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RESEARCH ARTICLE

Statistical characteristics, probability distribution, and power potential of sea water velocity in Turkey

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Abstract: Sea currents have the potential to supply electricity from a renewable energy source to coastal regions. The assessment of the potential energy that could be generated is the first step toward developing this resource. In this study, the data was collected at 5 m and 35 m depths below the sea surface level, including sea current velocity and direction. A detailed field measurement, of the probability of sea water velocity at three stations (Antalya, Silivri, Istanbul) for 5 months is carried out. The sea current power density values in these stations were 10.41, 4.92, and 7.91 W/m^2 at 5 m depth, respectively. Besides, average sea current power density values were seen to be closely arranged with 11.44, 4.07, and 9.06 W/m^2 at 35 depths, respectively. In addition, statistical analysis applying Weibull and Rayleigh models is also presented. It is shown that the use of a Weibull probability distribution facilitates the analysis of sea velocity conditions and is also able to predict the power density with a high degree of accuracy. The results of this study are useful for the understanding of the marine hydrokinetic energy of these areas, where sea current power projects may be started in Turkey.

Keywords: Marine hydrokinetic, Ocean power, Sea current velocity, Turkish seas, Weibull, and Rayleigh probability function.

1. Introduction

In the last decade or so, renewable energy resources (RES) have become a necessity and sought after all over the world, with their uptake rapidly increasing in most developing and/or developed countries. [1]. Especially in terms of generating electricity, the RES has been thought to play a central role. The power generation from the RESs is considered to be sustainable, cleaner, environmentally friendly, and cost-effective, compared to the power from traditional power resources. Moreover, they are much more cost-effective as well. The Increasing deployment of the RESs for the future power grid is an indication of the appropriateness of sustainable energy generation [2]. Although the main forms of renewable energy such as biomass, hydroelectricity, wind, solar, and geothermal energy still predominate the entire energy landscape, other sources such as various forms of ocean energy have also proved promising and extensive discussions about the feasibility of them have taken place during the last decades [3]. It has been estimated that the share of RES in the total primary energy supply will see a dramatic increase from 14% in 2015 to 63% in 2050. This increase corresponds to an annual average growth rate of 1.4%. Simultaneously, the share of fossil fuels would drop from 86% to 37%. Though energy consumption from 2015 to 2050 is expected to be almost constant, economic activity is predicted to triple. The growth of the RES together with the spectacular increase in energy efficiency could provide a 94% reduction that would enable it to stay within the limits of the Paris Climate Agreement. All these have repercussions and consequences not simply related to the energy sector, but also to the way societies are organized in their entire ecosystem [4].

Ocean energy technologies are typically classified according to the source of energy they use. The most widely used technologies across geographies are tidal stream and wave energy converters. Other types of ocean energy technologies, such as those that harness energy from differences in salinity or temperature, or those that use ocean currents, could become more relevant over the long run. The current total installed capacity for all ocean energy technologies is 534.7 MW. Tidal barrage technology accounts for more than 98% of the total combined capacity currently operational, or 521.5 MW. Thus, ocean energy resources have the potential to be a significant source of RES, with estimates indicating that up to 337 GW of installed capacity could be available globally by 2050 [6].

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Ocean currents are streams formed by the vertical and horizontal components of the ocean's circulation system which are produced by wind friction, gravity, and variations in water density in different parts of the ocean. These currents, like winds in the atmosphere, transfer large amounts of heat from the equator to the poles and thus play an important role in determining the climates of coastal areas. Moreover, atmospheric circulation and ocean currents influence one another [8]. The relatively constant flow of ocean currents carries large amounts of water across the earth's oceans. Technologies are being developed so that this energy can be extracted from ocean currents and converted to usable power Ocean currents have a wide range of effects on marine life, moving not only plants and animals around the ocean but also redistributing nutrients and heat [9]. However, they also cause erosion, accretion, and change the coastal morphodynamics of beaches and ocean water intake structures [10].

Long-term and oceanographic monitoring in the open sea is a well-recognized key topic for scientists studying the oceans, atmosphere, and their interactions. Long-term open-sea data are important for the possible climate changes, weather phenomena, and analysis of air-sea exchange processes. The use of real-time data for regional forecasts and nowcasts is to be used by various user groups dealing with the marine environment for operational activities such as fishing, natural hazards warnings, recreational boating, and rescue operations [11]. In general, databases can result from numerical oceanographic reanalysis or satellite altimetry campaigns. In situ, ship, buoy, or high-frequency radar (HFR) can also be sources of basin-scale long-time series of ocean current data [12]. Examples of these data are given in the following literature study.

HFR measures surface currents in coastal oceans using high-frequency radio waves. HFR has working ranges of up to 200 km and spatial resolutions ranging from 300 to 1000 m. HFR datasets have been heavily used in the last two decades to supplement the understanding of basin scale and circulation in the Atlantic and the Pacific oceans [13]. For example, mesoscale surface current features were studied in the Gulf Stream region [13], in the Monterey Bay [14], in the Monterey Bay [15], in the Long Island [16], in the Kuroshio region [17], in the Gulf of the Farallones [18], for Mid-Atlantic Bight [19], etc. HFR surface current measurements provide insight into the fine structure of nearshore tidal and residual circulations [14,16,20]

The use of satellite products provides data with global coverage but is discontinuous in time, particularly for single-point instruments like altimeters. Furthermore, satellite data must be validated in order to determine the overall precision of the derived dataset [21,22] Ships are a valid support for proper data collection, but they are expensive, prone to problems due to bad weather, and in any case, limited by time and space. When attention is centered on a particular zone, the problem can be successfully solved, at least in terms of time continuity, by using permanent custom-made facilities such as drifting – for example, moored buoys [23] – and ARGO network [23]. These systems, if properly designed, may be able to collect data series in situ for long periods, even in rough seas [11].

