table 1.

Table 1: Probability Distribution Functions.

S/No.	Distribution of random variable x	PDF and CDF	Distribution Probability Plot	
			X- axis	Y- axis
1.	Fisher- -Tippett	$F(H) = \exp\left[-\exp\left(\frac{H-A}{B}\right)\right]$	$-\log[-\log(P)]$	Y=H
2.	Weibull(2)	$f(H) = \left(\frac{K}{\alpha}\right)\left(\frac{H}{\alpha}\right)^{K-1} \exp\left[-\left(\frac{H}{\alpha}\right)^{K}\right]$ $F(H) = 1 - \exp\left[-\left(\frac{H}{\alpha}\right)^{K}\right]$	$\log[-\log(1-P)]$	$\log(H)$
3.	Rayleigh	$f(H) = \left(\frac{H}{\alpha^2}\right)\exp\left[-\frac{x^2}{2\alpha^2}\right]$ $F(H) = 1 - \exp\left(\frac{-H^2}{2\alpha}\right)$	$\log[-\log(1-P)]$	$\log(H)$
4.	Lognormal	$f(H) = \frac{1}{H\sqrt{2\pi}}\exp\left[\frac{-(\log H - ч_y)^2}{2\delta_y^2}\right]$	$\phi^{-1}(P)$	$\log(H)$
5.	Weibull(3)	$f(H) = \left(\frac{K}{\alpha}\right)\left(\frac{H-m}{\alpha}\right)^{K-1} \exp\left[-\left(\frac{H-m}{\alpha}\right)^{K}\right]$ $F(H) = 1 - \exp\left[-\left(\frac{H-m}{\alpha}\right)^{K}\right]$	$\log[-\log(1-P)]$	$\log(H-A)$

2.3 Wave Evaluation Metrics

Statistical metrics applicable to evaluation of wave models were used to assess the performance of the probability distributions. The metrics are coefficient of determination, demanded root mean square error (demeaned RMSE), Scatter Index (SI), Normalized root mean square error (NRMSE), and Performance Score index(d_1). For each of the measures given, Hso represents the observed significant wave heights, Hsp represents the predicted significant wave heights, N is the number of observations and $\overline{H}_{os}$ is mean significant wave height. The computational forms of the above metrics are:

(i)   The bias estimate; b = 1/N $\sum$(Hsp – Hso) …………………………………   …(1)

(ii)   RMSE (demeaned) RMSE $= \sqrt{\dfrac{1}{N-1}\sum(Hsp - Hso - b)^2}$ ………………….. (2)

The RMSE is a measure of the residuals between the model predictions and measured observations, where larger number indicate greater variance. RMSE can range from zero to infinity and lower the value, the better the model. RMSE (demeaned) is RMSE estimate corrected for the bias, resulting in its equivalence to the standard deviation of the difference normalized (NRMSE) are RMSE estimates which include components of variance and bias (Ardhuin et al., 2010).

(iii)   NRMSE - $\sqrt{\dfrac{\sum(Hsp - Hso_i)^2}{\sum Hso^2}}$ ………………………………………….. (3)

By presenting the RMSE as unbiased, a more complete picture of the error distribution is provided (Chai and Draxler, 2014).

(iv)   Scatter index (SI): SI $= \dfrac{RMSE}{Hso}$ ……………………………………………. (4)

The SI is a normalized measure of error, often reported as a percent. Low values of the SI are an indication of better model performance.

(v)   Performance Score (d_1) gives a large overall performance scores. It is reported as the Willmott et al. (1985) index defines as the following:

Performance Scores (d_1) $= 1 - \dfrac{\sum|Hsp - Hso|}{\sum\left(\left|Hsp - \overline{Hso}\right| + \left|Hso - \overline{Hso}\right|\right)}$ …………………… (5)

d_1 is based on the absolute values of the errors and is less sensitive to errors concentrated in outliers compared to its original formulation. The R^2 in Equation indicates the proportion of observed variation that can be explained by the model. The higher the value of R^2, the more successful is the linear regression model in explaining the variation.

