

## Extreme Sea Level Analysis and Return Period Estimation Along Alexandria Coast Using Gumbel Cumulative Distribution Functions

Prepared By

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### المستخلص

تهدف الورقة البحثية الى تحليل فترة اعادة التكرار لأقصى مستويات لسطح البحر على ساحل الإسكندرية باستخدام نموذج احصائي يعتمد على دوال التوزيع التراكمي لمعادلات جامبل و التي تعمل على ايجاد إطار عملي قوى للتنبؤ بأقصى مستويات لسطح البحر و فترة اعادة تكرارها نظرا لأنه من المتوقع زيادة معدلات تكرار اقصى مستويات لسطح البحر خلال العقود القادمة نتيجة لتغير المناخ و زيادة درجة الحرارة المحيطة بالأرض. تم استخدام رادار قياس مستوى سطح البحر خلال هذه الدراسة للحصول على بيانات مستوى سطح البحر كل ساعة باجمالى ١٣٩٨٦ ساعة لمدة ١٩,٣ شهر فى الفترة من ٥ يونيو ٢٠١٨ الى ٩ يناير ٢٠٢٠ ، و قد تبنت هذه الدراسة الإسلوب الكمي التحليلي فى تحليل البيانات وحساب اقصى مستوى لسطح البحر على اساس شهرى للبيانات المرصودة. استخدمت معادلات جامبل فى قياس احتمالية حدوث اعلى ارتفاع لمستوى سطح البحر بقيمة تساوى او أقل من اقصى ارتفاع فعلى تم رصده و تم تطبيق هذه الاحتمالات على اقصى ارتفاع لكل شهر.

تركز الورقة البحثية على حساب فترة إعادة التكرار لحدوث اقصى ارتفاعات لمستوى سطح البحر بما يتناسب مع الفترات القصيرة فى رصد بيانات مستوى سطح البحر، و بالتالى تم حساب فترة إعادة التكرار للمستويات القصوى لسطح البحر بالشهور بدلا من حساب معدل تكرارها بالسنوات. وقد خلصت النتائج الى أن متوسط اقصى ارتفاع لمستوى سطح البحر ٠,٧٧ متر و بالنسبة لأقصى ارتفاعات شهرية تراوحت بين ٠,٦ متر و ١,٠٤ متر خلال فترة الدراسة لمدة ١٩,٣ شهر، وتظهر الدراسة باستخدام معادلات جامبل ان أعلى احتمالات للحدوث تكون مع اقصى ارتفاعات لمستوى سطح البحر مقترنة باطول فترة زمنية لإعادة التكرار بالشهور. و قد القت الدراسة الضوء على اهمية حساب فترات اعادة التكرار لتحقيق لدعم الإدارة الساحلية المرنة، وتقديم خطة دقيقة لتقييم المخاطر مع رؤية واضحة لإحتمالية تعرض مدينة الإسكندرية لتكرار المستويات القصوى لمستوى سطح البحر بمعدلات عالية فى المستقبل القريب.

### Abstract

The study Analise the return period of extreme sea levels at Alexandria coast with a different approach of statistics model, the cumulative distribution function method based on Gumbel equations provides a robust framework in statistics of extreme sea level prediction and recurrence

estimation. Return period of extreme sea level heights are expected to occur more frequently in the next decades influenced by climate change and global warming. The study utilizes sea level radar hourly data, with total 13,986 measurements over 19.3 months, between 18<sup>th</sup> of June 2018, to 9<sup>th</sup> of January 2020. The study methodology underpinning an analytical quantitative method to analyze observed data and determines the monthly extreme sea level value in random data. The Gumbel distribution measures the probability  $F(x)$  for each extreme sea level  $X$  to be equal or less than this value. The study focuses on the methods to estimate return period for short term of data observation; however, the study estimates the return period for extreme sea level in months instead of usual estimation in years. The results revealed that the average extreme sea level in Alexandria is 0.77 meters, with monthly extreme sea level range between 0.6 to 1.04 meters. The findings highlight the highest probability of occurrence concurrently with the highest sea level value and has the longest return period in months.

The study shed the light on the short pattern intervals of extreme sea level recurrence to support resilient coastal management, and precisely present risk assessment plan with clear vision to how far could Alexandria vulnerable to adverse conditions in near future.