The key point is to provide data in an inner sea, where both satellites detected numerical model and physical parameters outputs may show a lack of reliability and accuracy, to complement with open sea ones, the data taken on land. As a result, in the 1970s, the buoy was used to test instruments and components that would later be used on buoys, such as radio transmission systems and electronic acquisition systems. Over the years, the buoy has also been available to outside users. So many research organizations have used the buoy extensively, for specific measurement campaigns as well as the data collected on board regularly. Simultaneously, partnerships with a few small and medium-sized businesses were formed to equip the buoy with data acquisition and updated measurement systems. Wave buoy-based current velocity estimation will also supply a separate current velocity dataset for a variety of global regions where data is currently unavailable. This can be utilized to calibrate and validate numerical models as well as utilized directly for offshore designs [11]. An example of the work done on buoys took place between 2007 and 2009 by the Icelandic Meteorological Office (IMO) which conducted meteorological buoy measurements in the central Iceland Sea [25]. Oliveira et al. observed the current surface circulation and energetics of Brazil with buoys [26].

Various mathematical models for long-term ocean current speed distributions can be considered. The two-parameter Weibull and Rayleigh models are among them. These models are thought to be the current speed distribution in stochastic processes. Given that the two-parameter Weibull distribution and Rayleigh are appropriate for ocean current speed, it is practical to consider and investigate the effect of reflecting ocean current speed in the three-parameter Weibull distribution. Acceptable statistical estimates of the distribution parameters are required for the probability density function to be used successfully [27]. The parameters of the Weibull distribution over the global ocean were estimated based on geostrophic altimetry-based velocities [28]. For example, Chu [29] discussed the Weibull parameters of the upper equatorial Pacific current speed estimated using six stations' hourly ADCP data. Kim et al. [30] applied a statistical model for actual sea current data. They showed that the suggested model can be considered a dependable method that is very simple and has satisfactory results. Kabir et al. [6] analyzed ocean current statistics from the Gulf Stream (North Carolina shore) and found that the Weibull distribution properly fits the current speed PDF. Ashkenazy and Gildor [31] determined the probability density function of sea surface currents obtained with HF radar. They showed that the density of sea surface current velocities can be estimated by the Weibull function model. Ocean energy and offshore wind will have similar development constraints. However, the statistics of sea currents, in contrast to wind speed, have attracted much less attention.

The main aims of the present study are as follows:

a) Measuring hourly sea current velocities at Antalya, Silivri, Istanbul (Istanbul strait) stations, which are located in the Mediterranean sea, a sea of Marmara, and the Black sea of Turkey at 5 and 35 m depths below the sea surface for five months.

b) To model frequency distributions of hourly sea current velocities by utilizing the Weibull and Rayleigh probability density functions.

c) To determine and compare for three stations the sea current velocity probability distributions, frequency distributions of sea current directions, sea current velocity, sea current hydrokinetic power potential, and standard deviations.

d) To shed light on the specificity of Turkey which is surrounded by a sea on three sides including also an important internal sea, the Sea of Marmara, located between the straits of the Bosphorus and the Dardanelles. Turkey has experienced impressive growth in renewables in the past decade (especially wind, solar and geothermal). However, little research has been made about the amount of energy possessed by the sea in Turkey. In addition, there are no marine power plants installed in its seas. Hence a study based on the field measurement of sea water velocity in Turkey is particularly important. In this sense, this study may also provide the necessary information for the potential investors on the costs and economical aspects of planning the sea energy project. Therefore, in addition to other alternative energy sources, we propose to use sea energy resources as a way to expand Turkey's energy matrix in the coming decades.

2. Method

2.1. Statistical Variables and Probability Density

Mean sea current velocity (μ) is simply a numerical average, and is calculated as;

$$\mu = \left(\frac{1}{n}\right)\sum_{i=1}^{n} v_i \tag{1}$$

Standard deviation is expressed as;

$$\sigma = \left(\frac{1}{n-1}\sum_{i=1}^{n}(v_i-\mu)^2\right)^{1/2} \tag{2}$$

It seems easier and more comprehensible to make statistical analysis by converting the sea current velocity (*v*) data prepared in time-series format into a probability distribution format. In this way, the sea current velocity probability distributions can be used as the primary tools for marine current energy analyses. For each velocity class, the probability density is defined as;

$$f(v_i) = f_i \Big/ \sum_{i=1}^{n} f_i \tag{3}$$

Here, *N* indicates the time during the defined period, and repeatability of the same magnitude sea current velocity or frequency is symbolized by f_i.

If a random variable is discrete, the mean or expected value and variance of this variable with probability distribution *f (v)* are respectively calculated as follows:

$$\mu = E(V) = \sum_{v} v f(v) \tag{4}$$

$$\sigma^2 = E[(V-\mu)^2] = \sum_{v}(v-\mu)^2 f(v) \tag{5}$$

Several methods can be used to get the distribution of sea current velocity frequency to generate an adequate statistical model that can predict marine current power capacity. Weibull distribution and Rayleigh distribution are among the most used methods in the literature.

2.2. Weibull Distribution

Weibull distribution can be used as a way of defining sea current velocity density. The Weibull probability distribution is defined as [32,33];

$$f_W(v) = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1} exp\left[-\left(\frac{v}{c}\right)^k\right] \tag{6}$$

The cumulative Weibull probability distribution is expressed as;

$$F_W(v) = 1 - exp\left[-\left(\frac{v}{c}\right)^k\right] \tag{7}$$

where *v* is the sea current velocity. The *c* and *k* parameters are called scale and shape coefficients, and they are obtained from the sea current velocity data arranged in time-series format. The shape factor is calculated as:

$$k = \left(\frac{\sigma}{v_m}\right)^{-1.086} \quad (1 \le k \le 10) \tag{8}$$

Later, the scale parameter equation is given as follows:

$$c = \left(\frac{v_m}{\Gamma(1+\frac{1}{k})}\right) \tag{9}$$

2.3. Rayleigh Distribution

A special case of the Weibull model is called the Rayleigh function. Assuming that the shape factor *c* of the Weibull function is equal to 2, the Rayleigh function is obtained. The Rayleigh probability density function and the cumulative density function can be calculated as follows:

$$f_R(v) = \frac{\pi v}{2\mu^2} exp\left[-\left(\frac{\pi}{4}\right)\left(\frac{v}{\mu}\right)^2\right] \tag{10}$$

$$F_R(v) = 1 - exp\left[-\left(\frac{\pi}{4}\right)\left(\frac{v}{\mu}\right)^2\right] \quad (11)$$

