Journal of Engg. Research Vol. 7 No. (2) June 2019 pp. 143-166

Probability distribution, statistical characteristics, and power potential of seawater velocity around Boubyan Island in Kuwait

S. Neelamani* and Yousef Al-Osairi

Coastal Management Program, Environment and Life Sciences Research Center, Kuwait Institute for Scientific Research, P.O. Box : 24885, 13109 Safat, KUWAIT

**Corresponding Author: nsubram@kisr.edu.kw*

ABSTRACT

Seawater velocity is responsible for exerting drag forces on marine structures, movement of sediments and nutrients from one place to other, varying the water quality due to mixing of water and is also the main input for electric power generation using marine water current. A detailed field measurement, probability, and statistical analysis of seawater velocity at five stations (Boubyan port, Sabiya military area, Warba Island, Failaka Island, and Sabiya coast guard area) for a year around Boubyan Island, Kuwait, is carried out. The annual average measured velocities in these locations were 25.30, 22.22, 27.44, 19.66, and 18.35 cm/s, respectively. However, the maximum velocity in a year has reached 81.72, 82.38, 80.25, 85.49, and 72.54 cm/s, respectively. For the theoretical probability distribution analysis, four theoretical distributions were considered, namely, Rayleigh, Exponential, Gumbel, and Log-Normal distribution. Based on the study, it was found that none of these distributions consistently represented the measured sea water velocity for these locations. The seawater velocity value for 20% exceedance is 35.5, 33.5, 39.5, 26.3, and 25.5 cm/c for these locations, respectively. It is found from this study that Warba marine area is the most suitable location for marine current power generation with incident energy density of 189.18 Mwh. The results of this study are useful for more understanding of marine hydrodynamics of this area, where many mega projects are ongoing such as Boubyan port and Failaka Island development.

Keywords: Tidal variation, Shatt Al-Arab, Khor Sabiya, Khor Abdallah, Current velocity.

INTRODUCTION

One of the important physical phenomena of seawater is its velocity. It varies in both space and time. The seawater velocity at a particular point depends on many parameters, such as tidal variation, seawater density difference in space (which again depends on seawater temperature and salinity), wind speed and direction, wave climate, and the movement of ships and large marine mammals. The velocity of seawater causes shear stress on the seabed material and is responsible for sediment transport from one place to another. Moving seawater transports mass as well as heat. The north and southward movement of warm seawater from equatorial region are the main natural forces responsible for moderating the air temperature of the globe. The moving seawater is the main forcing function for transporting nutrients, pollutants, planktons, and minerals from one place to another and is the main force for coastal upwelling activities. Seawater velocity is the main parameter for inducing drag forces on all the elements of marine structures as submarine pipelines, vertical, horizontal, and inclined members of offshore drilling platforms, gravity structures, moored and moving vessels, etc. The seawater velocity is also responsible for erosion, accretion, and changing the coastal morphodynamics of beaches and seawater intake structures. It is responsible for accumulating sediments inside the marina, port, and harbor and in the approach channels. The velocity of the seawater also affects the marine water quality. Seawater velocity is the main parameter for spatial and temporal variation of seawater turbidity. During high velocity, sediments that are more cohesive are under suspended mode. A detailed understanding of the seawater velocity is hence important.

For a marine site, understanding the basic statistical parameters such as minimum, maximum, mean, and variance of the current velocity is important for planning field activities and for designing and operating of marine facilities. In particular, the probability distribution of the seawater velocity over a full year will be useful for clearly understanding the velocity regime in a specific area and for planning power generation activities. Kuwait is located in the north-western corner of the Arabian Gulf (Fig. 1) and is surrounded by Iraq and Saudi Arabia. Recently, the Kuwaiti government has planned to develop Boubyan, Warba, and Failaka islands. Site-wise, these islands are located near the estuary of Shatt Al-Arab (Fig. 1), which is considered to be the main supplier of freshwater including fine sediment to the Arabian Gulf (Al-Osairi et al., 2011). Consequently, this would have various effects on the hydroenvironmental characteristics of this region, where various projects are intended to be undertaken (Al-Osairi, 2011). The effects include water dynamics (Xia et al., 2010), water quality (Baker, 1976), and marine ecology (Wiese et al., 2001). One of the major projects in Boubyan Island is the mega port (Fig. 2). The construction of the port is in progress. Kuwait is also planning to build resorts, Lake Boubyan development project, etc. on the Boubyan Island (Fig. 2 and 3).

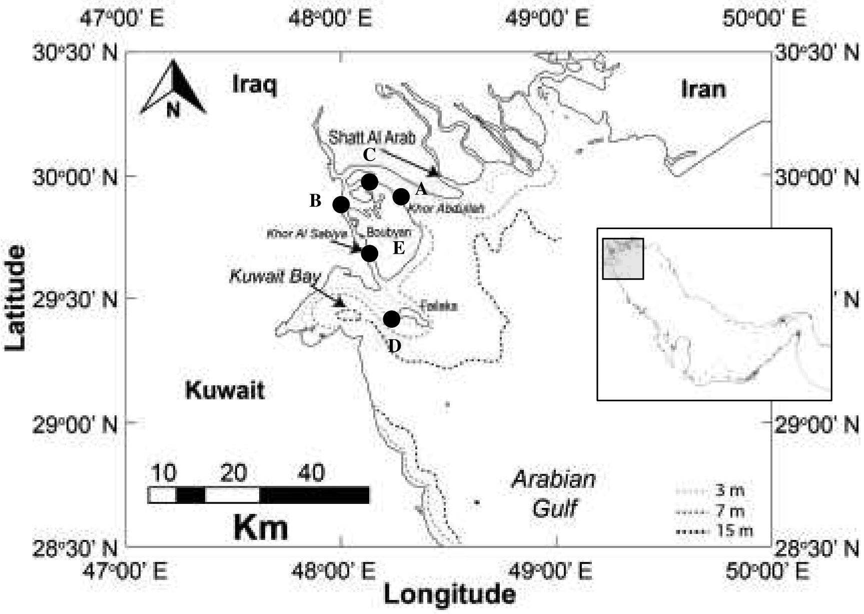

Fig. 1. North-western region of the Arabian Gulf including Kuwait Bay, Boubyan Island and Shatt Al-Arab; the field survey stations are in black circles and letters (Al-Osairi et al. (2017)).

A clear understanding of the seawater velocity will help plan and optimally design the marine infrastructures around Boubyan Port area. Failaka Island, located south of Boubyan Island (Fig. 1), has a marina (Fig. 4), and the annual siltation of about 2.35 m (Neelamani et al., 2016) is the biggest issue for this marina. Sabiya power plant located at the entrance of Khor Sabiya (Fig. 2 and 5) is also suffering with significant sedimentation because of high turbidity in the seawater. Maintenance dredging of about 400,000 m^3/yr is carried out with a total annual maintenance cost of about US $ 5.0 million (Neelamani and Al-Hulail, 2008).

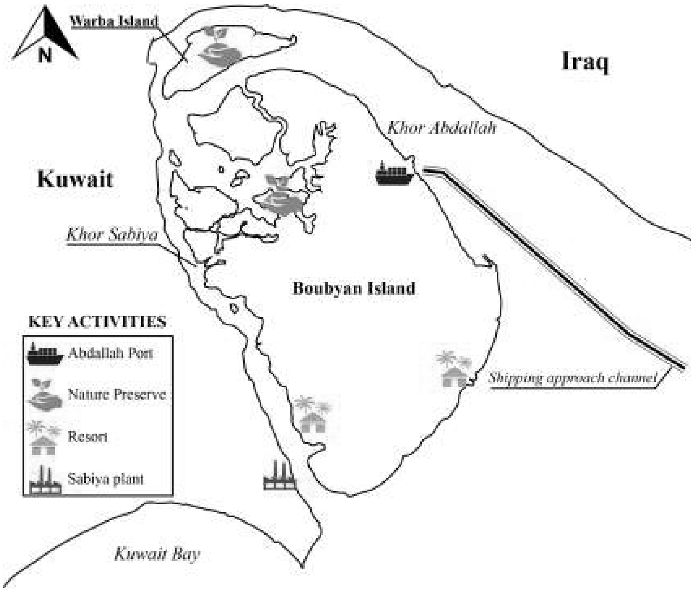

Fig. 2. Key activities existing and planned on and near Boubyan Island (Al-Osairi et al., 2017).

.