3. Analysis, Results and Discussion
3.1 Analysis

Tables 2 and 3 show the probability distribution of inshore and offshore significant wave height calculations for 1989 – 1990. The class intervals in Table 2 is 50mm (0.05m) each. Ni in column 4 indicates, the total number of waves in each class interval per year. In column 5, ΣNi signifies the number of observations up to and including the present class interval. Column 6 gives the probability that any wave height H' is equal to or less than a specified wave height H , defined as Q(H'>H) = 1-P. The values in column 6 may be presented in equation form as;

$$P(H' \leq H) = \frac{number\ of\ data \leq H}{total\ number\ of\ data} = \frac{\sum N_i\ (Tot.in\ each\ \text{int}erval)}{8,870,933}$$ ………… .(6)

Equation 6 is the empirical cumulative distribution function (CDF). Since the most robust relationship for both interpolation and extrapolation is a straight line, the CDF or the Plot of column 6 (probability) against wave height H is transformed into a linear model as:

Y = αX +β   ……………….. (7)

Where Y is the transformed probability axis, also called the reduced variate and X is the transformed wave height axis. The X and Y axes of the probability distributions used in the study are shown in Table 1. For normal distribution, each coordinate point is plotted as (H, z = $\Phi^{-1}(P_i)$), where $\Phi^{-1}(P_i)$ is inverse function $\Phi^{-1}(.)$ is calculated using the Ms Excel built-in function Norm.Si Inv(P_i). In this way column 8 (z = $\Phi^{-1}(P_i)$) is plotted against H (column 3). The coefficients α and β are the slope and intercept of Equation 7, they represents the mean and standard deviation, and in turn can be used to calculate the distribution parameters. Accordingly for Log-normal distribution, z = $\Phi^{-1}(P)$ is plotted against LnH. In the case of Fisher-Tippett 1(FT-1) distribution, the reduced variate Y = -Ln(Ln P^{-1}_i). In column 10 (G) is plotted against H (column 3). For the 2-parameter Weibull distribution, column 9 is plotted against x = Ln(-Ln(Q)); the Q – value are given column 7. In the case of three-parameter Weibull distribution, LN(H-A) is plotted against Ln(-Ln(1-P_i), the parameter "A" is chosen by trial, until the best straight line is obtained. The above analysis is repeated for Table 3.

Table 2: Probability Distribution of Inshore Hs. Calculations (1989 - 1990)

S/N	Class Interval		Mid. Class(H)	Ni/year	∑Ni	P(≤ H)	Q	Z=Φ⁻¹(P)	Ln H	G	W2
1	2		3	4	5	6	7	8	9	10	11
1	0	0.05	0.025	0	0	0	1		-3.68888		
2	0.05	0.1	0.075	16601	16601	0.001871	0.998129	-2.89906	-2.59027	-1.83754	-6.28014
3	0.1	0.15	0.125	593412	610013	0.068765	0.931235	-1.48505	-2.07944	-0.98472	-2.64164
4	0.15	0.2	0.175	1566856	2176869	0.245393	0.754607	-0.68906	-1.74297	-0.33996	-1.26741
5	0.2	0.25	0.225	1681219	3858088	0.434913	0.565087	-0.16388	-1.49165	0.183192	-0.56076
6	0.25	0.3	0.275	1530593	5388681	0.607454	0.392546	0.272689	-1.29098	0.696193	-0.0671
7	0.3	0.35	0.325	1292573	6681254	0.753162	0.246838	0.684475	-1.12393	1.260634	0.335776
8	0.35	0.4	0.375	981013	7662267	0.86375	0.13625	1.097323	-0.98083	1.92092	0.689773
9	0.4	0.45	0.425	624935	8287202	0.934197	0.065803	1.507802	-0.85567	2.687254	1.001034
10	0.45	0.5	0.475	313948	8601150	0.969588	0.030412	1.874772	-0.74444	3.477515	1.250737
11	0.5	0.55	0.525	149208	8750358	0.986408	0.013592	2.208861	-0.64436	4.291428	1.458211
12	0.55	0.6	0.575	79272	8829630	0.995344	0.004656	2.600383	-0.55339	5.367268	1.680753
13	0.6	0.65	0.625	26606	8856236	0.998343	0.001657	2.937049	-0.47	6.402063	1.85675
14	0.65	0.7	0.675	8347	8864583	0.999284	0.000716	3.188195	-0.39304	7.241722	1.979909
15	0.7	0.75	0.725	4218	8868801	0.99976	0.00024	3.491303	-0.32158	8.333355	2.120281
16	0.75	0.8	0.775	2132	8870933	1	0		-0.25489	"	"
17	0.8	0.85	0.825		8870933	1	0	"	-0.19237	"	"
"	"	"	"	"	"	"	"	"	"	"	"
30											