2.4. Power Potential of Sea Current Velocity

The power of the sea current that flows at velocity v through a turbine-swept area A increases as the cube of its velocity, and it is calculated as follows [34,35]:

$$P(v) = \frac{1}{2}\rho A v^3 \quad (12)$$

On the other hand, the current power density of the turbine per unit area considered based on any probability density function can be calculated as follows:

$$P(v) = \sum_v \frac{1}{2}\rho v^3 f(v) \quad (13)$$

3. Results and Discussion

3.1. Study Areas

The country is located at the crossroads of the three continents that make up the old world: Europe, Asia, and Africa. The Turkish peninsula is bathed by four seas: the Black Sea to the north, the Sea of Marmara to the northwest, the Aegean to the west, and, the Mediterranean to the south. The Sea of Marmara between the Asian and European land masses includes the Bosphorus and Dardanelles Straits. The entire coastline is over 8,000 kilometers long.

As presented in Figure 1, sea currents velocities and directions were measured by the buoy for 3 stations in Turkish seas by the Turkish State Meteorological Service. Information about the device feature is given in Table 1 and for measurement stations in Table 2. The current measurements, which yield a time series of hourly sea current velocities and directions, were performed with an ensemble interval of 1 hour. The measurements obtained from 5 and 35 m depths below the sea surface level were carried out from May 1, 2019, to September 30, 2019, covering 5 months period The sea water data consists of hourly sea current velocities and their corresponding current directions. The variations of hourly measured sea current velocity values for two depths over 5 months are shown in Figure 2.

Table 1. Information about device feature

Measuring station and device feature	Information and properties
Measuring instrument	ODAS04TR(MAS)
Height	4.51 m
Tower type	1.80 m
Power supply	Solar energy
Connection	GSM / GPRS

Table 2. Information about measurement stations

Station Names	Station numbers	Station areas	Station latitude	Station longitude
Antalya (Antalya gulf)	1	Mediterranean Sea	36°43'00" N	31°01'00" E
Silivri	2	Marmara Sea	41°04'23" N	28°14'22" E
Istanbul (Istanbul strait black sea exit)	3	Black sea	40°55'58" N	28°56'56" E

3.2. Current Flow Direction Structure of the Sea

It is very important to find out the prevailing current sea directions and velocities so that the optimal position of the current turbine can be determined in future studies. Figure 4 summarizes the current sea characteristics for a specific time at three stations, at 5 m and 35 m depth. Throughout the five months for Silivri and Antalya, with approximately similar tendencies observed for both locations, the dominant current flow directions level is mainly towards the 270° at 5 m depths, and the prevailing current sea is a primarily 240° direction at 35 m sea surface below. The most common dominant current directions are 90° to 150°, approximately 42% of the time and the least common current directions are 210° to 240° at both depths in Istanbul.

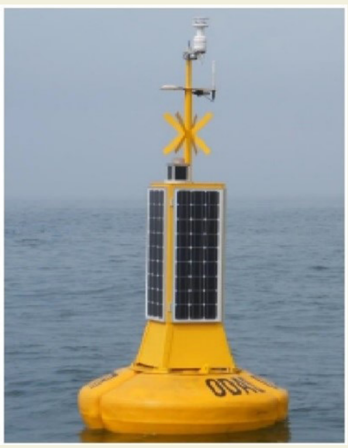

Figure 1. Study areas, location of the measurement stations, and map of the region