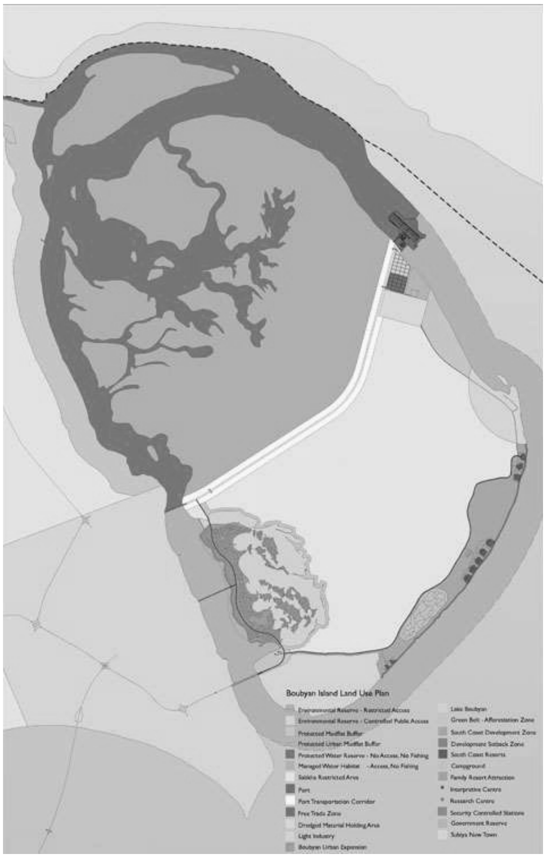

Fig. 3. Boubyan port land use plan (http://gckuwait.com/boubyan-island-environmental-study-and-master-plan#image-gallery)

Fig. 4. Failaka marina with sedimentation problem (Source: Google Earth).

Fig. 5. Sabiya power plant intake structure in Khor Sabiya with sedimentation problem (Source: Google Earth).

Hence a study based on the field measurement of seawater velocity around Boubyan Island is needed. The main aims of the present study are as follows:

a. Measuring seawater velocity at five different locations around Boubyan Island, Kuwait, for a span of one year.

b. Analyzing the data for understanding the probability distribution, probability of non-exceedance of seawater velocity and other statistical parameters such as minimum, maximum, mean, median, mode, standard deviation, skewness, and kurtosis of the measured seawater velocity for a span of one year.

c. Comparing the measured probability of velocity with four different theoretical probability distribution functions such as Rayleigh, Exponential, Gumbel, and Log-Normal distribution to find out which distribution fits best with the field measured velocity.

d. Identifying the most suitable site for marine current based power generation.

Field measurement, analysis, and understanding of ocean current is one of the important activities for coastal civil engineers around the world for optimal design of marine structures and for the study of dispersion of marine pollutants. National Oceanic and Atmospheric Administration (NOAA), USA, integrates ocean currents observations from a variety of instruments containing different resolutions and methods, as well as spatial and temporal variability, into a common database (https://www.nodc.noaa.gov/General/current.html). Many technologies are used for measurement of ocean currents (2010). Each technology has its own merits and demerits. Gopalakrishnan (1985) has numerically estimated the maximum current around Failaka Island and reported the highest value of 0.8 m/s during spring tide and this value is used by Al-Sarawi et al. (1996) for the coastal zone management study of Failaka Island. High current and turbidity in the coastal area near Sabiya power plant, south-west of Boubyan Island, are the main reason for significant sedimentation of the Sabiya power plant and the coastal morphodynamic changes around the seawater intake structures (Neelamani and Saif Uddin, 2010). Abou-Seida and Al-Sarawi (1990) as well as Baby (2015) stated that the maximum current velocity never exceeds 0.5 m/s in Kuwait Bay, and in the southern coast of Kuwait, the maximum current velocity extends up to 1.0 m/s. For the numerical simulation of the oil spill movement in the Arabian Gulf during 1991 Gulf war, Venkatesh and Murthy (1994) have numerically predicted the current velocity. The numerical model is used for computing the currents due to tides, winds, and bathymetric influences. Government of Kuwait has proposed a new master plan for developing a new city in Sabiya area. Al-Hasem (2010) revealed that the master plan is based on socioeconomic aspects only and that little attention was given for the physical and biological environment. It is stressed that the development of new city will result from changes to the hydrodynamic regime and other aspects such as effect on inter tidal flat and impact of future sea level rise. Dames and Moore (1983) and Al-Nafisi et al. (2009) stated that, at the center of Sulaibikhat bay, current velocity during ebb tide could reach closer to 1.0 m/s. Akhyani et al. (2015) numerically simulated the current profiles in the Arabian Gulf and Gulf of Oman to understand the power density of currents for electricity generation. The results show that the current energy, in the upper 50 m layer, increases in two periods of the year, late winter to early spring and late summer to early autumn. It can be asserted that the current energy in the study area increases during monsoon periods. According to the model results, the marine current energy in the Arabian Gulf and the Gulf of Oman is rather substantial. Elhakeem et al. (2015) have developed a 3D prognostic baroclinic hydrodynamic model of the Arabian Gulf (AG) using Delft3D-FLOW. The model was forced with long-term time averaged climatological data over the computational domain and long-term salinity and temperature boundary conditions applied at its tidal open boundary. The model simulation results were thoroughly validated against measured tides from 5 stations and measured currents at 4 locations in the central and southern parts. Water salinity and temperature were validated in space and time using observations spanning over 73 years from 1923 to 1996 for the AG, the Strait of Hormuz, and the Gulf of Oman. The bottom flow of the AG basin at the vicinity of the Strait of Hormuz was also validated against the available measurements. Seasonal evaporation and surface density spatial distribution maps were produced and compared with available records. The developed model setup successfully generated the AG seasonal stratification and hydrographic conditions. This study helps for a general understanding of the hydrodynamics of the AG. Peng and Bradon (2016) have carried out a comprehensive 3D hydrodyanmic model study of the Arabian Gulf by employing the latest bathymetry data, multiple vertical layers, calibrated atmospheric conditions and tidal forcing, HYbrid Coordinate Ocean Model reanalysis data, as well as the spatial- and temporal-varying climatological data, including cloudiness, relative humidity, air temperature, and net solar radiation. This 3D comprehensive hydrodynamic model in the Arabian Gulf was extensively calibrated and validated across the whole Arabian Gulf for water levels, currents, salinity, and temperature. Model results are in good agreement with measurements and satellite data. The authors claim that this newly developed model is capable of accurately simulating hydrodynamics and the climatology over the whole Arabian Gulf. Cresswell and Wood (2016) have developed a coupled hydrodynamic-meteorological model of the Arabian Gulf for coastal outfall studies. The tidal variation is the main contributor for the currents in most of the places in the Arabian Gulf. This model can be widely used for the design of marine outfalls in this region. The hydrodynamics and water quality characteristics of the upper Arabian Gulf area were studied by Pokavanich and Al-Osairi (2013), Pokavanich et al. (2014). Recently, Alosairi and Pokavanich (2017) have assessed the seasonal circulation pattern of the Northern Arabian/Persian Gulf. A three-dimensional model was used to study the seasonal hydrographical features of the Northern Arabian/Persian Gulf. The hydrodynamic condition was validated with Mt. Mitchell expedition data and some recent field. It is found that the model successfully reproduced the seasonal hydrographic characteristics and showed variations from season to season. The seasonal three-dimensional residual currents of the NAG were reproduced by the model. The Kuwait Institute for Scientific Research (KISR) measured currents around Boubyan and Failaka Island for some of the client projects (Al-Osairi et al., 2017). The literature shows that there are not many studies on the seawater velocity based on field measurements in this region, despite many major projects under development. This is the main motivation for the present study.

STUDY LOCATION AND BASIC DESCRIPTION OF OCEANOGRAPHIC PARAMETER

The current measurements are carried out at five locations around Boubyan Island, as shown in Fig. 1. The study area has tides with the spring tide range of up to 4.0 to 4.5 m. The tides are mostly semidiurnal or mixed. Based on the recent measurements, the annual seawater salinity was found to vary from 34.14 to 48.31 ppt. The annual seawater temperature was measured in the range of 10.83 ^{o}C to 35.67 ^{o}C. The measured annual seawater turbidity ranges from 7 to 58,008 ppm in a year. The waves are meager with height ranging up to 1.0 m and wave period in the range of 3.0 to 6.0 s. The predominant wave direction near Failaka is to the northwest and southeast. The water depth is shallow, with depth varying up to 8.0 to 9.0 m at the middle of Khor Abdallah.

METHODOLOGY

The objectives were executed through the following tasks: collection of data on seawater velocity; probability and statistical analysis of the measured velocity data; and analysis of four different theoretical distributions to select the suitable theoretical probability distribution to describe the measured velocity at these five locations. The energy density for the marine currents for all these five locations for a year is assessed. The details of works carried out in each task are subsequently explained.

Collection of data on seawater velocity

INFINITY-EM is the instrument used for velocity measurements in the field. The specification of the instrument is provided in Table 1.

Table 1. Specification of INFINITY-EM.

Parameter	Principle	Range	Resolution	Accuracy
Velocity	2D electromagnetic velocity sensor	0 to +/- 500 cm/s	0.02 cm/s	+/- 1 cm/s or +/- 2%
Direction	Hole element	0 to 360	0.01^{o}	+/- 2%
Temperature	Thermistor	-3 to 45 ^{o}C	0.001 ^{o}C	+/- 0.02 ^{o}C (3 to 31 ^{o}C)

The station name, its longitude and latitude, date of deployment and retrieval are provided in Table 2.

Table 2. The Station Name, Longitude and Latitude, Date of Deployment, and Retrieval.