Total: 8,870,933

Table 3: Probability Distribution of Offshore Hs. Calculations(1989 - 1990)

S/N	Class Interval		Mid. Class (H)	Ni/year	∑Ni	P	Q	Z	LnH	G	W2
1	2		3	4	5	6	7	8	9	10	11
1	0	0.1	0	0	0	0	1				
2	0.1	0.3	0.2	0	0	0	1		-1.60944		
3	0.3	0.5	0.4	0	0	0	1		-0.91629		
4	0.5	0.7	0.6	451954	451954	0.076681	0.923319	-1.42776	-0.51083	-0.94317	-2.52848
5	0.7	0.9	0.8	2130205	2582159	0.438102	0.561898	-0.15578	-0.22314	0.192005	-0.55089
6	0.9	1.1	1	1603497	4185656	0.71016	0.28984	0.553851	0	1.072169	0.21384
7	1.1	1.3	1.2	936916	5122572	0.869122	0.130878	1.122248	0.182322	1.96417	0.709752
8	1.3	1.5	1.4	509543	5632115	0.955573	0.044427	1.701476	0.336472	3.091276	1.13588
9	1.5	1.7	1.6	173344	5805459	0.984984	0.015016	2.169658	0.470004	4.191058	1.434754
10	1.7	1.9	1.8	63858	5869317	0.995818	0.004182	2.637019	0.587787	5.474894	1.700555
11	1.9	2.1	2	10553	5879870	0.997609	0.002391	2.821306	0.693147	6.034667	1.797719
12	2.1	2.3	2.2	3872	5883742	0.998266	0.001734	2.922802	0.788457	6.356176	1.849564
13	2.3	2.5	2.4	5809	5889551	0.999251	0.000749	3.175109	0.875469	7.196528	1.973651
14	2.5	2.7	2.6	3376	5892927	0.999824	0.000176	3.573512	0.955511	8.6443	2.15691
15	2.7	2.9	2.8	1038	5893965	1	0	"	1.029619	"	"
16	2.9	3.1	3	"	"	"	"	"	1.098612	"	"
17	3.1	3.3	3.2	"	"	"	"	"	1.163151	"	"
18	3.3	3.5	3.4	"	"	"	"	"	1.223775	"	"
"	"	"	"	"	"	"	"	"	"	"	"
30											

Total :   5,893,965

3.2 Results

The goodness – of – fit (GoF) tests have been selected based on wave evaluation criteria mostly cited in literature (e.g. Bryant et al. 2016, Akpinar et al. 2012). They indicate how well a probability distribution fits the observed wave climate. The results of GoF tests are given in Table5. The recommended performance rating for each test was used to assess each probability distribution. For example, the range of R^2 lies between 0 and 1 which describes how much of the observed dispersion is explained by the prediction. A value of zero means not correlation at all whereas a value of 1.0 means a perfect fit (Krause et al., 2005). The range of performance scores index (d_1) is similar to that of R^2 and lies between zero (poor performance) and one (excellent performance). The scatter index (SI) is a normalized measure of error. Lower values of the SI are an indication of the better model performance. The RMSE is a measure of the residuals between the model predictions and measured observations, where larger values indicate greater variance. The RMSE is corrected for bias resulting in RMSE (demeaned) and the other forms of RMSE which includes components of variance and bias as normalized (NRMSE). Accordingly, a perfect model has a bias, RMSE including RMSE (demeaned and normalized RMSE), and SI of 0.0. Based on the above performance rating, the 3 – parameter Weibull distribution is scored 1 with R^2 value of 0.9937 in the offshore category. Similarly, the 3-paramter Weibull distribution is also scored 1 with R^2 value of 0.9935 being the highest in the inshore category. The inshore and offshore wave climates were scored separately in order to account for the different wave height attenuation processes. Table 6 shows the scored results of each probability distribution. The total score of each distribution was obtained by summing the individual point scores obtained from all the GoF tests (Izinyon and Ajumuka, 2013). The best-fit model for each distribution was selected based on the lowest score obtained as shown in

Table 7.