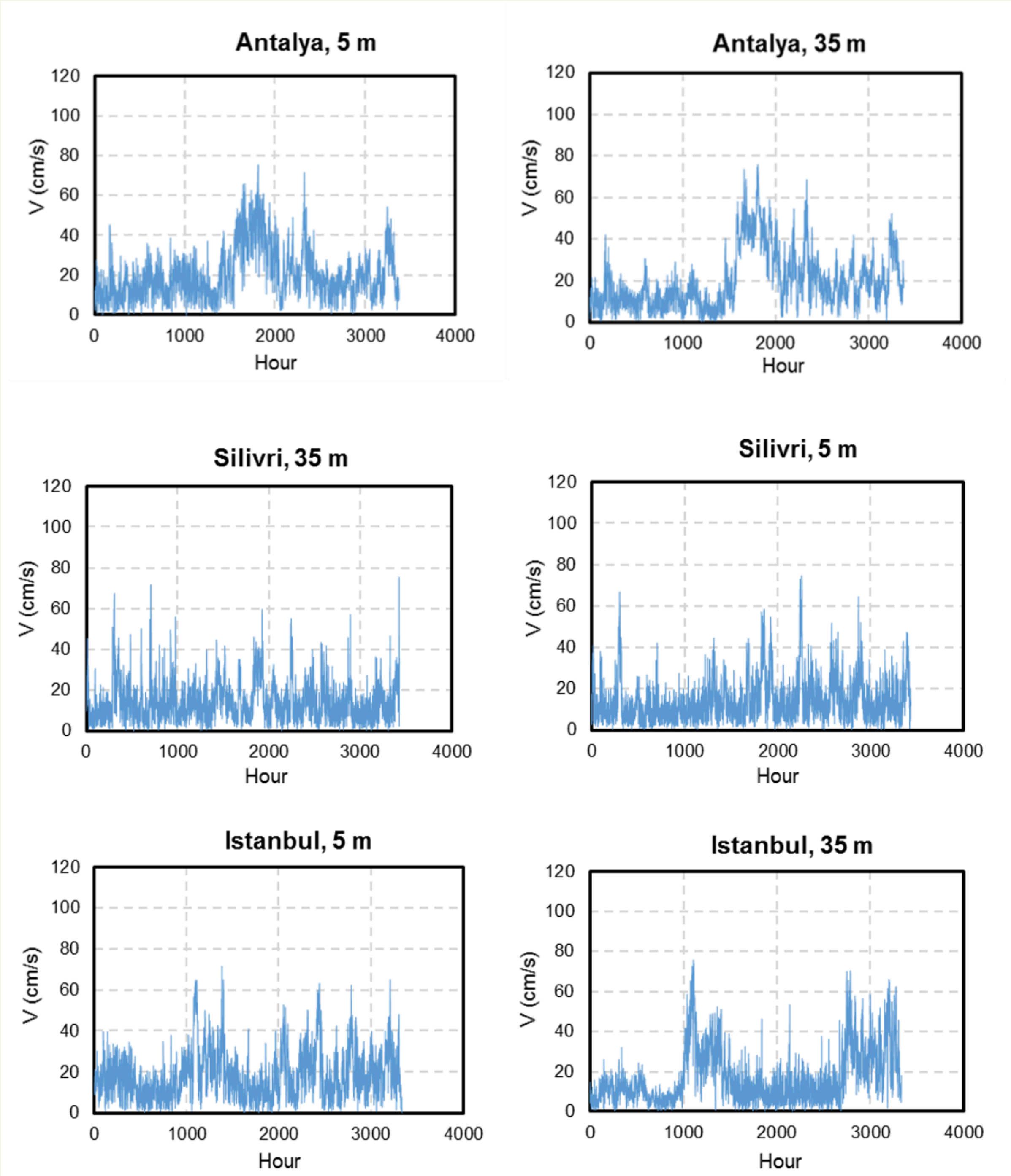

Figure 2. Hourly sea current velocity values of stations at 5 and 35 m below the sea surface level throughout five months

A complete assessment of the potential for hydrokinetic energy in areas of interest benefits from the evaluation of the changes in current velocity. According to the measurement results, the mean sea current speed is given in Figure 4a. As can be seen from the Figure, the mean sea current speeds of stations varied between 14.28 cm/s and 20.18 cm/s at 5 and 35 m below the sea surface level. The lowest value of the mean current speed is 14.28 cm/s at Silivri station at 5 m depth, while the highest value is 20.18 cm/s at Antalya station, at 5 m below the sea surface level. It is another significant point that Antalya presents a higher value of sea current speed than the other stations. There is currently no turbine installation for electricity generation in these stations. It is important to emphasize that these sea current velocities are ideal for the use of sea current energy conversion systems.

In Figure 4b, the average sea current power density values of Antalya, Silivri, and Istanbul stations are 10.42, 4.92, and 7.91 W/m2 calculated at depths of 5 m below the sea surface level, respectively. Besides, average sea current power density values are seen to be arranged with 11.44, 4.08, and 9.06 W/m2 in Antalya, Silivri, and Istanbul stations at 35 m depths below the sea surface level, respectively. Especially, Antalya is the most promising and convenient site to produce electricity from sea current power.

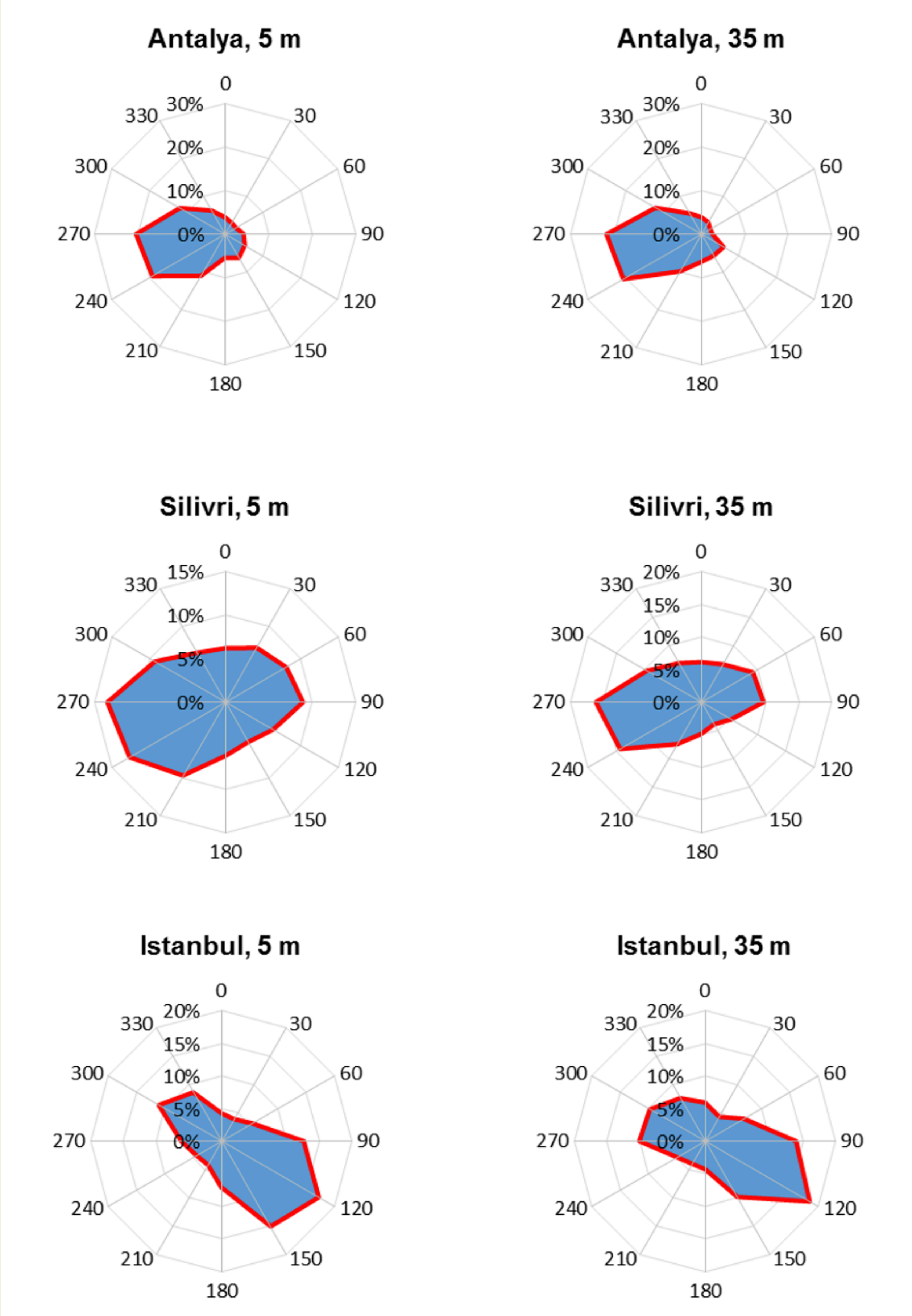

Figure 3. Sea current direction frequency distributions of stations at 5 and 35 m below the sea surface level