Station Name	Longitude (East)	Latitude (North)	Date of Deployment	Date of Retrieval
Location A (Boubiyan port)	48°19'29.46"	29° 52'36.06"	26.03.2015	31.12.2015
Location B (Sabiya military camp)	48°01'22.74"	29° 55'3.84"	25.03.2015	17.02.2016
Location C (Warba Island)	48°08'15.48"	29° 59'57.72"	25.03.2015	31.12.2015
Location D (Failaka Island)	48°16'0.12"	29° 26'4.38"	25.03.2015	15.02.2016
Location E (Sabiya coast guard)	48°19'29.46"	29° 52'36.06"	26.03.2015	17.02.2016

The instrument is fixed using bottom mounted frame, and the sensors are located about 15 cm from the sea bed. The burst time of the instrument is selected as 20 minutes. The instruments acquire 10 samples at a sampling speed of 1 sample/s, and the average of these 10 samples is stored once every 20 minutes. Hence, for a day, the instrument stores 72 velocity values, and for a year each instrument stores 26,280 numbers of velocity values. It is clear from the table that the data is available for almost a year to cover all the four seasons in Kuwait, summer, spring, winter, and autumn.

Selecting a suitable theoretical probability that compares well with the measured velocity of seawater

The random events occurring in nature as wind, ocean waves, flow velocity in river, etc. mostly follow certain probability distribution (Neelamani and Al-Osairi, 2016) like Rayleigh, Exponential, Gumbel, Log Normal, etc. For example, the linear ocean wave heights in general follow the Rayleigh distribution, and the wave elevation follows the normal or Gauss distribution. Since wave height follows the Rayleigh distribution, and this distribution depends on the root mean square value of the wave height, it is possible to obtain any statistically important parameter like the most frequent wave height, average wave height, significant wave height, average height of the highest 10% wave height, etc., which are required for the design and operational purposes of marine structures. Similarly, if the seawater velocity around Boubyan Island follows a theoretical distribution, then it is possible to obtain velocity values of 1%, 10%, 20% exceedance, etc., for engineering applications such as the design of marine structures and estimation of sediment movement and settlement in marinas, ports, and approach channels. An attempt was made to compare the measured velocity data with these theoretical probability distributions, and the distribution, which correlated well with the measured velocity, was selected to represent the velocity around Boubyan Island and for other study applications, as described in the introduction.

The formula for probability density function (PDF) and cumulative density function (CDF) for the four distributions, and the equation to estimate the parameters of these distributions from the measured velocity values, are provided in Table 3 (Neelamani and Al-Osairi, 2016). Rayleigh and Exponential distributions are one-parameter distributions, whereas Gumbel and Log-Normal are two-parameter distributions.

Table 3. Four Different Probability Density Functions and Cumulative Density Functions and the Formula for the Parameter Estimation of the Functions.

Name of the Distribution	**PDF**	**CDF**	**Formula for the Parameter Estimation**
Rayleigh	$(x/\sigma^2)\exp(-x^2/2\sigma^2)$	$1-\exp(-x^2/2\sigma^2)$	$\sigma = \text{Mean}/(\pi/2)^{1/2}$
Exponential	$(\lambda)\exp(-\lambda x)$	$1-\exp(-\lambda x)$	$\lambda=1/\text{Mean}$
Gumbel	$(1/\beta)\exp[-\{z+\exp(-z)\}]$ where $z=(x-\mu)/\beta$	$\exp[-\exp(-z)]$	$\mu=\text{Mode}$ $\beta=(\text{Standard deviation})/(\pi/6^{1/2})$
Log-Normal	$(1/(x\sigma(2\pi)^{1/2})(\exp[-(\log_e x-\mu)^2/2\sigma^2)]$	$\Phi[(\log_e x-\mu)/\sigma)]$	$\mu=\log_e(\text{Median})$ $\sigma=[2(\log_e(\text{Mean})-\mu)]^{1/2}$

PDF: Probability density functions; CDF: Cumulative Density Functions.

The mean, median, mode, and standard deviations were estimated from the measured velocity data. The σ, λ, μ, and β are called the parameters of the respective distributions, and Φ is the cumulative distribution function for Log-Normal distribution.

The theoretical and measured probability distributions are compared, and the closeness of the comparison needs to be assessed in order to select the best theoretical probability density function. The accuracy of the comparison between the observed CFD value, C_o, and predicted CFD values, C_p, is assessed by using rigorous statistical procedure such as Fractional Bias (FB), Normalized Mean Square Error (NMSE), and Factor of 2 (FAC2), where FB is given by

$$FB = 2 \times [(\text{Average } C_o - \text{Average } C_p)/(\text{Average } C_o + \text{Average } C_p)] \quad (1)$$

NMSE is given as

$$NMSE = [(\text{Average } (C_o - C_p)^2] / [(\text{Average } C_o \times \text{Average } C_p)] \quad (2)$$

Factor of 2, FAC2, is defined as a percentage of predictions within a factor of two of the observed values. The ideal value for the Factor of 2 should be 100%.

RESULTS AND DISCUSSIONS

In this section, the characteristics of probability and statistical analysis of the measured velocity around Boubyan Island are presented and discussed. The measured and theoretical cumulative distribution functions of the velocity for all five stations are revealed. Finally, a detailed assessment of incident marine energy density for a year for each location is assessed.

Typical measured time series of seawater velocity

A typical time series of measured seawater velocity at Warba Island area during 15th April to 17th June 2015 is presented in Fig. 5. The fluctuations in velocity from 0.0 cm/s to about 75 cm/s are mainly because of tidal variation to the order of 3.5 m.

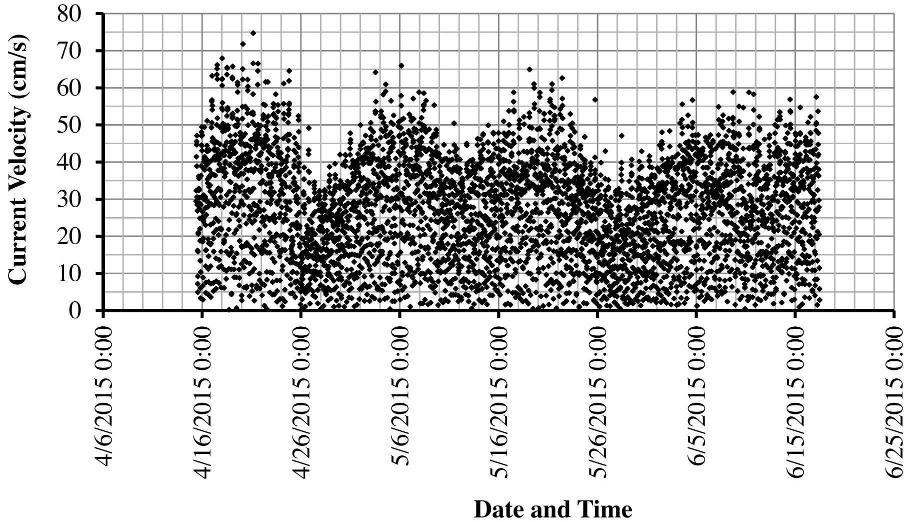

Fig. 5. Current velocity at Boubyan port area (Location A) from 15th April 2015, 10.00 am, to 17th June 2015, 11.40 am.

The current velocity and the direction for the same data are provided in Fig. 6. It is found that the dominant current direction is from north-west and south-east.

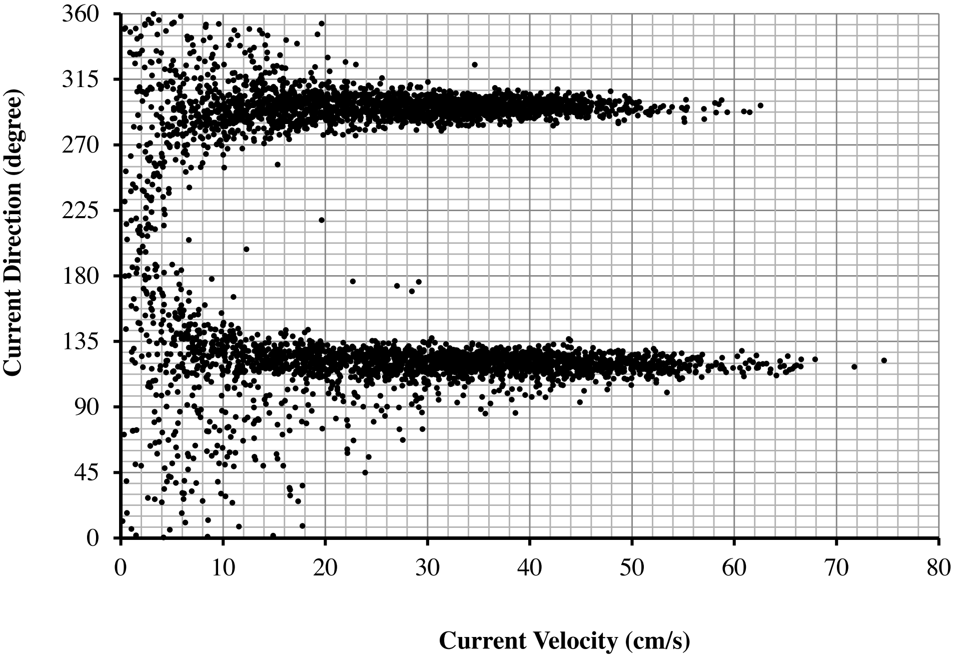

Fig. 6. Variation of current velocity and direction at Boubyan port area (Location A) from 15th April 2015, 10.00 am, to 17th June 2015, 11.40 am.

