

ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

**CURRENT AND WAVE POWER DERIVATIONS AND THEIR
APPLICATIONS BY USING PERTURBATION THEORY**



Ph.D. THESIS

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Department of Coastal Sciences and Engineering

Coastal Sciences and Engineering Programme

FEBRUARY 2022

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

**AKINTI VE DALGA GÜCÜ FORMÜLLERİNİN PERTURBASYON TEORİSİ
İLE TÜRETİLMESİ VE UYGULAMALARI**

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To the nature,



FOREWORD

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ABBREVIATIONS

AS	: Cape Ashizuri
CDF	: Cumulative distribution function
E	: East
EAC	: East Australian Current
ECMWF	: European Center for Medium-Range Weather Forecasts
GGD	: Generalized gamma distribution
H-5	: 5 meter water depth
H-10	: 10 meter water depth
H-15	: 15 meter water depth
H-20	: 20 meter water depth
H-25	: 25 meter water depth
H-30	: 30 meter water depth
H-35	: 35 meter water depth
H-40	: 40 meter water depth
H-45	: 45 meter water depth
H-50	: 50 meter water depth
HYCOM	: Hybrid Coordinate Ocean Model
K-S	: Kolmogorov Smirnov
LP3	: log Pearson type 3
MLM	: Maximum likelihood method
MRE	: Marine renewable energy
MS	: Mediterranean Sea
N	: North
NE	: North East
NE	: North East
NE	: North East
OECD	: Organisation for Economic Co-operation and Development
P	: Current power
PDF	: Probability distribution function
RESs	: Renewable energy sources
RMSE	: Root mean square error
S	: South
SH	: Cape Shionomisaki
SW	: South West
SW	: South West
SWH	: Significant wave height
TSS	: Turkish Strait System
W	: West
WBCs	: Western Boundary Currents
WRF	: Weather Research and Forecast
WW3	: WaveWatch3
H	: Significant wave height
T	: Wave period

V : Current speed



SYMBOLS

$\hat{\gamma}_3$	: Skewness
$\hat{\gamma}_4$	: Kurtosis
$\bar{H}$	: Arithmetic mean of significant wave height
H'	: Perturbation element of significant wave height
$\bar{T}$	: Arithmetic mean of wave period
T'	: Perturbation element of wave period
T_h	: Time period
$\bar{V}$	: Average current speed
$r_{T,H}$	: Correlation coefficient between wave period and significant wave height
$\bar{x}$	: Mean value
μ_H	: Location characteristic of significant wave height
μ_T	: Location characteristics of wave period
$\sigma_{P_{CL}}$	: Standard deviation of wave power with lognormal distribution by classical method
σ_{P_L}	: Standard deviation of wave power with lognormal distribution by perturbation method
σ_H	: Scale parameter of significant wave height
σ_H	: Standard deviation of significant wave height
σ_T	: Scale parameter of wave period
σ_T	: Standard deviation of wave period
CO_2	: Carbon Dioxide
$E(.)$	: Expectation operator
P_i	: Probability of exceeding
R^2	: Coefficient of determination
χ^2	: Chi-square error
V'	: Perturbation term of current speed
a	: Scale parameter of generalized gamma distribution
b	: Shape parameter of generalized gamma distribution
c	: Shape parameter of generalized gamma distribution
d	: Scale parameter of log Pearson type 3 distribution
e	: Shape parameter of log Pearson type 3 distribution
f	: Location parameter of log Pearson type 3 distribution
g	: Gravitational acceleration
x	: Random variable
λ	: Inverse scale parameter of exponential distribution
μ	: Location parameter of lognormal distribution
π	: Pi number
ρ	: Density of the seawater
σ	: Scale parameter of lognormal distribution



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CURRENT AND WAVE POWER DERIVATIONS AND THEIR APPLICATIONS BY USING PERTURBATION THEORY

SUMMARY

Due to the developments in both industry and technology over the last century, the need for energy resources continues to increase day by day. Although most of the energy needs are still met by fossil fuels, it should be kept in mind that fossil fuel resources are limited and negatively affect the environment. In addition, price fluctuations in fossil fuels adversely affect developing countries, causing them to sometimes have difficulties accessing energy. Thus, especially developing countries search for sustainable energy sources to reduce their energy imports.

In developed countries, however, it is a different matter. Increasing environmental awareness creates public opinion against environmental pollution caused by fossil fuels since the gases released from burning fossil fuels harm both the environment and the health of living things. In particular, excessive carbon dioxide emissions change the gas balance in the atmosphere. In this context, it causes climate change, of which we have witnessed the impacts of in recent years, and accelerates this process.

One of the most effective ways to eliminate or reduce the harmful effects of fossil fuels is to use clean and renewable energy sources. The leading clean and renewable energy sources are solar, wind, biomass, geothermal, and ocean energies.

This thesis examines the current and wave energies, which are renewable ocean energy sources. The current energy is formed by tides, as well as the differences in water density and elevation. This study investigates the energy of stratified streams arising from the difference in water density.

Unlike the classical method, the perturbation theory was used in examining current and wave energies. The primary reason for using the perturbation method is to consider the turbulence factor among the variables used to calculate the current and wave energies. Since the turbulence factor is not considered in classical method calculations, a lower amount of potential energy can be calculated. As a result of using the perturbation method, it is predicted that both more reliable and higher potential energy can be calculated.

The turbulence factor of the velocity variable was taken into account in calculating the current energy using the perturbation theory. The classical method uses the equation $P = \frac{1}{2}\rho V^3$ to calculate the current power. In this equation, P is the current power, ρ is the water density, and V is the current velocity. In perturbation theory, on the other hand, the current velocity V is studied as two components: $V = \bar{V} + V'$. V is denoted as $\bar{V}$: the average current velocity and V' : perturbation term (turbulence component). The major difference between the perturbation theory and the classical method is the perturbation term.

The turbulence factors of the wave period and the significant wave height are taken into account to calculate wave energy. The wave power is calculated with the formula

$P = 0.49TH^2$ in the classical method. In this equation, P : the wave power, T : the wave period, and H : the significant wave height. The turbulence factors of random variables T and H were also taken into account in the perturbation theory. Thus, it can be expressed as $T = \bar{T} + T'$ and $H = \bar{H} + H'$. Here, $\bar{T}$ and $\bar{H}$ are the arithmetic means of the wave period and the significant wave height, respectively, and T' and H' are the perturbation terms of the wave period and the significant wave height.

This thesis first includes literature studies on current and wave power. Then, both classical method formulas are given for current and wave power calculations, and equations are derived with the perturbation theory. The equations derived by the perturbation method are general ones and are arranged to adapt to the distribution parameters of the random variable to which the time series will fit. Therefore, after the moment of the distribution to which the random variable adjusts is known, the expected power value can be calculated by the perturbation method using the relevant data due to the following operations.

After the current and wave power formulas are derived and presented, information about the study areas where the data set in which the related equations will be used is provided. Within the scope of this thesis, the energies of the upper current of the Dardanelles, the bottom current of the Dardanelles, the current of a location close to the north of the Bosphorus, and the wave energies at two stations in Mersin and Antalya regions were estimated. The current strength in the Dardanelles was examined for the first time in the literature within the scope of this thesis.

Current rose was prepared first when examining the upper layer current of the Dardanelles. Afterwards, it was determined that the distribution in which the current velocity was compatible was found to fit the generalized gamma distribution, and the parameters of the relevant distribution were determined. By using the moment equations of the generalized gamma distribution function, current power formulas were derived by perturbation method. After deriving the current power formulas, the power of the upper layer current of the Dardanelles was estimated with the determined parameters of the generalized gamma distribution function.

For bottom layer of the Dardanelles Strait, current rose was formed. Then, the parameters of the exponential distribution to which the current velocity conformed were obtained. By using the moment equation of the exponential distribution, the current power formulas were derived by the perturbation method. The power of the bottom layer of the Dardanelles Strait was estimated using the parameters of the exponential distribution by means of the derived equations.

Current rose for current data in the area close to the northern part of the Bosphorus was prepared. Later, the current data were examined, and it was determined that the current velocities matched the log-Pearson type 3 distribution. Current power equations were derived using the log-Pearson type 3 distribution and the perturbation method. The current power in the region close to the northern part of the Bosphorus was estimated using the distribution parameters through the related equations.

Two stations in Mersin and Antalya regions were selected to determine the wave power by the perturbation method. First, wave roses were prepared using the related wave data. Then, the data on the wave period and the significant wave height, which are the variables in the current power formula, were examined. As a result of the examination, it was determined that the wave period and significant wave height data were in accordance with the lognormal distribution. Wave power formulas were derived using both classical and perturbation methods using the lognormal

distribution. The wave power was estimated using the derived equations and the parameters of the wave period and the significant wave height.

In conclusion, the current and wave power estimations within the scope of this thesis were made with the perturbation approach, different from the classical method. The major difference between this approach and the classical approach is that this one takes into account the turbulence factor. As a result of the estimations, it was revealed that the perturbation approach provided a higher and more accurate potential energy estimation than the classical method.





AKINTI VE DALGA GÜCÜ FORMÜLLERİNİN PERTURBASYON TEORİSİ İLE TÜRETİLMESİ VE UYGULAMALARI

ÖZET

Dünya üzerinde son yüzyılda gerek sanayide gerek ise teknolojiye yaşanan gelişmeler neticesinde enerji kaynaklarına olan ihtiyaç her geçen gün artarak devam etmektedir. Günümüzde enerji ihtiyacının büyük bölümü halen fosil yakıtlardan karşılanırsa da fosil yakıt kaynaklarının sınırlı olduğu ve çevreye olumsuz etkilerinin olduğu unutulmamalıdır. Ayrıca gelişmekte olan ülkeler fosil yakıtlarda yaşanan fiyat dalgalanmalarından olumsuz etkilenip enerjiye ulaşmakta bazı dönemlerde güçlük çekmektedirler. Bu sebeple özellikle gelişmekte olan ülkeler enerji ithalatını azaltmak için sürdürülebilir enerji kaynağı arayışı içerisinde.

Gelişmiş ülkelerde ise durum daha farklıdır. Artan çevre bilinci fosil yakıtların neden olduğu çevre kirliliğine karşı kamuoyu oluşturmaktadır. Çünkü fosil yakıtların yanması sonucu açığa çıkan gazlar hem çevreye hem de sağlığa zarar vermektedir. Özellikle aşırı karbondioksit salınımı hem canlıların sağlığına zarar vermekte hem de atmosferdeki gaz dengesini değiştirebilmektedir. Bu bağlamda özellikle son yıllarda etkisini gördüğümüz iklim değişikliğine sebep olmakla birlikte sürecini de hızlandırmaktadır.

Fosil yakıtların ortaya koyduğu olumsuz etkilerden kurtulmanın veya etkilerini azaltmanın en etkili yollarından bir tanesi ise temiz ve yenilenebilir enerji kaynaklarını kullanmaktır. Temiz ve yenilenebilir enerji kaynaklarının başlıcaları ise: Güneş, Rüzgar, Biyokütle, Jeotermal ve Okyanus enerjileridir.

Bu tez çalışmasında yenilenebilir okyanus enerji kaynaklarından akıntı ve dalga enerjileri incelenmiştir. Akıntı enerjisi gel-git ile oluşmakla birlikte su yoğunluğu ve kot farklılıklarından da oluşmaktadır. Bu çalışma kapsamında su yoğunluğu farklılığından kaynaklanan tabakalı akıntı enerjisi incelenmiştir.

Akıntı ve dalga enerjileri incelenirken klasik yöntemden farklı olarak perturbasyon teorisi kullanılmıştır. Perturbasyon yönteminin kullanılmasının esas amacı akıntı ve dalga enerjilerinin hesaplanmasında kullanılan değişkenlerin içerisindeki çalkantı faktörünün de dikkate alınmasıdır. Çünkü klasik yöntemde çalkantı faktörü hesaplamalarda dikkate alınmadığından potansiyel enerji daha düşük hesaplanabilmektedir. Perturbasyon yönteminin kullanılması neticesinde hem daha güvenilir hem de daha yüksek potansiyel enerjinin hesaplanması öngörülmüştür.

Akıntı enerjisinin perturbasyon teorisi kullanılarak hesaplanılmasında hız değişkeninin çalkantı faktörü dikkate alınmıştır. Klasik yöntem ile akıntı gücü hesaplanırken $P = \frac{1}{2} \rho V^3$ denklemi kullanılmaktadır. Bu denklemde, P : Akıntı gücü, ρ : Su yoğunluğu ve V : Akıntı hızı olarak simgelenmektedir. Perturbasyon teorisi kullanılarak ise akıntı hızı (V) iki bileşen olarak incelenmektedir: $V = \bar{V} + V'$. Burada, $\bar{V}$: Ortalama akıntı hızı ve V' : Perturbasyon terimi (çalkantı bileşeni) olarak

simgelenmektedir. Perturbasyon teorisinin klasik yöntemden en büyük farkını perturbasyon terimi oluşturmaktadır.

Dalga enerjisinin hesaplanmasında da dalga periyodunun ve belirgin dalga yüksekliğinin çalkantı faktörleri dikkate alınmıştır. Klasik yöntem kullanılarak dalga gücü $P = 0.49TH^2$ formülü ile hesaplanmaktadır. Bu denklemde, P : Dalga gücü, T : Dalga periyodu ve H : Belirgin dalga yüksekliği olarak ifade edilmektedir. Perturbasyon teorisi kullanılarak T ve H rastgele değişkenlerinin çalkantı faktörleri de dikkate alınmıştır. Böylelikle, $T = \bar{T} + T'$ ve $H = \bar{H} + H'$ olarak ifade edilebilmektedir. Burada, $\bar{T}$ ve $\bar{H}$ sırasıyla dalga periyodunun ve belirgin dalga yüksekliğinin aritmetik ortalamaları ve T' ve H' ise sırasıyla dalga periyodunun ve belirgin dalga yüksekliğinin perturbasyon terimleridir.

Bu tez çalışmasında öncelikle akıntı ve dalga gücüne dair literatür çalışmalarına yer verilmiştir. Daha sonra ise akıntı ve dalga gücü hesaplamaları için hem klasik yöntem formülleri verilmiş olup hem de perturbasyon teorisi ile denklemler türetilmiştir. Perturbasyon yöntemi ile türetilen denklemler genel denklemler olup rastgele değişkenin zaman serisinin uyum göstereceği dağılım parametrelerine adapte olacak şekilde düzenlenmiştir. Dolayısıyla rastgele değişkenin uyum gösterdiği dağılımın momenti bilindikten sonra takip eden işlemler neticesinde ilgili veri kullanılarak perturbasyon yöntemi ile beklenen güç değeri hesaplanabilmektedir.

Akıntı ve dalga gücü formülleri türetilip sunulduktan sonra ilgili denklemlerin kullanılacağı veri setinin temin edildiği çalışma alanları hakkında bilgi verilmiştir. Bu tez kapsamında Çanakkale Boğazı'nın üst akıntısının, Çanakkale Boğazı'nın alt akıntısının, İstanbul Boğazı'nın kuzeyine yakın bir konumun akıntısının enerjileri ile Mersin ve Antalya bölgesindeki iki istasyonda dalga enerjileri tahmin edilmiştir. Çanakkale Boğazı'ndaki akıntı gücü literatürde ilk defa bu tez kapsamında incelenmiştir.

Çanakkale Boğazı'nın üst akıntısı incelenirken öncelikle akıntı gülü gösterilmiştir. Daha sonra akıntı hızının uyum gösterdiği dağılımın genelleştirilmiş gamma dağılımına uyduğu tespit edilip ilgili dağılıma dair parametreler belirlenmiştir. Genelleştirilmiş gamma dağılım fonksiyonunun moment denklemleri kullanılarak perturbasyon yöntemi ile akıntı gücü formülleri türetilmiştir. Akıntı gücü formülleri türetildikten sonra genelleştirilmiş gamma dağılım fonksiyonunun tespit edilen parametreleri ile Çanakkale Boğazı'nın üst akıntısının gücü tahmin edilmiştir.

Çanakkale Boğazı'nın alt akıntısı için akıntı gülü tespit edilmiştir. Akıntı gülünün tespitinden sonra akıntı hızının uyum gösterdiği üstel dağılıma dair parametreler elde edilmiştir. Üstel dağılımın moment denklemi kullanılarak perturbasyon yöntemi ile akıntı gücü formülleri türetilmiştir. Türetilen denklemler marifetiyle üstel dağılımın parametreleri kullanılarak Çanakkale Boğazı'nın alt akıntısının gücü tahmin edilmiştir.

İstanbul Boğazı'nın kuzey kısmına yakın bölgedeki akıntı verilerine dair akıntı gülü hazırlanmıştır. Daha sonra ise akıntı verilerine dair incelemeler yapıp akıntı hızlarının log Pearson Tip 3 dağılımına uyduğu tespit edilmiştir. Log Pearson Tip 3 dağılımı ile perturbasyon yöntemi kullanılarak akıntı gücü denklemleri türetilmiştir. İlgili denklemler vasıtasıyla dağılım parametreleri kullanılarak İstanbul Boğazı'nın kuzey kısmına yakın bölgedeki akıntı gücü tahmin edilmiştir.

Dalga gücünün perturbasyon yöntemi ile tespit edilmesi için Mersin ve Antalya bölgesindeki iki istasyon seçilmiştir. İlgili dalga verileri kullanılarak öncelikle dalga

g  lleri hazırlanmıřtır. Daha sonra ise akıntı g  c   form  l  ndeki deęiřkenler olan dalga periyoduna ve belirgin dalga y  kseklięine dair veriler incelenmiřtir. İnceleme neticesinde dalga periyodu ve belirgin dalga y  kseklięi verilerinin lognormal daęılıma uygun olduęu tespit edilmiřtir. Lognormal daęılım kullanılarak hem klasik hem de perturbasyon y  ntemleri ile dalga g  c   form  lleri t  retilmiřtir. T  retilen denklemler ile dalga periyoduna ve belirgin dalga y  kklіğine ait parametreler kullanılarak dalga g  c   tahmininde bulunulmuřtur.

Sonuç olarak, bu tez kapsamında akıntı ve dalga g  c   tahminleri klasik y  ntemden farklı olarak perturbasyon yaklařımı ile gerekleřtirilmiřtir. Bu yaklařımın klasik yaklařımdan en b  y  k farkı alkantı fakt  r  n   dikkate almasıdır. Yapılan tahminler neticesinde perturbasyon yaklařımının klasik y  ntemden daha y  ksek ve daha isabetli potansiyel enerji tahmininde bulunduęu ortaya konulmuřtur.





1. INTRODUCTION

The world is evolving rapidly, especially since the industrial revolution and advancements in technology started in the 18th century. As a result, energy resource utilization is one of the most essential and contentious issues of our age. In 2018, primary energy consumption increased at a 2.9 % level, over above the 10-year average and the highest since 2010 (Dudley, 2017). As demand for power keeps increasing with supply mostly reliant on fossil fuels, concerns about CO₂ emissions are increasing. These CO₂ emissions lead to global warming and climate change, both of which have become visible risks to our daily lives (Altunkaynak, 2014). Thus, there is increasing concern about the effect of global warming and climate change, which has led to an additional pressure on researchers and manufacturers of clean energy technology.

Climate change awareness and the Kyoto Protocol have pressured the globe to adopt a variety of carbon-dioxide reduction methods (Vidal-Amaro et al., 2015). Nevertheless, many countries currently depend heavily on fossil fuels such as coal, natural gas, and oil to meet their energy requirements and the extraction of such materials would be more harmful to the environment (Alper and Oguz, 2016). Furthermore, fossil fuels are expected to be the primary type of power until at least 2050 in several scenarios, as the use of computers and new technologies in the oil and gas industry regenerate plate tectonics and the organic source theory, and large areas in deserts, piedmont belts, and oceans have been discovered one by one (Brockway et al., 2019; Caineng et al., 2015).

The situation is more serious for Turkey since economic and population growth, consumption for energy and natural resources has grown faster than the global average. Turkey has been the OECD member with the fastest rising power consumption in recent years, with an annual increase of 5.5 % since 2002. On the other hand, Turkey is unable to supply its own energy demands and therefore must rely on imports of fossil fuels from other countries. Furthermore, Turkey has been suffering from polluted air, which has a severe impact on human health, causes numerous diseases, some of which

are deadly, raises health-care costs, and results in considerable workday losses, because air pollution is mostly produced by the combustion of fossil fuels (Bulut and Muratoglu, 2018).

In this manner, renewable energy sources (RESs) provide some solutions to the problems of energy production. RESs currently provide 14% of global energy consumption (Nguyen and Kakinaka, 2019). Moreover, if supported by policies that encourage their development, RESs could meet about 80% of the world's energy demands by 2050. Furthermore, Turkey's geographic position provides numerous benefits for extensive use of most RESs as it is located on the humid and warm weather zone that covers much of Europe, the Near East, and Western Asia (Kaya, 2006). On the other hand, Turkey is now in the early stages of recognizing the necessity for a transition from fossil energy sources to renewable energy sources, regarding EU and global experiences (Erdil and Erbiyik, 2015). Moreover, Turkey's renewable energy production has increased since the government approved a "Renewable Energy Law" in 2005. As a result, greater emphasis is being placed on the many forms of renewable energy sources found in nature, such as ocean, wind, and sun.

The ocean provides a widely accessible, safe, and sustainable power source. If less than 0.1 % of renewable energy resources in the oceans are converted into power, it will be more than five times the entire world energy consumption (Khan et al., 2017; Caillé et al., 2007). As the demand to replace fossil fuels with alternative energy sources grows, the need for marine renewable energy (MRE) development has demonstrated the need for reduced pollution threats, lower environmental costs, and a smaller environmental footprint (Soukissian et al., 2017). Marine current energy and near-shore ocean currents, which are mostly generated by tidal currents or rip currents, are considered the more efficient and promising forms of ocean energy. These can sometimes be a mix of tidal and rip currents (Goundar and Ahmed, 2014). In the first perspective, the primary benefit of marine current energy is that it is independent of seasonal and environmental conditions that impact the efficiency of solar and wind power generation, which is advantageous for the incorporation of marine current energy into the power network (Zhou et al., 2013). Furthermore, sea currents could generate as much energy as wind currents as the density of the oceans is approximately 850 times more than that of air, even though sea current speeds are typically lower than wind speeds (Sheng et al., 2017).

The theoretical marine current is estimated to be 800 TWh per year, which is equivalent to 3-4% of total power demand, and when compared to other renewable energy sources, marine current energy has a clear predictability advantage, as marine current charts can be used with up to 98% reliability (Chen et al., 2018). Submerged turbines in the oceans generate electricity from ocean currents at different vertical depths. Wind turbines and ocean turbines perform on very identical principles. While wind turbines capture the kinetic energy of the wind, ocean turbines transform the kinetic energy of current velocity; the kinetic energy of the current is transferred to spatial movement and then, simultaneously, to electrical energy.

Significant progress has been made in developing solar and wind energy technology as renewable energy sources over the last three decades, but there is another form of high potential energy that gradually continues to build up and promotes a great deal of interest from the academic community, wave energy (López et al., 2013). While the wind industry is more industrialized in general, ocean waves are known to be more powerful, in the vertical direction over 6-8 times that of wind power, because they are a dispersed form of wind power which is carried out over long distances with little energy losses (Liu et al., 2021; Rusu and Onea, 2015). Furthermore, it is stated that wave power systems can generate power around 90% of the time, compared to 20-30% for solar and wind power systems (Drew and Sahinkaya, 2009). Moreover, ocean waves are a significant sustainable energy source that, if widely utilised, will contribute considerably to the electrical power generation of countries with ocean-facing coastlines, since the global gross wave power potential is estimated to be around 3.7 TW (Mork et al., 2010).

In order to benefit from potential wave energy, wave energy converter devices are needed. While wave energy converter systems are relatively economical, due to infrastructure costs and regulatory requirements, detailed study of wave climate and usable power is essential for the identification of ideal locations (Arinaga and Cheung, 2012). Ocean wave characteristics, such as significant wave height (SWH) and average wave period, are critical components for ocean engineering applications like determining suitable locations (Altunkaynak, 2013; Özger, 2010). On this basis, long-term in situ analysis of wave characteristics is the best strategy to establish a wave climate for a location (Aydoğan et al., 2013). As a result, it is critical to determine the statistical properties of the SWH and wave period for long-term in situ analysis in

order to successfully assess the performance of the wave power system at a particular region.

The main focus of this thesis is to establish more accurate current and wave power estimation equations than the classical approach by using the perturbation method, which considers mean deviations (turbulent fluctuations). In this context, first of all, current power formulas were derived by perturbation method considering the turbulence effect on current velocity. Then, the formulas were rearranged according to the appropriate velocity distribution in the measurement area for the estimation of the current power. The same application was carried out for wave power estimation. In wave power formulas, wave period and SWH were chosen as independent variables and their fluctuations around the mean were taken into account.



2. LITERATURE REVIEW

2.1 Current Power

Current power studies will be examined in this section of the thesis. Firstly, current power estimates all around the world will be analyzed. Following that, studies for current power analyses in Turkey will be evaluated. The studies about marine current power in the literature are presented below.

Schaeffer et al. (2020) began by examining areas with considerable kinetic energy flux that are a practical distance from the coastline for energy collection and transportation. Then, due to their high current speeds (usually 1–2 m/s), Western boundary currents (WBCs) have been considered as the most attractive resource. While numerical models have been used in worldwide studies of WBCs, including the East Australian Current (EAC), they have poor resolutions and frequently underrate kinetic energy, which is the critical element that requires correct evaluation. They addressed this information gap by analyzing the potential of the EAC as a future renewable energy potential at different latitudes along the east Australian coast. In this context, they have used variety of current velocity datasets from moorings, high frequency radar, and satellite altimetry. Consequently, they have presented the optimal location for sustainable energy extraction chances with considerably high hydrokinetic currents with average of 500 W/m^2 at 50 m depth, steady direction, and viable location (25 km from shore in 400 m seawater depth) in combination with a high-resolution data incorporating model. Yang et al. (2014) altered a simplified ocean circulation model based on the Stommel model, with localized energy extraction, for assessing the potential of ocean current energy in the Gulf Stream system. The Gulf Stream system, particularly the Florida Current, contains kinetic power density more than 2000 W/m^2 (Yang et al., 2015). They used a numerical approach based on finite differences to handle the model. The study has indicated that considering extraction across a region approximating the whole Florida Current component of the Gulf Stream system, the average power consumed varies between 4 and 6 GW with an average around 5 GW which equates to around 45 TWh.

Liu et al. (2018) computed marine current power near the Japanese coastline utilizing a high-resolution, three-dimensional ocean model. They examined the variation of the current area for three feasible regions: near the Tokara Strait, south of Cape Ashizuri (AS), and south of Cape Shionomisaki (SH) to decide the ideal place for an ocean current power generation. The region south of AS was determined to be suitable for ocean current power generation since the current is steady and powerful despite the enormous meander, and the mean marine current power density may exceed 1 kW/m^2 . Shadman et al. (2019) performed an analysis of ocean renewable energy resources, which include wave, marine current and thermal gradient energy, around the Brazilian coastline. The marine current power density near Brazil's equatorial coast was estimated to be around 500 W/m^2 with yearly average current speed of 1.52 m/s . Kabir et al. (2015) studied the potential hydrokinetic power along the North Carolina coast employing data from the Hybrid Coordinate Ocean Model (HYCOM) and high-frequency radar observations. According to the study, the region around the North Carolina coast has a power density of at least 500 W/m^2 over 55% of the time, and it approaches 1000 W/m^2 on one-third of the days.

Şen (2012) analyzed current velocity data collected during several sorties over the Bosphorus on the southern coastline regions. A current power generation equation based on the probability distribution of current velocity in the Bosphorus has been established, and a basic numerical sample has been indicated. It was demonstrated that the current velocity probability distribution function (PDF) matched to the gamma PDF statistically. The model generated 0.736 kW power per unit m^2 turbine area and per second for current cut-in speed greater than 1.0 m/s . Ozturk et al. (2017) utilized calibrated and confirmed three-dimensional numerical model solutions to determine the yearly current power potential of Bosphorus. The numerical approach employed a cell-centered finite volume solution methodology and was depends on a set of unstructured flexible meshes. The major guiding processes of the numerical model as inputs were variations in water level and density impacting on the model open boundaries, as well as the meteorological composition of the region (wind velocity, direction, and air pressure variation). The results indicated that the strait's complicated structure (both horizontally and vertically) together with the highly dynamic hydrological and climatic characteristics of the neighbouring seas, the Marmara Sea and the Black Sea, represent a significant deviation in the kinetic energy potential. It was mentioned that even though it was not the narrowest region of the strait, the

southernmost region of the strait had the highest kinetic energy owing to both a decreases in cross-sectional area and the existence of a sill on the bottom.

2.2 Wave Power

This section of the research includes details about the literature on wave power. In this regard, sites with high wave potential in various areas of the world have been chosen. The following section contains information about the literature on wave power.

Stopa et al. (2011) used the worldwide WaveWatch3 (WW3) model to generate a layered computational grid across the major Hawaiian Islands and the Weather Research and Forecast (WRF) model to deliver high-resolution mesoscale wind forcing throughout the Hawaii basin. The outcomes revealed the wave energy potential in Hawaiian seas, as episodic swell occurrences have huge power exceeding 60 kW/m, while wind waves, enhanced by regional weather produce a constant energy supply of 15-25 kW/m all year. Sierra et al. (2016) examined the wave energy potential around Morocco's Atlantic coast utilizing a 44-year dataset derived by numerical modeling. The expected potential (average wave power of up to 30 kW/m and average yearly wave energy up to 262 MWh/m) are significant although slightly lower than the nearby Canary Islands. Moreover, the analysis of seasonal variations reveals a significant seasonal tendency, with the wave power potential being four times higher in the winter than in the summer.

Iglesias and Carballo (2009) analyzed the wave energy capacity along the Galician coast (NW Spain) using the SIMAR-44 sample data, including a 44-year period, and wave buoy statistics, with a focus on the Death Coast region (from Cape Finisterre to the Sisargas Isles). In the Death Coast region, yearly wave power was estimated to be around 50 kW/m, and yearly wave energy was determined to be around 400 MWh/m. Mirzaei et al. (2015) analyzed the wave power capacity in the South China Sea depending on a 31-year simulation of wave parameters employing the third generation spectral WW3 model. The northern part of the study site had the maximum yearly wave power, with amplitudes reaching 20 kW/m. Due to topography complexities, shadowing, and island blockage impacts, the values steadily drop towards the Sunda Shelf and become a minimum at coastal regions.

Ayat (2013) evaluated and described the wave energy capacity of the Eastern Mediterranean Sea Basin using a 3rd generation spectral wave model and wind

statistics from the European Center for Medium-Range Weather Forecasts (ECMWF) from 1994 to 2009. The mean wave power was determined to be less than 2 kW/m along the whole model area's coastlines. The Egyptian shore between the Nile Delta and the Libyan boundary was projected to be the most energetic coast in the Southern Mediterranean Basin, with a potential of more than 4 kW/m. Within the Aegean Sea Basin, several locations along the coastlines of various Greek Islands have been found to contain potential exceeding 4 kW/m. The model area's eastern side was discovered to be the least powerful. Moreover, the mean wave energy in winter was determined to be nearly twice as high as the yearly mean. Akpınar and Kömürcü (2012) investigated and described the wave energy potential along the southeastern of Black Sea coastlines using six-hourly data from a third generation wave model (SWAN) from 1995 to 2009. The annual wave energy of all sites was estimated to be around 6 MWh/m, with the exception of Sinop, which had an annual wave energy of 10 MWh/m.

3. POWER DERIVATIONS

In this part of the thesis, current and wave formulas are derived by using perturbation theory.

3.1 Perturbation theory

The perturbation technique, which consists of mathematical methods for obtaining an approximate solution to a problem that cannot be solved properly by beginning from the exact solution of a corresponding problem, may lead to more accurate predictions (Altunkaynak, 2014). To use the perturbation technique, it is required to consider that each variable contains random fluctuations (perturbations) around its average value (Şen and Altunkaynak, 2006). In this thesis, wave velocity was employed to estimate current power as random variable, while wave period and apparent wave height were utilized as random variables to estimate wave power.