It is clear from Figure 4c that at Antalya, Silivri, and Istanbul stations, the dominant sea current flow direction was obtained as 270, 240, and 120° at 5 m depths below the sea surface level, respectively. Besides, the dominant sea current flow direction is seen to be closely arranged with 270, 240, and 120° in Antalya, Silivri, and Istanbul stations at 35 m depths below the sea surface level, respectively. Dominant and average sea current flow directions are mostly similar at all stations for both depths. Istanbul station's dominant current flow direction is 120° for both depths.

3.3. Statistical Modelling of Sea Current Velocity

The frequency distribution and probability density of the sea current speeds help in answering the following questions: (1) how long a sea current power plant is out of production in the case of lack of sea current; (2) what the range of the most frequent sea current speeds is; and (3) how often the sea current power plant achieves its rated output. In this part of the study, the probability densities and statistical analysis of the measured sea current velocities at three stations in the Turkey Seas are presented and discussed.

Table 3. The correlation coefficient (R) values for theoretical distribution models as an accuracy criterion

City	Depth (m)	Weibull model	Rayleigh model
Antalya	5	0.9790	0.9742
	35	0.9791	0.9295
Silivri	5	0.9940	0.9589
	35	0.9955	0.9781
Istanbul	5	0.9973	0.9782
	35	0.9892	0.9963

To do so, first, the measured probability distribution density of the sea current velocities for all stations and depths are presented. Then, sea current velocity frequency distributions for all stations and depths were obtained by using the Weibull and Rayleigh probability density functions. To choose the best theoretical probability density model, the theoretical and measured probability distributions

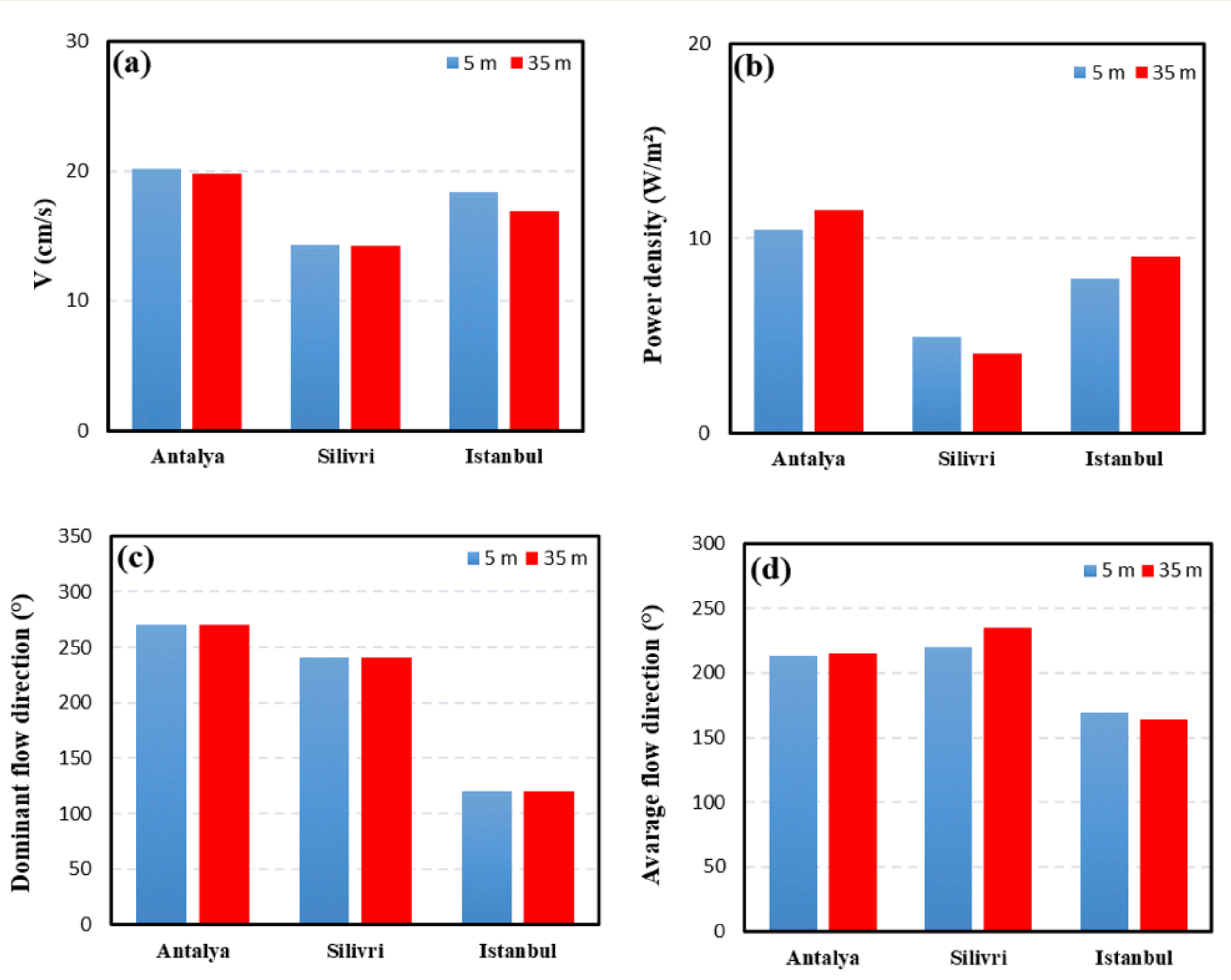

Figure 4. Sea current characteristics of stations a) Average mean velocity b) Power density c) Dominant flow direction (°) d) Average flow direction (°)

were compared, and the closeness and accuracy measures of the comparison were assessed in Table 3. The results showed that the Weibull probability function model provided better results than the Rayleigh probability density functions. Furthermore, the best performance was obtained from the 5 m depth below the sea surface level with a value of 0.9973 R at İstanbul station.