Probability density of measured seawater velocity

The measured velocity values are divided into a number of bins, as shown in Table 4. The probability of the velocity value for each bin width is estimated. For example, the probability of measured velocity at Boubyan port area for the range of 20.01 to 25 cm/s is 0.119 or 11.9%. Similarly, it is possible to get the probability of velocity for other stations and for any range of measured velocity. At Warba Island, the probability of velocity in the range of 20.01 to 25 cm/s is 0.096 or 9.6

Table 4. Probability of Measured Velocity at Five Different Stations around Boubyan Island.

Velocity Range (cm/s)		Mid Value (cm/s)	Probability of Velocity				
From	To		Boubyan Port	Failaka	Sabiya-Coast Guard	Sabiya-Military	Warba
0	5	2.5	0.066	0.095	0.113	0.133	0.075
5.01	10	7.5	0.096	0.131	0.160	0.141	0.095
10.01	15	12.5	0.105	0.165	0.168	0.121	0.091
15.01	20	17.5	0.116	0.175	0.163	0.113	0.092
20.01	25	22.5	0.119	0.145	0.131	0.107	0.096
25.01	30	27.5	0.122	0.109	0.099	0.093	0.104
30.01	35	32.5	0.119	0.071	0.072	0.080	0.110
35.01	40	37.5	0.101	0.045	0.046	0.062	0.104
40.01	45	42.5	0.075	0.027	0.025	0.049	0.090
45.01	50	47.5	0.041	0.017	0.014	0.038	0.067
50.01	55	52.5	0.023	0.011	0.005	0.028	0.043
55.01	60	57.5	0.010	0.005	0.001	0.019	0.022
60.01	65	62.5	0.005	0.002	0.001	0.010	0.009
65.01	70	67.5	0.002	0.001	0.000	0.004	0.004
70.01	75	72.5	0.000	0.000	0.000	0.001	0.001
75.01	80	77.5	0.000	0.000	0.000	0.000	0.000
80.01	85	82.5	0.000	0.000	0.000	0.000	0.000
85.01	90	87.5	0.000	0.000	0.000	0.000	0.000

The probability density plot of measured seawater velocity is provided in Fig. 7 for all the five locations. As discussed, the peak value of velocity indicates the mode for each location. It is found from this plot that, in Failaka and Sabiya coast guard area, the low value of velocity is contributing more, whereas, in the Boubyan port area and Warba area, high velocity is sustained for a longer period of time in a year. This can be verified by looking into the peak value of the probability density function.

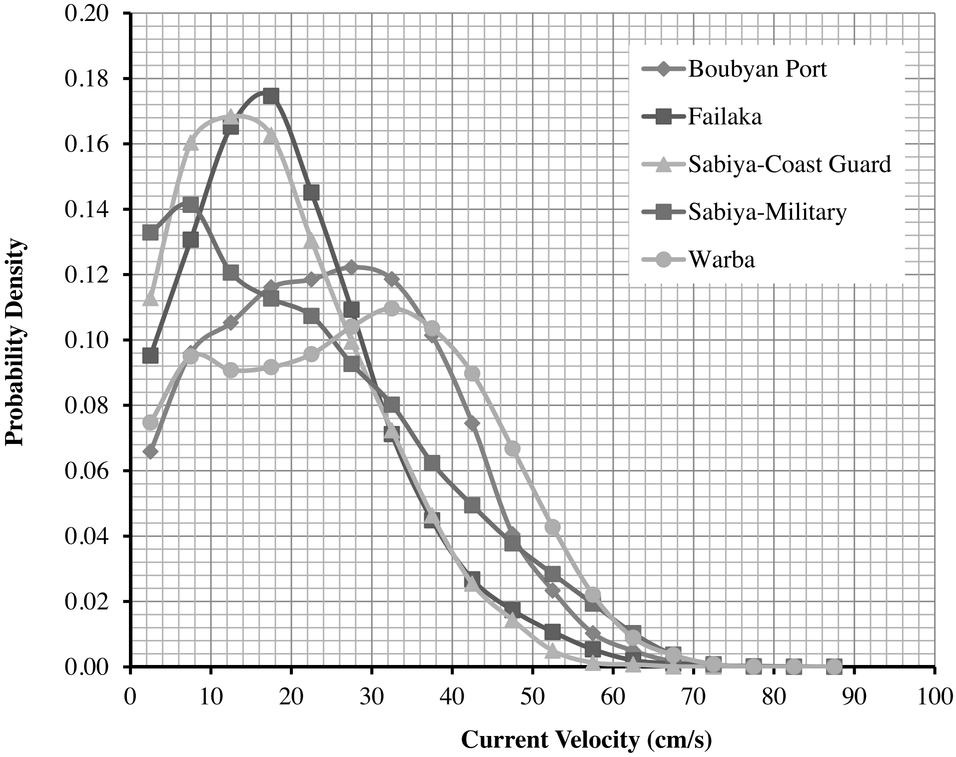

Fig. 7. Measured probability density of seawater velocity at five locations around Boubyan Island in Kuwait.

Probability of non-exceedance of measured seawater velocity

The probability of non-exceedance of seawater velocity based on measurements for each location is displayed in Table 5 and in Fig. 8. For example, in Boubyan port area, 81% of the time in a year, the seawater velocity will not exceed 40 cm/s. It means that the seawater velocity at Boubyan port area exceeds 40 cm/s for 19% of the time in a year. This information is useful for analysis of sediment movement around Boubyan port area. Similar interpretation and information can be extracted for different values of velocity and for different locations. It is to be noted that, for Failaka area, 95% of the time in a year, the velocity does not exceed 40 cm/s. That means the velocity value exceeds 40 cm/s in Failaka area for 5% of the time in a year. The probability of exceedance of velocity by a value of 40 cm/s is 3%, 12.5%, and 19%, respectively, for Sabiya-coast guard area, Sabiya-military area, and Warba.

Table 5. Probability of Non-exceedance of the Measured Velocity at Five Different Stations around Boubyan Island.

Velocity Range (cm/s)		Mid Value (cm/s)	Probability of Non-Exceedance of Seawater Velocity				
From	To		Boubyan Port	Failaka	Sabiya-Coast Guard	Sabiya-Military	Warba
0	5	2.5	0.066	0.095	0.113	0.133	0.075
5.01	10	7.5	0.162	0.226	0.273	0.274	0.170
10.01	15	12.5	0.267	0.391	0.442	0.395	0.261
15.01	20	17.5	0.383	0.566	0.604	0.508	0.352

20.01	25	22.5	0.502	0.711	0.735	0.615	0.448
25.01	30	27.5	0.624	0.820	0.834	0.708	0.552
30.01	35	32.5	0.743	0.891	0.907	0.788	0.662
35.01	40	37.5	0.844	0.936	0.953	0.850	0.765
40.01	45	42.5	0.918	0.963	0.979	0.900	0.855
45.01	50	47.5	0.959	0.980	0.993	0.937	0.922
50.01	55	52.5	0.982	0.991	0.998	0.966	0.965
55.01	60	57.5	0.993	0.996	0.999	0.985	0.987
60.01	65	62.5	0.998	0.998	1.000	0.995	0.995
65.01	70	67.5	0.999	0.999	1.000	0.999	0.999
70.01	75	72.5	1.000	1.000	1.000	1.000	1.000
75.01	80	77.5	1.000	1.000	1.000	1.000	1.000
80.01	85	82.5	1.000	1.000	1.000	1.000	1.000
85.01	90	87.5	1.000	1.000	1.000	1.000	1.000

The median value of the seawater velocity (median is defined as the value at which 50% of the measured velocity value exceeds or do not exceed that value) is extracted from the probability of non-exceedance plot for each location. The highest median value obtained is 25 cm/s at Warba Island area and the lowest median value is 14.3 cm/s at Sabiya coast guard area.