3.2 Current power derivation

As the marine current's kinetic energy is captured by the ocean current turbine and converted into mechanical energy, the current power for a unit turbine area and the unit time is described as (Xupeng et al., 2020; Alonso et al., 2017):

$$P = \frac{1}{2} \rho V^3 \quad (3.1)$$

Here,

P : Current power (kg/s^3)

ρ : the density of the seawater (kg/m^3) which is generally specified as 1025 kg/m^3 (Badaruddin et al., 2017; Birdas et al., 2015)

V : the mean current speed (m/s)

The mean speed of the current is described by:

$$V_{avg} = \frac{1}{n} \left[\sum_{i=1}^n V_i \right] \quad (3.2)$$

Here,

n : number of data

In the following part of the study, the current power formulas are derived both by perturbation method and specified by the classical method.

3.2.1 Current power derivation by perturbation approach

In this part of the study, equations are derived for the estimation of the current power using the perturbation method. By applying the definition of expectation in the stochastic approximation, equation 3.3 can be reordered as shown below (Altunkaynak et al., 2012):

$$E(P) = \frac{1}{2} \rho E(V^3) \quad (3.3)$$

Here,

$E(\cdot)$: The expectation operator, which is equal to the probability-weighted mean of all possible values over a very long time series (Altunkaynak et al., 2012).

As the current flow displays a turbulent motion in the ocean, the deviations around the arithmetic mean are autonomous from each other. Thus, the instantaneous current speed, V , actually has two variables in this respect, namely, $\bar{V}$, the average current speed, and the perturbation term V' , as follows:

$$V = \bar{V} + V' \quad (3.4)$$

The expected value of current power can exist in the form below when the equation 3.4 is inserted to the equation 3.1 as:

$$E(P) = \frac{1}{2} \rho [E^3(V) + 3E^2(V)E(V') + 3E(V)E(V'^2) + E(V'^3)] \quad (3.5)$$

where,

$$\begin{aligned} E(V'^2) &= E(V'^2) = E(V^2) - 2E(V)E(V) + E^2(V) \\ &= E(V^2) - E^2(V) \end{aligned} \quad (3.6)$$

$$E(V'^3) = E(V - \bar{V})^3 = E(V^3) - 3E(V^2)E(V) + 2E^3(V) \quad (3.7)$$

By basic definition the expected value of perturbation term is equal to zero here as (Altunkaynak et al., 2012):

$$E(V') = 0 \quad (3.8)$$

Therefore, equation 3.5 can be simplified to equation 3.9 as:

$$E(P) = \frac{1}{2}\rho[E^3(V) + 3E(V)E(V'^2) + E(V'^3)] \quad (3.9)$$

In addition, the generalized stochastic variance formulation of a random variable such as current power, is described as follows:

$$Var(P) = E(P^2) - E^2(P) \quad (3.10)$$

The second term of the right-hand side in equation 3.10 is already the square of expectation set out in equation 3.9. Thereafter, in order to investigate the first term of the right-hand side in equation 3.10, it is required to insert equation 3.4 to equation 3.1. Accordingly, after certain numerical manipulations, $E(P^2)$ can be written as follows:

$$E(P^2) = \frac{1}{4}\rho^2 E[\bar{V}^6 + 6\bar{V}^5 V' + 15\bar{V}^4 V'^2 + 20\bar{V}^3 V'^3 + 15\bar{V}^2 V'^4 + 6\bar{V} V'^5 + V'^6] \quad (3.11)$$

As $E(\bar{V}') = 0$ by description, equation 3.11 takes the following specific structure:

$$E(P^2) = \frac{1}{4}\rho^2 [E^6(V) + 15E^4(V)E(V'^2) + 20E^3(V)E(V'^3) + 15E^2(V)E(V'^4) + 6E(V)E(V'^5) + E(V'^6)] \quad (3.12)$$

And the second term, $E^2(P)$ takes the following form:

$$E^2(P) = \frac{1}{4}\rho^2 [E^6(V) + E^2(V'^3) + 6E^4(V)E(V'^2) + 2E^3(V)E(V'^3) + 6E(V)E(V'^2)E(V'^3) + 9E^2(V)E^2(V'^2)] \quad (3.13)$$

If the terms obtained from equation 3.11 and equation 3.13 are replaced in equation 3.10, the variance function is derived after algebraic manipulations as:

$$Var(P) = \frac{1}{4}\rho^2 [9E^4(V)E(V'^2) + 15E^2(V)E(V'^4) - 9E^2(V)E^2(V'^2) - E^2(V'^3) + 18E^3(V)E(V'^3) - 6E(V)E(V'^2)E(V'^3) + E(V'^6) + 6E(V)E(V'^5)] \quad (3.14)$$

Here,

$$\begin{aligned}
E(V'^4) &= E(V - \bar{V})^4 \\
&= E(V^4) - 4E(V)E(V^3) + 6E^2(V)E(V^2) \\
&\quad - 4E^3(V)E(V) + E^4(V)
\end{aligned} \tag{3.15}$$

$$\begin{aligned}
E(V'^5) &= E(V - \bar{V})^5 \\
&= E(V^5) - 5E(V)E(V^4) + 10E^2(V)E(V^3) \\
&\quad - 10E^3(V)E(V^2) + 5E^4(V)E(V) - E^5(V)
\end{aligned} \tag{3.16}$$

$$\begin{aligned}
E(V'^6) &= E(V - \bar{V})^6 \\
&= E(V^6) - 6E(V)E(V^5) + 15E^2(V)E(V^4) \\
&\quad - 20E^3(V)E(V^3) + 15E^4(V)E(V^2) - 6E^5(V)E(V) \\
&\quad + E^6(V)
\end{aligned} \tag{3.17}$$

Equation 3.9 and equation 3.14 are the power and the variance equations that can be used specifically for dealing fluid turbulence, which are absent from the classical equations.

3.2.2 Current power estimation by classical method

The time-mean power density cannot be derived by directly substituting the average current speed into the power density equation 3.1 since the power density varies with the cube of velocity (Hagerman et al., 2006). The distribution of power densities can be simply estimated and averaged to determine the time mean power density once the time variety of speeds for each location of the regular grid is determined (Thiébaut and Sentchev, 2016). Thus, following equation, which requires integration, can be used to estimate current power by classical method:

$$\frac{P}{A} = \int_0^{\infty} \frac{1}{2} \rho V^3 f(V) d(V) \tag{3.18}$$

Here,

A: Area

3.3 Wave power derivations

Offshore wave power is not affected by refraction and shoaling and can therefore be computed employing the following equation from wave measurements (Kamranzad et al., 2013; Kim et al., 2011):

$$P = \frac{\rho g^2}{64\pi} TH^2 \approx 0.49TH^2 \quad (3.19)$$

Where,

g : Gravitational acceleration

π : Pi number

T : Wave period

H : SWH

It is apparently difficult to independently quantify both heights and periods, so the average process is used to estimate the total power. Therefore, H is equivalent to the average of the highest 1/3 of all waves and T is the mean period of all waves in a span of time.

In the following part of the study, wave power formulas are derived using both the perturbation method and the classical method within the concept mentioned above.

3.3.1 Wave power derivation by perturbation approach

In this part of the study, wave power calculation formulas are derived using the perturbation method. In this context, if the wave period and the SWH are considered to be autonomous of each other, the wave power definition can be modified in stochastic concept with the principle of the expectation process as follows:

$$E(P) = 0.49E(T)E(H^2) \quad (3.20)$$

In addition, SWH and wave period statistics indicate fluctuations in their mean values and are assumed to be perturbation variables, as the Perturbation Theory is dependent on an assumption that implies fluctuations in the mean value of the variable (Altunkaynak, 2014). Since the wave period and SWH are stochastic variables, the perturbation of each term can be written in the following form.

$$T = \bar{T} + T' \quad (3.21)$$

$$H = \bar{H} + H' \quad (3.22)$$

Here,

$\bar{T}$: Arithmetic mean of wave period

$\bar{H}$: Arithmetic mean of SWH

T' : Perturbation element of wave period

H' : Perturbation element of SWH

Regarding some numerical manipulations, the addition of these two definitions of perturbation into equation 3.20 refers to the following equations:

$$P = 0.49(\bar{T} + T')(\bar{H} + H')^2 \quad (3.23)$$

$$P = 0.49(\bar{T} + T')(\bar{H}^2 + 2\bar{H}H' + H'^2) \quad (3.24)$$

$$P = 0.49(\bar{T}\bar{H}^2 + 2\bar{T}\bar{H}H' + \bar{T}H'^2 + T'\bar{H}^2 + 2T'\bar{H}H' + T'H'^2) \quad (3.25)$$

$$P = 0.49\bar{T}\bar{H}^2 \left(1 + 2\frac{H'}{\bar{H}} + \frac{H'^2}{\bar{H}^2} + \frac{T'}{\bar{T}} + 2\frac{T'H'}{\bar{T}\bar{H}} + \frac{T'H'^2}{\bar{T}\bar{H}^2} \right) \quad (3.26)$$

The classic characteristic of the perturbation principle is that the phrases of T' and H' are equivalent to zero as (Altunkaynak, 2014):

$$E(T') = 0 \quad (3.27)$$

$$E(H') = 0 \quad (3.28)$$

By conducting the necessary algebraic computations on equation 3.26 and evaluating expectations on both sides of the equation, the equation can be shown as follow:

$$E(P) = 0.49E(T)E^2(H) \left(1 + \frac{E(H'^2)}{E^2(H)} + 2\frac{E(T'H')}{E(T)E(H)} + \frac{E(T'H'^2)}{E(T)E^2(H)} \right) \quad (3.29)$$

The variance is equal to the simultaneous wave period and the SWH records and can be mentioned as:

$$Var(T) = E(T'^2) = \sigma_T^2 \quad (3.30)$$

$$Var(H) = E(H'^2) = \sigma_H^2 \quad (3.31)$$

Where,

σ_T : Standard deviation of wave period

σ_H : Standard deviation of SWH

Furthermore, the covariance is specifically associated to the element of the standard deviation for each variable and the coefficient of correlation between the wave period and the SWH and can be described as:

$$Cov(T, H) = E(T'H') = r_{T,H}\sigma_T\sigma_H \quad (3.32)$$

Here,

$r_{T,H}$: The correlation coefficient between wave period and the SWH

The inclusion of the covariance expression in the equation is important for expressing the connection between the wave period and SWH. By conducting the necessary computational procedures on equation 3.29, the description in the parenthesis on the right side of equation 3.29 can be achieved by the following equation:

$$\alpha = \left[1 + \frac{\sigma_H^2}{E^2(H)} + 2 \frac{r_{T,H}\sigma_T\sigma_H}{E(T)E(H)} + \frac{r_{T,H}^2\sigma_T^2\sigma_H^2}{E(T)^2E^2(H)} \right] \quad (3.33)$$

As a result, the substitution of equation 3.33 with equation 3.29 yields the expectation of wave power as shown below:

$$E(P) = \alpha 0.49 E(T) E^2(H) \quad (3.34)$$

In addition, the simple stochastic variance description of a random variable, such as wave power, is described as:

$$Var(P) = E(P^2) - E^2(P) \quad (3.35)$$

$E^2(P)$ can be obtained by taking the square of equation 3.34 as mentioned below:

$$E^2(P) = \alpha^2 (0.49)^2 E^2(T) E^4(H) \quad (3.36)$$

It is then required to generate $E(P^2)$ in order to predict $Var(P)$. In order to calculate $E(P^2)$, equation 3.23 can be used by taking the square of both sides as regards:

$$P^2 = (0.49)^2 (\bar{T} + T')^2 (\bar{H} + H')^4 \quad (3.37)$$

$$P^2 = (0.49)^2 (\bar{T}^2 + 2\bar{T}T' + T'^2) (\bar{H}^4 + 4\bar{H}^3H' + 6\bar{H}^2H'^2 + 4\bar{H}H'^3 + H'^4) \quad (3.38)$$

$$P^2 = (0.49)^2 \bar{T}^2 \left(1 + 2\frac{T'}{\bar{T}} + \frac{T'^2}{\bar{T}^2} \right) \bar{H}^4 \left(1 + 4\frac{H'}{\bar{H}} + 6\frac{H'^2}{\bar{H}^2} + 4\frac{H'^3}{\bar{H}^3} + \frac{H'^4}{\bar{H}^4} \right) \quad (3.39)$$

With some mathematical computations P^2 can be obtained as follows:

$$P^2 = (0.49)^2 \bar{T}^2 \bar{H}^4 \left[\begin{array}{c} 1 + 4\frac{H'}{\bar{H}} + 6\frac{H'^2}{\bar{H}^2} + 4\frac{H'^3}{\bar{H}^3} + \\ \frac{H'^4}{\bar{H}^4} + 2\frac{T'}{\bar{T}} + 8\frac{T'H'}{\bar{T}\bar{H}} + 12\frac{T'H'^2}{\bar{T}\bar{H}^2} + \\ 8\frac{T'H'^3}{\bar{T}\bar{H}^3} + 2\frac{T'H'^4}{\bar{T}\bar{H}^4} + \frac{T'^2}{\bar{T}^2} + 4\frac{T'^2H'}{\bar{T}^2\bar{H}} + \\ 6\frac{T'^2H'^2}{\bar{T}^2\bar{H}^2} + 4\frac{T'^2H'^3}{\bar{T}^2\bar{H}^3} + \frac{T'^2H'^4}{\bar{T}^2\bar{H}^4} \end{array} \right] \quad (3.40)$$

Equation 3.40 can be reformed by applying the definition of expectation in the stochastic equation as:

$$E(P^2) = (0.49)^2 E^2(T) E^4(H) \left[\begin{array}{c} 1 + 4\frac{E(H')}{E(H)} + \\ 6\frac{E(H'^2)}{E^2(H)} + 4\frac{E(H'^3)}{E^3(H)} + \frac{E(H'^4)}{E^4(H)} + \\ 2\frac{E(T')}{E(T)} + 8\frac{E(T'H')}{E(T)E(H)} + \\ 12\frac{E(T'H'^2)}{E(T)E^2(H)} + 8\frac{E(T'H'^3)}{E(T)E^3(H)} + \\ 2\frac{E(T'H'^4)}{E(T)E^4(H)} + \frac{E(T'^2)}{E^2(T)} + \\ 4\frac{E(T'^2H')}{E^2(T)E(H)} + 6\frac{E(T'^2H'^2)}{E^2(T)E^2(H)} + \\ 4\frac{E(T'^2H'^3)}{E^2(T)E^3(H)} + \frac{E(T'^2H'^4)}{E^2(T)E^4(H)} \end{array} \right] \quad (3.41)$$

Equation 3.41 has the following basic expression, since the estimated value of the disruption perturbation is equal to zero:

$$E(P^2) = (0.49)^2 E^2(T) E^4(H) \left[\begin{aligned} &1 + 6 \frac{E(H'^2)}{E^2(H)} + 4 \frac{E(H'^3)}{E^3(H)} + \\ &\frac{E(H'^4)}{E^4(H)} + 8 \frac{E(T'H')}{E(T)E(H)} + \\ &12 \frac{E(T'H'^2)}{E(T)E^2(H)} + 8 \frac{E(T'H'^3)}{E(T)E^3(H)} + \\ &2 \frac{E(T'H'^4)}{E(T)E^4(H)} + \frac{E(T'^2)}{E^2(T)} + \\ &4 \frac{E(T'^2 H')}{E^2(T)E(H)} + 6 \frac{E(T'^2 H'^2)}{E^2(T)E^2(H)} + \\ &4 \frac{E(T'^2 H'^3)}{E^2(T)E^3(H)} + \frac{E(T'^2 H'^4)}{E^2(T)E^4(H)} \end{aligned} \right] \quad (3.42)$$

Phrases in the parenthesis can be simply described by β as:

$$\beta = \left[\begin{aligned} &1 + 6 \frac{E(H'^2)}{E^2(H)} + 4 \frac{E(H'^3)}{E^3(H)} + \\ &\frac{E(H'^4)}{E^4(H)} + 8 \frac{E(T'H')}{E(T)E(H)} + \\ &12 \frac{E(T'H'^2)}{E(T)E^2(H)} + 8 \frac{E(T'H'^3)}{E(T)E^3(H)} + \\ &2 \frac{E(T'H'^4)}{E(T)E^4(H)} + \frac{E(T'^2)}{E^2(T)} + \\ &4 \frac{E(T'^2 H')}{E^2(T)E(H)} + 6 \frac{E(T'^2 H'^2)}{E^2(T)E^2(H)} + \\ &4 \frac{E(T'^2 H'^3)}{E^2(T)E^3(H)} + \frac{E(T'^2 H'^4)}{E^2(T)E^4(H)} \end{aligned} \right] \quad (3.43)$$

Here,

$E(H'^3)$: the skewness of a distribution

$E(H'^4)$: the kurtosis of a distribution

They are also expressed by the following descriptions:

$$E(H'^3) = E[(H - \bar{H})^3] \quad (3.44)$$

$$E(H'^4) = E[(H - \bar{H})^4] \quad (3.45)$$

After all, equation 3.43 can be edited in the following form:

$$\beta = \left[\begin{aligned} &1 + 6 \frac{\sigma_H^2}{E^2(H)} + 4 \frac{E[(H - \bar{H})^3]}{E^3(H)} + \\ &\frac{E[(H - \bar{H})^4]}{E^4(H)} + 8 \frac{r_{T,H} \sigma_T \sigma_H}{E(T)E(H)} + \\ &12 \frac{r_{T,H^2} \sigma_T \sigma_{H^2}}{E(T)E^2(H)} + 8 \frac{r_{T,H^3} \sigma_T \sigma_{H^3}}{E(T)E^3(H)} + \\ &2 \frac{r_{T,H^4} \sigma_T \sigma_{H^4}}{E(T)E^4(H)} + \frac{\sigma_T^2}{E^2(T)} + \\ &4 \frac{r_{T^2,H} \sigma_{T^2} \sigma_H}{E^2(T)E(H)} + 6 \frac{r_{T^2,H^2} \sigma_{T^2} \sigma_{H^2}}{E^2(T)E^2(H)} + \\ &4 \frac{r_{T^2,H^3} \sigma_{T^2} \sigma_{H^3}}{E^2(T)E^3(H)} + \frac{r_{T^2,H^4} \sigma_{T^2} \sigma_{H^4}}{E^2(T)E^4(H)} \end{aligned} \right] \quad (3.46)$$

When the necessary terms are inserted in equation 3.41, $E(P^2)$ is expressed as follows:

$$E(P^2) = \beta(0.49)^2 E^2(T)E^4(H) \quad (3.47)$$

After substituting equation 3.36 and equation 3.47 into equation 3.35, the following definition is obtained:

$$Var(P) = \beta(0.49)^2 E^2(T)E^4(H) - \alpha^2(0.49)^2 E^2(T)E^4(H) \quad (3.48)$$

Finally, equation 3.48 can be summarized as follows:

$$Var(P) = (\beta - \alpha^2)(0.49)^2 E^2(T)E^4(H) \quad (3.49)$$

This final equation, which can be developed for the possible probability distribution function, corresponds to the general definition of the variance resulted from the perturbation of wave period and SWH.

3.3.2 Wave power derivation by classical method

The expected value of both sides of equation 3.19 can be obtained in order to compute the wave power using the classical method as:

$$E(P) = 0.49E(T)E(H^2) \quad (3.50)$$

This equation can be used in the estimation of wave power by classical method. In addition, description should be made to $E(P^2)$ and $E^2(P)$ for the calculation of the

general variance expression in the classical method. $E(P^2)$ is indicated after taking the square and the expectation of equation 3.50 as:

$$E(P^2) = (0.49)^2 E(T^2) E(H^4) \quad (3.51)$$

$E^2(P)$ can be mentioned on the basis of the expectation and the square of both sides equation 3.50, respectively as:

$$E^2(P) = (0.49)^2 E^2(T) E^2(H^2) \quad (3.52)$$

After the necessary mathematical operations are done, the variance equation developed for the classical method is obtained as follows:

$$Var(P) = (0.49)^2 [E(T^2)E(H^4) - E^2(T)E^2(H^2)] \quad (3.53)$$

This equation defines the general representation of the variance developed for the estimation of the classical wave power formulation.



4. STUDY AREA AND DATASET

In this section of the thesis, the research regions for which current and wave power potentials are estimated are examined.. Current power potentials in the Dardanelles Strait and the northern Bosphorus have been identified. Moreover, the potential for wave power was studied at the Antalya and Mersin sites on Turkey's southern coast.

4.1 The Dardanelles Strait

The Dardanelles Strait is a water passage which is located between the Aegean Sea in the southwest and the Marmara Sea in the northeast. The width of the Dardanelles Strait ranges from 1.2 to 7 km, the tightest part of which is situated in a sharp bend named the Nara Pass, about 25 km east of its Aegean Sea connection and the mean depth is 55 m; the maximum depth is more than 100 m (Yaltırak et al., 2000). The hydrography of the Dardanelles Strait is regulated by a two-layer structure of currents. The two-layer stratification through the Turkish Straits are forced by the differences in density between the Black Seas and the Aegean Seas and the level difference between these seas (Jarosz et al., 2012). On the other hand, the disparity in the sea level between the Sea of Marmara and the Aegean Sea is rarely greater than 10 cm; thus, the transfer of water across the Dardanelles is mostly motivated by the variations in the density of the water masses of the adjacent seas (Stashchuk and Hutter, 2001). The currents of the Aegean are always heavier than the upper layer of the Marmara Sea, sinking under the surface of the Dardanelles and passing towards the bottom of the Dardanelles Strait through the Marmara Sea (Beşiktepe, 2003). Moreover, the low salinity streams of the Black Sea, caused by heavy precipitation and run-off over evaporation, are transferred to the Mediterranean through the Turkish Straits System (TSS) as an upper layer flow (Ünlülata et al., 1990). The two separate volumes of water are divided by a strong pycnocline at a depth of 25 m (Beşiktepe et al., 1993). Ünlülata et al. (1990) reported that, Black Sea water with salinity ~17.8 ppt, which passes across the Bosphorus as an upper layer, reaches the Sea of Marmara with salinity ~19.4 ppt. Its salinity rises by about 6 ppt as it passes the Marmara Sea. After a rise of another 4 ppt, it leaves the Dardanelles with a salinity of 29.62 ppt. Nevertheless, the Aegean

water with a salinity of 38.9 ppt, which joins the Dardanelles, crosses the straits with very few variations in its salinity. A decrease of about 2 ppt is noticed in the salinity of this steam in the Marmara Sea. After being reduced by another 2 ppt in movement across the Bosphorus, the Mediterranean waters reach the Black Sea with about 35 ppt salinity. The schematic representation of the two-layer structure of the Dardanelles is shown in Figure 4.1.

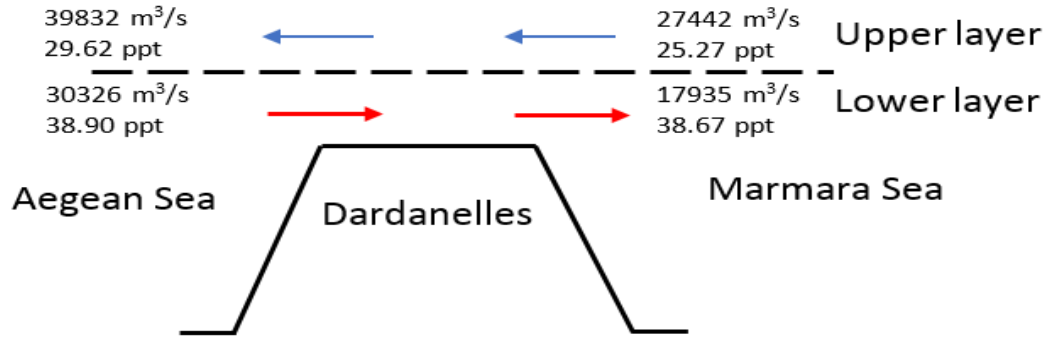


Figure 4.1 : The two-layer structure of the Dardanelles Strait.

In this thesis, continuous current-speed measurements near the Dardanelles Strait have been used. The geographical coordinates of the buoy station are 40.04 N latitude and 26.04 E longitude, indicated by a map position mark in Figure 4.2.



Figure 4.2 : Location of the study area and the measurement buoy.

The observations have been carried out by the Turkish State Meteorological Service (<https://www.mgm.gov.tr/>) and the measurement buoy is explicitly placed out of the shipping route so as not to disturb traffic in the strait. Current speed observations near the southern exit of the Dardanelles are obtained hourly and vertically at a depth level of 5 m from below to the surface of the strait until 50 m. The period of the data source is 3 years and the dataset was obtained between January 2016 and December 2018. The range and parameters of current speed are shown in Table 4.1.

Table 4.1 : Current speed values along the water depth in the Dardanelles Strait.

Water Level	Period	Current Speed (m/s)					
		Minimum	Average	Maximum	Standard Deviation	Skewness	Kurtosis
H-5	Jan 2016- Dec 2018	0.01	0.33	4.95	0.21	3.84	50.19
H-10	Jan 2016- Dec 2018	0.01	0.34	3.62	0.22	2.48	18.85
H-15	Jan 2016- Dec 2018	0.01	0.31	3.68	0.23	2.65	18.69
H-20	Jan 2016- Dec 2018	0.01	0.28	3.86	0.24	2.98	22.60
H-25	Jan 2016- Dec 2018	0.01	0.26	3.33	0.23	2.79	18.31
H-30	Jan 2016- Dec 2018	0.01	0.24	3.65	0.23	3.63	28.02
H-35	Jan 2016- Dec 2018	0.01	0.22	4.21	0.23	4.21	37.54
H-40	Jan 2016- Dec 2018	0.01	0.22	4.35	0.24	4.58	39.38
H-45	Jan 2016- Dec 2018	0.01	0.21	4.74	0.26	5.66	54.03
H-50	Jan 2016- Dec 2018	0.01	0.22	4.71	0.27	5.64	54.39

Here, H-5, H-10, H-15, H-20, H-25, H-30, H-35, H-40, H-45 and H-50 are water depths of 5 m, 10 m, 15 m, 20 m, 25 m, 30 m, 35 m, 40 m, 45 m and 50 m from the water surface to the bottom, respectively. Also, standard deviation represents the standard deviation. The statistical properties of current speed are assessed using the following equations (Wang et al., 2016):

$$\bar{x} = \frac{1}{n} \sum_{i=1}^n x_i \quad (4.1)$$

$$STD = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (x_i - \bar{x})^2} \quad (4.2)$$

$$\hat{\gamma}_3 = \frac{1}{(T-1)} \sum_{t=1}^T (X_T - \bar{X})^3 / s^3 \quad (4.3)$$

$$\hat{\gamma}_4 = \frac{1}{(T-1)} \sum_{t=1}^T (X_T - \bar{X})^4 / s^4 - 3 \quad (4.4)$$

Here,

$\bar{x}$: represents the mean value

$\hat{\gamma}_3$: indicates skewness, which is an expression of the asymmetry of the probability distribution of a real-valued random variable by its mean.

$\hat{\gamma}_4$: denotes kurtosis which defines the shape of the probability distribution

The positive skewness explains that the current speed distribution has longer or thicker tails on the right side than on the left and that this type of distribution is assumed to be right-skewed, right-skewed or right-skewed. The distribution of positive excess Kurtosis is referred to as leptokurtic and the leptokurtic distribution has fatter tails with a wide kurtosis relative to either the normal distribution or the exponential distribution. A careful investigation of current speeds is required for a reliable estimation of potential energy production. As a result, current speed classification has been formed, and the range of current speeds can be observed in Figures 4.3 to 4.12.

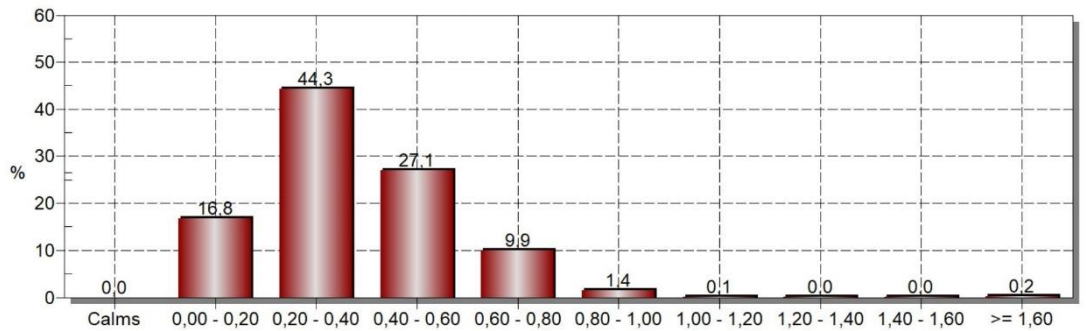


Figure 4.3 : Current class of the Dardanelles Strait at H-5.

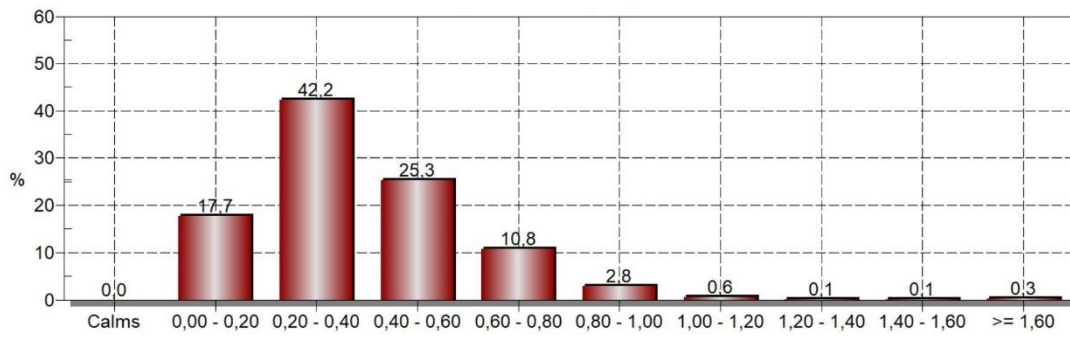


Figure 4.4 : Current class of the Dardanelles Strait at H-10.

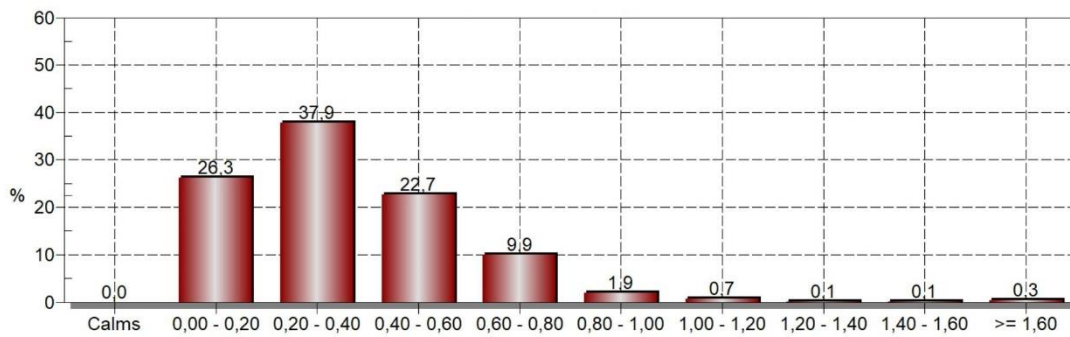


Figure 4.5 : Current class of the Dardanelles Strait at H-15.

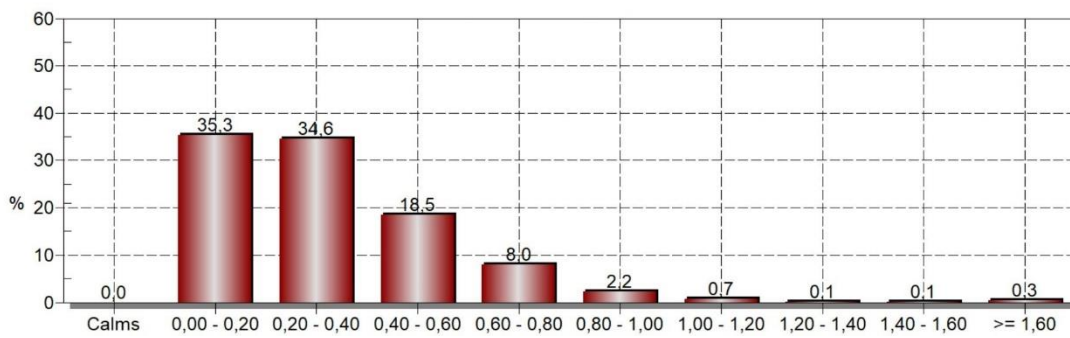


Figure 4.6 : Current class of the Dardanelles Strait at H-20.