To perform both Weibull and Rayleigh we required shape and scale parameters (k and c). The shape parameter value decides the type of distribution whether it should be Weibull or Rayleigh. In this study, Figure 5 shows the comparison between sea current speed frequency distribution for Weibull or Rayleigh models and the measured distribution. In addition, Figure 5 revealed that histogram of the actual frequency distribution for five months with the Weibull and Rayleigh function for fitting a sea

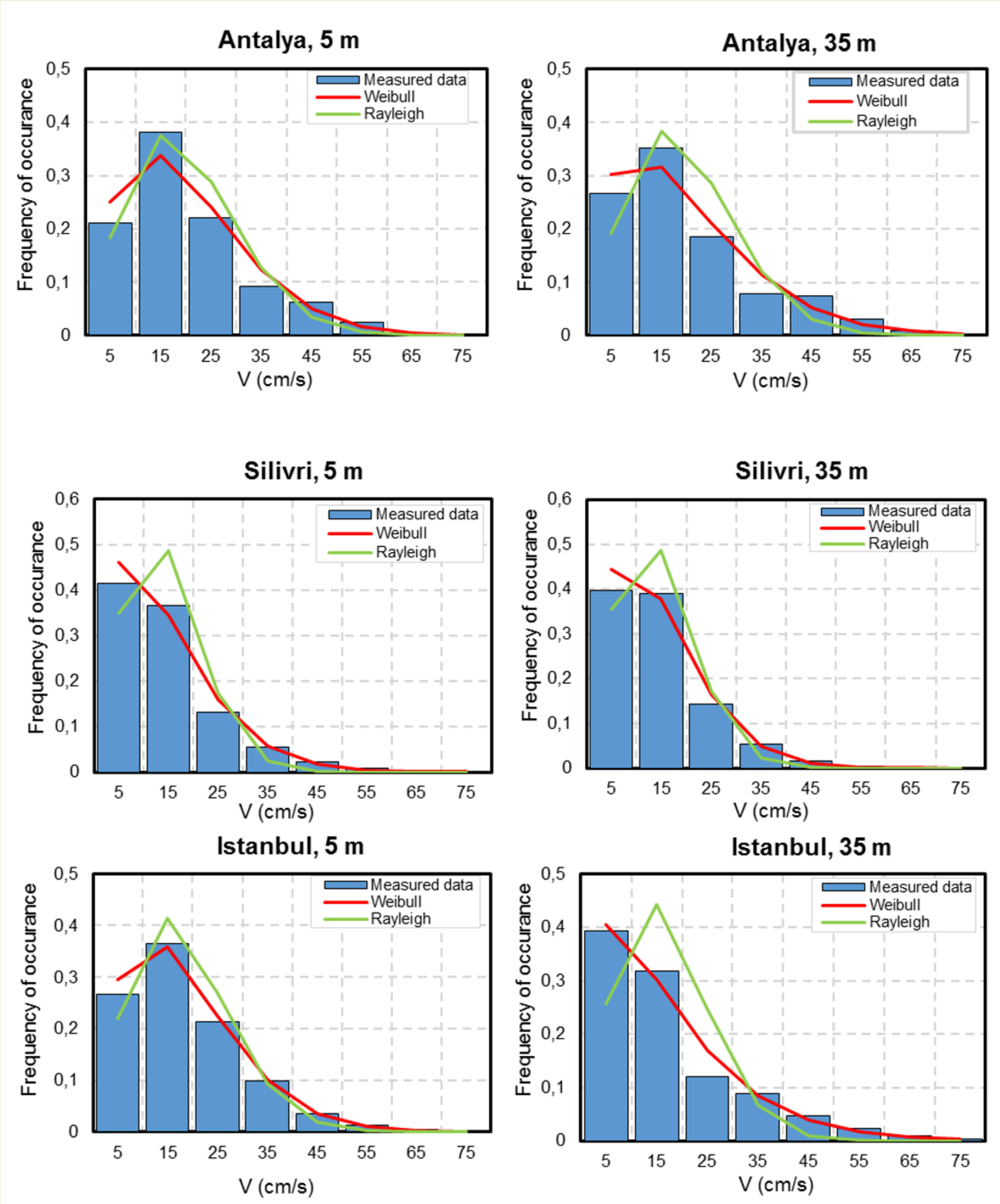

Figure 5. Comparison of observed and predicted sea current speed frequencies of all stations at 5 and 35 m below the sea surface level

current data probability distribution. As shown in the figure, in contrast to the Rayleigh distribution, the Weibull distribution perfectly fits the time series data.

The regression plots of actual and Weibull model (theoretical) values for probability density data of the sea current velocities are shown in Figure 6. The coefficient of determination, R2, indicates how much variance occurs between actual and theoretical values, which can be derived using a linear regression analysis method. It can provide a measure of the discrepancy between them. It is apparent from Figure 6 that Silivri presents a higher val-