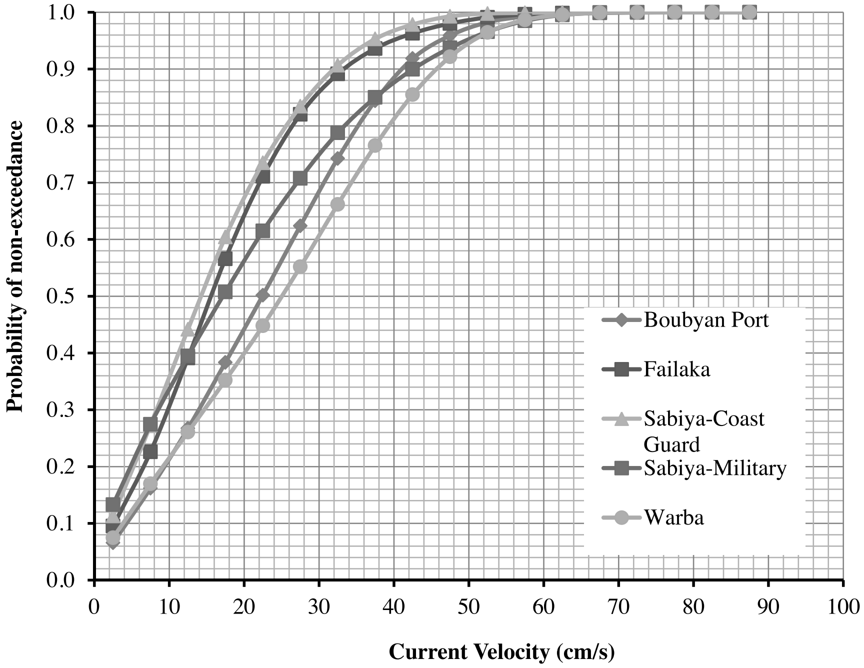

Fig. 8. Measured probability of non-exceedance of seawater velocity at five locations around Boubyan Island in Kuwait.

Statistical analysis of seawater velocity

Using the measured velocity data, a detailed statistical analysis is carried out. Table 6 provides the observed minimum, maximum, mean, median, mode, standard deviation, skewness, and kurtosis of the seawater velocity for all the five locations.

Table 6. Observed Minimum, Maximum, Mean, Median, Mode, Standard Deviation, Skewness, and Kurtosis of the Seawater Velocity for all the Five Locations.

Statistical Properties of Seawater Current Velocity (cm/s)	Boubyan Port	Failaka	Sabiya-Coast Guard	Sabiya-Military	Warba
Minimum	0.071	0.054	0.05	0.03	0.12
Maximum	81.72	85.49	72.54	82.38	80.25
Mean	25.30	19.66	18.35	22.22	27.44
Median	22.50	15.50	14.20	17.30	25.10
Mode	27.50	17.50	12.50	7.50	32.50
Standard Deviation	13.87	12.00	11.42	15.57	15.48
Skewness	0.270	0.818	0.672	0.662	0.160
Kurtosis	-0.519	0.739	0.042	-0.313	-0.836

Seawater velocity is fairly symmetrical for Boubyan port area and Warba since the skewness value is between -0.5 and 0.5. For Failaka, Sabiya-Coast Guard, and Sabiya-Military, it is moderately positively skewed, since skewness is between +1 and + 0.5.

The value of Kurtosis is negative for Boubyan port, Sabiya-Military, and Warba. It means that it has less in the tail compared to normal distribution. The value of Kurtosis for Failaka is positive and hence it is heavy tailed when compared to normal distribution. Sabiya-Coast Guard has Kurtosis closer to zero and hence closer to normal distribution.

Theoretical probability distribution for the seawater velocity

The parameters of the theoretical probability distribution are estimated based on the formula provided in Table 3 and is presented in Table 7 for all five locations.

Table 7. Parameters of the Theoretical Probability Distribution Functions.

Location	Rayleigh	Exponential	Gumbel		Log-Normal	
	σ	λ	μ	β	μ	σ
Boubyan Port area	20.182	0.03953	27.50	10.81	3.114	0.484
Sabiya Military area	17.725	0.04500	7.50	12.13	2.851	0.708
Warba Island	21.890	0.03644	32.50	12.06	3.223	0.422
Failaka Island	15.683	0.05086	17.50	9.35	2.741	0.690
Sabiya coast guard area	14.638	0.05450	12.50	8.90	2.653	0.716

Both the probability density and cumulative probability values are estimated by using these parameters for all the four different distributions.

Comparison of theoretical and measured values of cumulative probability distribution of velocity

A comparison of measured and theoretical cumulative probability density (CFD) of seawater velocity at Boubyan Port is depicted in Fig. 9. The estimated FB, NMSE, and FAC2 values are also provided in Table 8. Fig. 9 shows that Log-Normal and Rayleigh distribution are showing better fit for the measured velocity in this area, especially for velocity greater than 45 cm/s. Rayleigh distribution fits well for velocity in the range of 20 to 45 cm/s.

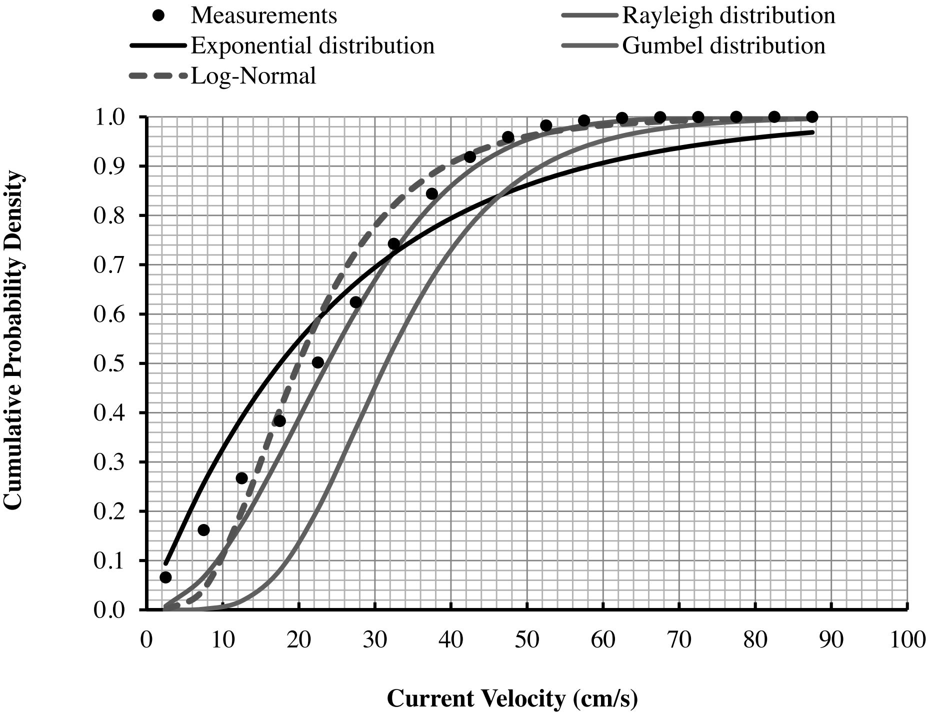

Fig. 9. Comparison of measured and theoretical cumulative probability density of seawater velocity at Boubyan Port.

Table 8. FB, NMSE, and FAC2 Values for the Measured and Predicted CFD Values of Seawater Velocity Data for Boubyan Port Area.

Method	Rayleigh	Exponential	Gumbel	Log-Normal
Fractional Bias	0.038	0.026	0.177	-0.001
Normalized Mean Square Error	0.003	0.012	0.054	0.005
Factor of 2	88.889	100.000	72.222	88.889

A comparison of measured and theoretical CFD of seawater velocity at Sabiya military area is shown in Fig. 10. The estimated FB, NMSE, and FAC2 values for this location are also provided in Table 9. It is found from Fig.10 that Gumbel and Rayleigh distribution fit better for the measured velocity, especially for velocity greater than 50 cm/s. Exponential distribution fits well for the measured velocity up to 30 cm/s.

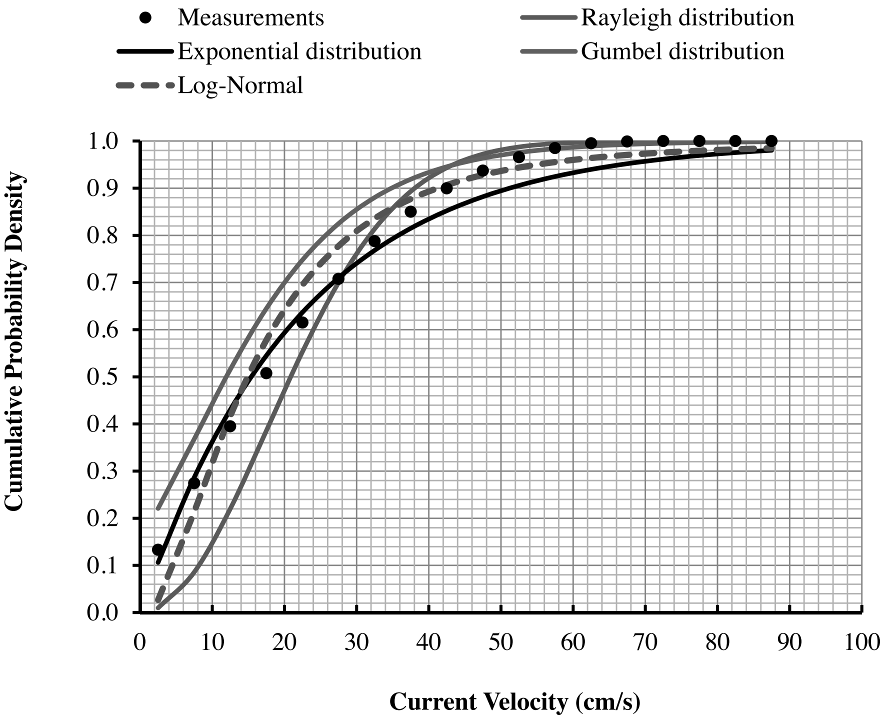

Fig. 10. Comparison of measured and theoretical cumulative probability density of seawater velocity at Sabiya military area.