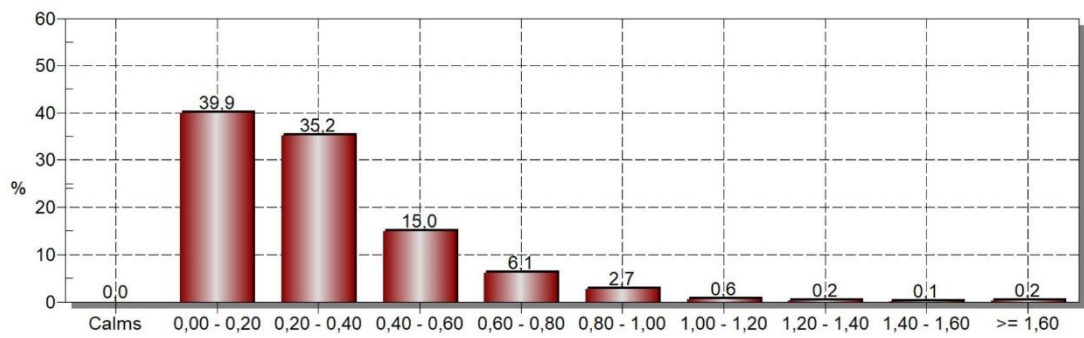


Figure 4.7 : Current class of the Dardanelles Strait at H-25.

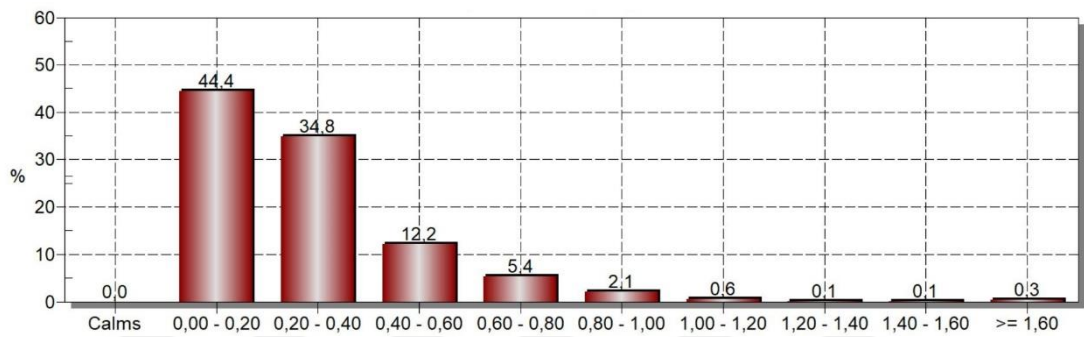


Figure 4.8 : Current class of the Dardanelles Strait at H-30.

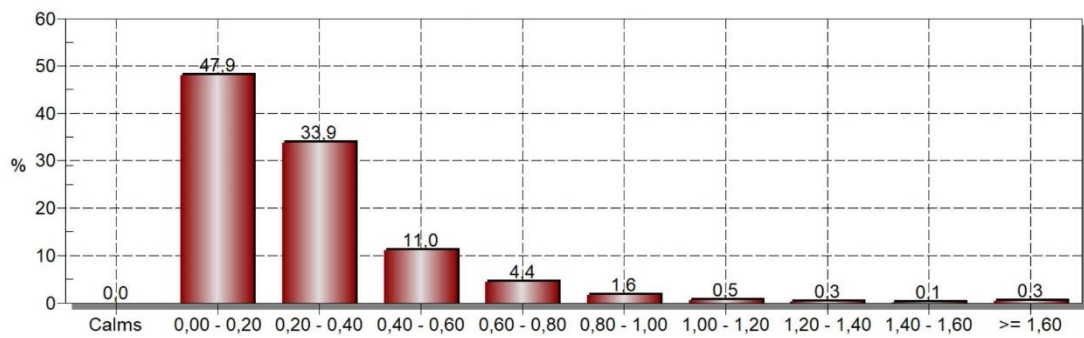


Figure 4.9 : Current class of the Dardanelles Strait at H-35.

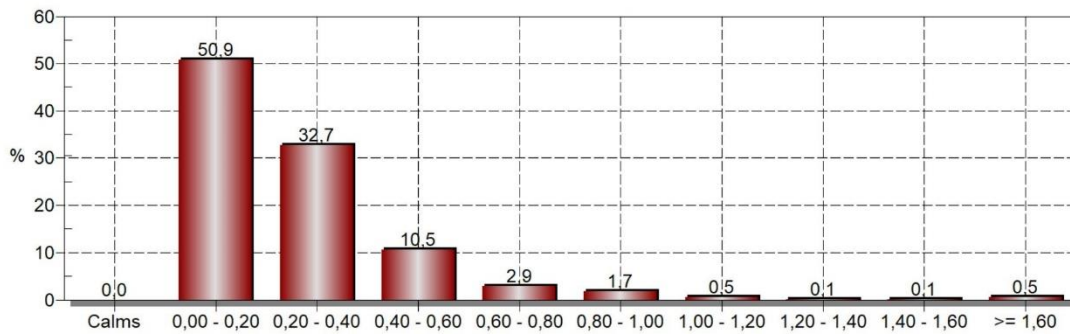


Figure 4.10 : Current class of the Dardanelles Strait at H-40.

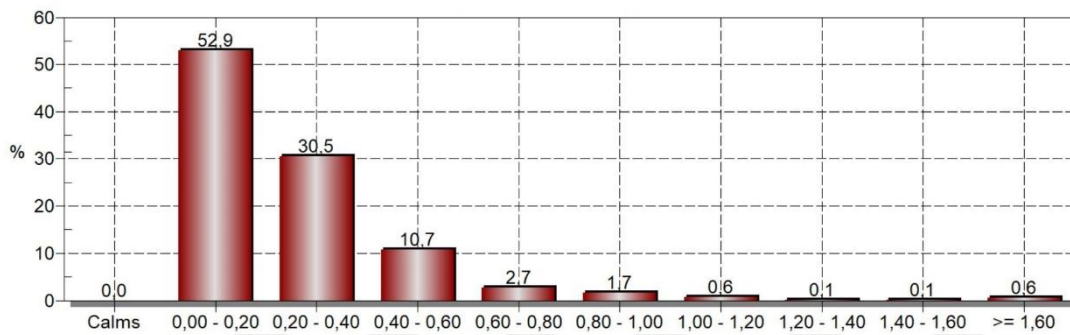


Figure 4.11 : Current class of the Dardanelles Strait at H-45.

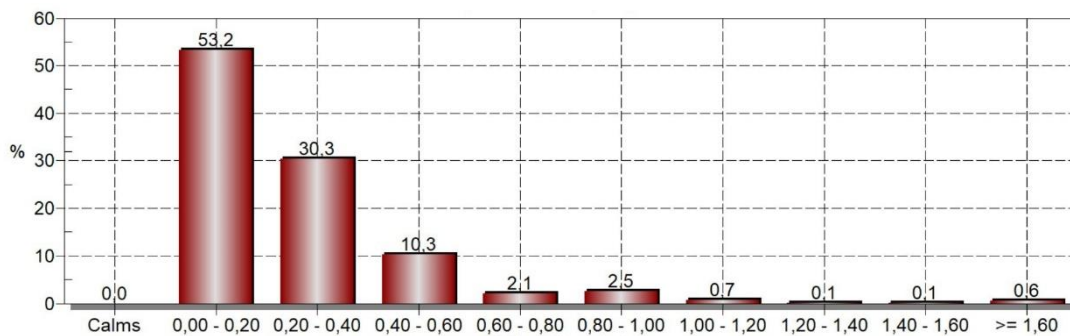


Figure 4.12 : Current class of the Dardanelles Strait at H-50.

When the upper layer currents of the Dardanelles Strait are examined, Figure 4.3 shows that 16.8 % H-5 speeds occur between 0.00 and 0.20 m/s. In addition, 44.3 % of current velocity range between 0.20-0.40 m/s. The remaining 38.9 % is composed of current speeds greater than 0.40 m/s. Figure 4.4 demonstrates that at H-10, 17.7 % of the current speed is between 0.00-0.20 m/s and 42.2 % of the current velocity is between 0.20-0.40 m/s. The current speed with in 40.1 % section is more than 0.40

m/s. Figure 4.5 displays that 26.3 % of the current speed at H-15 is between 0.00-0.20 m/s and 37.9 % of the current speed is between 0.20-0.40 m/s. The current speed in the 35.8 % part is more than 0.40 m/s. Furthermore, Figure 4.6 (H-20) indicates that 35.3 % of the current speed remains between 0.00-0.20 m/s and 34.6 % of the current speed remains between 0.20-0.40 m/s. The 30.1 % portion's current speed is more than 0.40 m/s.

When the Dardanelles Strait's bottom layer currents are analyzed, according to Figure 4.7 (H-25), 39.9 % H-25 speeds are between 0.00 and 0.20 m/s, whereas 35.2 % speeds are between 0.20 and 0.40 m/s. The other 24.9 % is formed of current speeds greater than 0.40 m/s. Figure 4.4 depicts that at H-30, 44.4 % of the current speed exists between 0.00-0.20 m/s and 34.8 % of the current velocity exists between 0.20-0.40 m/s. The current speed in the 20.8 % portion is more than 0.40 m/s. Figure 4.9 shows that 47.9 % of the current speed at H-15 is between 0.00-0.20 m/s and 33.9 % of the current speed is between 0.20-0.40 m/s. The current speed in the 18.2 % part is more than 0.40 m/s. Also, Figure 4.10 (H-40) indicates that 50.9 % of the current speed remains between 0.00-0.20 m/s and 32.7 % of the current speed remains between 0.20-0.40 m/s. The 16.4 % portion's current speed is more than 0.40 m/s. Furthermore, Figure 4.11 (H-45) demonstrates that 52.9 % H-25 speeds are between 0.00 and 0.20 m/s and 30.5 % are between 0.20 and 0.40 m/s. The rest 16.6 % is composed of current speeds higher than 0.40 m/s. Finally, Figure 4.12 (H-50) indicates that 53.2 % of the current speed remains between 0.00-0.20 m/s and 30.3 % remains between 0.20-0.40 m/s. The current speed of the 16.5 % part is higher than 0.40 m/s.

4.2 The Northern Bosphorus

The Bosphorus Strait, placed between both the Marmara Sea and the Black Sea, is part of the Turkish Strait System (TSS). The TSS is distinctive in its geographical characteristics, linking the two large water bodies and the medium-sized intercontinental canal system of the Marmara Sea by means of the Dardanelles and Bosphorus straits, which are among the few narrowest and longest straits in the European zone (Özsoy, 2016). Although the scale of the region is much smaller than the adjacent seas, the TSS is an ocean theater where extreme non-linear and turbulent dynamics arise under circumstances of heavy stratification, forming the fundamental event characteristics of the system (Sannino et al., 2015).

As a part of TSS, the Bosphorus Strait is a long (nearly 30 km), narrow (<3,0 km) and shallow (<80 m) strait. This region is also a significant maritime corridor in the world, with an average of 132 ships moves every day (Akten, 2003). Moreover, the Bosphorus is the main strait of this system as a result of the expected maximum-exchange regime, formed by flow movements over a sill close to the access of the Black Sea and by deceleration in the southern part of the system (Sözer and Özsoy, 2017). The northern and southern sills regulate the lower and upper layers, which cause maximum interaction and are periodically influenced by significant hydrological processes (Oguz et al., 1990). Furthermore, it has been observed that the interaction is often partly formed by friction (Gregg and Özsoy, 2002). Hence, in the Bosphorus, powerful northerly winds often lead lower layer blockage throughout high sea rates in the Black Sea, while strong southerly winds lead upper layer blockage (so-called Orkoz) during low sea rates in the area (Özsoy and Altıok, 2016).

The other unique features of the Bosphorus Strait is the two-layer current and density variation as the less saline Black Sea surface water is transferred to the surface of the Marmara Sea, while the underlying lower water from the Marmara Sea, which originates from the Mediterranean Sea, is transported in the reverse direction to the Black Sea (Yuce, 1990). Thus, the Bosphorus Strait is composed of two contrary currents: the upper layer of the Black Sea with a salinity varying from 18 to 20 psu and the lower layer of the Aegean Sea with a salinity varying from 36 to 38 psu (Oguz, 2005).

Continuous upper layer (0-25 m) current observations close to the inlet of the Bosphorus Strait were considered for this thesis. The measurement station's proximity to the Black Sea's south-west shore also allows for the assessment of coastal current power. The period of the data collection was 12 months and the dataset was obtained between September 2015 and September 2016. Current speed and direction observations were collected hourly at a resolution of 5m from the water surface to the bottom, at a depth of 25m. The measurement process was operated by the Turkish Meteorological Service and the geographical location of the measurement buoy station which is mentioned with map position mark is 41.24 N latitude and 28.42 E longitude as shown in Figure 4.13.



Figure 4.13 : Position of the study area and the measurement buoy.

The current speed level and parameters are displayed in Table 4.2.

Table 4.2 : Current speed values along the water depth in the vicinity of the northern Bosphorus.

Water Level	Period	Current Speed (m/s)					
		Minimum	Average	Maximum	Standard deviation	Skewness	Kurtosis
H-5	Sep 2015- Sep 2016	0.001	0.183	3.526	0.126	4.392	76.254
H-10	Sep 2015- Sep 2016	0.002	0.176	3.554	0.127	4.536	76.438
H-15	Sep 2015- Sep 2016	0.002	0.175	3.544	0.138	4.578	64.586

Table 4.2 (continued): Current speed values along the water depth in the vicinity of the northern Bosphorus.

Water Level	Period	Current Speed (m/s)					
		Minimum	Average	Maximum	Standard deviation	Skewness	Kurtosis
H-20	Sep 2015-Sep 2016	0.002	0.196	3.559	0.185	5.048	47.045
H-25	Sep 2015-Sep 2016	0.001	0.243	4.401	0.285	5.518	45.875

For more comprehensive study, the average current speed statistics for all water levels are displayed on a monthly scale in Table 4.3. When Table 4.3 is analyzed depending on the months for all water levels, the lowest average current speed along the water depth is 0.148 m/s in June and the maximum mean current speed is 0.36 m/s in September.

Table 4.3 : Monthly current speed analysis in the vicinity of the northern Bosphorus.

Water Level	Period	Monthly Current Speed (m/s)											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
H-5	Sep 2015-Sep 2016	0.19	0.22	0.23	0.12	0.19	0.12	0.15	0.19	0.28	0.27	0.15	0.18
H-10	Sep 2015-Sep 2016	0.17	0.19	0.19	0.12	0.16	0.14	0.15	0.18	0.31	0.26	0.15	0.17
H-15	Sep 2015-Sep 2016	0.15	0.18	0.17	0.13	0.15	0.15	0.15	0.19	0.33	0.25	0.14	0.16
H-20	Sep 2015-Sep 2016	0.16	0.22	0.19	0.16	0.17	0.15	0.16	0.2	0.4	0.26	0.16	0.17
H-25	Sep 2015-Sep 2016	0.18	0.32	0.26	0.26	0.26	0.18	0.16	0.21	0.48	0.28	0.19	0.19

The hourly average current speed is presented in Figure 4.14. According to Figure 4.14, the lowest annual average current speed was between 21.00 and 24.00 (midnight) with a value of 0.18 m/s, while the highest speed was between 12.00 and 15.00 (midday) with a value of 0.212 m/s.

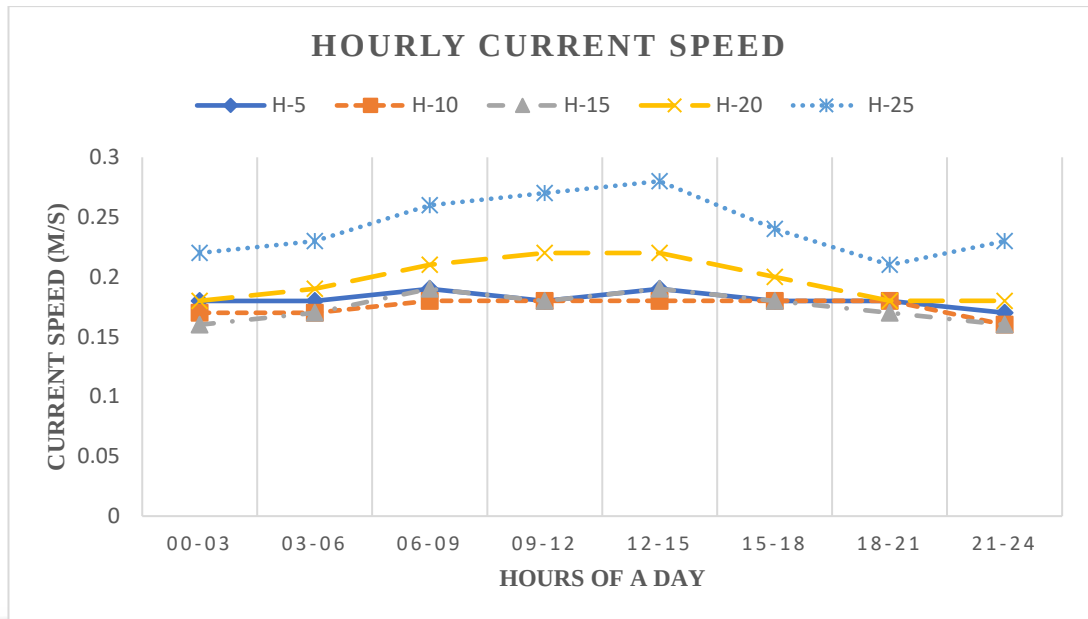


Figure 4.14 : Hourly current speed graph in the vicinity of the northern Bosphorus.

For the reliable calculation of possible energy production, a detailed analysis of current speeds is necessary. For this reason, the classification of current speeds has been developed and the variation of current speeds can be seen in Figures 4.15 to 4.19.

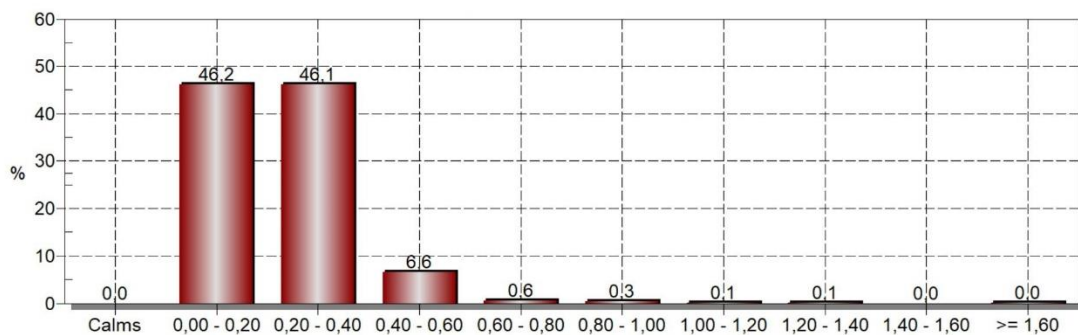


Figure 4.15 : Current class in the vicinity of the northern Bosphorus at H-5.

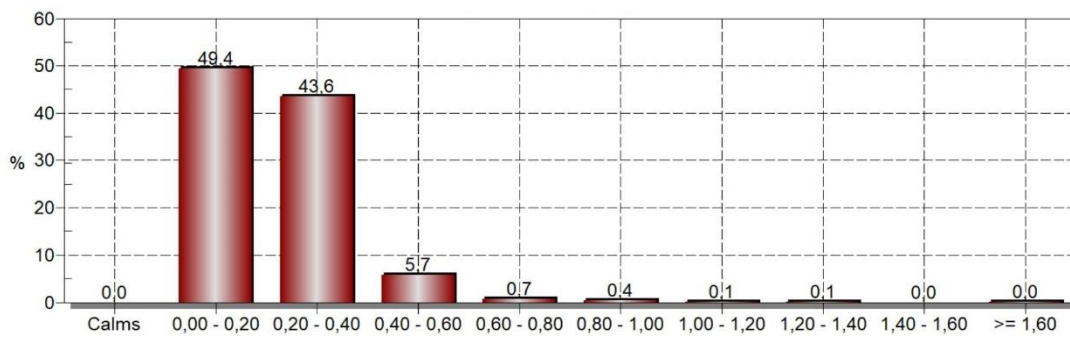


Figure 4.16 : Current class in the vicinity of the northern Bosphorus at H-10.

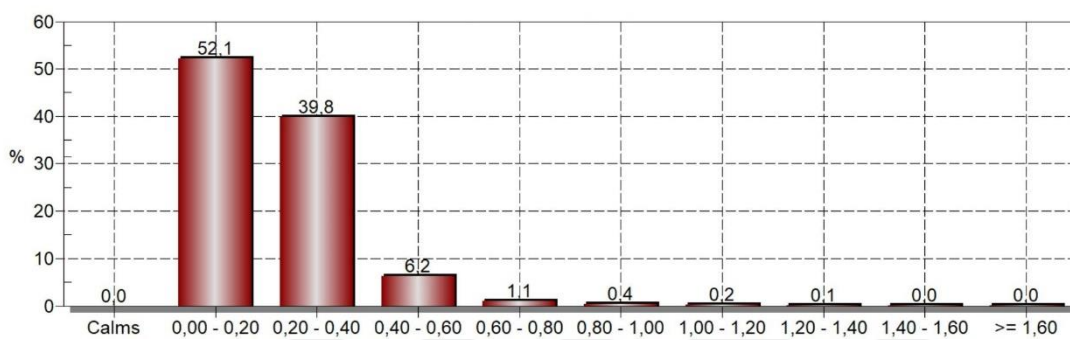


Figure 4.17 : Current class in the vicinity of the northern Bosphorus at H-15.

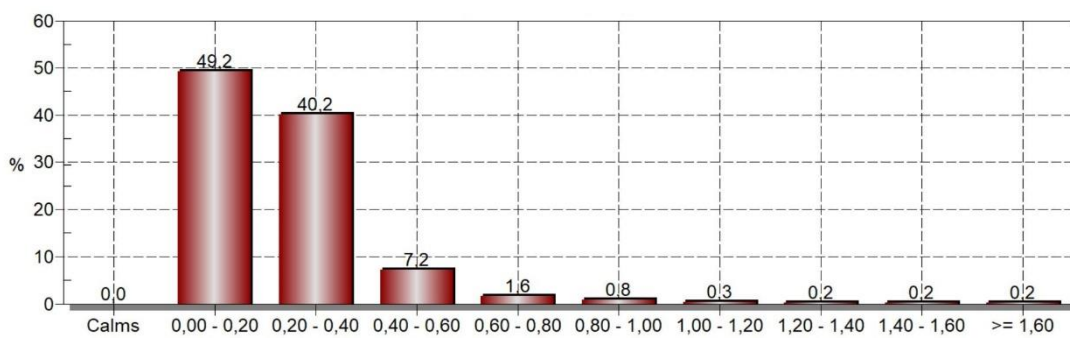


Figure 4.18 : Current class in the vicinity of the northern Bosphorus at H-20.

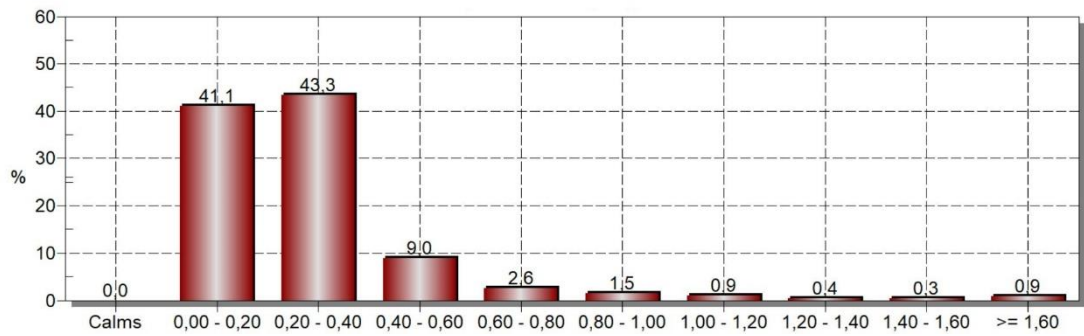


Figure 4.19 : Current class in the vicinity of the northern Bosphorus at H-25.

It can be observed in Figure 4.15 that 46.2% of current H-5 speeds appear between 0.00 and 0.20 m/s. Furthermore, 46.1% of current speeds are between 0.20-0.40 m/s. The remaining 7.7% consists of current speed value higher than 0.40 m/s. At H-10, it is shown in Figure 4.16 that 49.4% of the current speed exist between 0.00-0.20 m/s and 43.6% of the current velocity is between 0.20-0.40 m/s. The 7% section has a current speed higher than 0.40 m/s. Figure 4.17 demonstrates that 52.6 % of the current speed is still between 0.00-0.20 m/s at H-15 and 39.8% of the current speed remain between 0.20-0.40 m/s. The 7.6% portion has a current speed of more than 0.40 m/s. Additionally, Figure 4.18 (H-20) displays that 49.2% of the current speed is still between 0.00-0.20 m/s and 40.2% of the current speed stays between 0.20-0.40 m/s. The current speed of the 10.4% portion is higher than 0.40 m/s. Consequently, Figure 4.19 (H-25) indicates that 41.1% of current H-25 speeds are between 0.00 and 0.20 m/s and 43.3% of current speeds are between 0.20 and 0.40 m/s. The remaining 15.6% consists of a current speed value greater than 0.40 m/s.

4.3 The South Coast of Turkey (Antalya and Mersin)

The Mediterranean Sea (MS) is positioned at the border of three ordinary weather systems: the oceanic climate of the North-East Atlantic Ocean, dominated by both the location and motion of the Azores High Pressure Field and low-pressure patterns passing over the North-East Atlantic Ocean; the warm continental system originating from the deserts of North Africa; and the continental system aligned with the Eurasian continent and South Asia (Queffeulou and Bentamy, 2007). The coastline of the MS is incredibly long and chaotic and is predicted to be about 46,000 km long, of which almost 19,000 km are islands (UNEP/MAP, 2012). The shallowest section of the whole basin (50 m) is in the northern Adriatic, whereas the maximum depth (5121 m)

is in the North Matapan-Vavilov Trench, Ionian Sea (Danovaro et al., 2010). Moreover, the MS is separated into western and central-eastern basins, divided by the Sicilian Strait. The continental shelf of the eastern Mediterranean begins with the wide expanses of the Nile Delta and southern Israel, the shelf narrows to the north and is comparably steep and tight between Lebanon and Anatolia (Neev et al., 1976). The western Mediterranean region has a smooth seafloor, whereas the eastern one has a unique topography of the seabed (Anthony et al., 2014).

The water circulation of the MS is extremely complicated: the low-salinity surface waters exist from the Atlantic and transform into intermediary waters in the Eastern Mediterranean while the denser deep-Mediterranean sea waters flow into the Atlantic Ocean in the reverse direction (Danovaro et al., 2010). When the Atlantic waters flow eastwards, they get warmer than usual and the warmth has two contrasting impacts on the physical characteristics of the water: on the one side, the warmer water gets lighter; on the other side, the elevated temperature rises the evaporation, the salinity increases and the water gets denser (Galili et al., 2017). Mediterranean currents (with the exception of the Mid Mediterranean one) pass through the distal continental shelf and the upper slope, mixing with the longshore current originating from waves breaking through the shoreline (Rosentraub and Brenner, 2007). In the eastern Mediterranean, the longshore currents are the prevailing sediment movement system where the wave-induced current is very powerful during sea storms, and the influence of regional differences in wind direction and strength during these storms is insignificant (Galili et al., 2017).

In terms of wave energy supply, the Mediterranean Sea indicates an intermediate stage between the open seas and the restricted small-fetch basins, including the Black Sea or the Baltic Sea (Besio et al., 2016). The Mediterranean waves, which are short-crested and strongly reliant on the presence of wind forces, are much weaker than the Atlantic waves, as limited fetch distances in the region prevent waves from moving long ranges without significant dissipation (Soukissian et al., 2017). In addition, the Northern Hemisphere storm path provides a separate branch which passes the Mediterranean zone with cyclogenesis regions (mostly induced by orographic impacts) in the western Mediterranean and cyclolysis regions in the central and eastern Mediterranean (Lionello and Sanna, 2005; Buzzi and Tibaldi, 1978). Furthermore, as the Mediterranean is covered by a complicated structure of mountain chains, with crests varying from 1,500 m to 4,800 m, such complicated orography has the impact

of distorting wide synoptic systems and creating regional winds of continuous velocity (e.g. Bora, Mistral-Tramontana, Etesian winds) that, in some parts of the area, blow almost all year round (Lionello and Sanna, 2005). Thus, the structures of wave systems are controlled by such wind regimes.

In this thesis, the hourly data of the wave period, the SWH and the wave direction, obtained from the two buoy stations operated by the Turkish State Meteorological Service on the south coast of Turkey, were utilized to analyze the wave capacity of the south coast of Turkey. The period of the dataset is 12 months and the data were obtained between 1 April 2015 and 1 April 2016. Details on the buoy stations are identified in Table 4.4.

Table 4.4 : Details on the wave measurement buoys.

Station	Buoy Number	Latitude	Longitude	Energy Supply	Connection Type
Antalya	17393	36°43'00" N	31°01'00" E	Solar Energy	GSM/GPRS
Mersin	17394	36°04'50" N	33°49'50" E	Solar Energy	GSM/GPRS

In addition, the position map and the locations of the stations discussed in this thesis are displayed in Figure 4.20.



Figure 4.20 : Position of the measurement buoys.

As the analyses of other researches have demonstrated that the wave period and the SWH have key impact on wave power, the monthly features, including the average wave period and the SWH, have been analyzed. The findings of the analysis are displayed in Table 4.5 and Table 4.6.

Table 4.5 : The statistical characteristics of wave period between April, 2015 and April, 2016.

Station	Period	Wave Period (s)					
		Minimum	Average	Maximum	Standard deviation	Skewness	Kurtosis
Antalya	Apr 2015-Apr 2016	2	4.61	14.3	1.81	0.87	1.33
Mersin	Apr 2015-Apr 2016	2	5.58	15.4	1.93	1	2.07

Table 4.6 : The statistical characteristics of SWH during April, 2015 and April, 2016.

Station	Period	SWH (m)					
		Minimum	Average	Maximum	Standard deviation	Skewness	Kurtosis
Antalya	Apr 2015-Apr 2016	0.04	0.43	4.09	0.4	3.14	14.43
Mersin	Apr 2015-Apr 2016	0.01	0.73	4.85	0.47	1.79	5.77

In addition to the main characteristics, the deviations in the wave period and the SWH contain useful information on the generation of wave power. Thus, the monthly fluctuations of the mean wave period and the SWH collected from the data sets at two different stations are displayed by using daily average values in Figure 4.21 to 4.24.

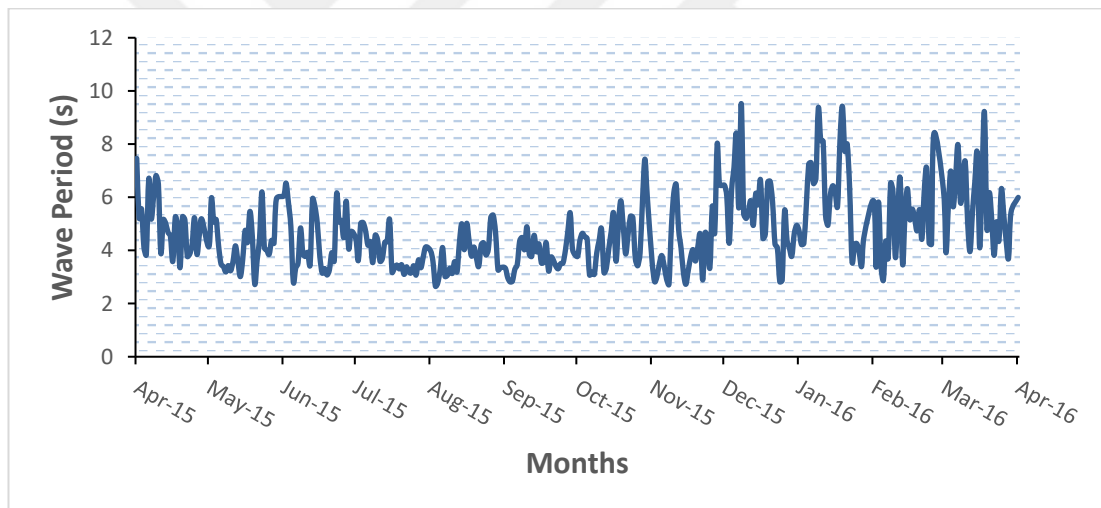


Figure 4.21 : Monthly variation of the wave period at Antalya station.