Table 5: Results of Goodness – of – fit Tests(GoF)

GOF	Probability Distributions									
	Rayleigh		Log normal		FT-1		Weibull 2		Weibull3	
	Inshore	Offshore	Inshore	Offshore	Inshore	Offshore	Inshore	Offshore	Inshore	Offshore
R^2	0.936	0.913	0.988	0.9912	0.986	0.9904	0.936	0.9132	0.9935	0.9937
RMSE(Dm)	0.278	0.347	0.258	0.268	0.261	0.258	0.278	0.592	0.197	0.261
NRMSE	0.127	0.122	0.073	0.044	0.053	0.036	0.127	0.222	0.146	0.041
S.I.	0.696	0.217	0.646	0.167	0.652	0.161	0.695	0.370	0.491	0.163
P.S.Index	0.850	0.923	0.929	0.975	0.937	0.981	0.850	0.866	0.835	0.977

Where R^2 is coefficient of determination, RMSE(Dm) is RMSE(demeaned), NRMSE is normalized RMSE, S.I. is scatter index and P.S Index is performance score index.

Table 6: Probability distributions of scoring based on Tests(GoF)

GOF	Probability Distributions									
	Rayleigh		Log normal		FT-1		Weibull 2		Weibull3	
	Inshore	Offshore	Inshore	Offshore	Inshore	Offshore	Inshore	Offshore	Inshore	Offshore
R^2	4	5	2	2	3	3	4	4	1	1
RMSE(Dm)	4	4	2	3	3	1	4	5	1	2
NRMSE	3	4	2	3	1	1	3	5	4	2
S.I.	5	4	2	3	3	1	4	5	1	2
P.S.Index	3	4	2	3	1	1	3	5	4	2
Total Score	19	21	10	14	11	7	18	24	11	9