Table 9. FB, NMSE, and FAC2 Values for the Measured and Predicted CFD Values of Seawater Velocity Data for Sabiya military area.

Method	**Rayleigh**	**Exponential**	**Gumbel**	**Log-Normal**
Fractional Bias	0.036	0.030	-0.063	0.003
Normalized Mean Square Error	0.010	0.003	0.008	0.004
Factor of 2	88.889	100.000	100.000	94.444

A comparison of measured and theoretical CFD of seawater velocity at Warba area is shown in Fig. 11. The estimated FB, NMSE, and FAC2 values for these locations are also provided in Table 10. It is found that Rayleigh distribution fits well for the measured upper velocity regime (velocity greater than 25 cm/s) in this area.

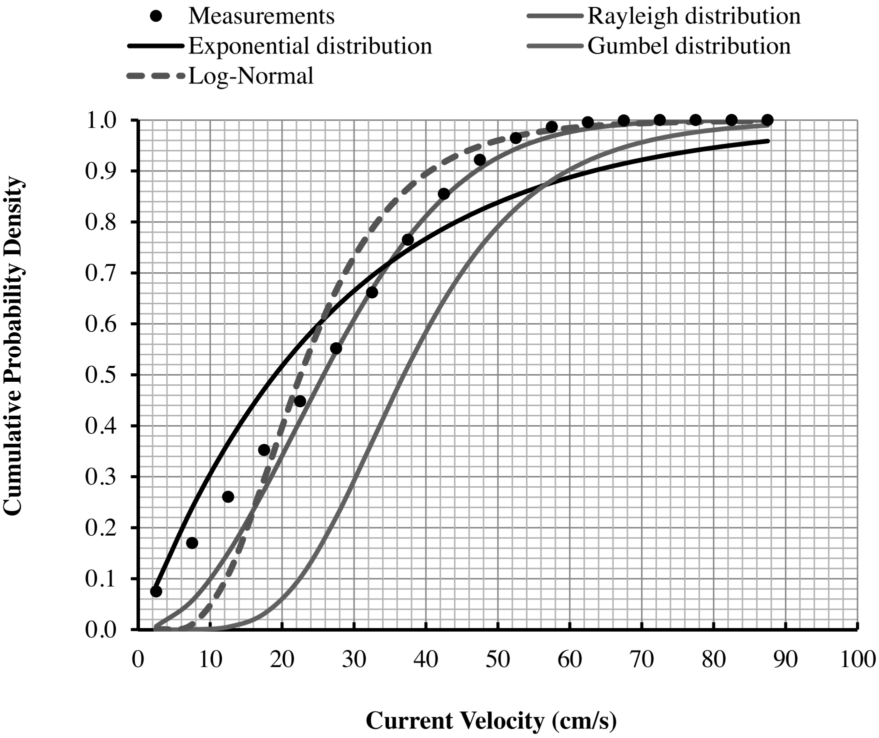

Fig. 11. Comparison of measured and theoretical cumulative probability density of seawater velocity at Warba area.

Table 10. FB, NMSE, and FAC2 Values for the Measured and Predicted CFD Values of Seawater Velocity Data for Warba Island Area.

Method	**Rayleigh**	**Exponential**	**Gumbel**	**Log-Normal**
Fractional Bias	0.039	0.022	0.249	0.000
Normalized Mean Square Error	0.004	0.013	0.095	0.011
Factor of 2	88.889	100.000	66.667	83.333

A comparison of measured and theoretical CFD of seawater velocity at Failaka Island area is shown in Fig. 12. The estimated FB, NMSE, and FAC2 values for these locations are also provided in Table 11. It is found that Gumbel distribution fits better for higher velocity range in this area.

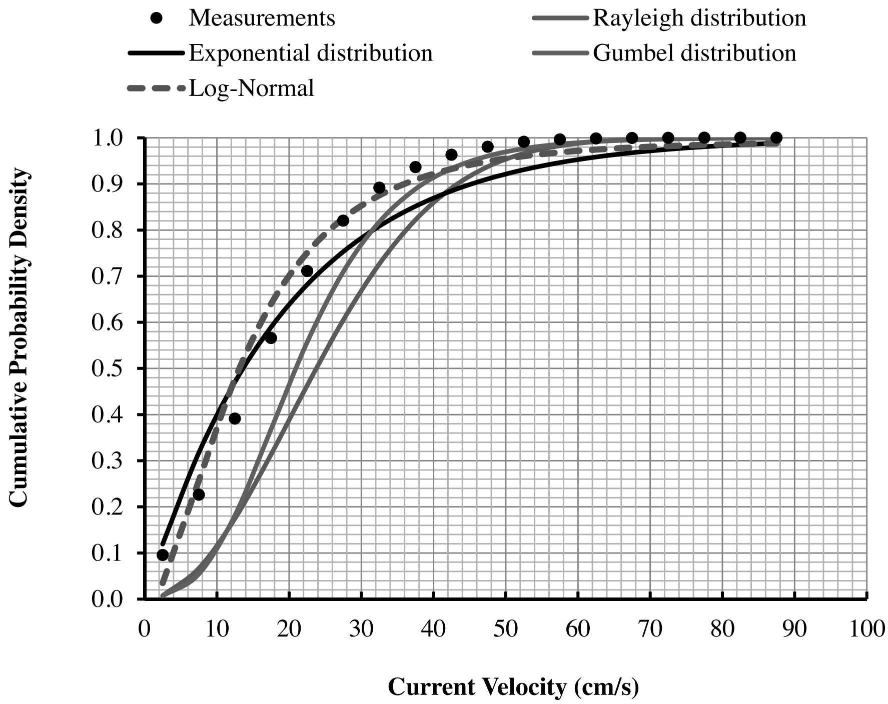

Fig. 12. Comparison of measured and theoretical cumulative probability density of seawater velocity at Failaka Island area.

Table 11. FB, NMSE, and FAC2 Values for the Measured and Predicted CFD Values of Seawater Velocity Data for Failaka Island Area.

Method	Rayleigh	Exponential	Gumbel	Log-Normal
Fractional Bias	0.118	0.031	0.082	0.006
Normalized Mean Square Error	0.029	0.005	0.015	0.002
Factor of 2	83.333	100.000	83.333	94.444

A comparison of measured and theoretical CFD of seawater velocity at Sabiya coast guard area is shown in Fig. 13. The estimated FB, NMSE, and FAC2 values for these locations are also provided in Table 12. It is found that Rayleigh and Gumbel distributions fit better for higher measured velocity in this area.

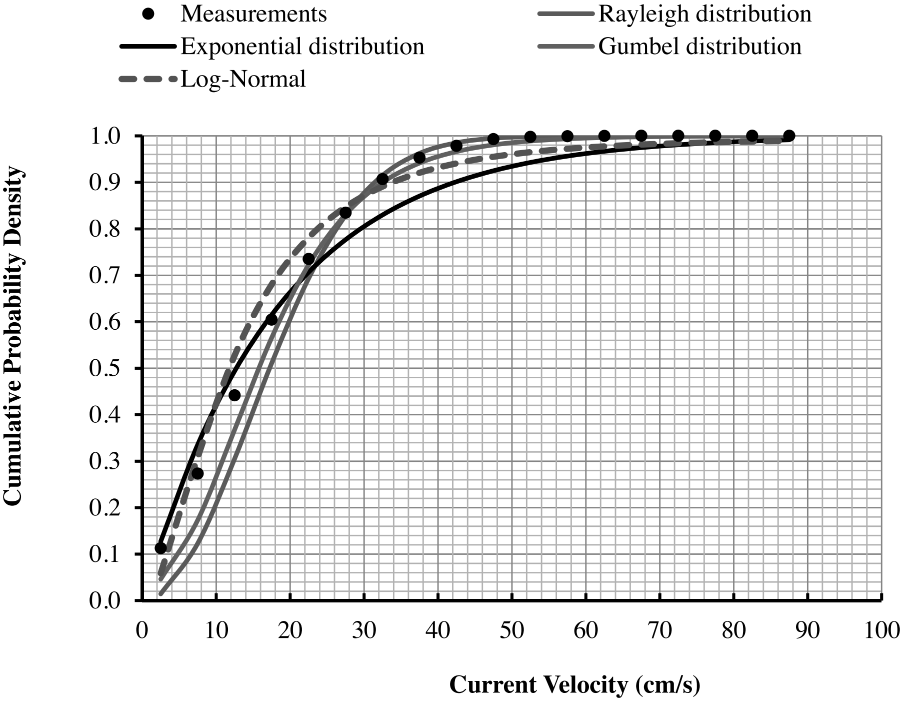

Fig. 13. Comparison of measured and theoretical cumulative probability density of seawater velocity at Sabiya coast guard area.