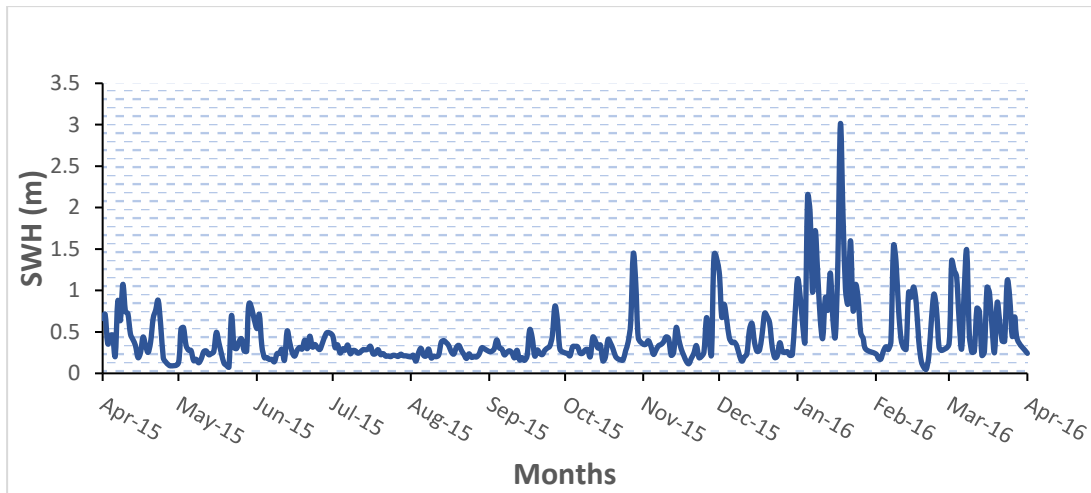


Figure 4.22 : Monthly variation of the SWH at Antalya station.

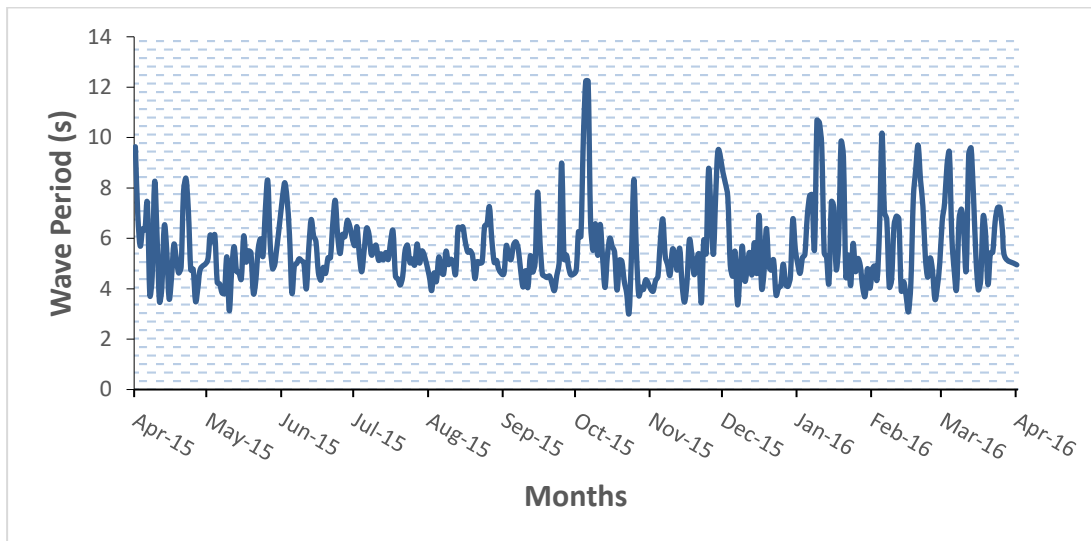


Figure 4.23 : Monthly variation of the wave period at Mersin station.

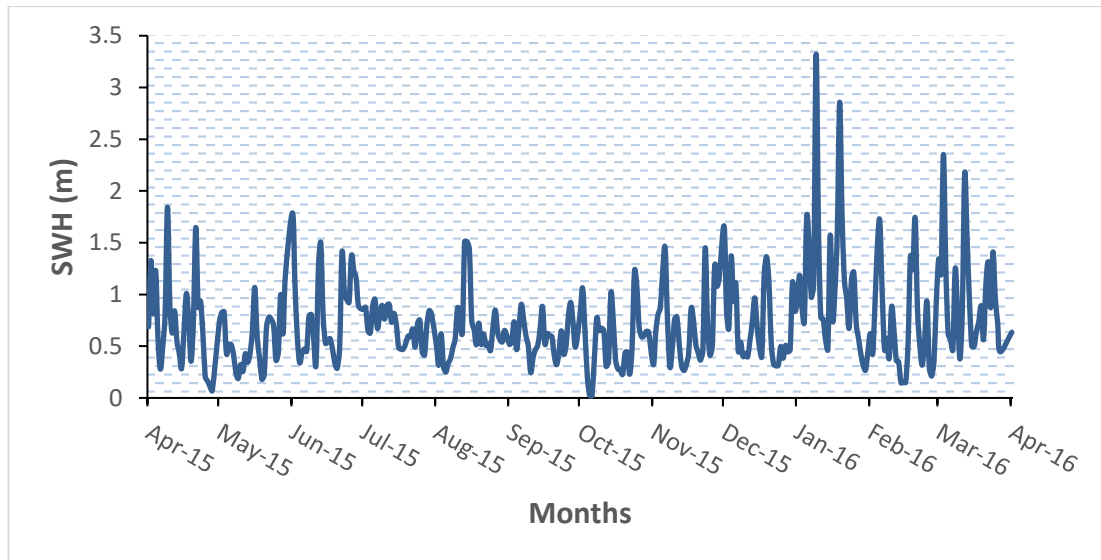


Figure 4.24 : Monthly variation of the SWH at Mersin station.

The average maximum monthly mean wave period occurs between January and February, and the minimum mean wave period is estimated between July and August at both stations. Furthermore, the average maximum SWHs exist between January and February at both stations. Also, the lowest SWHs are usually viewable at both stations between July and August.



5. APPLICATIONS AND DISCUSSIONS

This part of the thesis includes applications and discussions.

5.1 The Dardanelles Strait

5.1.1 Upper layer

In this part of the study, the upper layer currents of the Dardanelles Strait are examined. First, current roses are generated and examined in this context. Then, the distribution that corresponded to the current velocities is determined. Following the determination of the distribution corresponding to the current velocities, details about the related distribution is provided. After that, the perturbation method is used to determine the current power density formulas by using the generalized gamma distribution (GGD) that describe the upper layer current velocities. Finally, the power potential of the Dardanelles Strait's upper layer current is estimated by using equations which are derived by perturbation process.

5.1.1.1 Current roses

In order to establish the overall current direction, the current rose diagram has been generated. The current direction intensity over the time span (2016-2018) is mentioned in from Figure 5.1 to Figure 5.4.

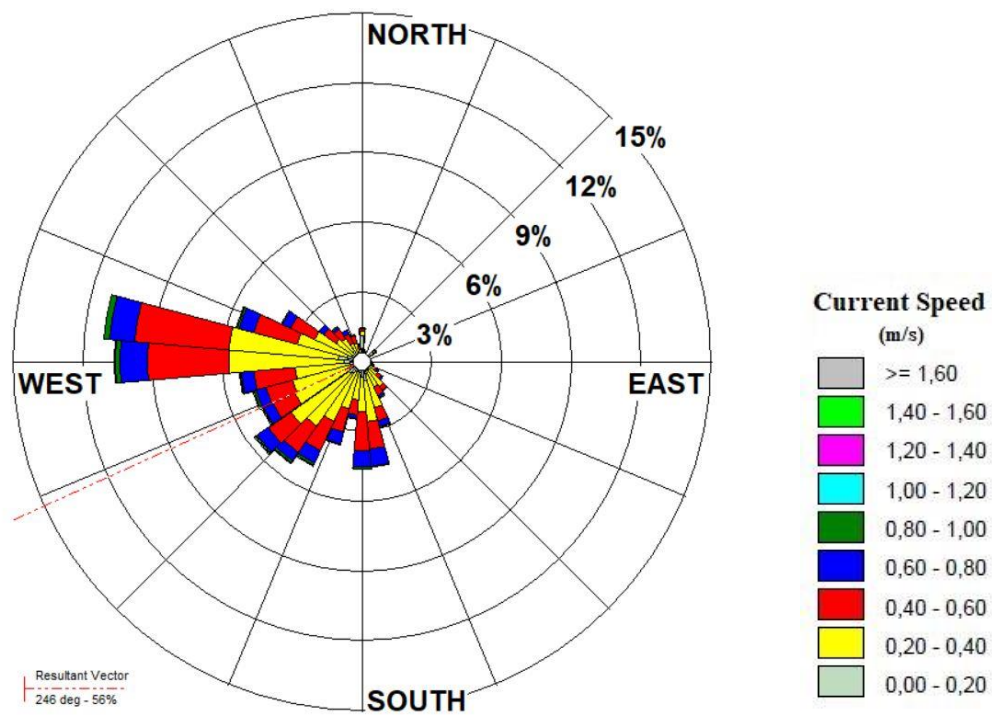


Figure 5.1 : Current rose chart for H-5.

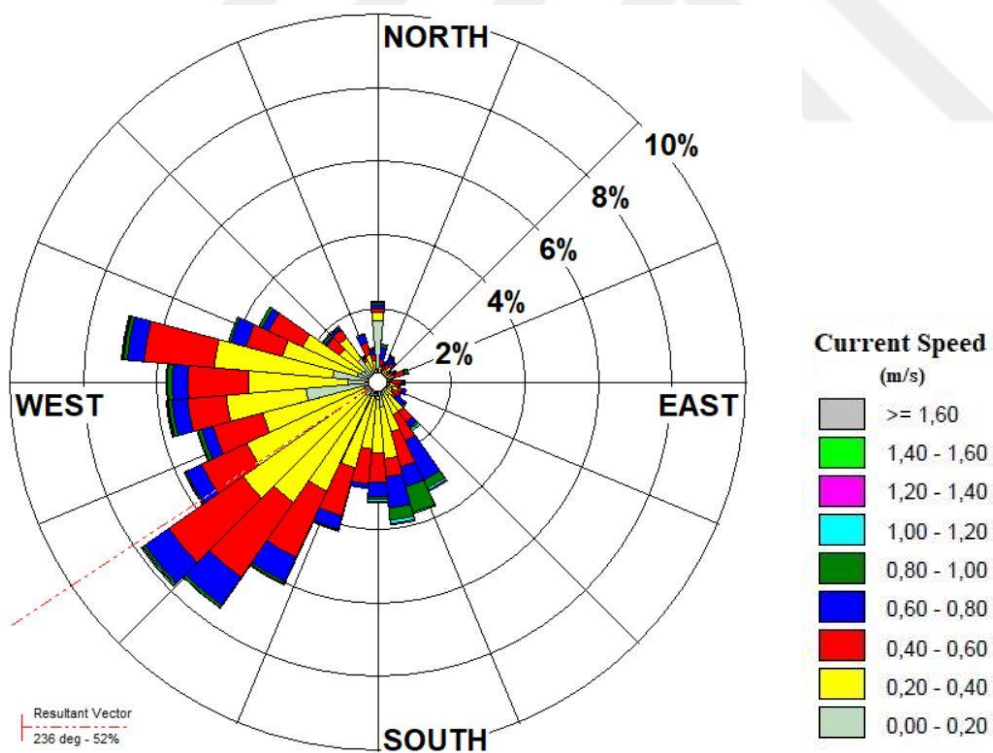


Figure 5.2 : Current rose chart for H-10.

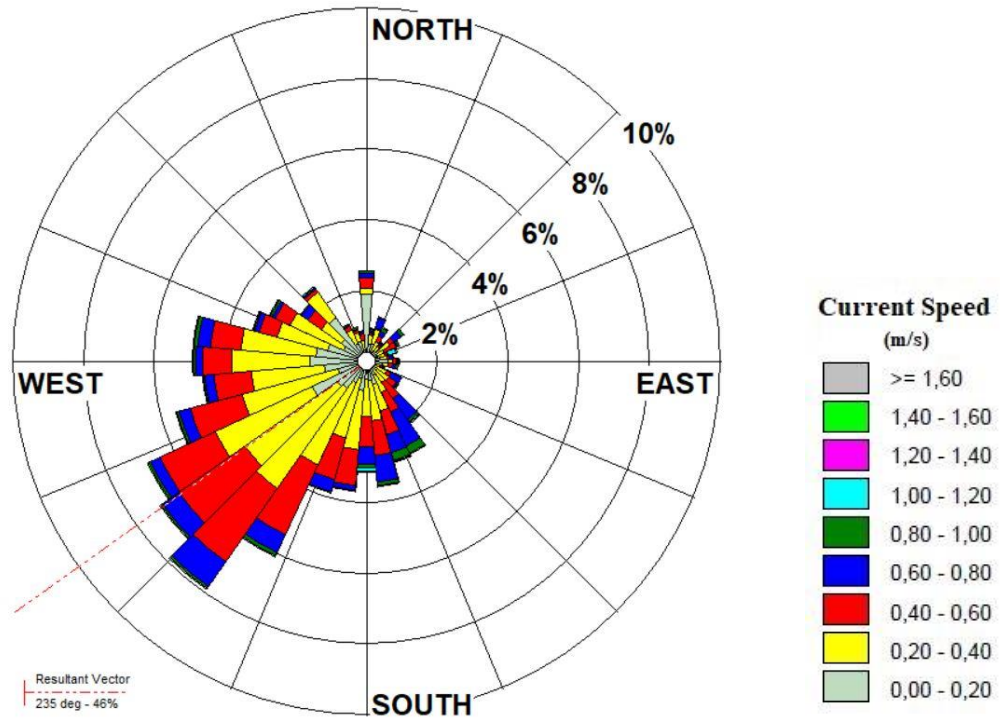


Figure 5.3 : Current rose chart for H-15.

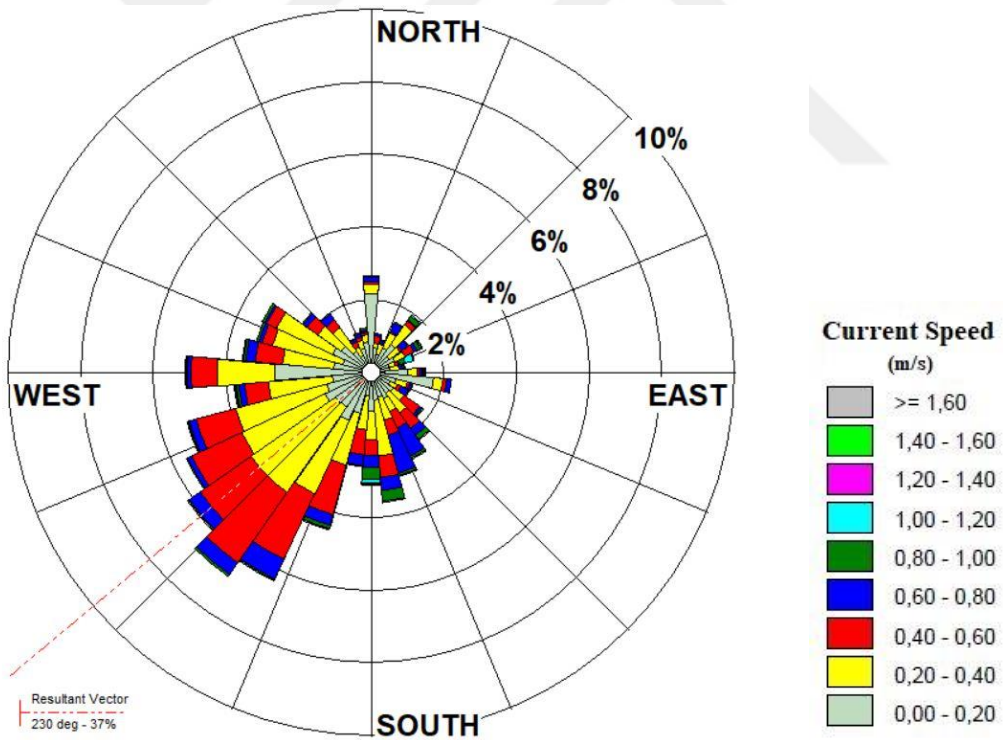


Figure 5.4 : Current rose chart for H-20.

The vast bulk of the flow path comes from North East (NE), signifying the lesser saline Black Sea waters joining the Dardanelles Strait (Blain et al., 2009).

5.1.1.2 Distribution characteristics of current speed

In this chapter, the numerous probabilistic distributions are statistically checked to match the calculated upper layer current velocity at each depth. As a consequence of the Kolmogorov Smirnov (K-S test), GGD is preferred to adapt the current speed data at each depth with a 5% significance level, because the K-S test is widely referenced in the literature for the current speed distribution analysis (Liu et al., 2015; Lee et al., 2009; Lindquist and Shaw, 2005). Furthermore, a strong correlation can be simply viewed from Figure 5.5 to Figure 5.8 between the measured data and the theoretical function for each water depth, including H-5, H-10, H-15 and H-20, respectively.

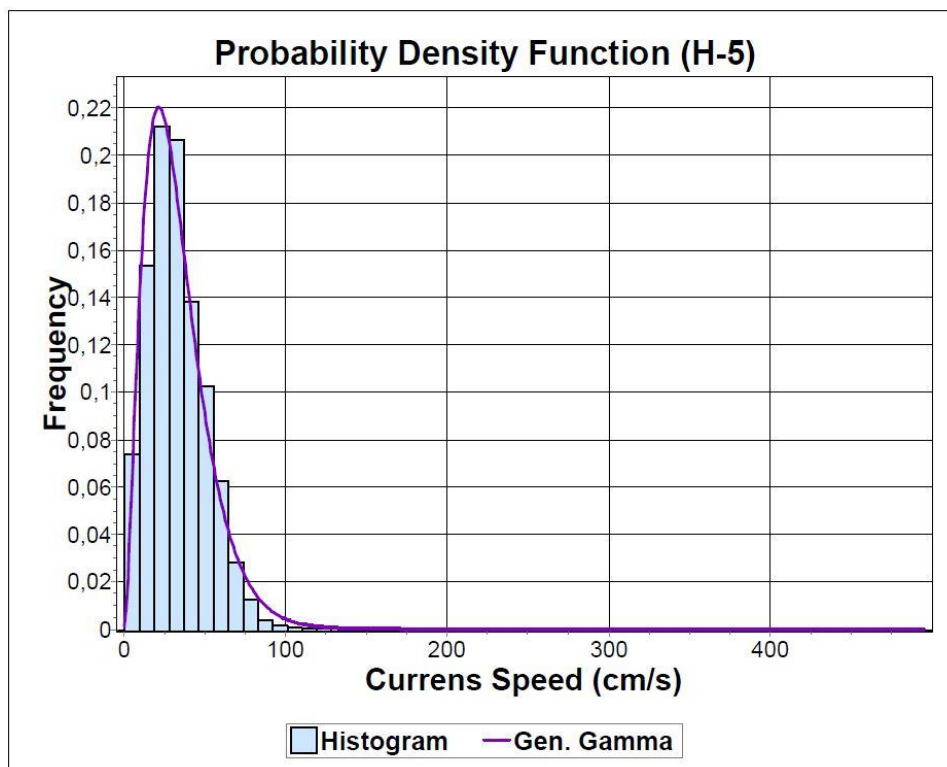


Figure 5.5 : Probability of density functions based on H-5.

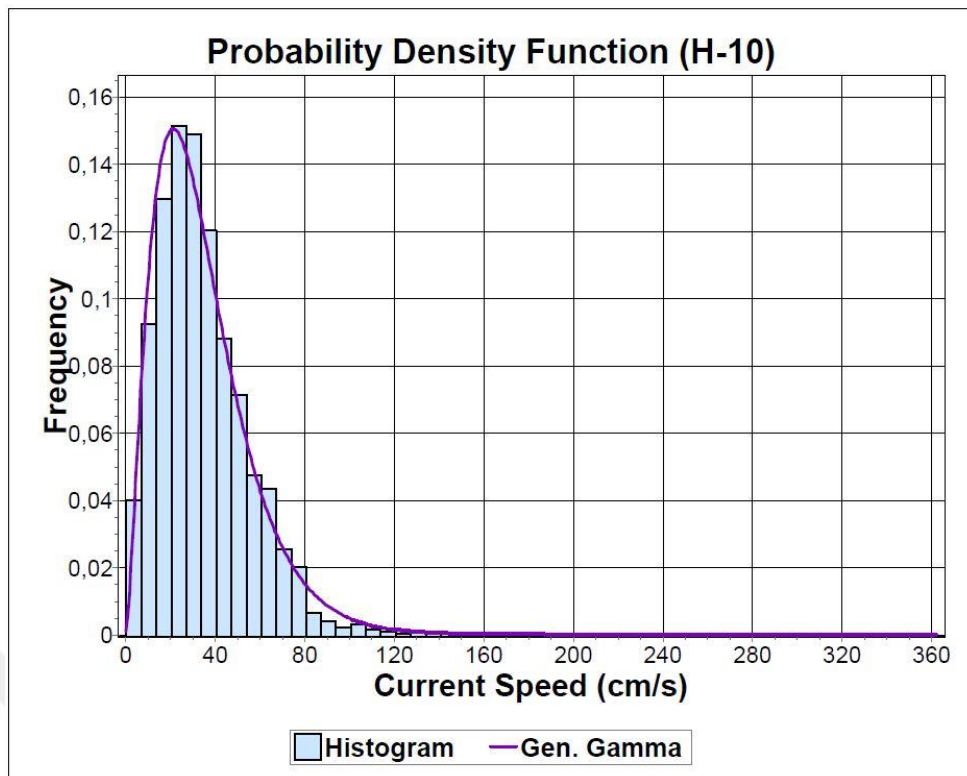


Figure 5.6 : Probability of density functions based on H-10.

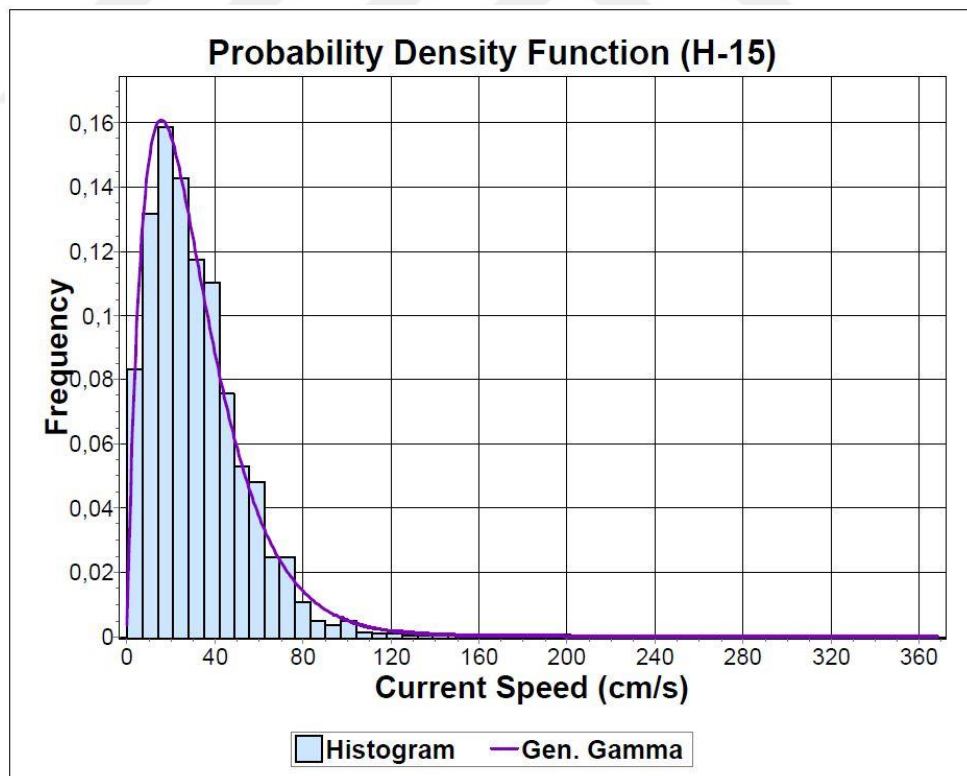


Figure 5.7 : Probability of density functions based on H-15.

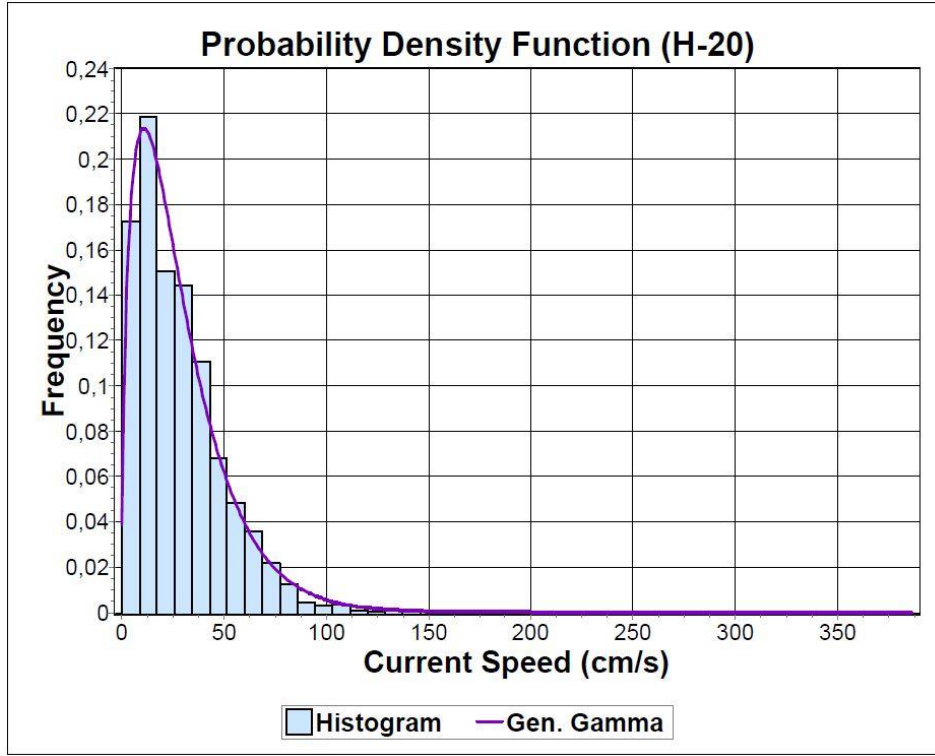


Figure 5.8 : Probability of density functions based on H-20.

5.1.1.3 Generalized gamma distribution

The GGD is a fairly young distribution (1962) than the normal distribution (1774), as it was developed by Stacy and Mihran to merge the strength of two distributions: the gamma distribution and the Weibull distribution (Gomès et al., 2008). The GGD has widely been considered as a significant probability distribution in accuracy simulation and analysis (Parr and Webster, 1965). The GGD's flexibility allows it particularly appealing as a conceptual model for fitting reliability data whose actual distribution is uncertain (Wingo, 1987). Because of these characteristics, GGD has been used in a wide range of research fields, including engineering, hydrology, and survival studies (Liu et al., 2015; De Pascoa et al., 2011), and more recently, sea current speed distributions (Campisi-Pinto et al., 2020).

The 3-parameter GGD that will be the focus of our thesis for upper layer of the Dardanelles Starit has two shape parameters and one scale parameter. If x a random variable, PDF of GGD is mentioned as (Rama and Kamlesh Kumar, 2019; Gomès et al., 2008):

$$f(x) = \frac{|c|a^{bc}x^{bc-1}e^{-(ax)^c}}{\Gamma(b)} \quad (5.1)$$

Here,

- x is random variable ($x>0$)
- a is scale parameter
- c and b are shape parameters

In addition, certain statistical moments of the GGD are extracted using algebraic moments. The n -th order statistical moment of the current velocity V , for GGD is generally defined as (Maur 2001):

$$E(V^n) = a^n \frac{\Gamma(b + \frac{n}{c})}{\Gamma(b)} \quad (5.2)$$

As a consequence, the expected value (for $n=1$) from equation 5.2 can be presented analytically as shown below:

$$E(V) = a \frac{\Gamma(b + \frac{1}{c})}{\Gamma(b)} \quad (5.3)$$

5.1.1.4 Current power perturbation with generalized gamma distribution

Considering the statistical moment expectation in equation 5.2, equation 3.9 parameters are presented as follows:

$$E^3(V) = a^3 \frac{\Gamma^3(b + \frac{1}{c})}{\Gamma^3(b)} \quad (5.4)$$

$$E(V'^2) = E(V^2) - E^2(V) = \frac{a^2}{\Gamma(b)} \left[\Gamma(b + \frac{2}{c}) - \frac{\Gamma^2(b + \frac{1}{c})}{\Gamma(b)} \right] \quad (5.5)$$

$$\begin{aligned} E(V'^3) &= E(V - \bar{V})^3 = E(V^3) - 3E(V^2)E(V) + 2E^3(V) \\ &= \frac{a^3}{\Gamma(b)} \left[\Gamma(b + \frac{3}{c}) - 3 \frac{\Gamma(b + \frac{2}{c}) \Gamma(b + \frac{1}{c})}{\Gamma(b)} \right. \\ &\quad \left. + 2 \frac{\Gamma^3(b + \frac{1}{c})}{\Gamma^2(b)} \right] \end{aligned} \quad (5.6)$$

Finally, the estimated sea current power for the dataset that conforms to GGD can be described as following:

$$E(P) = \frac{1}{2} \rho a^3 \frac{\Gamma(b + \frac{3}{c})}{\Gamma(b)} \quad (5.7)$$

Aside from this derived equation, the estimated energy density, $E(E)$, for a unit area can be determined as follows:

$$E(E) = \frac{1}{2} \rho a^3 \frac{\Gamma(b + \frac{3}{c})}{\Gamma(b)} T_h \quad (5.8)$$

Where,

T_h : The period of time (h)

Similar to the power formula derivation with GGD, the parameters for equation 3.9 are determined by considering statistical moments in equation 5.2, as regards:

$$E^2(V) = a^2 \frac{\Gamma^2(b + \frac{1}{c})}{\Gamma^2(b)} \quad (5.9)$$

$$E^3(V) = a^3 \frac{\Gamma^3(b + \frac{1}{c})}{\Gamma^3(b)} \quad (5.10)$$

$$E^4(V) = a^4 \frac{\Gamma^4(b + \frac{1}{c})}{\Gamma^4(b)} \quad (5.11)$$

$$E^2(V'^2) = \frac{a^4}{\Gamma^2(b)} \left[\Gamma^2\left(b + \frac{2}{c}\right) - 2 \frac{\Gamma\left(b + \frac{2}{c}\right) \Gamma^2\left(b + \frac{1}{c}\right)}{\Gamma(b)} + \frac{\Gamma^4\left(b + \frac{1}{c}\right)}{\Gamma^2(b)} \right] \quad (5.12)$$

$$\begin{aligned}
E^2(V'^3) &= \frac{a^6}{\Gamma^2(b)} \left[\Gamma^2\left(b + \frac{3}{c}\right) + 9 \frac{\Gamma^2\left(b + \frac{2}{c}\right) \Gamma^2\left(b + \frac{1}{c}\right)}{\Gamma^2(b)} \right. \\
&\quad + 4 \frac{\Gamma^6\left(b + \frac{1}{c}\right)}{\Gamma^4(b)} - 6 \frac{\Gamma\left(b + \frac{3}{c}\right) \Gamma\left(b + \frac{2}{c}\right) \Gamma\left(b + \frac{1}{c}\right)}{\Gamma(b)} \\
&\quad \left. - 12 \frac{\Gamma\left(b + \frac{2}{c}\right) \Gamma^4\left(b + \frac{1}{c}\right)}{\Gamma^3(b)} + 4 \frac{\Gamma\left(b + \frac{3}{c}\right) \Gamma^3\left(b + \frac{1}{c}\right)}{\Gamma^2(b)} \right]
\end{aligned} \tag{5.13}$$

$$\begin{aligned}
E(V'^4) &= E(V - \overline{V})^4 \\
&= \frac{a^4}{\Gamma(b)} \left[\Gamma\left(b + \frac{4}{c}\right) - 4 \frac{\Gamma\left(b + \frac{3}{c}\right) \Gamma\left(b + \frac{1}{c}\right)}{\Gamma(b)} \right. \\
&\quad \left. + 6 \frac{\Gamma\left(b + \frac{2}{c}\right) \Gamma^2\left(b + \frac{1}{c}\right)}{\Gamma^2(b)} - 3 \frac{\Gamma^4\left(b + \frac{1}{c}\right)}{\Gamma^3(b)} \right]
\end{aligned} \tag{5.14}$$

$$\begin{aligned}
E(V'^5) &= E(V - \overline{V})^5 \\
&= \frac{a^5}{\Gamma(b)} \left[\Gamma\left(b + \frac{5}{c}\right) - 5 \frac{\Gamma\left(b + \frac{4}{c}\right) \Gamma\left(b + \frac{1}{c}\right)}{\Gamma(b)} \right. \\
&\quad + 10 \frac{\Gamma\left(b + \frac{3}{c}\right) \Gamma^2\left(b + \frac{1}{c}\right)}{\Gamma^2(b)} \\
&\quad \left. - 10 \frac{\Gamma\left(b + \frac{2}{c}\right) \Gamma^3\left(b + \frac{1}{c}\right)}{\Gamma^3(b)} + 4 \frac{\Gamma^5\left(b + \frac{1}{c}\right)}{\Gamma^4(b)} \right]
\end{aligned} \tag{5.15}$$

$$\begin{aligned}
E(V'^6) &= E(V - \bar{V})^6 \\
&= \frac{a^6}{\Gamma(b)} \left[\Gamma\left(b + \frac{6}{c}\right) - 6 \frac{\Gamma\left(b + \frac{5}{c}\right) \Gamma\left(b + \frac{1}{c}\right)}{\Gamma(b)} \right. \\
&\quad + 15 \frac{\Gamma\left(b + \frac{4}{c}\right) \Gamma^2\left(b + \frac{1}{c}\right)}{\Gamma^2(b)} \\
&\quad - 20 \frac{\Gamma\left(b + \frac{3}{c}\right) \Gamma^3\left(b + \frac{1}{c}\right)}{\Gamma^3(b)} \\
&\quad \left. + 15 \frac{\Gamma\left(b + \frac{2}{c}\right) \Gamma^4\left(b + \frac{1}{c}\right)}{\Gamma^4(b)} - 5 \frac{\Gamma^6\left(b + \frac{1}{c}\right)}{\Gamma^5(b)} \right]
\end{aligned} \tag{5.16}$$

To summarize, substituting all of these appropriate definitions into equation 3.14 provides the expected variance in current power as follows:

$$Var(P) = \frac{1}{4} \rho^2 a^6 \frac{\Gamma(b + \frac{6}{c})}{\Gamma(b)} - \frac{\Gamma^2(b + \frac{3}{c})}{\Gamma^2(b)} \tag{5.17}$$

5.1.1.5 Current power estimation

In order to estimate the current power by perturbation method using the GGD for the upper layer of the Dardanelles Strait, it is necessary to first determine the parameters of the GGD. The Maximum likelihood method (MLM), which is frequently used in the literature, was used to determine the parameters of the GGD (Morgan et al., 2011; Balakrishnan and Peng, 2006; Shin et al., 2005). The simultaneous solution of equations provides maximum likelihood estimators for the parameters a, b, and c (Nadarajah, 2008):

$$nb = \sum_{i=1}^n \left(\frac{X_i}{a}\right)^c \tag{5.18}$$

$$\frac{n}{c} = \left(\frac{X_i}{a}\right)^c \log\left(\frac{X_i}{a}\right) - b \sum_{i=1}^n \left(\frac{X_i}{a}\right) \tag{5.19}$$

and

$$n\varphi(x) = c \sum_{i=1}^n \left(\frac{X_i}{a}\right) \tag{5.20}$$

Here,

$$\varphi(x) = d \log\left(\frac{\Gamma(x)}{dx}\right) \text{ represents the digamma function.}$$

Consequently, GGD parameters that estimated with MLM are presented in Table 5.1.