**Keywords:** Return period; Extreme Sea level; Alexandria coast; Cumulative distribution function, Gumbel method.

## **Introduction**

Climate change, Global warming, and consequently Sea level rise (SLR) are drivers to flooding, coastal erosion, and ecosystems deterioration. The 2023 IPCC assessment report revealed that sea levels could rise up to 2 m by year 2150, and between 3 m and 7 m by 2300 (Büyüksalih and Gazioğlu, 2024).

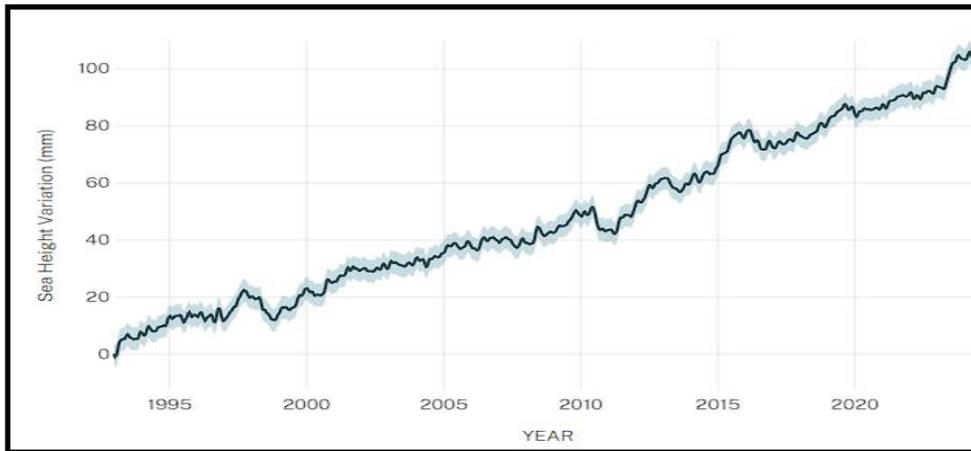
Extreme events and climate change could lead to hurricanes and typhoons in many areas in the world recognized by warmer ocean temperatures; causing widespread destruction (Griggs and Reguero, 2021).

Low-lying coastal areas face significant risks from inundation due to extreme sea levels (Baldan et al., 2023). Alexandria, as a low-lying city, is particularly vulnerable to these dangers. Globally, communities, critical infrastructure, and essential socio-economic assets are becoming increasingly vulnerable to coastal flooding (Oppenheimer et al., 2019; Andrée, 2022). Although tides in Alexandria typically exhibits a very short range, during special events, extreme sea levels often occur, particularly during spring tides. Storm surges significantly contribute to these events, playing a major role in SLR (El-Geziry and Dabbous, 2021). Observations indicate that extreme sea levels have increased over the last century in various regions, resulting mainly from variations in sea level rather than significant changes in storm surge parameters (Menéndez and Woodworth, 2010)

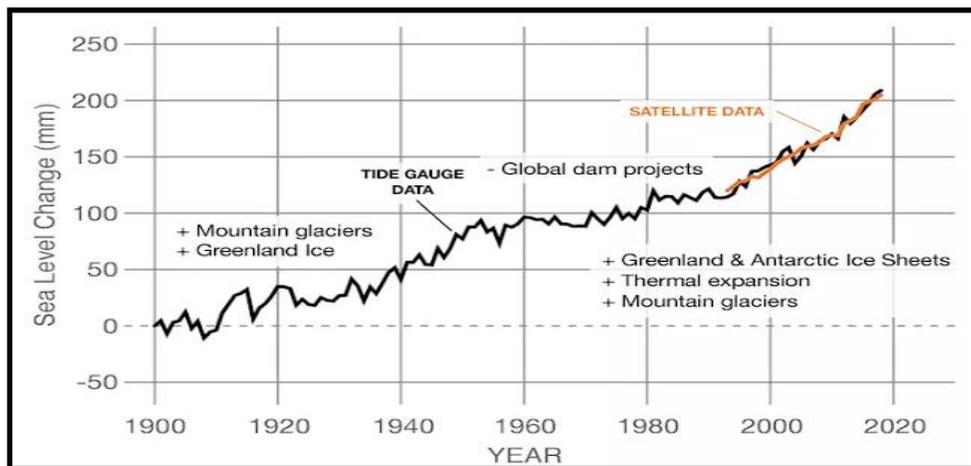
Future hazard scenarios project that the mean sea level (MSL) will rise by 14 cm by 2030, which is sufficient to inundate 15% of Alexandria (Noby et al., 2022b).