Table 12. FB, NMSE, and FAC2 Values for the Measured and Predicted CFD Values of Seawater Velocity Data for Sabiya Coast Guard Area.

Method	Rayleigh	Exponential	Gumbel	Log-Normal
Fractional Bias	0.034	0.032	0.025	0.005
Normalized Mean Square Error	0.005	0.004	0.002	0.002
Factor of 2	88.889	100.000	94.444	100.000

It is clear from the study that, out of the four theoretical distributions studied, none of them consistently predict the measured velocity covering the whole range of measured velocity values. Some of the distributions are good for predicting the velocity at high velocity range and some of the theoretical distributions are good for predicting low velocity range. This area needs further scientific investigation.

Measured and theoretical seawater velocity at different locations for 80% and 90% non-exceedance or 20% and 10% exceedance

The measured as well as the theoretically predicted velocity value for 80% non-exceedance (20% exceedance) based on the four different theoretical probability density functions is shown in Table 13. It is found that Rayleigh distribution is closer to the measured values for Boubyan port, Sabiya military camp, and Warba Island area. For Failaka Island, Log-Normal distribution fits well, whereas, for Sabiya coast guard area, Gumbel distribution fits well. It is clear from the measurements that, in Warba Island area, the current velocity exceeds 39.5 cm/s for 20% of the time in a year (i.e., about 1752 hours), whereas, in Sabiya coastal area, the current velocity exceeds 25.6 cm/s only for 1752 hours.

Table 13. Measured and Theoretical Seawater Velocity at Different Locations for 80% Non-Exceedance or 20% Exceedance.

Location	Velocity based on measurements (cm/s)	Velocity based on theory (cm/s)			
		Rayleigh	Exponential	Gumbel	Log-Normal
Boubyan Port	35.5	36.2	40.5	43.5	31.2
Sabiya-Military Camp Area	33.5	32.0	35.7	25.8	29.3
Warba Island	39.5	39.3	44.2	50.6	33.1
Failaka Island	26.3	36.2	31.6	31.5	25.5
Sabiya-Coast Guard Area	25.6	26.3	29.5	25.8	23.8

A similar table (Table 14) is depicted for 90% non-exceedance (10% exceedance). The predicted value by Rayleigh distribution is closer to the measurements for Boubyan port area and Warba Island area. For Sabiya military and Failaka Island areas, Log-Normal predicts well. For Sabiya coast guard area, Gumbel distribution predicts closer to the measured values.

Table 14. Measured and Theoretical Sea Water Velocity at Different Locations for 90% Non-Exceedance or 10 % Exceedance.

Location	Velocity based on measurements (cm/s)	Velocity based on theory (cm/s)			
		Rayleigh	Exponential	Gumbel	Log-Normal
Boubyan Port	41.5	43.4	58.1	52.0	39.5
Sabiya-Military Camp Area	42.5	38.0	51.0	35.0	41.3
Warba Island	46.0	47.0	63.5	59.5	40.6
Failaka Island	33.4	43.2	45.1	38.5	36.0
Sabiya-Coast Guard Area	32.4	31.3	42.0	32.5	34.0

Application of this study for power generation

Based on the field measurements and data analysis, it is found that the current velocities around Boubyan Island are reasonable for extracting electric power using small underwater turbines. The incident energy density available for different velocities for a year in kilo watt hour per square metre flow area can be estimated using the formula,

$$P = 0.5\, \rho \times 365 \times 24 \sum_{i=1}^{N} v_i^3 \times p_i \qquad (3)$$

where ρ is the density of sea water in kg/m^3 (the average density of seawater around Boubyan Island is 1040 kg/m^3), v_i is the current velocity in m/s, and p_i is the probability density for the current velocity v_i.

Table 15 shows the available incident energy density of the marine current for a year per square metre vertical area for different velocity values. The probability density for different current velocity is used from Table 4.

The last row shows the total incident energy density of the marine current for a year per per square metre vertical area in Megawatt hour. The last row of Table 15 shows the total incident energy density of the marine current for a year per per square metre vertical area in Mwh, with a threshold value of 0.3 m/s. The threshold value of 0.3 m/s is considered as the minimum current velocity required to overcome the inertia of the mini turbines of about 2.0 m diameter.

Table 15. The Available Incident Energy Density of the Marine Current in Mwh for a Year per m^2 Vertical Area for Different Velocities at Five Different Locations around Boubyan Island.

Current Velocity, m/s	Boubyan Port	Failaka	Sabiya-Coast Guard	Sabiya-Military	Warba
0.025	0.005	0.007	0.008	0.009	0.005
0.075	0.184	0.252	0.307	0.271	0.183
0.125	0.934	1.468	1.495	1.077	0.810
0.175	2.832	4.272	3.979	2.759	2.246
0.225	6.175	7.524	6.797	5.552	4.981
0.275	11.56	10.326	9.379	8.810	9.852
0.325	18.61	11.102	11.26	12.510	17.20
0.375	24.26	10.810	11.05	14.893	24.98
0.425	26.23	9.441	8.742	17.134	31.47
0.475	20.02	8.299	6.835	18.551	32.71
0.525	15.16	7.251	3.296	18.456	28.34
0.575	8.66	4.330	0.866	16.454	19.05
0.625	5.56	2.224	1.112	11.121	10.01
0.675	2.80	1.401	0.000	5.604	5.604
0.725	0.00	0.00	0.00	1.736	1.736
0.775	0.00	0.00	0.00	0.00	0.00
0.825	0.00	0.00	0.00	0.00	0.00
0.875	0.00	0.00	0.00	0.00	0.00
Total incident energy density for a year per m^2 vertical area in Mwh	142.98	78.71	65.13	134.94	189.2
Total incident energy density for a year per m^2 vertical area in Mwh, with a threshold value of 0.3 m/s	121.29	54.858	43.16	116.46	171.1

From the Table 15, it is clear that Warba marine area is the most attractive location for marine current power generation. The next attractive location is the Boubyan Port area, followed by Sabiya military area.

CONCLUSIONS

The seawater velocity around Boubyan Island in Kuwait was measured at five locations, that is Boubyan port, Sabiya military camp, Warba Island, Failaka Island, and Sabiya coast guard area for a span of about one year. The probability density and cumulative probability density analysis was carried out. The measured probability values were compared with four different theoretical probability functions, that is, Rayleigh, Gumbel, Exponential, and Log-Normal distributions. The following are the conclusions derived:

- Among the five locations around Boubyan Island, the measured annual mean velocity is minimum in Sabiya coast guard area (18.35 cm/s) and maximum in Warba Island area (27.44 cm/s).
- Among the five locations around Boubyan Island, the measured annual standard deviation of the velocity is also minimum in Sabiya coast guard area (11.42 cm/s) and maximum in Warba Island area (15.48 cm/s) and Sabiya military area (15.57 cm/s).
- The highest velocity value of 85.49 cm/s is recorded in Failaka Island area.
- Seawater velocity is fairly symmetrical for Boubyan port area and Warba since the skewness value is between -0.5 and 0.5. For Failaka, Sabiya-Coast Guard, and Sabiya-Military, it is moderately positively skewed, since skewness is between +1 and + 0.5.
- The value of Kurtosis is negative for Boubyan port, Sabiya-Military, and Warba. It means that it has less in the tail compared to normal distribution. The value of Kurtosis for Failaka is positive and hence it is heavy tailed when compared to normal distribution. Sabiya-Coast Guard has Kurtosis closer to zero and hence is closer to normal distribution.
- Out of the four theoretical distributions studied, none of them consistently predict the measured velocity covering the whole range of measured velocity values. Some of the distributions are good for predicting the velocity at high velocity range and some of the theoretical distributions are good for predicting low velocity range.
- Based on one-year field measurements, the velocity value for 20% exceedance is 35.5, 33.5, 39.5, 26.3, and 25.6 cm/s for Boubyan port, Sabiya military area, Warba Island, Failaka Island, and Sabiya coast guard area, respectively. The theoretical prediction based on Rayleigh distribution is 36.2, 32.0, 39.3, 36.2, and 26.3 cm/s for these locations, respectively.
- Since many millions of dollars is being invested for Boubyan port development and many more millions of dollars will be invested in the near future for Boubyan and Failaka Island development projects, the results of this study will be useful for the optimal design of marine structures and estimating the sediment deposits in the port, approach channel, marina, and seawater intake systems and the associated problems.
- Warba marine area is the most attractive location for marine current power generation. The next attractive location is the Boubyan Port area, followed by Sabiya military area.
- In the Warba marine area, the incident energy density of 189.184 Mwh is available for a year. With 0.3 m/s as threshold velocity for power generation by mini-marine current convertors, the incident energy density of 171.107 Mwh is available for a year.