Table 5.1 : Current speed parameters of GGD for the upper layer of the Dardanelles Strait.

GGD Parameters			
Water Depth (m)	<i>a</i>	<i>b</i>	<i>c</i>
5 m (H-5)	12.739	2.6882	1.0314
10 m (H-10)	14.092	2.5085	1.0202
15 m (H-15)	17.14	1.8794	1.0268
20 m (H-20)	19.889	1.4886	1.0466

Once the necessary parameters of the GGD have been determined, the current power estimation can be generated by perturbation and classical methods using equation 5.7 and equation 3.18, respectively, with considering 1024 kg/m³ upper layer water density of the Dardanelles Strait as water density. The mean power and energy production of the sea current at the upper layer of the Dardanelles Strait Outlet with perturbation and classical methods is estimated and shown in Table 5.2.

Table 5.2 : Average current power and energy densities with classical and perturbation methods for the upper of the Dardanelles Strait.

Mean Power and Energy in upper layer of the Dardanelles Strait				
Water Depth (m)	Current Power with Classical Method (W/m ²)	Current Power with Perturbation (W/m ²)	Standard Deviation with Perturbation (W/m ²)	Current Energy with Perturbation (kWh/m ² /year)
H-5	18.19	42.4	92.82	371.68
H-10	21.22	51.73	120.41	453.47
H-15	15.96	48.29	133.7	423.31

Table 5.2 (continued): Average current power and energy densities with classical and perturbation methods for the upper of the Dardanelles Strait.

Mean Power and Energy in upper layer of the Dardanelles Strait				
Water Depth (m)	Current Power with Classical Method (W/m ²)	Current Power with Perturbation (W/m ²)	Standard Deviation with Perturbation (W/m ²)	Current Energy with Perturbation (kWh/m ² /year)
H-20	11.9	43.4	134.89	380.44

Maximum and minimum power (energy) are achieved by the GGD for the upper layer of the Dardanelles Strait at H-10 and H-5, respectively with 51.73 W/m² (453.47 kWh/m²/year) and 42.40 W/m² (371.68 kWh/m²/year). The average power (energy) in the upper layers of the Dardanelles is determined by the GGD to be 46.45 W/m² (407.23 kWh/m²/year). Moreover, the power values determined using the classical method are calculated to be 18.19, 21.22, 15.96 and 11.90 W/m² at H-5, H-10, H-15 and H-50 respectively. Similarly, the average current power determined using the classical method is calculated to be 16.82 W/m² in the upper layers of the Dardanelles. It can be easily seen that the average power values obtained by the perturbation method have been estimated to be higher than those obtained from the classical method. The reason for this is that the turbulence component (deviations from mean velocity) is coupled with the perturbation process.

In addition, for better examination, a single depth of water, H-10, which has both the highest power and energy density in the upper layer of the Dardanelles Strait, is split into four seasons for one year. Table 5.3 indicates the GGD parameters for the winter, spring, summer and fall seasons dependent on the H-10 water depth.

Table 5.3 : Seasonal current speed parameters of GGD for H-10 for the upper layer of the Dardanelles Strait.

Seasonal Mean Power For H-10 Water Layer			
Season	GGD Parameters		
	<i>a</i>	<i>b</i>	<i>c</i>
Winter	10.032	3.4553	0.9679
Spring	9.6085	2.8253	0.9877

Table 5.3 (continued): Seasonal current speed parameters of GGD for H-10 for the upper layer of the Dardanelles Strait.

Seasonal Mean Power For H-10 Water Layer			
Season	GGD Parameters		
	<i>a</i>	<i>b</i>	<i>c</i>
Summer	16.932	2.4087	1.0375
Fall	16.848	2.6483	1.0361

As seen in Table 5.3, the parameter has values between 10.032 and 9.6085, the *b* parameter has values between 3.4553 and 2.4087, and the *c* parameter has values between 1.0375 and 0.9679. Moreover, the seasonal current power values of the H-10 water layer estimated by the parameters in Table 5.3 are shown in Table 5.4.

Table 5.4 : Seasonal average current power for H-10 for the upper layer of the Dardanelles Strait.

Seasonal Mean Power For H-10 Water Layer		
Season	Current Power (W/m ²)	Standard Deviation (W/m ²)
Winter	51.96	107.22
Spring	25.24	57.38
Summer	75.86	176.33
Fall	92.83	203.68

According to Table 5.4, current power value varies from 92.83 W/m² in fall to 25.24 W/m² in spring. The highest and lowest variation exists in fall and spring, respectively, with 203.68 and 57.38 W/m².

In addition, the power prediction analysis for the upper Dardanelles layer in Figure 5.9 shows the relationship between the risk level (on the vertical axis) and the sum of predicted current power (on the horizontal axis) for H-10.

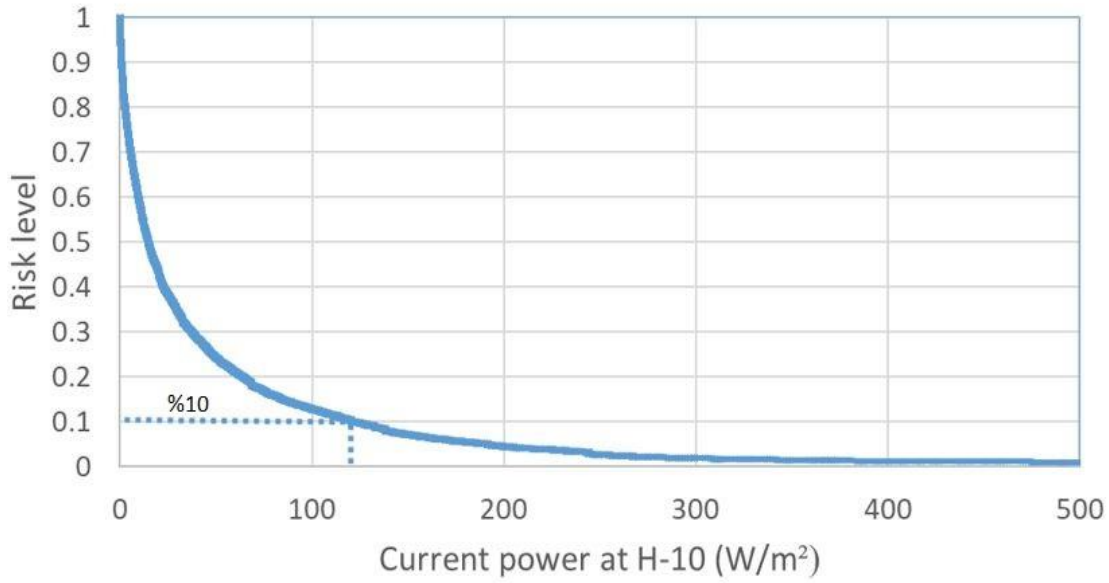


Figure 5.9 : Relationship between current power and risk level at H-10 for the upper layer of the Dardanelles Strait.

Current power levels are calculated for each time period of the current velocity records for the upper layer of the Dardanelles Strait. The probability of exceeding (P_i) power rates is estimated using $P_i = i/(n+1)$, since i is the data grade in increasing order and n is the total sum of data. Figure 5.9 shows that the degree of current power generation declines as the amount of risk increases. For the realistic spectrum of risk (%10), the current power at H-10 is determined to be 120.96 W/m².

5.1.2 Bottom layer

The power potential of the Dardanelles Strait's bottom (density) current is investigated in this section of the study. Current roses are produced and analyzed first in this context. Then, the probability density distribution referring to the current velocities is determined. The Exponential distribution is determined to represent the density current velocities of the Dardanelles Strait. The current power formula is then derived using both the exponential distribution that corresponds to the current velocities and the perturbation process. After that, the current power potential for the Dardanelles Strait density currents is estimated by using both the derived equation and the classical method. Finally, a section in the Dardanelles Strait is selected and the cross-sectional current power which is created by the density currents in this section is estimated.

5.1.2.1 Current roses

Current rose diagram can be used to determine current directions for the bottom layer of the Dardanelles Strait. Current roses were formed from Figure 5.10 to Figure 5.15.

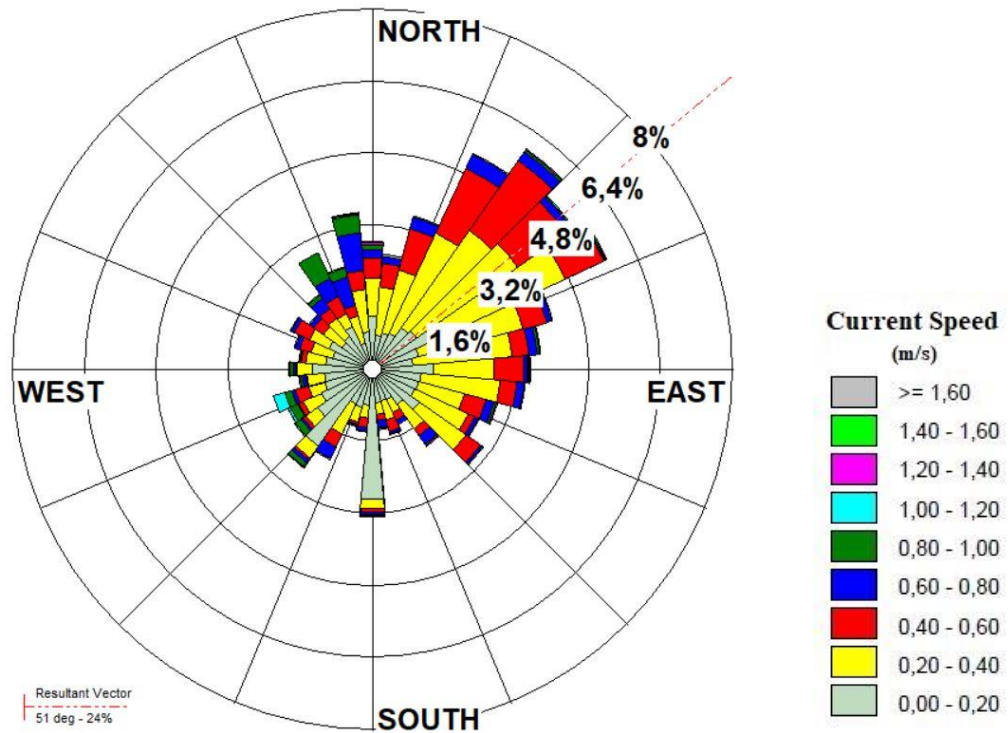


Figure 5.10 : Current rose diagram for H-25.

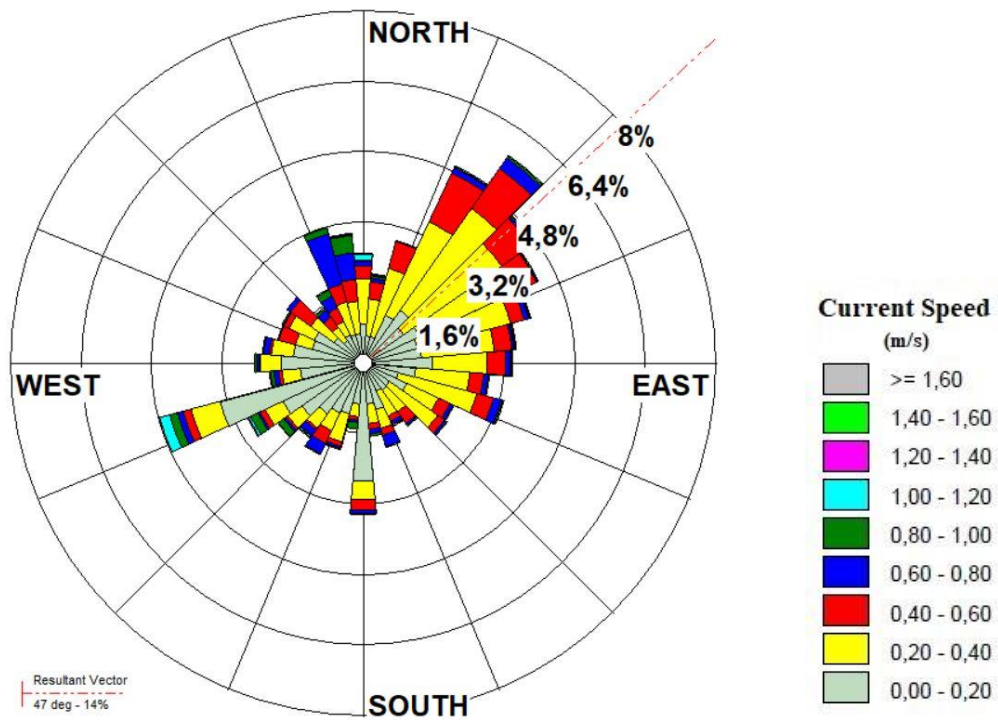


Figure 5.11 : Current rose diagram for H-30.

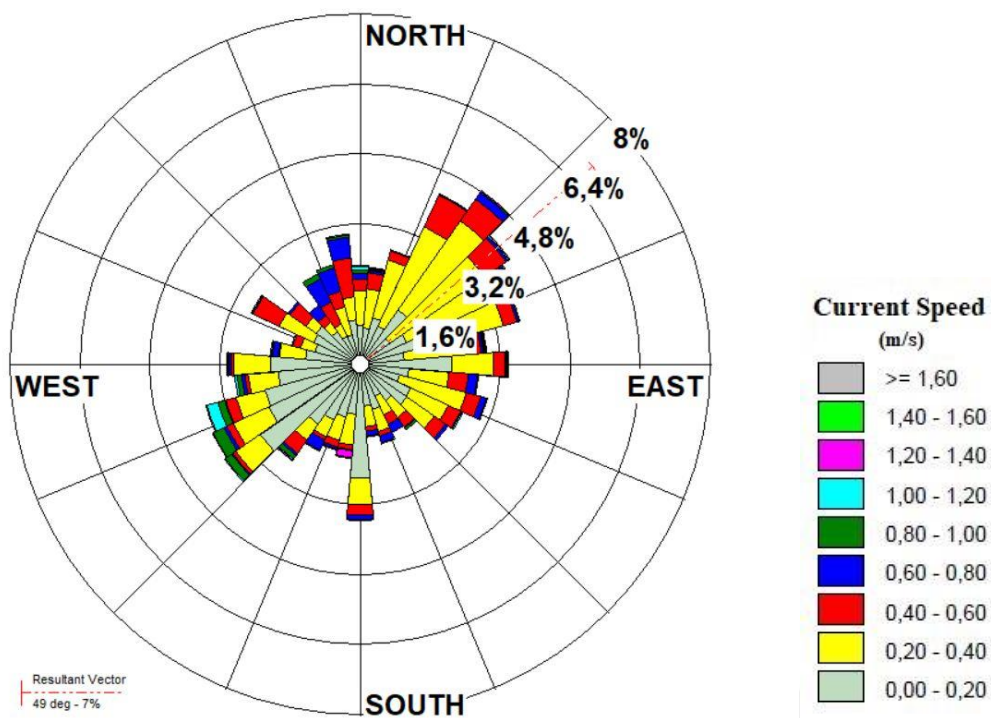


Figure 5.12 : Current rose diagram for H-35.

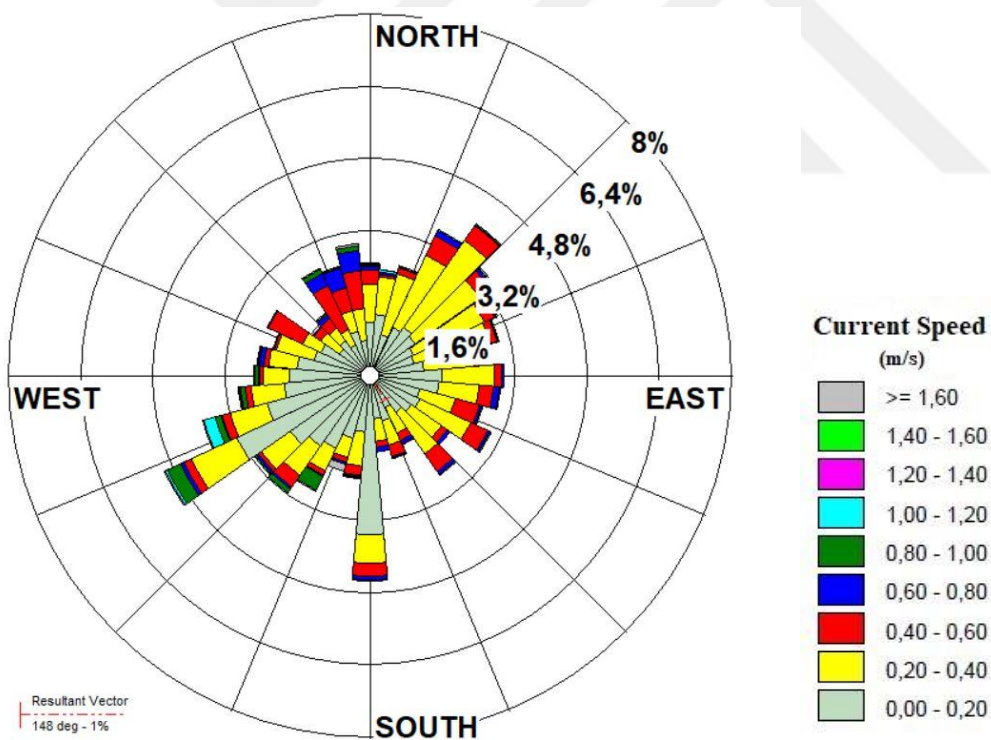


Figure 5.13 : Current rose diagram for H-40.

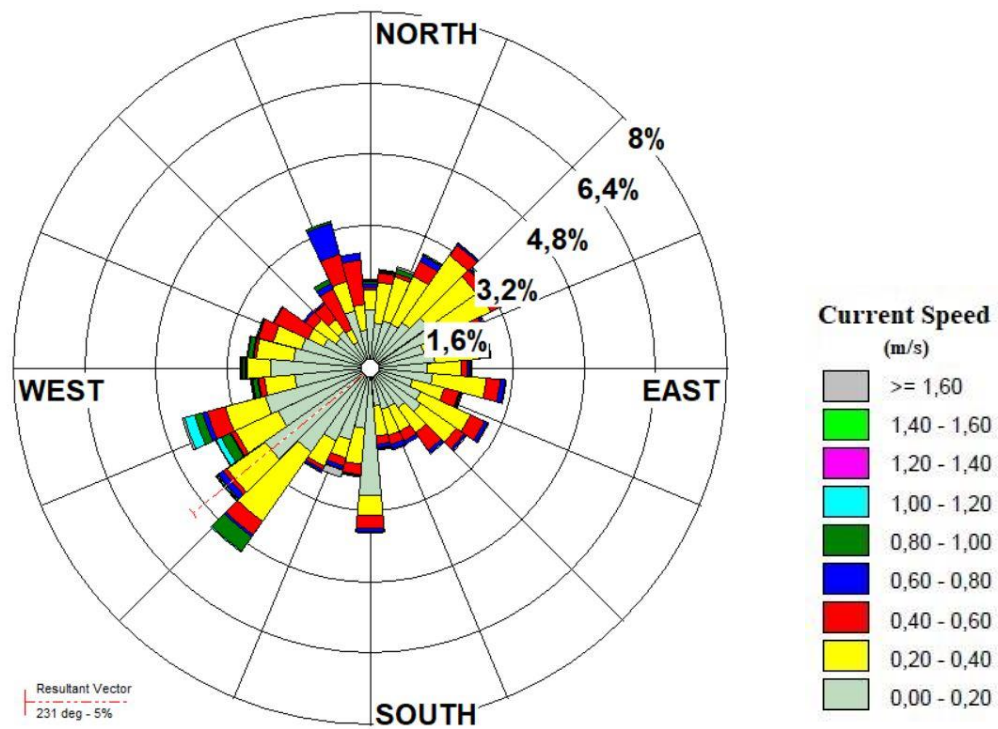


Figure 5.14 : Current rose diagram for H-45.

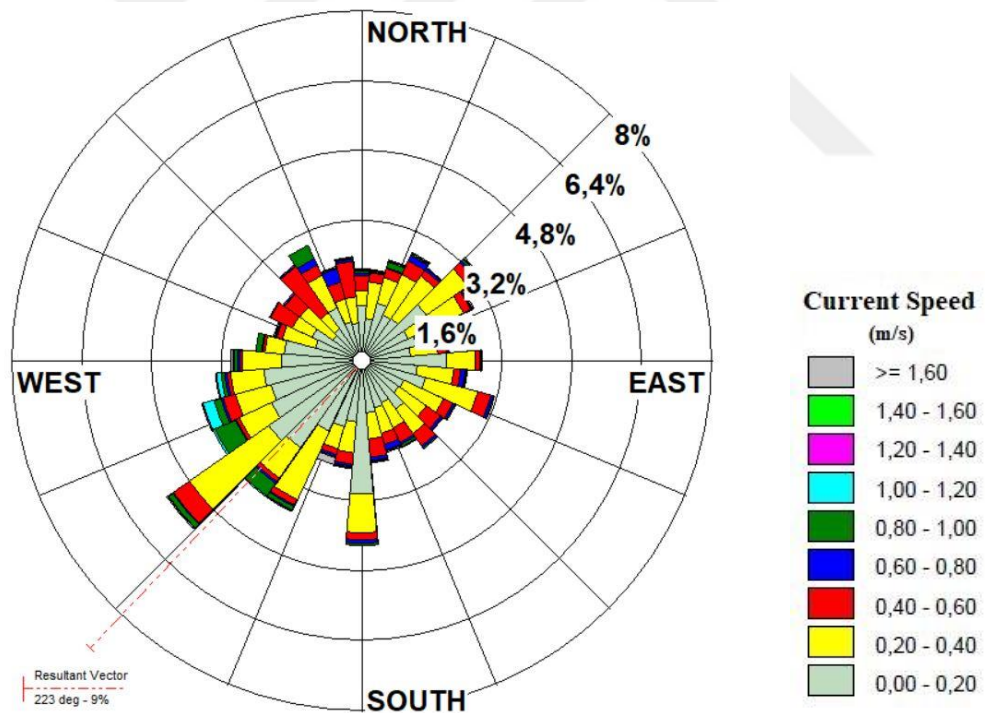


Figure 5.15 : Current rose diagram for H-50.

As can be seen from the figures above, the prevailing direction for water levels H-25, H-30 and H-35 is South-West (SW). It is also difficult to predict the dominant direction for the H-40 level. Besides that, in the case of the H-45 and H-50 water levels, while

the North-East (NE) direction is not dominant, it can be determined as the leading direction.

5.1.2.2 Distribution characteristics of current speed

In this section, buoy measurements near the southern exit of the Dardanelles Strait are adapted to the theoretical exponential PDF for the bottom layer of the Dardanelles Strait using MLM displayed from Figure 5.16 to Figure 5.21. The K-S test is used to assess whether or not the theoretical probability density function is suitable for the research of current speed records.

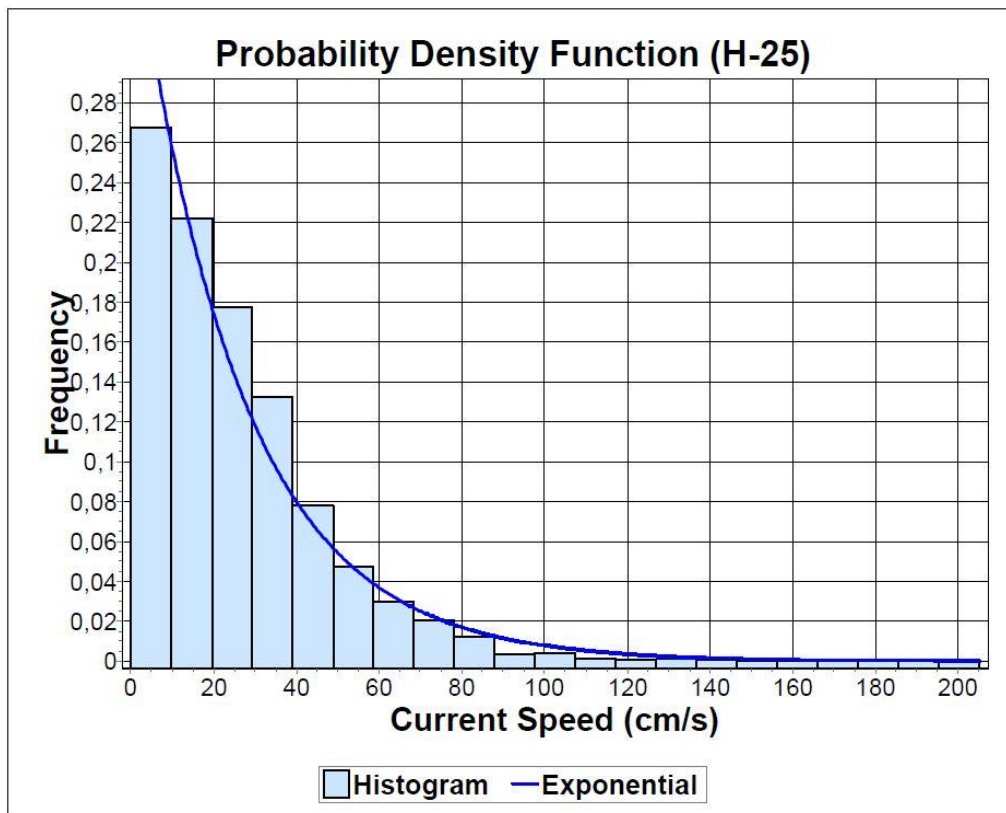


Figure 5.16 : Probability of density functions based on H-25.

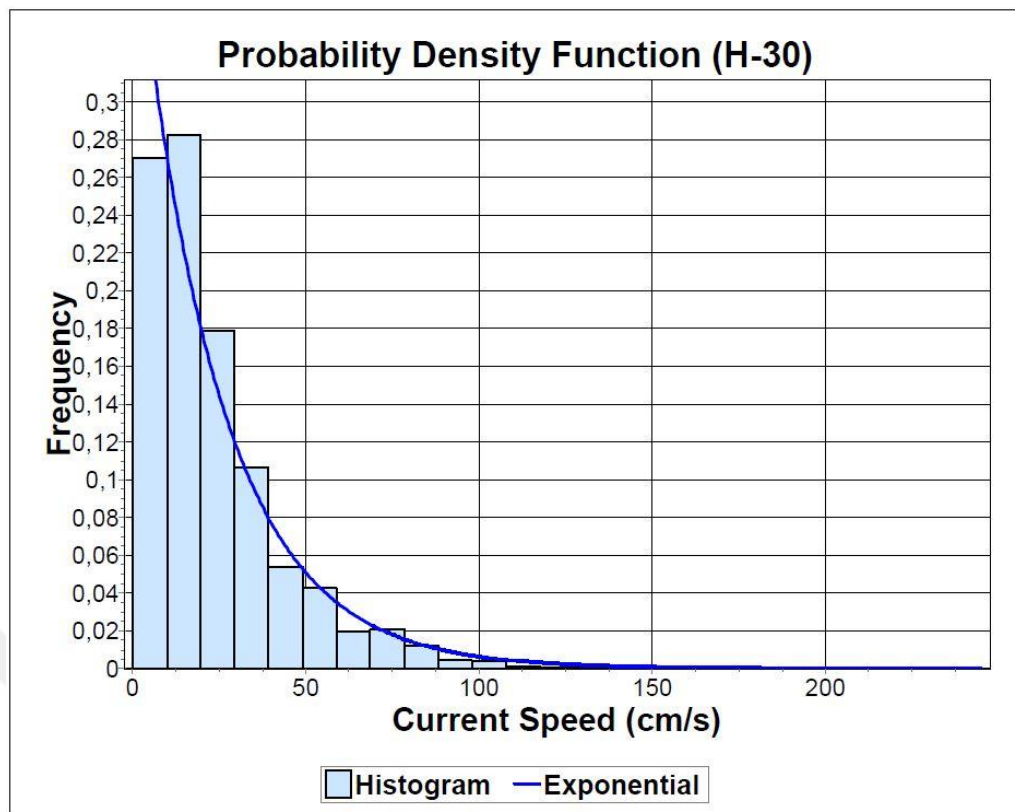


Figure 5.17 : Probability of density functions based on H-30.