Table7: Best – fit Models

Location	Distribution type
Inshore	2-Parameter Lognornal, FT-1, 3-P Weibull distribut.
Offshore	Fisher – Tippett 1 and 3- Parameter Weibull distribu.
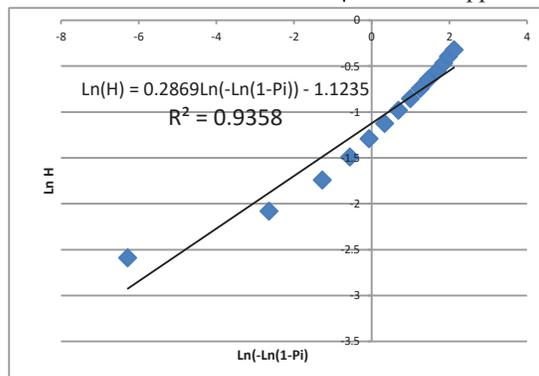
Figure 3 Rayleigh Distribution for Inshore data
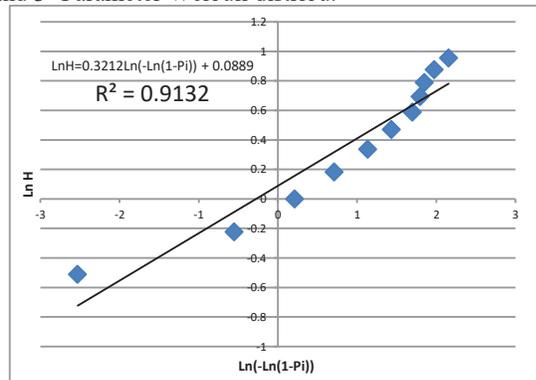
Figure 4 Rayleigh Distribution for Offshore Data
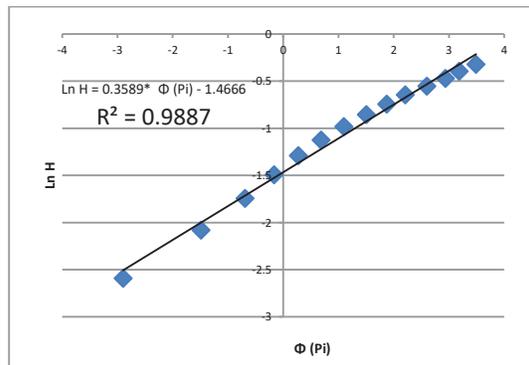
Figure 5 Lognormal Distribution for Inshore Data
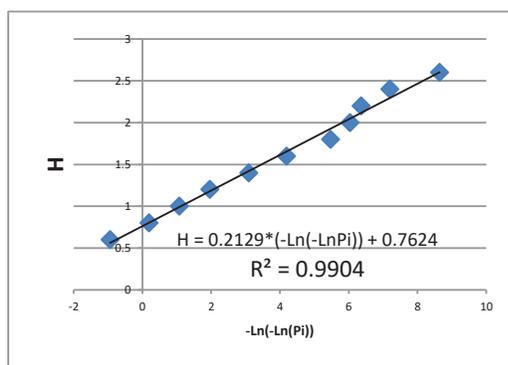
Figure 6 Log normal Distribution for Offshore Data
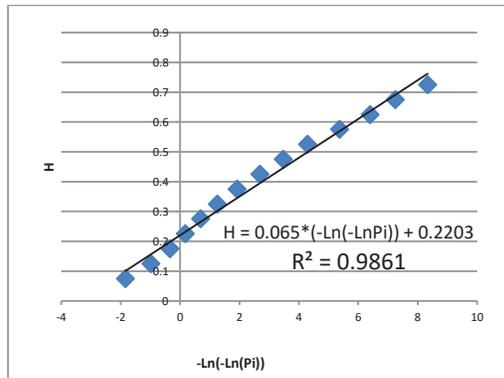
Figure 7 FT - 1 Distribution for Inshore Data
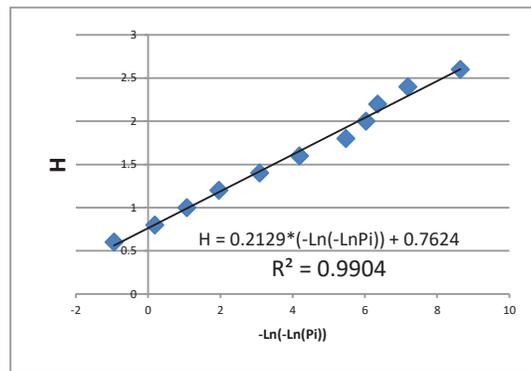
Figure 8 FT - 1 Distribution for Offshore Data
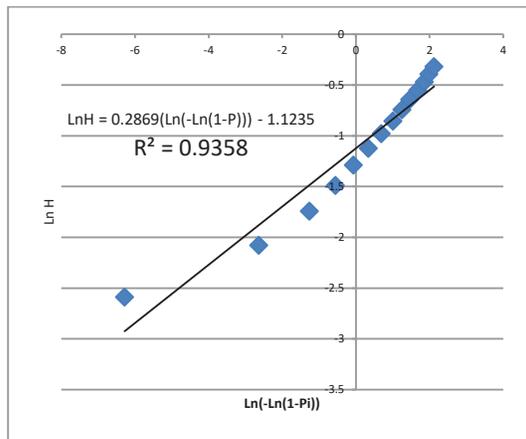
Figure 9 2-Para.Weibull Dist. For Inshore Data
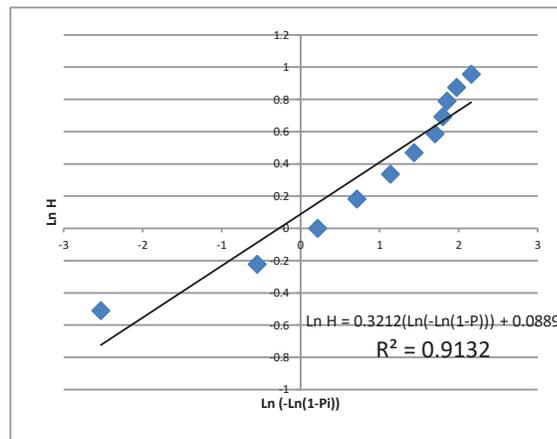
Figure 10 2-Para.Weibull Dist. for Offshore Data
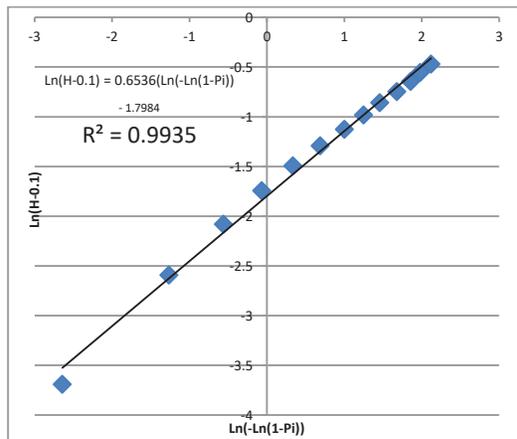
Figure 11 3-Para.Weibull Dist. For Inshore Data
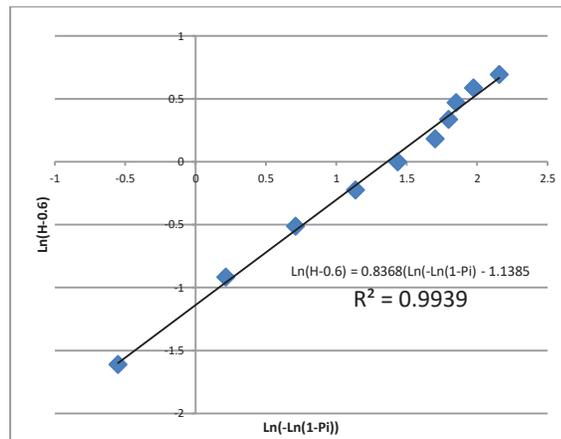
Figure 12 3-Para.Weibull Distrib. for Offshore Data