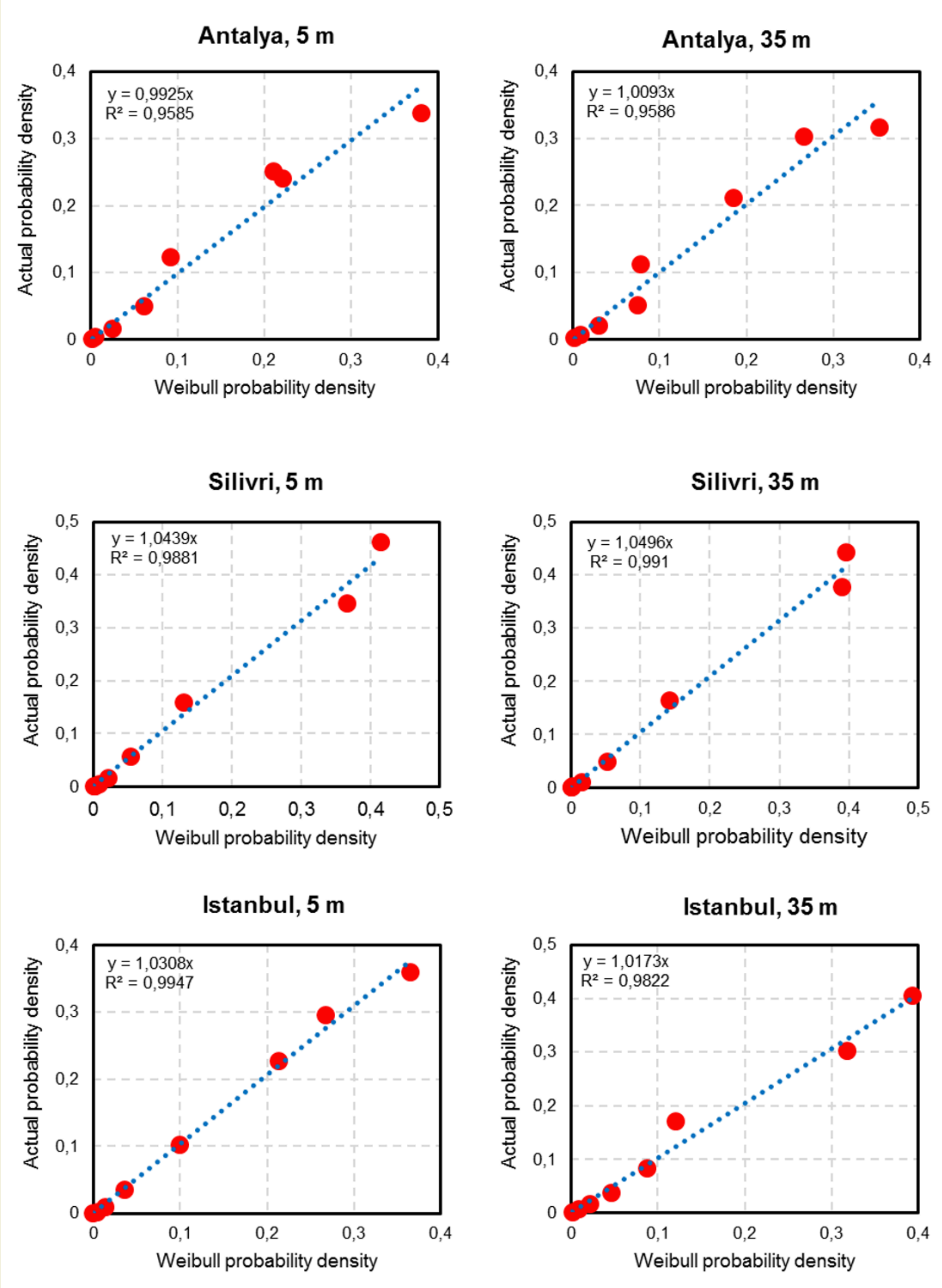

Figure 6. Relation between the Weibull probability density and the actual probability density for sea current velocities of all stations at 5 and 35 m below the sea surface level

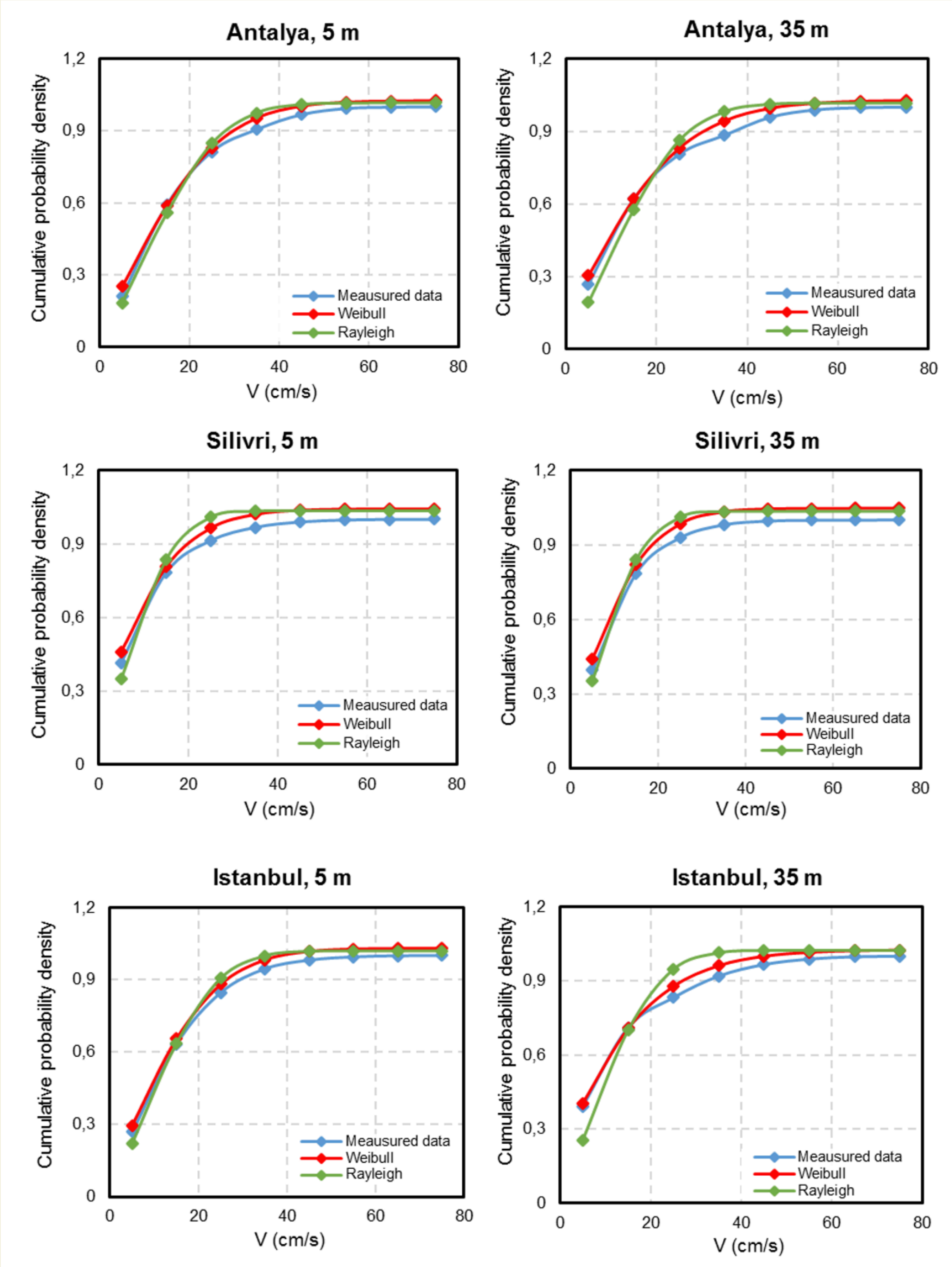

Figure 7. Cumulative probability distributions of sea current velocities for all stations at 5 and 35 m below the sea surface level