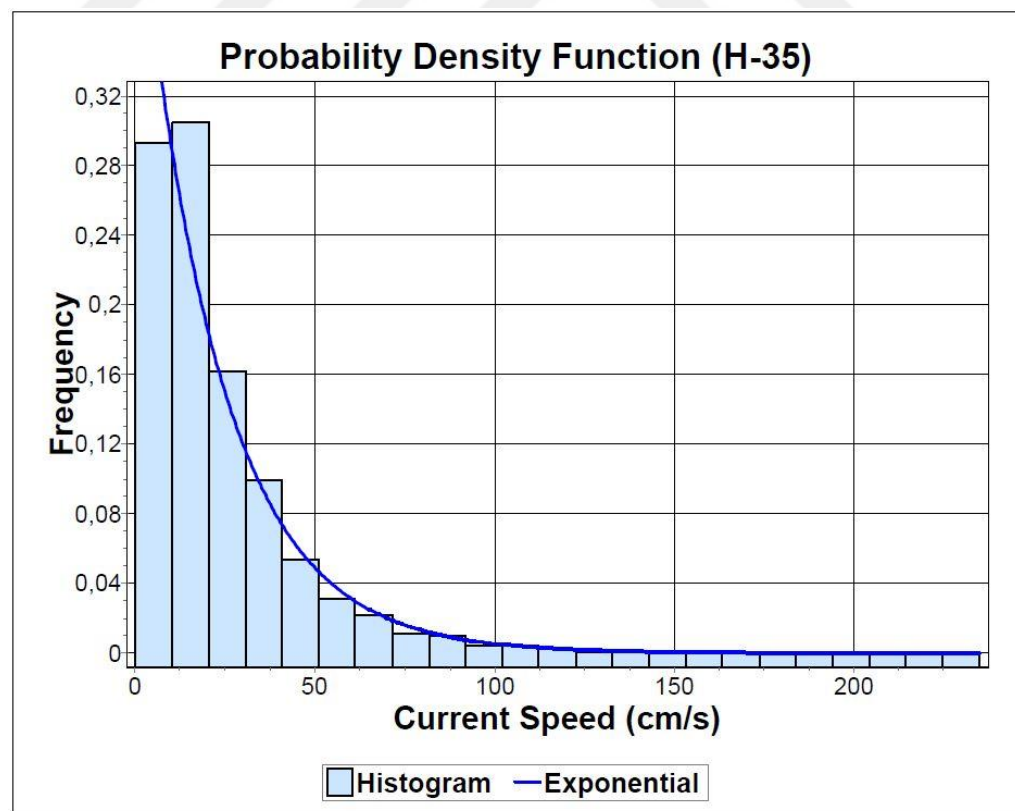


Figure 5.18 : Probability of density functions based on H-35.

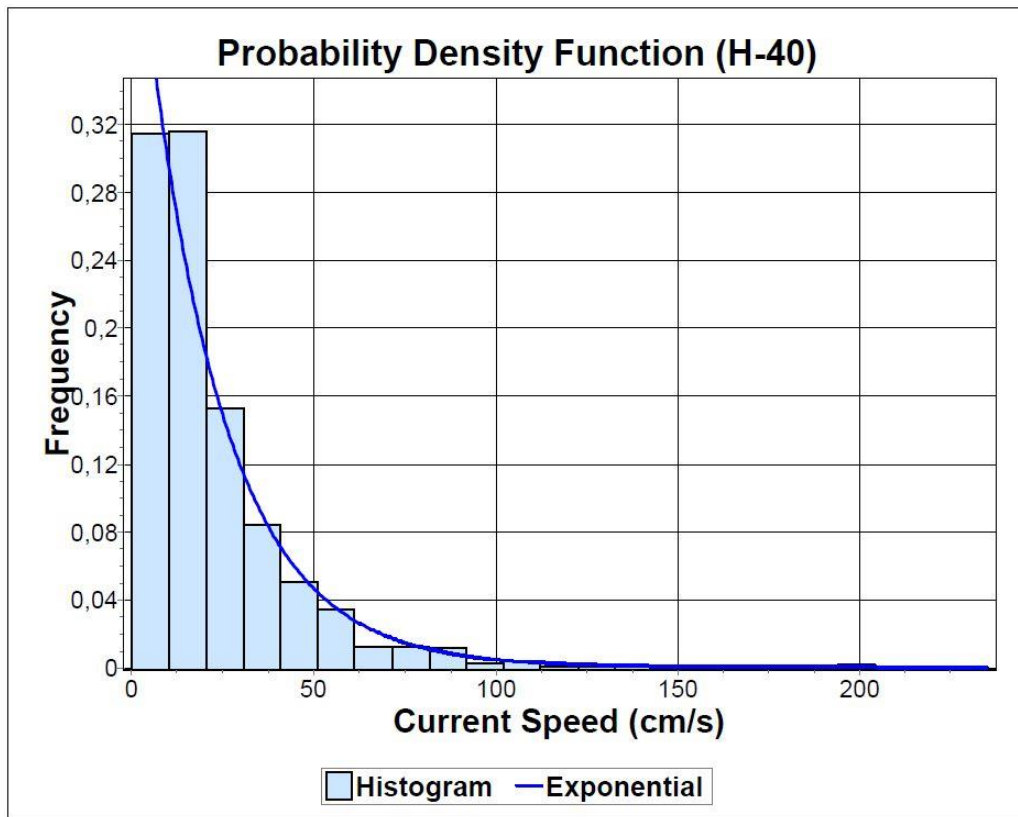


Figure 5.19 : Probability of density functions based on H-40.

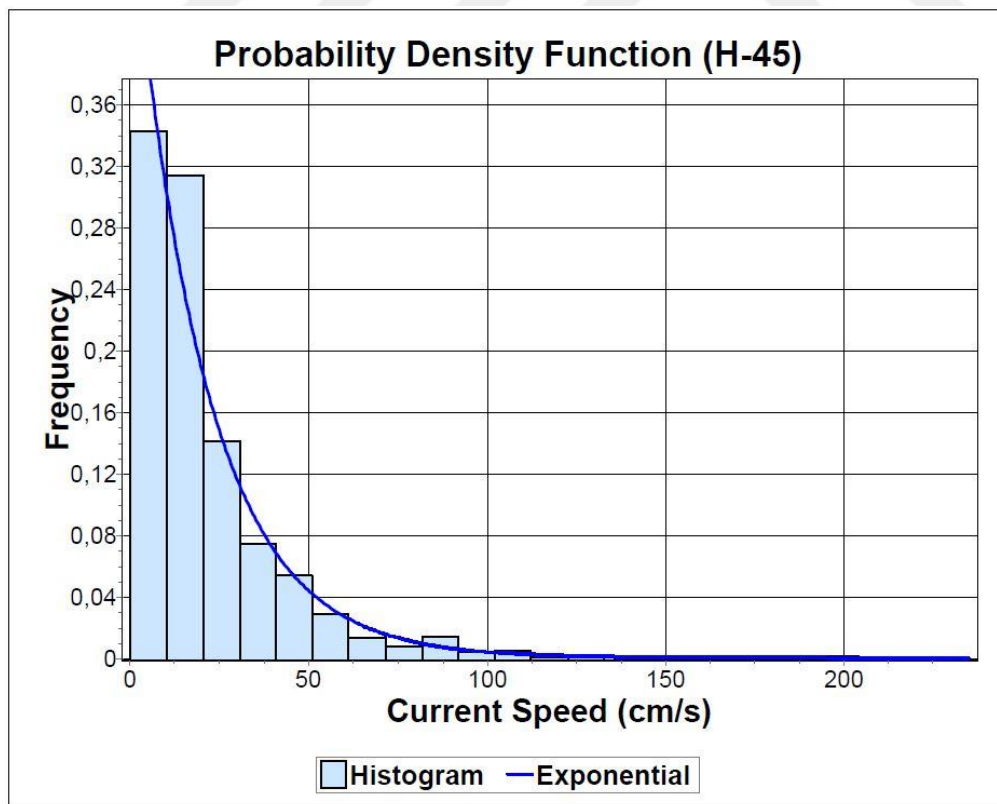


Figure 5.20 : Probability of density functions based on H-45.

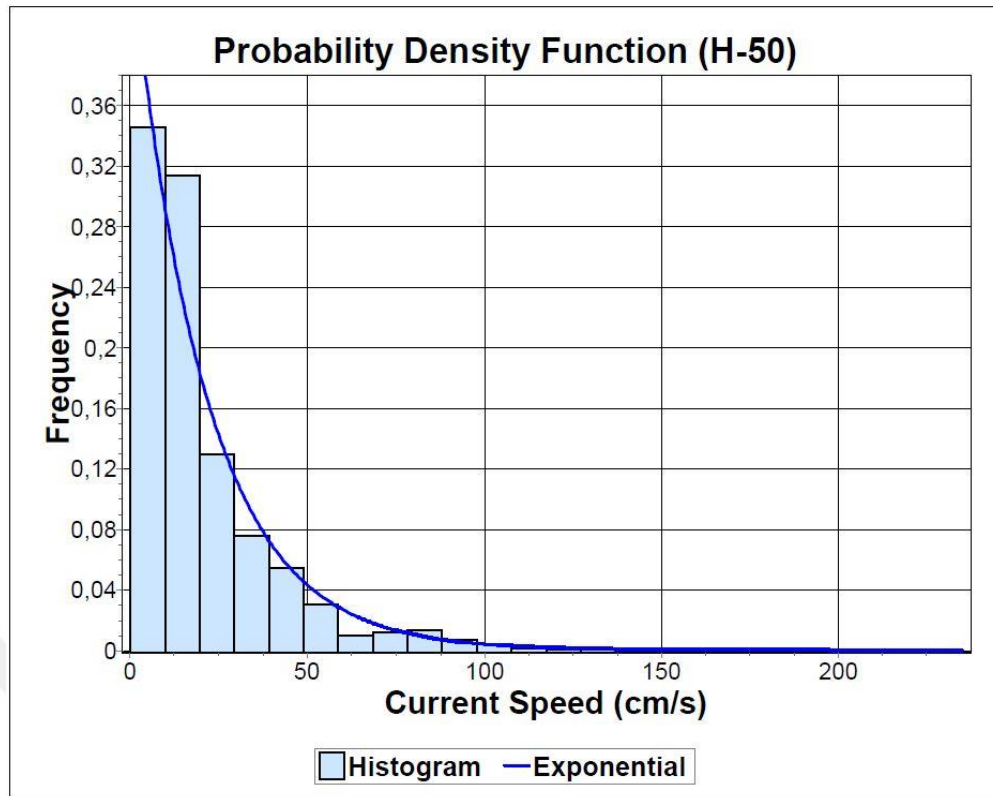


Figure 5.21 : Probability of density functions based on H-50.

In addition to the K-S criterion, theoretical models were tested with empirical ones by the coefficient of determination (R^2) and Root Mean Square Error (RMSE) and presented in Table 5.5, where better distribution is achieved if the p-value or R^2 -magnitude is higher and the RMSE value is lower (Akdağ and Dinler, 2009).

Table 5.5 : Error statistics for exponential PDF depending on water depth for the bottom layer of the Dardanelles Strait.

Water Depth (m)	Exponential PDF		
	p-Value	R^2	RMSE
H-25	0.48	0.9958	0.034034
H-30	0.26	0.9935	0.035282
H-35	0.26	0.9919	0.039462
H-40	0.22	0.9898	0.04352
H-45	0.19	0.9915	0.045555
H-50	0.2	0.9913	0.047508

All in all, there is a clear correlation between the observable and theoretical functions of the exponential PDF at all depths, as can be seen from Figure 5.16 to Figure 5.21.

5.1.2.3 Exponential distribution

The intensity of the sea condition is heavily influenced by the geographic region. As a result, several PDFs have been proposed to match a specific set of observed data (Ochi, 1993). According to Ashkenazy and Gildor (2011), the speed distribution of ocean currents can be estimated by a Weibull PDF (or exponential distribution, a special type of Weibull with shape parameter is 1). In this section, the expected current power and variance for exponential PDF, a simple and one parameter PDF, have been derived. The density function of the exponential distribution with one-parameter can be defined as follows (Ross, 2017):

$$F(V) = 1 - e^{-\frac{V}{\lambda}} \quad (5.21)$$

Here,

λ : Exponential distribution's inverse scale parameter.

Statistical moments are required to obtain certain empirical variables of the exponential distribution. The exponential PDF's n^{th} order statistical moment is usually described by the equation (Walck, 2007):

$$E(V^n) = \lambda^n n! \quad (5.22)$$

As a consequence, the expected value (for $n=1$) of equation 5.22 can be described mathematically as shown below:

$$E(V) = \lambda \quad (5.23)$$

5.1.2.4 Current power perturbation with exponential distribution

In order to obtain an analytical form for the exponential PDF's current speed, it is essential to determine the expected current power using equation 3.9. The following equations are the relevant parameters in equation 3.9:

$$E^3(V) = \lambda^3 \quad (5.24)$$

$$E(V'^2) = \lambda^2 \quad (5.25)$$

$$E(V'^3) = 2\lambda^3 \quad (5.26)$$

Consequently, using equation 3.9, the expected current power value, which is dependent on the exponential PDF, is defined as follows:

$$E(P) = 3\rho\lambda^3 \quad (5.27)$$

Furthermore, another perturbation concept, higher-order moment, should be evaluated in order to determine a specific formulation for the current power variance, as shown in equation 3.14. The parameters of equation 3.14 are listed as follow:

$$E^2(V) = \lambda^2 \quad (5.28)$$

$$E^3(V) = \lambda^3 \quad (5.29)$$

$$E^4(V) = \lambda^4 \quad (5.30)$$

$$E^2(V'^2) = \lambda^4 \quad (5.31)$$

$$E^2(V'^3) = 4\lambda^6 \quad (5.32)$$

$$E(V'^4) = E(V - \bar{V})^4 = 9\lambda^4 \quad (5.33)$$

$$E(V'^5) = E(V - \bar{V})^5 = 44\lambda^5 \quad (5.34)$$

$$E(V'^6) = E(V - \bar{V})^6 = 265\lambda^6 \quad (5.35)$$

The expected variance of current power with exponential PDF can be generated by replacement all necessary terms with equation 3.14, as follows:

$$Var(P) = 171\rho^2\lambda^6 \quad (5.36)$$

5.1.2.5 Current power estimation

The parameters of the distribution describing the current velocity should be determined in order to estimate the current power density using the perturbation method. For this purpose, the parameters of the exponential distribution determined by the MLM are presented in Table 5.6.

Table 5.6 : Fitted parameters of exponential PDF along water depth for the bottom layer of the Dardanelles Strait.

Water Depth (m)	Parameter of exponential PDF (λ)
H-25	0.03881
H-30	0.04173
H-35	0.04457
H-40	0.0464
H-45	0.04852
H-50	0.04754

After obtaining the appropriate parameters for the exponential PDFs, the mean current power density values are determined using the perturbation method for the bottom layer of the Dardanelles Strait with considering 1029 kg/m^3 bottom layer water density of the Dardanelles Strait as water density. The values of the power are determined using the generated equation 5.27. In addition, the current power density is obtained at the same depths for comparison with the classical method using equation 3.18. Consequently, the mean power density calculation of the current speed along the water depth is presented in Table 5.13.

Table 5.7 : Mean current power density of bottom layer of the Dardanelles Strait along water depth.

Water Depth (m)	Classical Method		Exponential PDF	
	Mean (W/m ²)	Standard Deviation (W/m ²)	Mean (W/m ²)	Standard Deviation (W/m ²)
H-25	29.96	77.04	52.83	229.29
H-30	25.19	69.62	42.51	184.45
H-35	22.26	61.06	34.88	151.39
H-40	20.84	60.32	30.91	134.17
H-45	18.8	54.88	27.04	117.34
H-50	20.64	62.46	28.75	124.75

The mean power density values achieved by the perturbation technique were found to be greater than those generated by the classical method at all depths of water . The variation between the classical approach and the exponential PDF increases near to the surface of the water, where the turbulence effect (deviations from the mean velocity) appears more obvious. This can only be utilized in the perturbation method.

After determining the current power densities along the water depths, the cross-sectional current power was determined by taking a cross-section of the Dardanelles Strait, which exits the Aegean Sea. The cross-section power of Dardanelles is determined by taking a 1-1' cross-section in Figure 5.22, described by a black line.

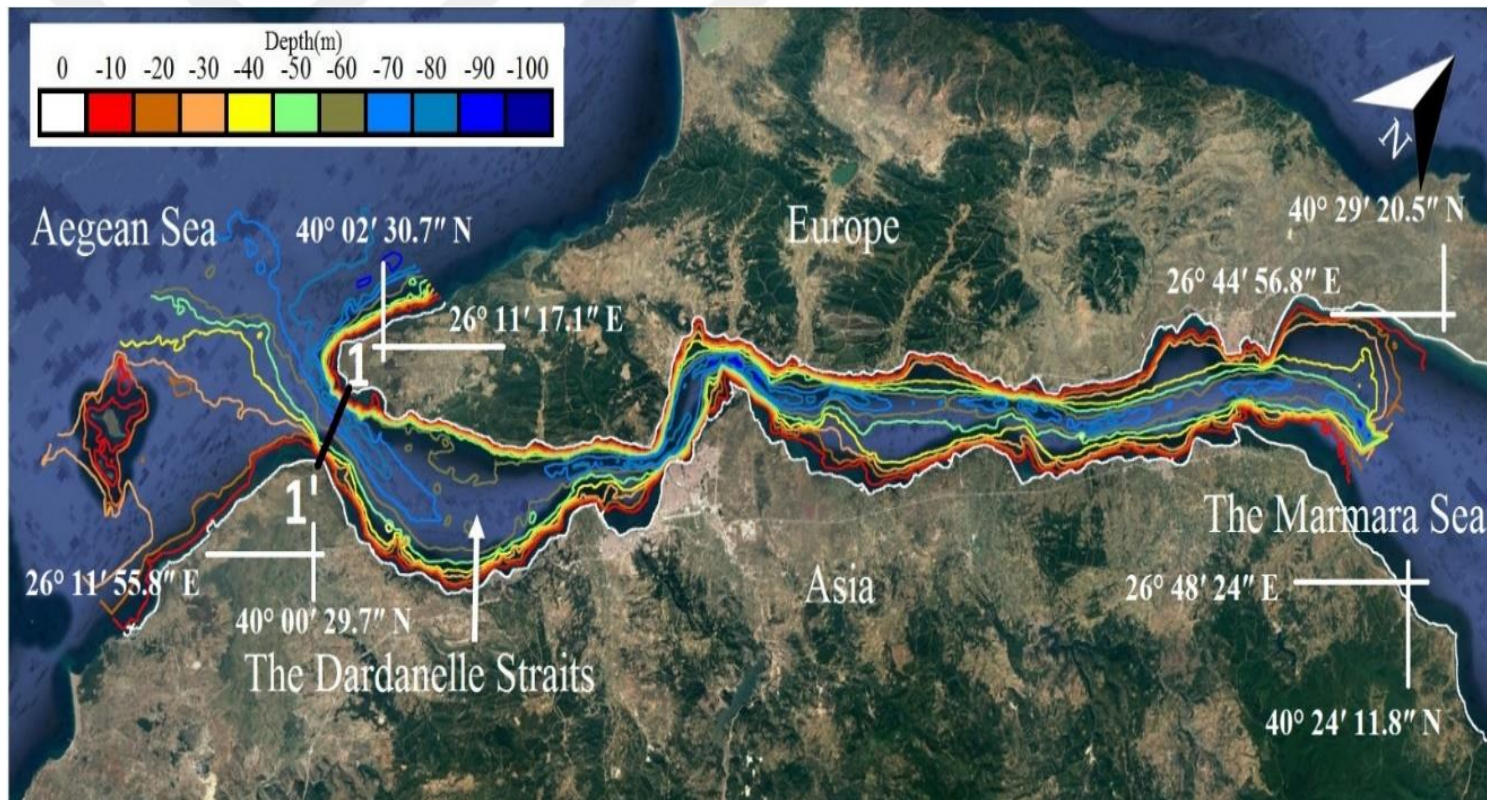


Figure 5.22 : Cross-section 1-1' at the southern exit of the Dardanelles Strait.

After obtaining the cross-section and measuring the appropriate areas, the cross-sectional current powers depending on water depths were determined using both the perturbation method and the classical method for the bottom layer of the Dardanelles Strait. The associated calculations are shown in Table 5.8.

Table 5.8 : Cross-Sectional power with perturbation (exponential PDF) and classical methods for the bottom layer of the Dardanelles Strait.

Water Depth (m)	Cross-Sectional Area (m ²)	Cross-Sectional Power (MW)	
		Classical Method	Exponential PDF
25	29030	0.87	1.53
30	27343	0.69	1.16
35	24753	0.55	0.86
40	18751	0.39	0.58
45	12419	0.23	0.33
50	6823	0.14	0.2

The final study in Figure 5.23 indicates the relationship between the intensity of risk on the vertical axis and the amount of current power on the horizontal axis at a depth of 25 m, which has the maximum mean power per m², which can be seen in Table 5.8.

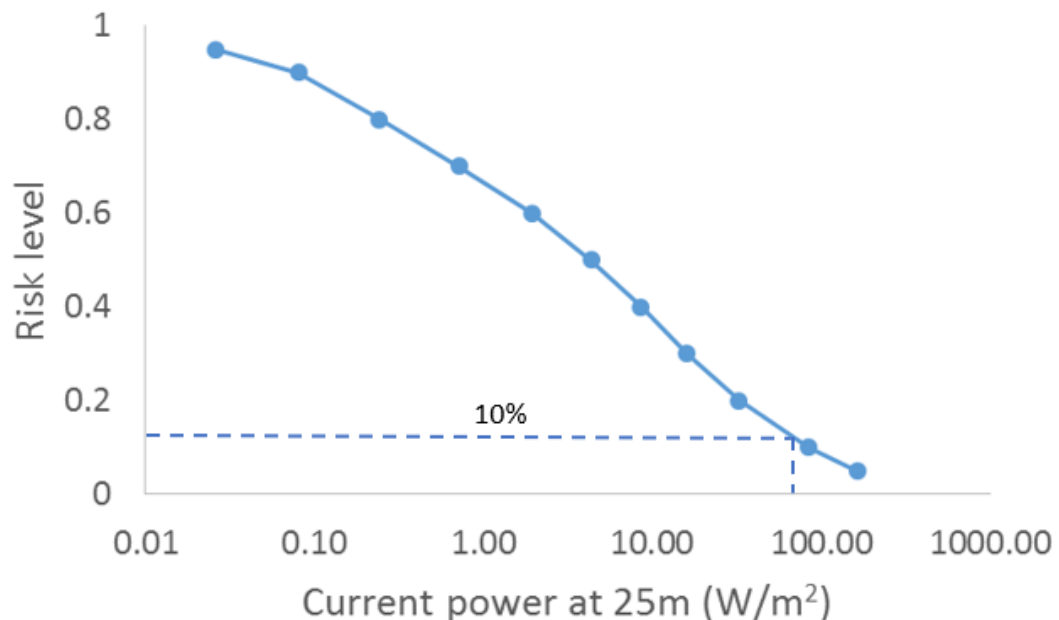


Figure 5.23 : Current power-risk level interaction for 25 m water depth.

It is evident from Figure 5.23, that the extent of current power generation is declining as the level of risk rises. For the practical risk level scale (10%), the Dardanelles water

depth of 25m is estimated to generate 84.80 W/m² current power for the bottom layer of the Dardanelles Strait .

5.2 The Vicinity of The Northern Bosphorus

In this part of the study, upper layer current velocities between 0-25 meters are examined using the measurement station data in a region close to the northern exit of the Bosphorus. Current roses are formed using the measured current velocities. Then, the probability density function representing the upper layer current velocities is determined. The probability density function representing the current velocities based on the measurement station data is determined as log Pearson Type 3 (LP3).

In addition to the K-S test, error statistics are also used to strongly prove that the LP3 distribution is a suitable distribution. As a result, it is concluded that the LP3 distribution is the appropriate distribution for the flow velocities in the measurement station. Then, general statistical information on LP3 distribution is given. Following these information, current power equations are derived by perturbation method using LP3 distribution. Finally, the current power estimation is determined with the derivative current power formulas and these estimates are compared with the current estimates calculated with the classical method.

5.2.1 Current roses

The current directional density through time (between September 2015 and September 2016) for water depths namely H-5, H-10, H-15, H-20 and H-25 are shown in Figures 5.24 through 5.28.

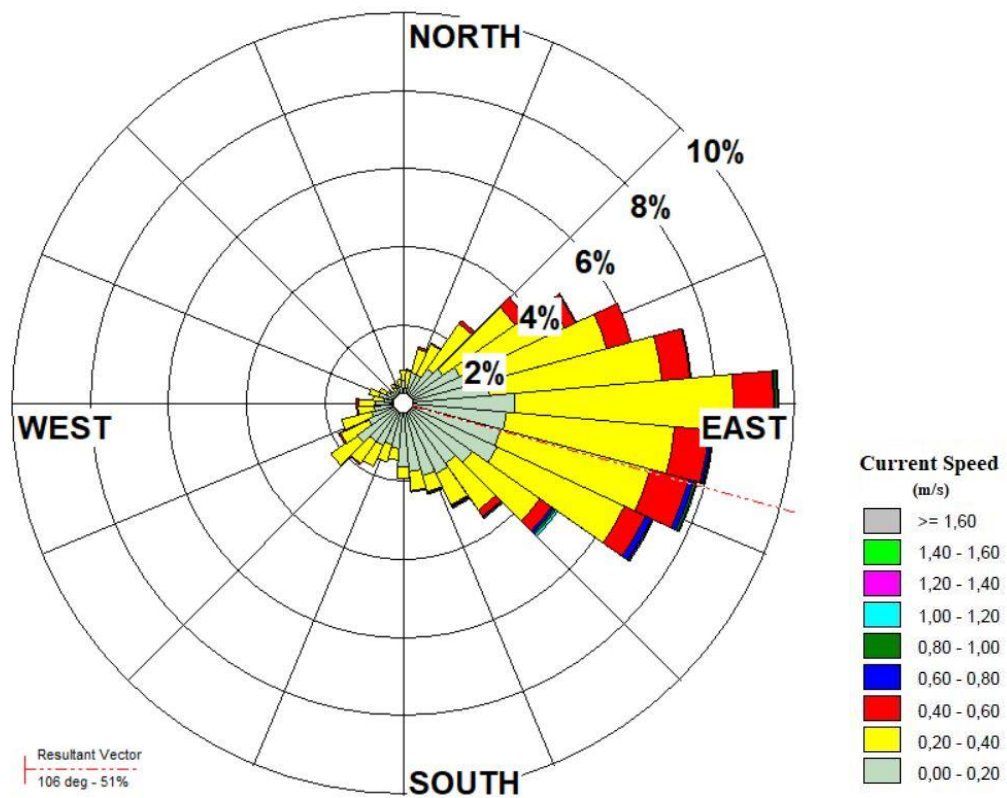


Figure 5.24 : Current rose diagram for H-5.

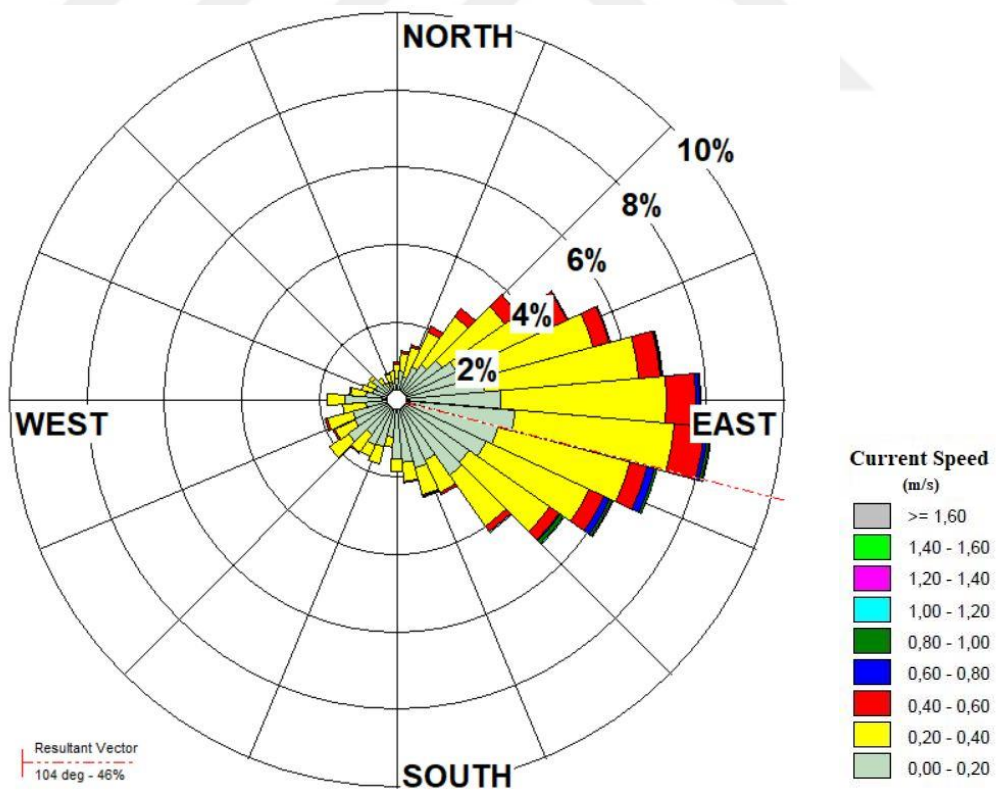


Figure 5.25 : Current rose diagram for H-10.

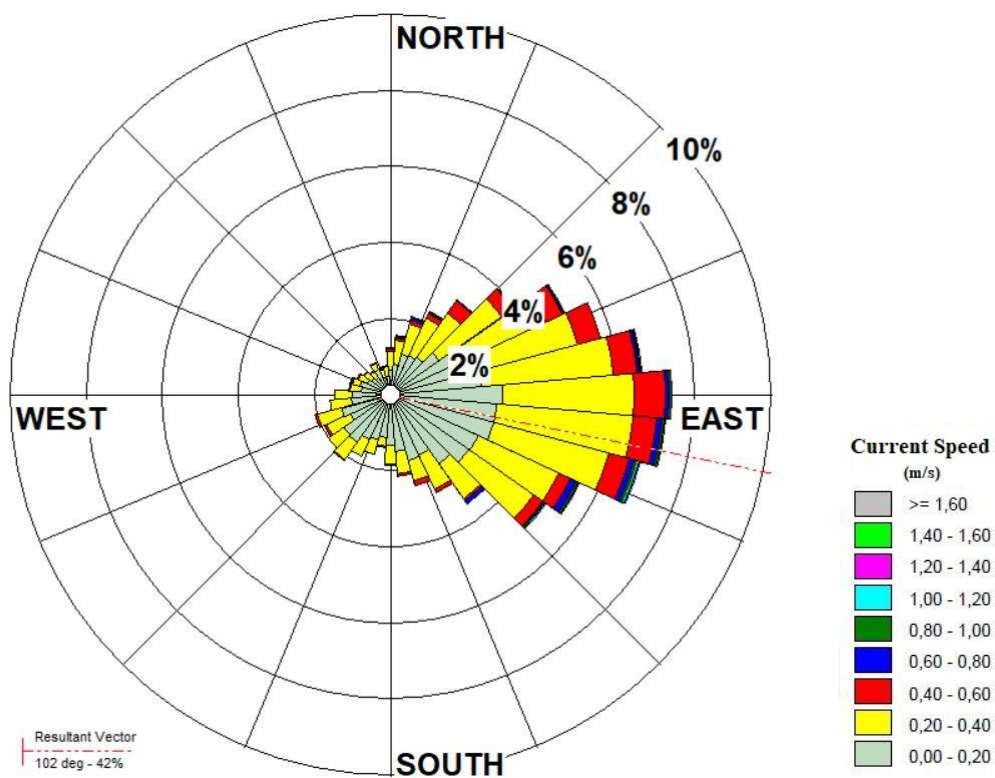


Figure 5.26 : Current rose diagram for H-15.

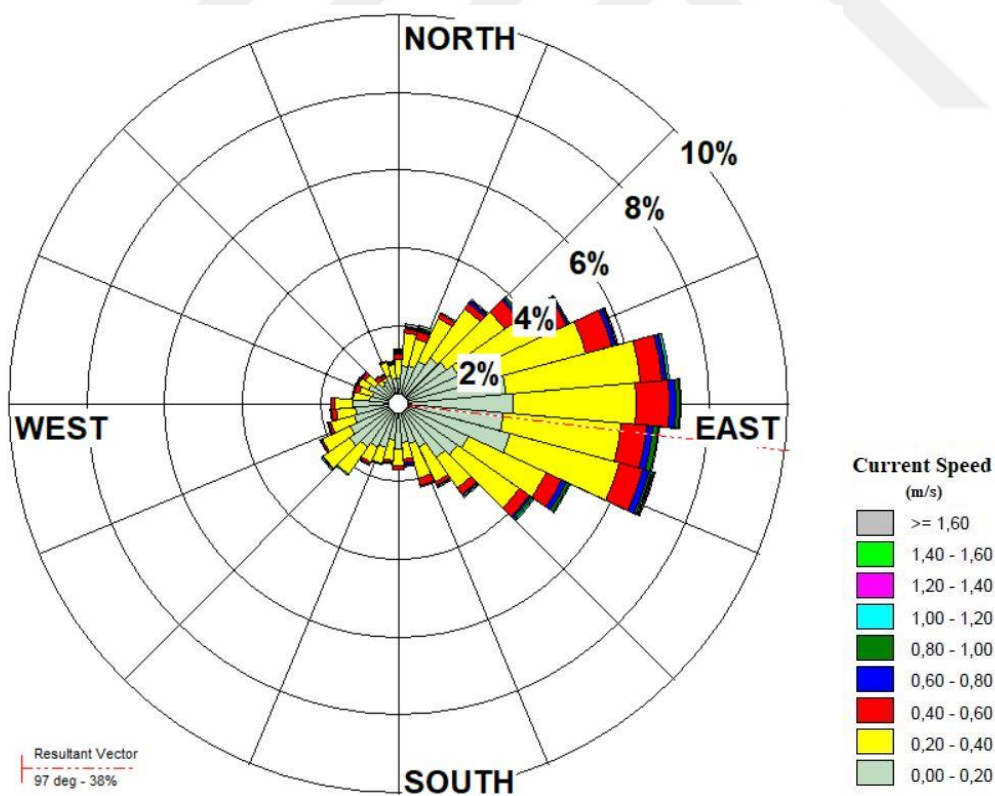


Figure 5.27 : Current rose diagram for H-20.