3.3 Discussion

The results obtained in this study agrees with those found under similar geographic settings in other parts of the world. The Nigerian NLNG found 3 – parameter Weibull distribution the best fit for both Inshore and Offshore stations. Conversely this study found 2 – parameter Lognormal the best – fit distribution for the Inshore station. and Fisher – Tippett Type1 the best – fit probability distribution for the Offshore station seconded closely by 3-parameter Weibull distribution. The findings of this report is also in agreement with WMO- No.702(pg. 106) report that Fisher – Tippett Type1 distribution is a good fit to 3 – hourly data from the North Atlantic and North Sea. WMO- No.702(1989) also recommended 3 – parameter Weibull distribution to be good fit , though it is not

the best fit in this study. Further , the good performance of 2-parameter Lognormal distribution for the inshore station may be attributed to the absence of seasonal effects in significant wave heights. It has been observed that the Inshore wave climate has a clear periodicity with the 12 – hourly tidal cycle. The Offshore wave climate did not show significant periodicity, implying that the Offshore wave climate is different from the Inshore probably due to the presence of the Bonny bar which separates the two stations, causing wave breaking in front of the Bonny bar (NLNG- 1990)

3.4 Conclusion

In this paper, the significant wave heights Inshore and Offshore of Bonny River estuary has been modelled statistically. The probability distribution employed are Rayleigh, 2- parameter Lognormal distribution, Fisher – Tippett Type 1, 2 – parameter and 3 – parameter Weibull distributions and the goodness –of- fit (GoF) tests are R^2, demeaned RMSE, normalized RMSE, Scatter index (SI) and Performance scores index(d_1) and the performance of each distribution was scored according to the GoF test rating . The distribution that satisfies the performance rating the best is giving a score of 1, the next is score 2, and so on. The total score of each distribution was obtained by summing all the individual point scores. The distribution that has the lowest score was adjudged the best – fit. In this way , for the Inshore station , the lognormal scored 10, seconded closely by FT-1 and 3- parameter Weibull distribution scoring 11 points each, 2 – parameter Weibull 18, and Rayleigh distribution 19, consequently   the best – fit distribution for the Inshore station is 2- parameter Lognormal distribution. Similarly , the FT-1 is the best fit distribution for the Offshore station. The most important outcomes of this study may be summarized as ;

(i)The best – fit probability distribution for the Inshore station is 2-parameter Lognormal distribution with a total score of 10, seconded closely by FT-1, 3-P Weibull distributions having scored of 11 points each.

(ii) The best – fit probability distribution for the Offshore station is FT-1 distribution   with a total score of 7 points, seconded closely by 3-Parameter Weibull distributions with a score of 9 points.

(iii)The wave climates Inshore and Offshore are different due to the presence of the Bonny bar which prevents the penetration of Offshore waves.

(iv) Reasoning from (iii) above, the seasonal effects observed Offshore was absence in the Inshore waves.

(v) The waves climate Inshore is mainly due to swell waves.

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