ACKNOWLEDGMENT

The study is partially supported by the Kuwait Foundation for the Advancement of Sciences (KFAS) (Project No. 2012-1401-01), Kuwait, and the Kuwait Institute for Scientific Research (KISR), Kuwait. This support is highly appreciated. Thanks are due to all the technicians and professionals for their help in the field work.

REFERENCES

Abou-Seida, M. M. & Al-Sarawi, M. A. 1990. Utilization and management of coastal areas in Kuwait. Coastal Management, **18**(4): 385-401.

Akhyani, M., Chegini, V. & Bidokhti, A. A. 2015. An appraisal of the power density of current profile in the Persian Gulf and the Gulf of Oman using numerical simulation, Renewable Energy **74**: 307-317.

Al-Hasem, A. M. 2010. Environmental evaluation of the master plan for Al-Sabiya new city, Kuwait. Journal of the Social Sciences, **38**(1): 11-30.

Al-Nasifi, R. S. Al-Ghadban, A., Gharib, I. & Bhat, N. R. 2009. Positive impacts of mangrove plantation in Kuwait's coastal environment. European Journal of Scientific Research, **26**(4): 510-521.

Al-Osairi, Y. Imberger, J. & Falconer, R. A. 2011. Mixing and flushing in the Persian Gulf (Arabian Gulf), Journal of Geophysical Research: Oceans, **116**(C3).

Al-Osairi, Y. Neelamani, S., Al-Sulaiman, N., Polikarpov, I., Kwarteng, A. & Small, C. 2017. Effects of Developments in Mesopotamian Marshland on Boubyan and Warba Island (EC060C). Final Report for Kuwait Foundation for the Advancement of Sciences. Kuwait Institute for Scientific Research, Kuwait.

Alosairi, Y. & Pokavanich, T. 2017. Seasonal circulation assessments of the Northern Arabian/Persian Gulf. Marine Pollution Bulletin, **116** (1–2): 270-290.

Al-Sarawi, M. A. Marmoush, Y. R., Lo, J. M. & Al-Salem, K. 1996. Coastal management of Failaka Island, Kuwait. Journal of Environmental Management, **47**(4): 299-310.

Baby, S. 2015. Monitoring of Kuwait coastline for spatial and temporal changes from space borne LANDSAT sensors. Indian Journal of Geo-Marine Sciences, **44**(6): 860-865.

Baker J. M. 1976. Marine ecology and oil pollution, John Wiley and Sons, U.S.A.

Cresswell, D. & Wood, M. 2016. Coupled hydrodynamic-meteorological models for Gulf coastal outfall studies. In: Arabian Coast 2016, 20-23 November 2016, Dubai, UAE.

Dames, A. & Moore, S. 1983. Studies for Subiya area, Kuwait Bay and development of electrical network. Ministry of Electricity and Water, Report No. MEW/CP/PGP-1113-90/81, Government of Kuwait.

Elhakeem, A., Elshorbagy, W. & Bleninger, T. 2015. Long-term hydrodynamic modeling of the Arabian Gulf. Marine Pollution Bulletin, **94** (1–2): 19-36.

Gopalakrishnan, T. C. 1985. A tidal circulation model for Kuwait territorial waters. In Proceedings of an International Conference on the Finite Element in Computation Mechanics, 2–6 December, Bombay, India, 589–597.

Kasinatha Pandian, P. Emmanuel, O., Ruscoe, J. P., Side, J. C., Harris, R. E., Kerr, S. A. & Bullen, C. R. 2010. An overview of recent technologies on wave and current measurement in coastal and marine applications. Journal of Oceanography and Marine Science, **1**(1). 1-10.

Neelamani, S. & F. Al-Hulail. 2008. Feasibility for a submarine pipeline type seawater intake structure at Sabiya Power Plant, EC068C. Final report to Ministry of Electricity and Water, Kuwait Institute for Scientific Research, 70 pages.

Neelamani, S. & Saif Ud din. 2010. Evolution of coast in the vicinity of a seawater intake structure in Kuwait. International Journal of Imaging, 2010 Spring, Special Issue on ARSiCOE (Applied Remote Sensing in Coastal and Ocean Engineering), **3(S10)**: 3-22.

Neelamani, S. Al-Ragum, A., Al-Sulaiman, N., Al-Salem, K. & Al-Osairi, Y. 2016. Investigation on the coastal engineering issues for the rehabilitation of Failaka Island Marina, EC025S. Final report to Ministry of Communications, Kuwait Institute for Scientific Research, Kuwait, 225 pages.

Neelamani, S. & Al-Osairi, Y. 2017. Probability Distribution of Seawater Turbidity around Boubyan Island in Kuwait. Arabian Journal of Geosciences **10**:417. https://doi.org/10.1007/s12517-017-3200-0.

Peng, Z. & Bradon, J. 2016. A Comprehensive 3-D Hydrodyanmic Model in Arabian Gulf. In: Vila-Concejo, A.; Bruce, E.; Kennedy, D.M., and McCarroll, R.J. (eds.), Proceedings of the 14th International Coastal Symposium (Sydney, Australia). Journal of Coastal Research, Special Issue, No. 75, pp. 547–551. Coconut Creek (Florida), ISSN 0749-0208.

Pokavanich, T., Alosairi, Y., de Graaff, R., Morelissen, R., Verbruggen, W., Al-Refail, K., Taqi, A. & Al-Said, T. 2014. Three-Dimensional Hydro-Environment Characterization and Modeling of the Northern Arabian Gulf, Coastal Engineering Proceedings, 34. DOI: https://doi.org/10.9753/icce.v34.management.41.

Pokavanich, T. & Al-Osairi, Y. 2013. Three-dimensional modelling of summer hydrodynamic and water quality characteristics of upper Arabian (Persian) Gulf. Proceeding of International Conference on Environmental Challenges in the ROPME Sea Area. 3-6 March 2013, Kish, Iran.

Venkatesh, S. & Murthy, T. S. 1994. Numerical simulation of the movement of the 1991 oil spills in the Arabian Gulf. Water, Air and Soil Pollution, **74**(3): 211-234.

Wiese, F. K. Montevecchi, W.A., Davoren, G. K., Huettmann, F., Diamond, A. W. & Linke, J. 2001. Seabirds at risk around offshore oil platforms in the north-west Atlantic. Marine Pollution Bulletin, **42**(12): 1285-1290.

Xia, J. Falconer, R. A. & Lin, B. 2010. Impact of different operating modes for Severn Barrage on the tidal power and flood inundation in the Severn Estuary, UK. Applied Energy, **87**(7): 2374-2391.

Submitted: 16/04/2017
Revised: 13/11/2017
Accepted: 30/01/2018

الاحتمالات والخصائص الإحصائية والطاقة الكامنة لسرعة مياه البحر حول جزيرة بوبيان في الكويت

د. سوبرامانيام نيلاماني و د. يوسف العسيري
برنامج أداة السواحل، مركز البيئة والعلوم الحياتية، معهد الكويت للأبحاث العلمية

الخلاصة

إن تيارات مياه البحر مسؤولة عن قوى السحب على المنشآت البحرية، وحركة الرواسب والمواد المغذية من مكان إلى آخر. كما أنها مسؤولة عن عمليات المزج التي تؤثر على جودة المياه. وتعتبر التيارات البحرية أحد أهم المصادر لتوليد الطاقة الكهربائية. في الدراسة الحالية، تم إجراء قياسات ميدانية مفصلة للتيارات المائية وإجراء دراسة احصائية في خمس محطات (ميناء بوبيان، خور الصبية (شمال)، وجزيرة وربة، وجزيرة فيلكا، خور الصبية (جنوب)) لمدة عام حول جزيرة بوبيان في الكويت، حيث بلغ متوسط السرعة السنوية المقاسة في هذه المواقع 25.30 و 22.22 و 27.44 و 19.66 و 18.35 سم / ثانية على التوالي. ومع ذلك، فإن السرعة القصوى في سنة وصلت 81.72، 82.38، 80.25، 85.49 و 72.54 سم / ثانية على التوالي. أما بالنسبة لتحليل التوزيع الاحتمالي النظري، فقد تم النظر في أربع توزيعات نظرية، وهي توزيع رايلي، الأسي، غومبل، و لوغ–نورمال. واستناداً إلى الدراسة، تبين أن هذه التوزيعات لا تمثل على الدوام تيارات مياه البحر المُقاسة لهذه المواقع. قد بلغت قيمة سرعة مياه البحر التي تتجاوز 20% 35.5 و 33.5 و 39.5 و 26.3 و 25.5 سم / ج لهذه المواقع على التوالي. كما تبين من هذه الدراسة أن منطقة وربة البحرية هي المكان الأنسب لتوليد الطاقة البحرية الحالية بكثافة طاقة 189.18 ميجاواط. نتائج هذه الدراسة مفيدة وترمي إلى فهم ديناميكا المياه في المنطقة حيث العديد من المشاريع الضخمة مثل ميناء مبارك وتطوير جزيرة فيلكا.