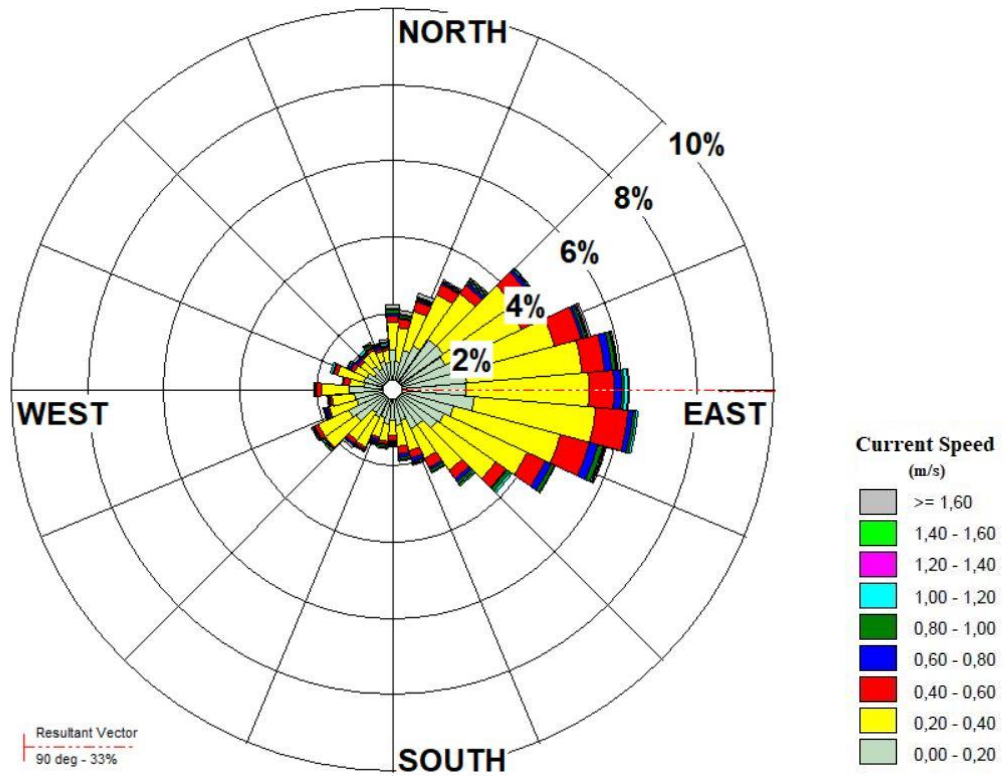


Figure 5.28 : Current rose diagram for H-25.

As the current roses are analyzed, it can be indicated that the prevailing path of the currents originates from the west.

5.2.2 Distribution characteristics of current speed

In this section, the various probabilistic distributions are theoretically tested to fit the observed upper layer current velocity. As a result of the K-S test, LP3 has agreed to adjust the current speed data at each depth with a 5% significance level. K-S testing depends on the maximum variance between the observed cumulative distributions and the overall theoretical distributions, and has been commonly used in many analyses (Jung and Schindler, 2019; Kollu et al., 2012; Sulaiman et al., 2002). The significant correlation between the observed data and the theoretical representation for each water depth as H-5, H-10, H-15, H-20 and H-25 can certainly be found in Figures 5.29 through 5.33.

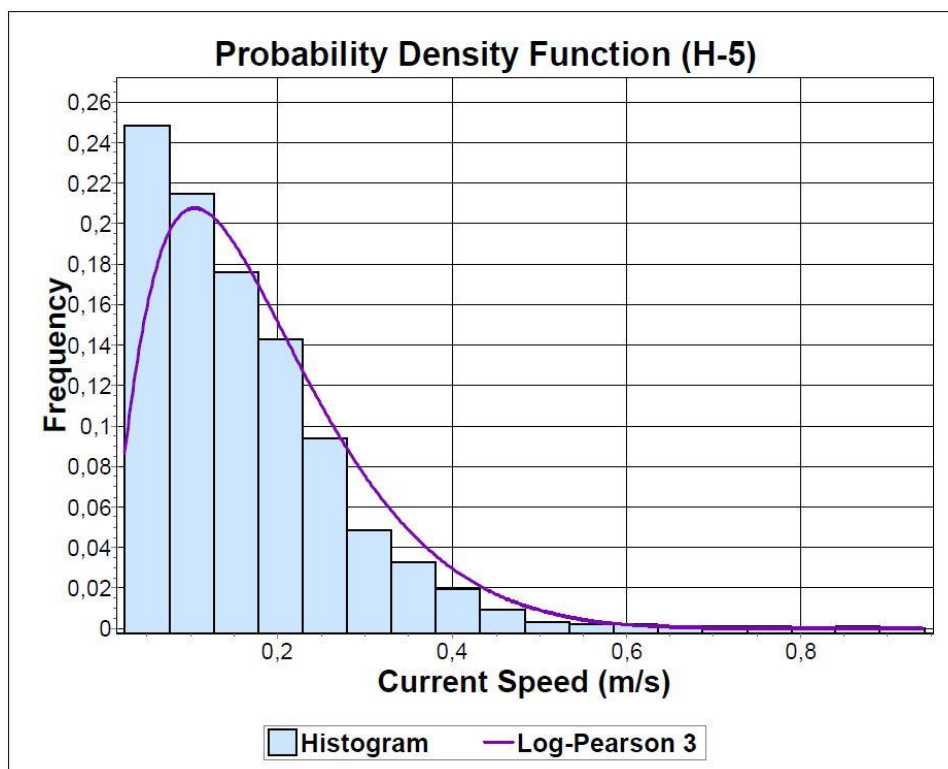


Figure 5.29 : Probability density functions of LP3 for H-5.

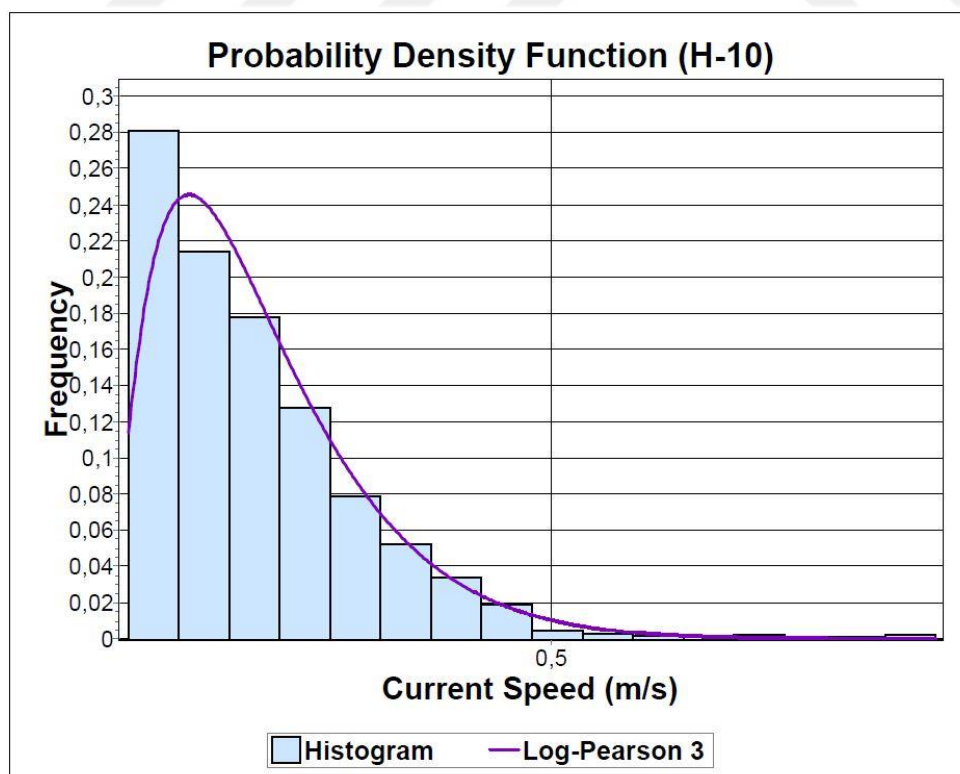


Figure 5.30 : Probability density functions of LP3 for H-10.

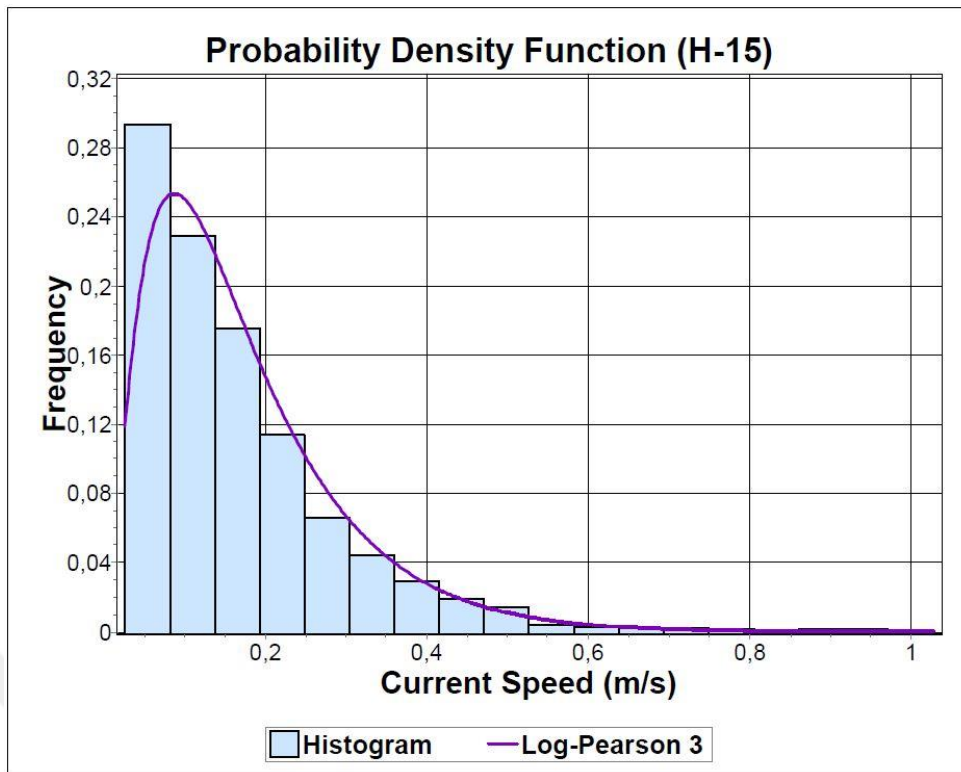


Figure 5.31 : Probability density functions of LP3 for H-15.

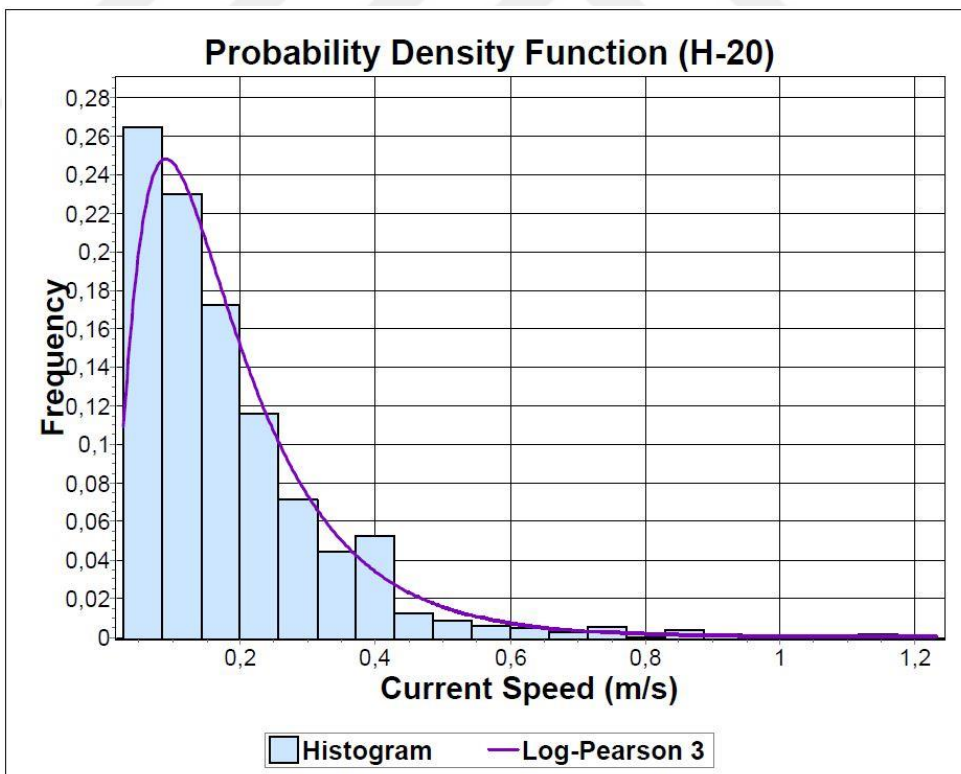


Figure 5.32 : Probability density functions of LP3 for H-20.

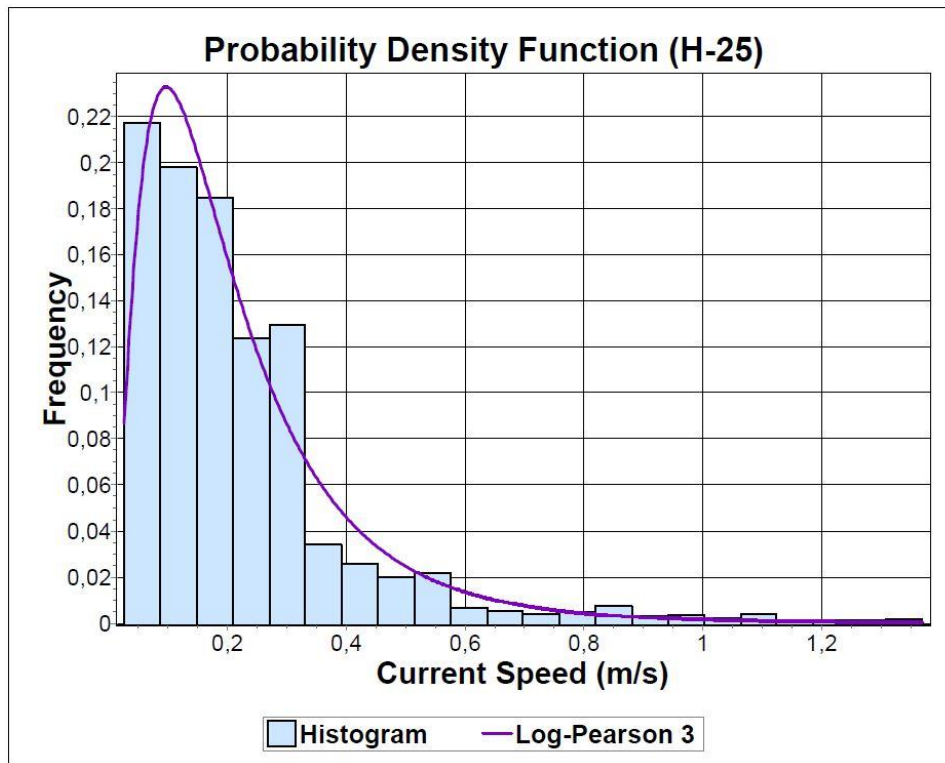


Figure 5.33 : Probability density functions of LP3 for H-25.

In addition to K-S test criteria, the Goodness-of-fit (Gof) statistical tests explains how well the measurement set matches. In general, Gof tests define the inconsistency between the observed data and the expected value of the model. In this analysis, similar to the K-S test, the probability density distributions obtained by the LP3 models were also analyzed using the p-value (from the K-S test), R^2 and RMSE. The result of the error statistics is mentioned in Table 5.9.

Table 5.9 : Error statistics of LP3 PDF.

Water Layer	Error Statistics		
	LP3 PDF		
	P-Value	R^2	RMSE
H-5	0.909	0.994	0.045
H-10	0.895	0.995	0.044
H-15	0.813	0.994	0.043
H-20	0.711	0.994	0.039
H-25	0.735	0.993	0.037

When the results in Table 5.9 is analyzed, it can be found that the p values are between 0.909-0.735, the R^2 values are between 0.995 and 0.993, and the RMSE values are

between 0.045 and 0.037. As a consequence of the data set out in Table 5.9, the LP3 distribution conforms to appropriate levels.

5.2.3 Log Pearson Type 3 distribution

The LP3 distribution is a component of the Pearson Form 3 distribution system, also widely regarded as the gamma distribution (Nick et al., 2011; Griffis and Stedinger, 2007). Many oceanographic studies in the literature have used the LP3 distribution (Bolgov and Korobkina, 2013; Ihimekpen et al., 2011; Lee, 2005). The LP3's probability density function is defined as follows (Koutrouvelis and Canavos, 2000):

$$f(x) = \frac{1}{|d|x\Gamma(e)} \left(\frac{\ln(x) - f}{d} \right)^{e-1} \exp \left[- \left(\frac{\ln(x) - f}{d} \right) \right] \quad (5.37)$$

Here,

d : scale parameter,

e : shape parameter,

f : location parameter,

The relevant cumulative distribution function (cdf) of the LP3 can be described as (Alam et al, 2018):

$$F(x) = \frac{1}{|d|\Gamma(e)} \int_0^\infty \frac{1}{x} \left(\frac{\ln(x) - f}{d} \right)^{e-1} \exp \left(- \left(\frac{\ln(x) - f}{d} \right) \right) dx \quad (5.38)$$

In order to obtain particular LP3 statistical moments, algebraic moments are used. If X is a random variable, the LP3's n th moment is defined as follows (Koutrouvelis and Canavos, 2000):

$$E(X^k) = e^{kf} (1 - kd)^{-e} \quad (5.39)$$

Furthermore, the n -th order statistical moment of the current velocity, V , for LP3 is established as:

$$E(V^k) = e^{kf} (1 - kd)^{-e} \quad (5.40)$$

As a consequence, the expected value (for $k=1$) from equation 5.40 can be described analytically as follows:

$$E(V) = e^f (1 - d)^{-e} \quad (5.41)$$

5.3 Current power perturbation with log Pearson type 3 distribution

The parameters for equation 3.9 were mentioned as follows, taking into account the analytical moment's expectations in equation 5.40:

$$E^3(V) = e^{3f}(1-d)^{-3e} \quad (5.42)$$

$$E(V'^2) = E(V^2) - E^2(V) = e^{2f}[(1-2d)^{-e} - (1-d)^{-2e}] \quad (5.43)$$

$$\begin{aligned} E(V'^3) &= E(V - \bar{V})^3 \\ &= e^{3f}[(1-3d)^{-e} - 3(1-2d)^{-e}(1-d)^{-e} \\ &\quad + 2(1-d)^{-3e}] \end{aligned} \quad (5.44)$$

Consequently, the estimated ocean current power for the LP3-compliant dataset can be determined by the following equation:

$$E(P) = \frac{1}{2}\rho e^{3f}(1-3d)^{-e} \quad (5.45)$$

The expected energy density, $E(E)$, for a unit area can be calculated using equation 5.46, as follows:

$$E(E) = \frac{1}{2}\rho e^{3f}(1-3d)^{-f}T_h \quad (5.46)$$

Similar to the LP3 Power equation derivation, the parameters for equation 3.14 are defined by using statistical moments mentioned in equation 5.40:

$$E^2(V) = e^{2f}(1-d)^{-2e} \quad (5.47)$$

$$E^3(V) = e^{3f}(1-d)^{-3e} \quad (5.48)$$

$$E^4(V) = e^{4f}(1-d)^{-4e} \quad (5.49)$$

$$E^2(V'^2) = e^{4f}(1-2d)^{-2e} - 2(1-2d)^{-e}(1-d)^{-2e} + (1-d)^{-4e} \quad (5.50)$$

$$E^2(V'^3) = e^{6f}[(1-3d)^{-e} - 3(1-2d)^{-e}(1-d)^{-e} + 2(1-d)^{-3e}]^2 \quad (5.51)$$

$$\begin{aligned} E(V'^4) &= E(V - \bar{V})^4 \\ &= e^{4f}(1-4d)^{-e} - 4(1-d)^{-e}(1-3d)^{-e} \\ &\quad + 6(1-d)^{-2e}(1-2d)^{-e} - 3(1-d)^{-4e} \end{aligned} \quad (5.52)$$

$$\begin{aligned} E(V'^5) &= E(V - \bar{V})^5 \\ &= e^{5f}(1-5d)^{-e} - 5(1-d)^{-e}(1-4d)^{-e} \\ &\quad + 10(1-d)^{-2e}(1-3d)^{-e} \\ &\quad - 10(1-d)^{-3e}(1-2d)^{-e} + 4(1-d)^{-5e}E^4(V) \\ &= e^{4f}(1-d)^{-4e} \end{aligned} \quad (5.53)$$

$$\begin{aligned} E(V'^6) &= E(V - \bar{V})^6 \\ &= e^{6f}(1-6d)^{-e} - 6(1-d)^{-e}(1-5d)^{-e} \\ &\quad + 15(1-d)^{-2e}(1-4d)^{-e} \\ &\quad - 20(1-d)^{-3e}(1-3d)^{-e} \\ &\quad + 15(1-d)^{-4e}(1-3d)^{-e} - 5(1-d)^{-6e} \end{aligned} \quad (5.54)$$

In conclusion, substituting equation 3.14 with all of these required terms yields the expected variance in current power as follows:

$$Var(P) = \frac{1}{4}\rho^2 e^{6f}(1-6d)^{-e} - (1-3d)^{-2e} \quad (5.55)$$

5.3.1 Current power estimation

Firstly, the parameters for the current speed data of the LP3 PDF need to be determined in order to evaluate the current power and energy according to equations 5.45 and 5.46. In this case, the parameters of the LP3 distribution are estimated by the MLM for each depth of water and are displayed in Table 5.10.

Table 5.10 : Parameters of LP3 PDF.

LP3 PDF's Parameters			
Water Layer	Parameters		
	<i>d</i>	<i>e</i>	<i>f</i>
H-5	-0.2717	6.8549	-0.0642
H-10	-0.2376	9.396	0.253
H-15	-0.1857	15.719	0.92125
H-20	-0.1531	24.07	1.754
H-25	-0.119	42.448	3.2595

After establishing the relevant parameters of the LP3 PDF, the mean power and energy production of the upper layer of the sea current in the vicinity of the northern Bosphorus is predicted and presented in Table 5.11 by using the perturbation theory.

Table 5.11 : Current power and energy estimation with the perturbation theory depending on LP3 PDF.

Perturbation Mean Power and Energy with Log Pearson Type 3			
Water Layer	Current Power Density (W/m ²)	Standard Deviation (W/m ²)	Current Energy (kWh/m ² /year)
H-5	7.1	13.63	62.24
H-10	6.98	15.55	61.19
H-15	7.71	21.26	67.59
H-20	11.05	37.19	96.86
H-25	21.24	95.04	186.19

According to Table 5.11, the current power density is determined to be between 6.98 W/m² and 21.24 W/m² using the perturbation method. The maximum current power density value at H-25 is 21.24 W/m². On the other hand, the lowest current power density value of 6.98 W/m² is calculated at H-10. When the standard deviation values are analyzed, it can be obtained that they range between 95.04 W/m² and 13.63 W/m². While the maximum standard deviation is 95.04 W/m² at H-25, the lowest standard

deviation is 13.63 W/m² at H-5. Current energy values are then estimated to vary between 61,19 kWh/m²/year and 186,19 kWh/m²/year. Whereas the maximum current energy is calculated at H-25 with 186.19 kWh/m²/year, the lowest current energy is predicted to be at H-10 with a value of 61.19 kWh/m²/year.

In addition, the current power density is estimated by the classical method at the same depth of water for comparative study. The current power density and energy values determined by the classical method using equation 3.18 are displayed in Table 5.12.

Table 5.12 : Current power and energy calculation with the classical method.

Classical Mean Current Power Density and Energy			
Water Layer	Current Power Density (W/m ²)	Standard Deviation (W/m ²)	Current Energy (kWh/m ² /year)
H-5	7.08	13.67	62.06
H-10	6.75	13.86	59.17
H-15	7.19	15.85	63.02
H-20	10.14	24.29	88.89
H-25	18.42	48.38	161.47

When the relevant values are Analyzed in Table 5.12, it is calculated that the current power density varies between 6.75 W/m² and 18.42 W/m² and that the highest power density is 18.42 W/m² at H-25, while the lowest current power density is 6.75 W/m² at H-10. The standard deviation value is calculated to be between 13,67 W/m² and 48,38 W/m². Moreover, current energy predictions with the classical approach range from 59.17 kWh/m²/year to 161.47 kWh/m²/year with the maximum current energy at H-25 with 161.47 kWh/m²/year and the lowest current energy at H-10 with 59.17 kWh/m²/year.

5.4 The South Coast of Turkey (Antalya and Mersin)

This part of the study includes wave power forecast for the southern coastline of Turkey. In this context, firstly, wave roses are formed and examined in detail. Then, wave period and SWH values, which are characteristic of wave power, were examined. As a result of the examination, the probability density distribution representing the wave period and SWH measurement data is determined as lognormal PDF. Error

statistics values for the lognormal distribution which is compatible with the measured wave period and SWH values are determined and presented.

After determining that the lognormal distribution is suitable for the measured wave period and SWH measurements by using K-S test, the equations for the wave power estimation are derived. First of all, equations are derived to estimate the wave power with the perturbation method by using the lognormal distribution. Then, equations are derived to estimate the wave power with the classical method by using the lognormal distribution. Finally, wave power estimation is made and presented at Antalya and Mersin stations on the southern coastline of Turkey with the derived wave power equations.

5.4.1 Wave roses

WRPLOT View, a rose plotting program, is used to display the roses. Although the software is intended for the development of wind roses, it can also be used to generate wave roses. Furthermore, the waves are connected to the SWH in meters. Then, as the spectrum of waves is divided by 9 intervals, SWH levels or intervals are defined as: 0.00-0.20, 0.20-0.40, 0.40-0.60, 0.60-0.80, 0.80-1.00, 1.00-1.20, 1.20-1.40, 1.40-1.60 and 1.6 and greater in meters. In this regard, Figure 5.34 and Figure 5.35 illustrate the wave roses, which offer a clear illustration of the path of the incoming waves for Antalya and Mersin stations, respectively.

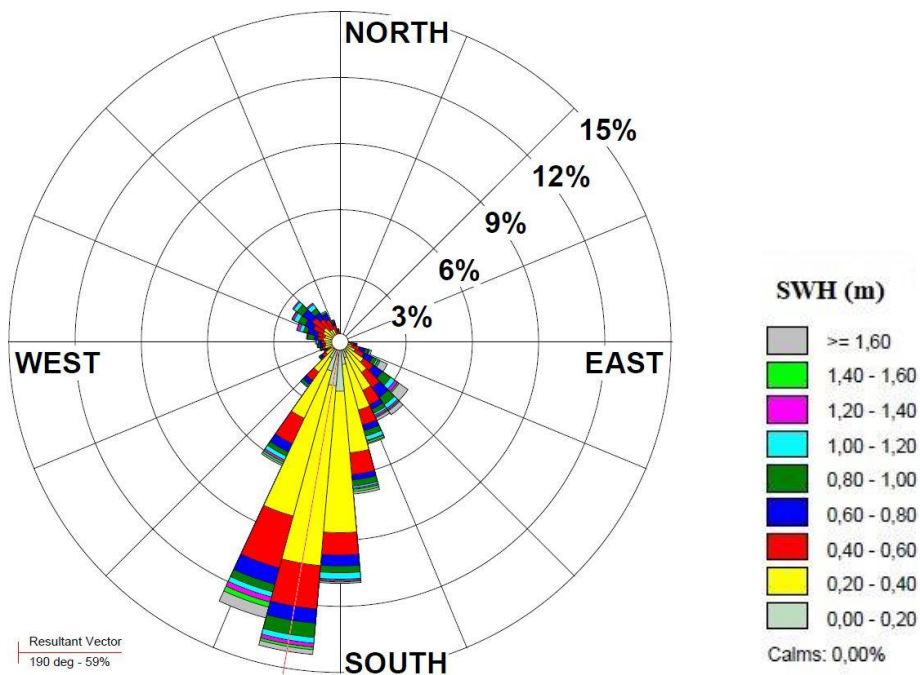


Figure 5.34 : Wave roses of Antalya station.

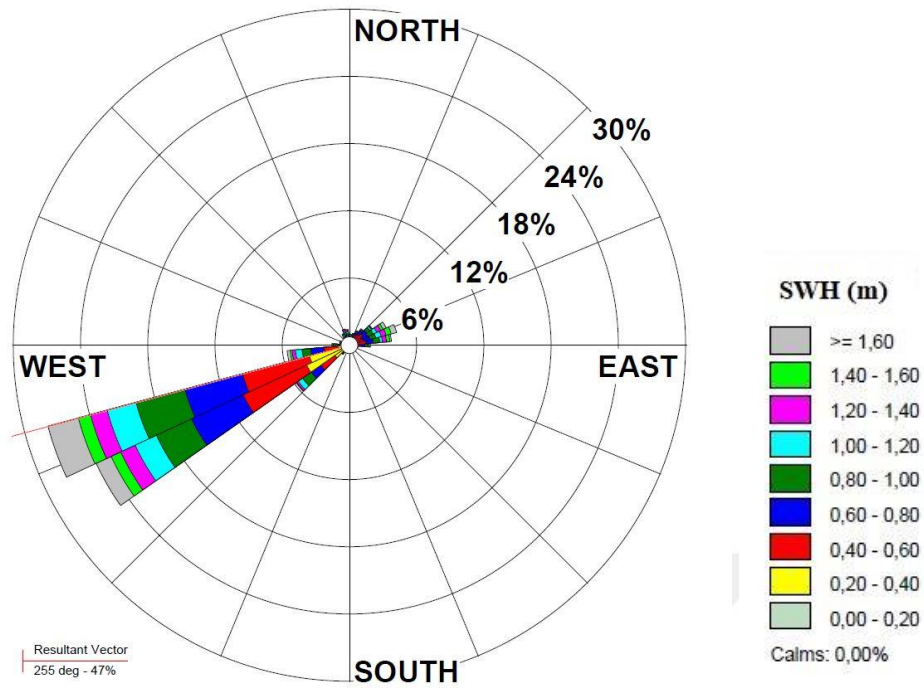


Figure 5.35 : Wave roses of Mersin station.

Since wave roses are analyzed, Figure 5.34 demonstrates that Antalya is primarily the target of South (S) to South-West (SW) waves. Furthermore, since the buoy station in the Antalya region is situated within the gulf, dominant waves are noticeable in the SSW direction. Moreover, the Mersin region is obviously affected by West (W) to SW waves. Aside from that, dominant waves can be seen in the WSW direction. The disparity in dominant wave directions at the two stations is due to the fact that the measuring buoy in the Antalya region is located within the Antalya Gulf and the measuring buoy in the Mersin region is relatively near to Cape Tisan.

5.4.2 Distribution characteristics

The whole year's wave record can be used to evaluate the parameters of the lognormal probability distribution equation, which can be used to determine the wave power potential. Therefore, wave data records for the whole year (over a 12-month period) are provided from the two stations, Antalya and Mersin, to assess the potential for wave power in this thesis.

5.4.2.1 Wave period

Since the wave period and the SWH are two variables of wave data over time, Figure 5.36 and Figure 5.37 indicate the probability density functions of the wave period for Antalya and Mersin stations respectively.