ue of R2 than the other stations. For example, the lowest value of R2 such as 95.85 occurs at Antalya station at 5 m depth, while on the other hand, a high level of R2 such as 99.47 occurs at Istanbul station at 5 m depth below the sea surface level.

In addition to the Weibull probability distribution model, the measured probability density values were compared with another probability function, that is, the Rayleigh distribution. For this aim, the measured and theoretical cumulative distribution functions of the velocity for all stations and depths were determined. The cumulative probability distributions of sea current velocities for all theoretical models are presented in Figure 7. Based on the results obtained here, the Weibull distribution model fitted the best to actual sea current velocity in the selected stations. In this regard, the probability density and cumulative probability density analysis for the Weibull model were carried out.

Mean sea current velocity and standard deviation of sea current velocity in Antalya, Silivri, and Istanbul stations were determined for all depths from measured data. The measured period, mean sea current velocity, and standard deviations for all stations and depths are presented in Table 4. According to this Table, Weibull probability distribution, very good results have been obtained. There is a significant difference in the mean sea current velocity among stations at different heights. The highest value of the mean sea current speed is 2.021 m/s at Antalya station at 5 m depth, while the lowest value is 0.981 m/s at Silivri station at 35 m depth below the sea surface level. It is apparent from the table that the sea current velocity of Antalya and Istanbul have a similar value during measurement times.

The last part of this study is a detailed assessment of sea current power potential values for all stations at different depths as given in Table 5. It is seen from the table that the Weibull model provides better power density estimations than the Rayleigh model for all stations and depths. The highest mean sea current power values of 5 m and 35 m are determined as 10.42 and 11.44 W/m^2, respectively at Antalya station. The lowest mean sea current power value is found to be 4.08 W/m^2 at Silivri station.

Table 4. The mean or expected value and standard deviation of the sea current velocities for all stations at different heights

Parameter	City	Depth (m)	Measured data	Weibull model	Rayleigh model
μ (m/s)	Antalya	5	2.021	2.021	2.019
		35	1.982	1.972	1.973
	Silivri	5	1.436	1.446	1.428
		35	1.416	1.432	1.418
	Istanbul	5	1.832	1.839	1.834
		35	1.691	1.697	1.692
σ (m/s)	Antalya	5	1.360	1.276	1.085
		35	1.417	1.375	1.488
	Silivri	5	1.078	1.040	0.788
		35	0.981	0.964	0.783
	Istanbul	5	1.199	1.182	0.991
		35	1.382	1.321	0.920

Table 5. The sea current power potential values for all stations at different heights

Station	Depth (m)	Measured data	Weibull model	Rayleigh model
Antalya	5	10.42	9.63	7.85
	35	11.44	10.43	7.34
Silivri	5	4.92	4.33	2.78
	35	4.08	3.71	2.72
Istanbul	5	7.91	7.41	5.89
	35	9.06	8.17	4.63

4. Conclusion

Turkey is heavily relying on imported fuels, and it is confronted with worldwide challenges such as increasing fuel prices, climate change, the threat of supply disruptions, and depleting indigenous energy resources. Turkey's energy demand is expected to rise by 4–6 percent per year until 2023, so Turkey intends to increase RES energy capacity to 30% by 2023. Among the RES, the untapped potential for energy supply from the seas, which currently seems to be difficult to estimate, seems to be quite promising as well. This is all the more ironic given the fact that a considerable portion of the Turkish population lives near the coastal areas since, except for a handful of studies, there has been almost no in-depth survey on the utility of sea energy and its conversion into electricity. The sea renewable energy potential for the Turkish seas seems to stand out.

The objective of the present study was to quantify the sea current potential in the seas of Turkey at 5 and 35 m depths below the sea surface level by using the Weibull and Rayleigh probability density functions. We can argue that the Weibull model provides better power density predictions than the Rayleigh model for all stations. In addition, our research has demonstrated that statistical models previously used in wind energy can be applied to the assessment of sea currents. Because many potential sites lack reliable, continuous data on current speed and conditions, the use of these statistical models has important practical consequences for the future development of sea current energy. As a result, statistical models capable of assessing potential power generation from ocean currents will be especially useful in the development of sea renewable energy.

Furthermore, in this study, we were also able to determine several fundamental properties such as sea current continuity, availability, behavior, and probability at three stations for both depths. We believe that our findings in this sense can pave the way to estimate the optimum position and power of the turbines to be implemented in the future.

The average sea current power density values of Antalya, Silivri, and Istanbul stations are 10.41, 4.92, and 7.91 W/m^2 calculated at depths of 5 m below the sea surface level, respectively. Besides, average sea current power density values are seen to be closely arranged with 11.44, 4.08, and 9.06 W/m^2 in Antalya, Silivri, and Istanbul stations at 35 m depths below the sea surface level, respectively. Average sea current power density values differ between stations. The highest value was calculated at the Antalya measurement station, and the lowest value was calculated at the Silivri station. Antalya is the most promising and convenient site at both depths to produce electricity from sea current power.

This is a feasibility study for determining sea current before investing in sea current energy for one region. Besides, the present study is a pre-research conducted for estimating the sea current energy analysis of selected regions. This work is expected to make a significant contribution to possible future sea current energy projects in Turkey.

5. Acknowledgments

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