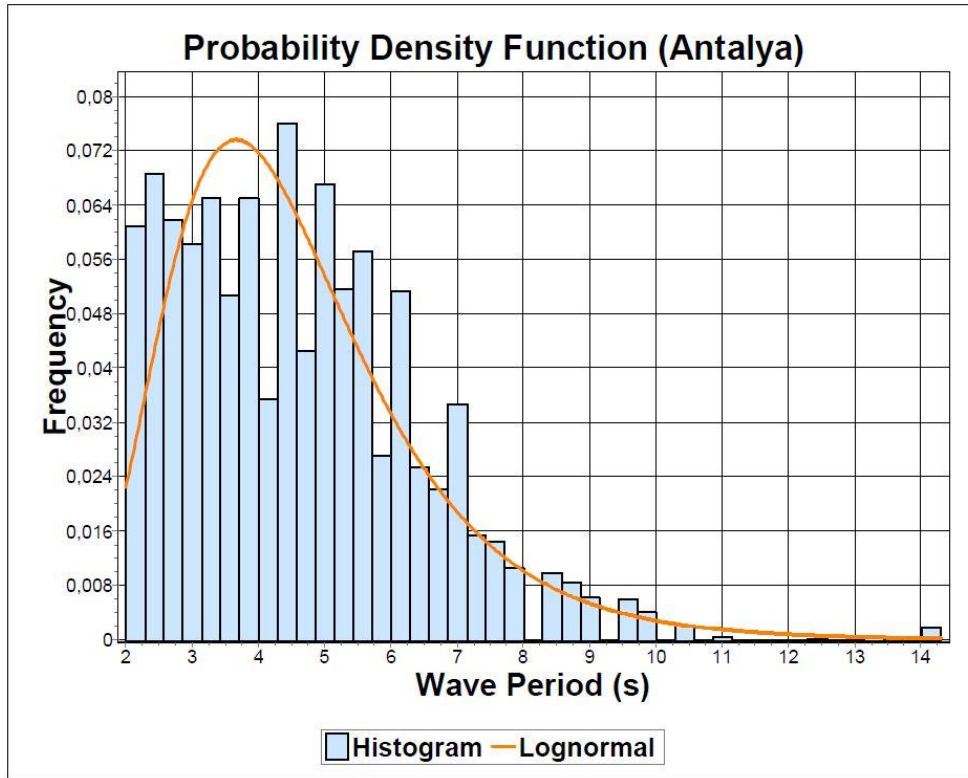


Figure 5.36 : Probability density functions of the wave period for Antalya station.

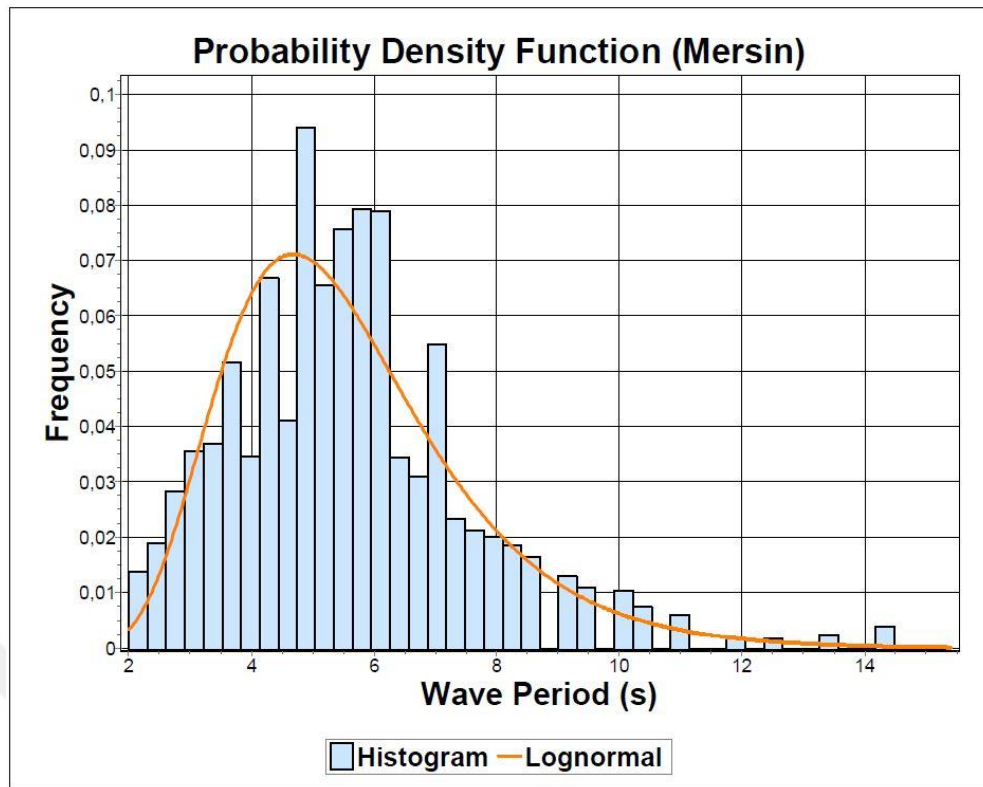


Figure 5.37 : Probability density functions of the wave period for Mersin station.

5.4.2.2 Significant wave height

Figure 5.38 and Figure 5.39 display the PDFs of the SWH for Antalya and Mersin stations, respectively.

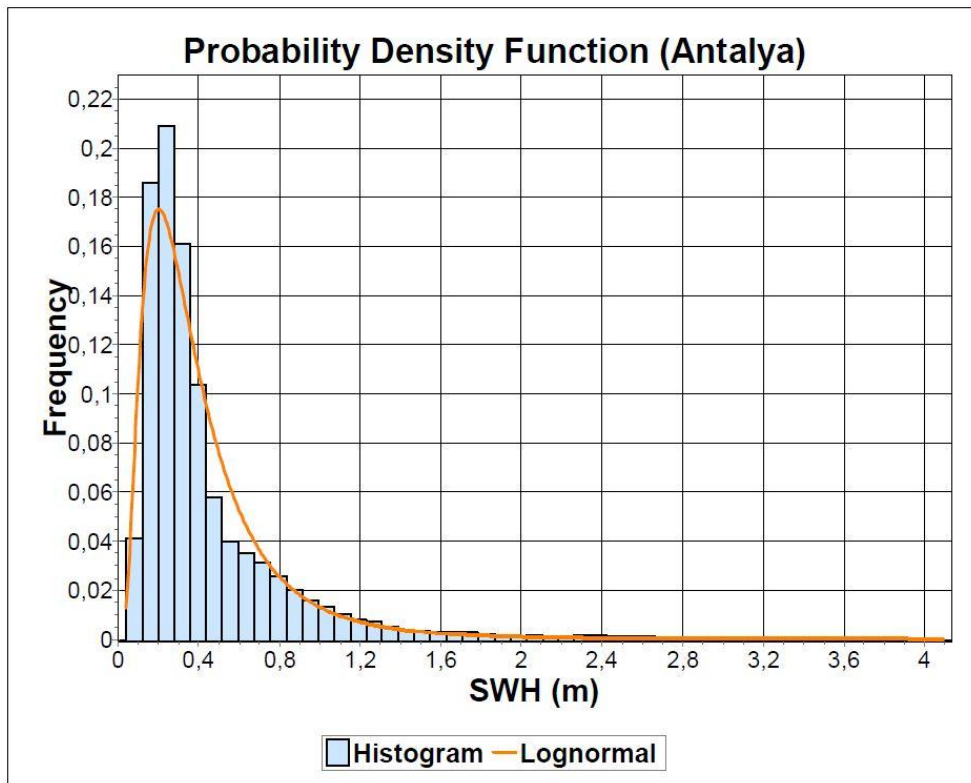


Figure 5.38 : Probability density functions of the SWH for Antalya station.

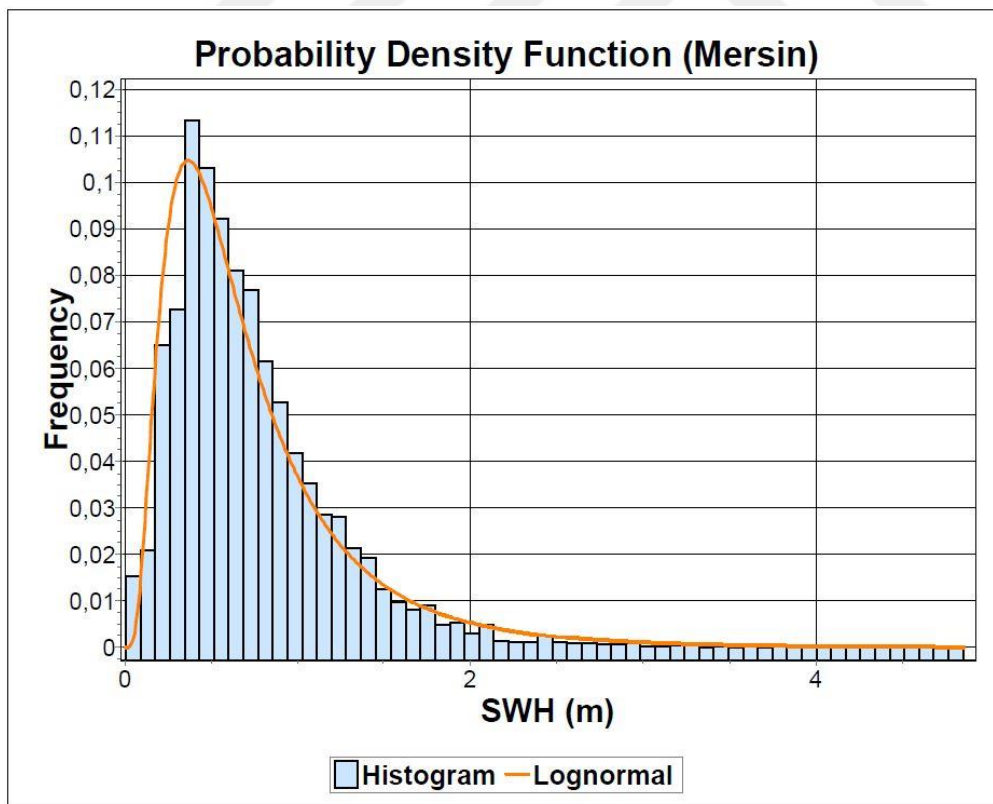


Figure 5.39 : Probability density functions of the SWH for Mersin station.

5.4.2.3 Error statistics

Lognormal probability density distributions, as seen in the figures mentioned previous section, are closely related to the observed probability density distributions. Hence, in order to assess if the lognormal PDF is suitable for wave data processing, the K-S is used, and a minimum 5 % significant level for both wave period and SWH is obtained at both locations.

In comparison to the K-S test, other Gof checks are used to examine the difference between the expected results and the original data using the lognormal PDF. The Gof test determines whether the fitted model correctly reflects the actuality of the data's observations (Hosmer and Lemeshow, 1980). In this thesis, three statistical errors are referred to as judgment criteria for evaluating the accuracy of lognormal PDF in addition to the K-S test.

The first is the R^2 , which is widely used in Gof tests since it represents the relationship between the observed and expected cumulative probabilities. RMSE is the next accuracy judgment, which proves the degree of distribution of two variables related around the mean expected value. The third and final assessment criterion is the Chi-square error (X^2), which is used to check if the measured probability differs from the expected probability, with a lower rate indicating a better match. The results of the Gof tests are presented in Table 5.13.

Table 5.13 : Error Statistics.

Station	Variable	Statistical tests of lognormal PDF		
		R^2	RMSE	X^2
Antalya	Wave Period (T)	0.9956	0.0248	0.0036
	SWH (H)	0.9946	0.0201	0.0008
Mersin	Wave Period (T)	0.9978	0.0185	0.0023
	SWH (H)	0.9984	0.0185	0.0066

Table 5.13 indicates that the values of R^2 , RMSE, and X^2 differ from 0.9984-0.9946, 0.0248-0.0185, and 0.0066-0.0008, respectively. As a result, these values obviously demonstrate that the lognormal PDF is a suitable function for the observed wave data.

5.4.3 Lognormal distribution

The lognormal distribution is a probability distribution of a random variable with a normally distributed logarithm (Kollu et al., 2012). The lognormal PDF obviously defined the probability distributions of the wave period and SWH histograms, that were dependent on all hourly observations (Lucas and Soares, 2015; Ruggiero et al., 2010; Haver, 1985). The PDF of two-parameter lognormal distribution is statistically expressed in the form (Liu et al., 2011; Celik et al., 2010):

$$f(x) = \frac{1}{x\sigma\sqrt{2\pi}} \exp\left[-\frac{(\ln(x) - \mu)^2}{2\sigma^2}\right] \quad (5.56)$$

Here,

μ : Location characteristic,

σ : Scale parameter,

Since statistical moments are required to evaluate certain statistical parameters of lognormal PDF, the following equations describe the n-th order statistical moment of lognormal probability distribution SWH, H, and wave period, T:

$$E(H^n) = e^{n\mu_H + \frac{1}{2}n^2\sigma_H^2} \quad (5.57)$$

$$E(T^n) = e^{n\mu_T + \frac{1}{2}n^2\sigma_T^2} \quad (5.58)$$

Where,

μ_H : Location characteristic of SWH,

μ_T : Location characteristic of wave period,

σ_H : Scale parameter of SWH,

σ_T : Scale parameter of wave period.

5.4.4 Wave power perturbation with lognormal distribution

The perturbation method and lognormal PDF can be used to estimate power and variance characteristics utilizing equations 3.34 and 3.49, respectively. In order to obtain a conceptual interpretation of wave power, the first and second terms of equation 3.34 can be represented as follows:

$$E(T) = e^{\mu_T + \frac{1}{2}\sigma_T^2} \quad (5.59)$$

$$E^2(H) = e^{2\mu_H + \sigma_H^2} \quad (5.60)$$

As a result, the expected wave power by using lognormal PDF can be obtained by necessarily substituting all related phrases into equation 3.34, which corresponds to the following representation:

$$E(P) = \alpha 0.49 e^{\mu_T + \frac{1}{2}\sigma_T^2} e^{2\mu_H + \sigma_H^2} \quad (5.61)$$

Furthermore, another disturbance expression of higher-order moments must be evaluated in order to achieve the basic formulation of the wave power variance with lognormal PDF as shown in equation 3.49. The terms of equation 3.49 are expressed in the form:

$$E^2(T) = e^{2\mu_T + \sigma_T^2} \quad (5.62)$$

$$E^4(H) = e^{4\mu_H + 2\sigma_H^2} \quad (5.63)$$

Consequently, after exchanging all of the required equations into equation 3.49, the variance of wave power with the lognormal PDF is obtained and defined as follows:

$$Var(P) = (\beta - \alpha^2)(0.49)^2 e^{2\mu_T + \sigma_T^2} e^{4\mu_H + 2\sigma_H^2} \quad (5.64)$$

By definition, the standard deviation of wave power with lognormal PDF, σ_{P_L} , is equal to the square root of equation 5.64, which is as follows:

$$\sigma_{P_L} = 0.49 \sqrt{(\beta - \alpha^2)} e^{\mu_T + \frac{1}{2}\sigma_T^2} e^{2\mu_H + \sigma_H^2} \quad (5.65)$$

Here,

σ_{P_L} : The standard deviation of wave power with using lognormal PDF by perturbation method.

5.4.5 Classical wave power derivation with lognormal distribution

On the basis of equation 3.50, it is possible to predict wave power using the classical method. Equation 5.59 already defines the first term in equation 3.50. After that, the second term of equation 3.50 can be written in the following form:

$$E(H^2) = e^{2\mu_H + 2\sigma_H^2} \quad (5.66)$$

By substituting all of these necessary terms into equation 3.50, the expected wave power is obtained using the classical method, as described below:

$$E(P) = 0.49e^{\mu_T + \frac{1}{2}\sigma_T^2} e^{2\mu_H + 2\sigma_H^2} \quad (5.67)$$

In order to determine the variance of wave power using the classical method, all of the terms in equation 3.53 need to be mentioned. Related terms are described as follows:

$$E(T^2) = e^{2\mu_T + 2\sigma_T^2} \quad (5.68)$$

$$E(H^4) = e^{4\mu_H + 8\sigma_H^2} \quad (5.69)$$

$$E^2(H^2) = e^{4\mu_H + 4\sigma_H^2} \quad (5.70)$$

By substituting all of these related terms into equation 3.53, the variance and standard deviation of wave power are presented by the classical method as stated in the definitions mentioned below:

$$Var(P) = (0.49)^2 [e^{2\mu_T + 2\sigma_T^2} e^{4\mu_H + 8\sigma_H^2} - e^{2\mu_T + \sigma_T^2} e^{4\mu_H + 4\sigma_H^2}] \quad (5.71)$$

$$\sigma_{P_{CL}} = 0.49 \sqrt{(e^{2\mu_T + 2\sigma_T^2} e^{4\mu_H + 8\sigma_H^2} - e^{2\mu_T + \sigma_T^2} e^{4\mu_H + 4\sigma_H^2})} \quad (5.72)$$

Here,

$\sigma_{P_{CL}}$: The standard deviation of wave power obtained with lognormal PDF by classical method.

5.4.6 Wave power estimation

After having the essential decision that the lognormal distribution is a suitable function, the lognormal PDF parameters can be calculated. The MLM, which has been utilized successfully in several studies, provides the distributional parameters of the lognormal PDF used in this thesis (Raju et al., 2020; Qin et al., 2012). The equations presented below generate estimates of the MLM for lognormal PDF parameters (Pobočiková et al., 2017):

$$\mu = \frac{1}{n} \sum_{i=1}^n \ln(x_i) \quad (5.73)$$

$$\sigma^2 = \frac{1}{n} \sum_{i=1}^n \left[\ln(x_i) - \frac{1}{n} \sum_{i=1}^n \ln(x_i) \right]^2 \quad (5.74)$$

The recorded wave period and SWH data from two separate buoy stations were used to estimate the lognormal PDF's location and shape parameters. Table 5.14 displays the results.

Table 5.14 : Statistical parameters for lognormal PDF.

Station	Variable	Parameters of Lognormal PDF	
		Location (μ)	Scale (σ)
Antalya	Wave Period (T)	1.4514	0.3923
	SWH (H)	-1.1102	0.70293
Mersin	Wave Period (T)	1.6619	0.34362
	SWH (H)	-0.5217	0.69272

As shown in Table 5.14, the location and scale parameters for the Antalya station are 1.45140 (μ_T), -1.11020 (μ_H), 0.39230 (σ_T) and 0.70293 (σ_H) for wave period and SWH, respectively. Furthermore, the Mersin station's location and shape parameters are determined to be 1.66190 (μ_T), -0.52170 (μ_H), 0.34362 (σ_T) and 0.69272 (σ_H) for wave period and SWH, respectively.

The expressions (μ_T , μ_H) are used to indicate that μ_T is a wave period location parameter and μ_H is a SWH location parameter. Correspondingly, the notations (σ_T , σ_H) are used to define that σ_T is a wave period's scale parameter and σ_H is a SWH's scale parameter.

After determining the appropriate lognormal PDF parameters, the wave power statistics, which include the mean power and the standard deviation amounts, are estimated using both perturbation and classical methods. Thus, the principles represented in the previous chapters are utilized to the hourly meteorological measurements available from Antalya and Mersin buoy stations from April 2015 to April 2016. Equations 5.61 and 5.65, respectively, are used to estimate the wave power and standard deviation using the perturbation method. Furthermore, equations 5.67 and 5.72 are used to calculate wave power and standard deviation using the classical method. The predictions of the analysis at Antalya and Mersin are presented in Table 5.15, with wave power data and standard deviations described in kW/m and annual wave energy expressed in MWh/m.

Table 5.15 : Mean wave power and energy estimation of Antalya and Mersin.

Wave Power and Energy with Lognormal PDF						
Station	By Perturbation Theory			By Classical Method		
	Mean Power (kW/m)	Standard Deviation (kW/m)	Annual Energy (MWh/m)	Mean Power (kW/m)	Standard Deviation (kW/m)	Annual Energy (MWh/m)
Antalya	1.13	11.31	9.91	0.66	1.79	5.78
Mersin	2.88	13.37	25.26	2.52	6.51	22.08

The mean wave power values for the Antalya and Mersin stations are determined to be 1.13 and 2.88 kW/m, respectively, using the perturbation method. The standard deviation values for the Antalya and Mersin stations are both 11.31 and 13.37 kW/m, respectively. Furthermore, the annual energy capacity for Antalya stations is calculated to be 9.91 MWh/m and 25.26 MWh/m for Mersin stations.

The classical method generates mean wave power values of 0.66 and 2.52 kW/m for the Antalya and Mersin stations, respectively. Moreover, the standard deviation values

for the Antalya and Mersin stations are calculated to be 1.79 and 6.51 kW/m, respectively. Furthermore, the annual energy capacity for Antalya stations is estimated to be 5.78 MWh/m and 22.08 MWh/m for Mersin stations.

When the Mersin and Antalya stations are compared, it is predicted that the Mersin station has more wave power capacity. Consequently, as shown by the analysis, the perturbation method can predict higher wave power values than the classical method. In the final analysis wave power values' empirical scatter is derived by applying the probability of exceedance, P_i , on the theory of the empiric probability calculation. Figure 5.40 depicts the relationship between the degree of risk on the vertical axis and the sum of wave power on the horizontal axis for Antalya and Mersin.

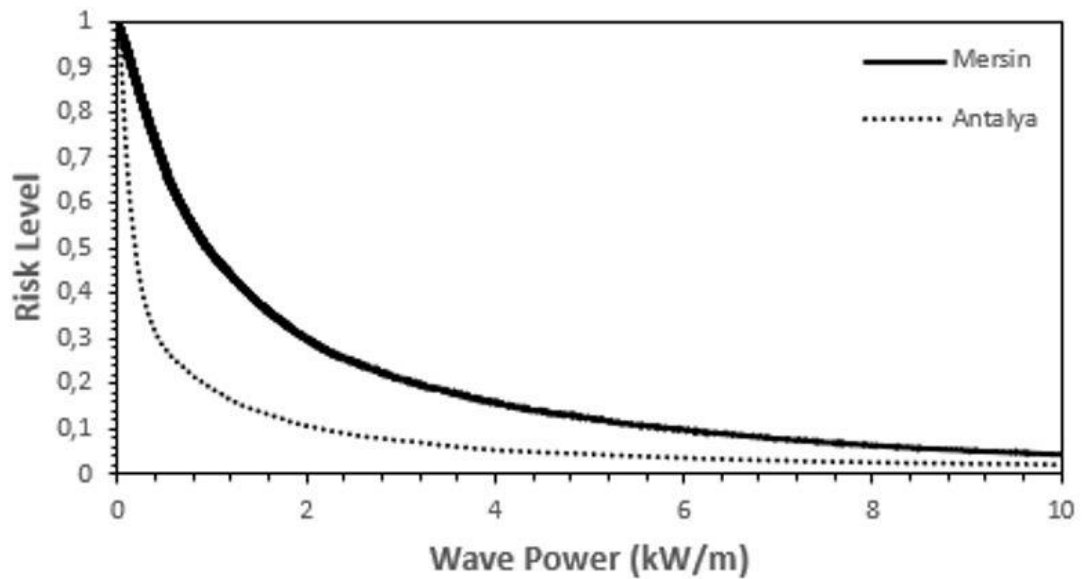


Figure 5.40 : Risk level study of Antalya and Mersin stations.

As a consequence, the unit power quantities corresponding to the 10% risk range for Antalya and Mersin are 2.13 kW/m and 5.87 kW/m, respectively .



6. CONCLUSIONS

In this study, current and wave power formulas are derived by using perturbation method. The current and wave power formulas derived by the perturbation method are different from the classical method with taking into account the fluctuation factor. Moreover, potential power capacities of the following locations are estimated with the derived power equations, respectively:

- The upper layer currents of the Dardanelles Strait,
- The bottom (density) layer currents of the Dardanelles Strait,
- The upper layer currents in the vicinity the northern Bosphorus and
- Wave power of Antalya and Mersin stations on the south coast of Turkey.

The results achieved for each of the listed locations are evaluated below. First, the results obtained for the upper layer currents of the Dardanelles Strait are indicated below:

In this study, estimating the current power values with a proper equation that takes into account the deviations from the mean current speed data was investigated. Towards this goal, the perturbation theory was applied to derive a new more accurate equation for the current dataset that abides by the GGD. By using new equations, the power and energy densities are estimated for the upper layers of the Dardanelles for H-5 to H-20 with 5 meter vertical intervals. The following conclusions can be made on the basis of the mentioned analysis:

- Based on the current rose, the bulk of the flow direction is from the Northeast.
- The yearly average current speeds are nearly equal around the depths, with H-10 being significantly more as 0.401 m/s while others are 0.381, 0.384 and 0.359 m/s for H-5, H-15 and H-20 individually. The significantly higher current speed values occur in late Summer and early Fall, with August being the maximum at 0.769 m/s for all depths, while the lower mean current speeds are identified during the warmer months, with May being the lowest at 0.225 m/s for all depths.
- The diurnal current speed variations can be found in a consistent structure and analysis indicates that higher current speeds of an average 0.355 m/s occur at

9 a.m. until 12 a.m. whereas the mean lower current speeds of 0.278 m/s are observed from midnight to 3 a.m. at all water levels.

- Numerous probabilistic distributions are statistically checked to fit the observed upper layer current speed for each water depth. Strong correlations with a 5% significance level by K-S test is observed between the recorded data and GGD in all depths from H-5 to H-20.
- The average value of sea current power and energy density using the relevant GGD equation are calculated as 46.45 W/m^2 and $407.23 \text{ kWh/m}^2/\text{year}$, respectively. Furthermore, the average current power value that was achieved with the classical method was determined as 16.82 W/m^2 .
- The average power values calculated with the perturbation methodology have been estimated to be higher than the classical method as the turbulence factor is added in the perturbation process.
- For a more detailed investigation, a single depth, H-10, was classified into four seasons for one year as H-10 depth yields the maximum power and energy densities than the others, with 51.73 W/m^2 and $453.47 \text{ kWh/m}^2/\text{year}$, respectively. The seasonal sea current power amounts ranged from 25.24 W/m^2 to 92.83 W/m^2 for H-10, where the minimum and maximum levels were obtained in Spring and Fall, respectively.
- The current power capacity at H-10 was expected to be 120.96 W/m^2 for the practicable range of risk (%10).

Secondly, the bottom (density) layer currents of the Dardanelles were examined. The results of the relevant study are given below:

This research is primarily dealing with the development of a current power formula that takes into account variations from the mean velocities. Power could be estimated more accurately if current speed data, whether wind or ocean current, is distributed according to the exponential distribution. The derived formula is applied to density currents in the Dardanelles Strait between 25m and 50m, at 5m intervals.

- Power densities for the exponential PDF are calculated to be in the range of 52.83 and 28.75 W/m^2 based on the equations obtained from the perturbation method.
- For the classical method, power density is estimated in the range of 29.96 to 20.64 W/m^2 .

- As a result of this analysis, it has been determined that the perturbation method predicts more power density than the classical method since turbulence (variations from the mean) is factored into the equation.
- Moreover, the maximum cross-sectional power is estimated to be 1.53 MW.

Then, the upper layer currents in the vicinity the northern Bosphorus were studied. The results of the associated research are summarized below:

Predictions of current turbine power and dynamics are critical for efficient use of current turbines. This study focuses on the derivation of current power equations using the perturbation theory, which calculates deviations from the mean velocity. The power and energy densities of the upper layers in the vicinity of the northern Bosphorus for H-5 to H-25 with vertical intervals of 5 meters were estimated using new derived equations. This study's major observations and findings are as follows:

- The current flow direction study shows that the bulk of the flow is coming from the West.
- The maximum current speed is calculated to be 1,379 m/s at H-25 water depth, with mean current speeds ranging from 0.173 to 0.221 m/s.
- It has been determined that current velocities ranging from 0.00 to 0.40 m/s account for more than 84.4% of the total mean current velocities.
- Numerous probabilistic distributions are statistically checked to fit the observed upper layer current speed. At water depths ranging from H-5 to H-25, there are clear correlations with the 5% significance point of the K-S test between reported data and LP3 PDF.
- The maximum value of ocean current and energy density at H-25 is estimated to be 21.24 W/m² and 186.19 kWh/m²/year by using derived LP3 equations. Furthermore, the estimated current and energy density achieved by the classical method are predicted to be 18.42 W/m² and 161.47 kWh/m²/year, respectively, at the same water depth.

Finally, wave power estimation has been made at Antalya and Mersin wave measurement stations on the south coast of Turkey. Assessments of the wave power estimation are presented below:

Wave power predictions are influenced by time series of wave period and SWH. Unlike previous study, which has typically focused on the classical approach, this study has used the perturbation method, which takes into account deviations from the

mean values of wave period and SWH, with lognormal PDF. The following are the main findings and conclusions of this study:

- Since the wave period and the SWH are stochastic components, each term was perturbed. The general expressions of the wave power and variance equations were then derived using both the perturbation and classical methods.
- An hourly recorded dataset of wave period, SWH, and wave direction collected from two buoy stations located on Turkey's south coast was used to investigate the wave capacity of Turkey's south coast. The data was collected over a 12-month duration, between April 2015 and April 2016. Monthly statistics such as the mean wave period, SWH, and standard deviation were estimated. Furthermore, monthly variations in the mean wave period and the SWH were determined using time series data. At both stations, the maximum monthly mean wave period was expected to be between January and February, and the minimum mean wave period was estimated to be between July and August. Besides that, the highest SWHs were recorded at both stations between January and February, while the lowest SWHs were recorded between July and August.
- To perform a statistical analysis of the observed observations, the predicted values for mean and variance are obtained by assuming that the wave period and SWH are fitted with lognormal PDF. For both perturbation and classical approaches, the equations of wave power and variance were obtained using statistical moments of lognormal PDF.
- The wave roses were extracted and described to provide a detailed description for the direction of the incoming waves. It was confirmed that the Antalya region was primarily the focus of S to SW waves, and the main waves were visible in the direction of SSW, as the Antalya region's buoy station is situated within the Antalya Gulf. Moreover, the Mersin area was normally dominated by W to SW waves, and the prevailing waves were visible in the WSW direction since the measuring buoy in the Mersin area was located near Cape Tisan.
- The cumulative distribution functions of the wave period and the SWH were provided for the Antalya and Mersin stations. The K-S test was then operated, and a minimum 5% significance rate for both wave period and SWH was achieved at both locations. In addition to the K-S test, the goodness-of-fit tests,

namely R^2 , RMSE and X^2 , were utilized. R^2 , RMSE and X^2 values varied from 0.9984-0.9946, 0.0248-0.0185, and 0.0066-0.0008, respectively. After determining the proper distribution, the parameters of the lognormal PDF were determined by MLM.

- The mean wave power and standard deviation values were calculated using both perturbation and classical methods. The mean wave power values for the Antalya and Mersin stations were determined using the perturbation method to be 1.13 kW/m and 2.88 kW/m, respectively. Furthermore, the standard deviation values for the Antalya and Mersin stations were determined to be 11.31 kW/m and 13.37 kW/m, respectively. According to the classical method, the average wave power values for the Antalya and Mersin stations are 0.66 kW/m and 2.52 kW/m, respectively. The standard deviation values for the Antalya and Mersin stations are also expected to be 1.79 kW/m and 6.51 kW/m, respectively.
- For the 10% practical risk level, the wave power capacity of Antalya and Mersin stations are determined to be 2.13 kW/m and 5.87 kW/m, respectively. Consequently, current energy has the potential to be one of the most efficient and beneficial options due to its sustainability and low environmental impact. Thus, a reliable study of predicted current capacities at different locations is crucial for determining the best locations for optimal capacity to produce current energy. The results of this research indicate that in order to achieve the optimal current turbine design, which has the greatest effect on increasing viable investment and current energy generation, it is critical to use fluctuations. For this reason, the perturbation theory was used to estimate mean current power density, which is expected to be higher than the classical approach when the turbulence factor is integrated to the perturbation process. In addition to current power estimation, the perturbation theory results were investigated and compared to the findings of the classical approach in order to achieve more improved investment of wave power generation. As a consequence of the analysis, it was determined that using perturbation theory generates improved results in wave power calculations as well as in current power predictions. The skewness of the data is also thought to play a role in the perturbation technique's values being different from those determined by the classical method. The difference between the values obtained by the perturbation theory and the value obtained by the classical technique increases as the skewness

of the data rises. Future studies should focus on the potential application of different current and wave energy conversion arrangements in the field.



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