As SLR is expected to have a significant impact on the beaches of Alexandria, with projections indicating a loss of 16.13% of the current total beach area by 2100 based on the mean value of SLR. The variations in extreme sea levels are influenced by both SLR and changes in storm surge activity. However, storm surges specifically contribute to extreme sea-level events, as they result solely from storms (Calafat et al., 2022).

The graphs in Figure (1) and Figure (2) track respectively the change in global sea levels since 1993 and changes in sea level from 1900 to 2018, based on satellite observations, As Figure (1) provides real-time data showing the steady increase in sea levels as global temperatures rise indicating the current rate of sea level rise is approximately 3.3 mm/year. This rate has been accelerating over last century, driven by the combined effects of melting ice sheets, glaciers, and the thermal expansion of seawater as the planet warms, While Figure (2) demonstrates various factors influencing sea level changes from 1900 to 2018, marked with pluses (+) for those contributing to the rise (like ice melting and thermal expansion) and minuses (-) for those contributing to sea level decrease (NASA, 2025).



**Figure (1) Changes in Global Sea Level since 1993 (NASA, 2025)**



**Figure (2) Changes in sea level from about 1900 to 2018 (NASA, 2025)**

Both Figures are shown according to the time period when they were most active in affecting global sea levels. This helps illustrate the gradual but persistent trend of rising sea levels over time (NASA, 2025).

The design of maritime and coastal structures requires consideration of extreme waves and extreme sea levels. These extreme conditions may occur only once within a specified period, known as the recurrence time of the extreme sea level height (Goda, 2010).

This recurrence time can be estimated through analysis by applying one of three methods: (Goda, 2010)

- a) Cumulative distributions function or total sample method used to fit an appropriate distribution function.
- b) The maxima method selects the highest values in a total period division (e.g. years in a number of years).
- c) The Peaks-Over-Threshold method focuses on analyzing peak values that exceed a specified threshold.

The annual maxima method is mostly used in extreme flood discharges, while peaks over threshold (POT) method, typically has relatively substantial data volume but with low range of confidence intervals.

The Cumulative distributions function method present the probability of continuous random variable  $X$  with values between two distinct numbers as minimum and maximum values ( $A$  and  $B$ ) to be equal or less than a specific value  $x$ , however the formula could be expressed as  $F(x) = \Pr(A \leq X \leq x]$  (Goldstein, et al., 2010).

The Cumulative Distribution Function method utilizing the Gumbel distribution for extreme sea levels exhibited high consistency with empirical distribution. Moreover, the Gumbel distribution is regarded as one of the most important statistical tools for analyzing extremes in hydrology and flood.

The return period and risk assessment of extreme sea level at Alexandria coast, particularly at Abu-Qir Bay, demonstrate that extreme sea levels and risk of flooding could reach to extreme flooding risk. Data Analysis of water level measurements over 21 years (1990–2010) shows that the highest probabilities for sea level levels within range between 45 cm to 60 cm (El-Geziry and El-Wakeel, 2023). Extreme sea levels indeed influenced by different factors such as seasonal variations and long-term trends, making them oscilate from year to year. New studies indicate that sea levels are usually changing, and consequently, extreme events impact coastal areas, recurring at intervals determined by their return period (Macpherson et al., 2021). Extreme sea levels in Alexandria have been calculated with their return periods: The sea level of range 165 cm is expected once every 100 years, while 181 cm could be occurred once every 500 years (Said et al., 2020). Risk assessment of extreme sea-level rise is the clue in designing vital coastal structures and estimate their expected lifespan (Said et al., 2020). Between several methods assigned for long return periods estimation, some involve numerous uncertainties, especially when large amounts of

data are filtered out of calculations. Average Conditional Exceedance Rate (ACER) method is a reliable approach as it utilizes the entire dataset in its analysis, and presents better accuracy compared to traditional techniques. Unlike conventional methods that often rely on extreme value analysis leading to the Generalized Extreme Value (GEV) distribution, the ACER method estimates the three essential GEV parameters: location, scale, and shape. This method provides a more comprehensive analysis of return levels over long periods (Ryden, 2024).

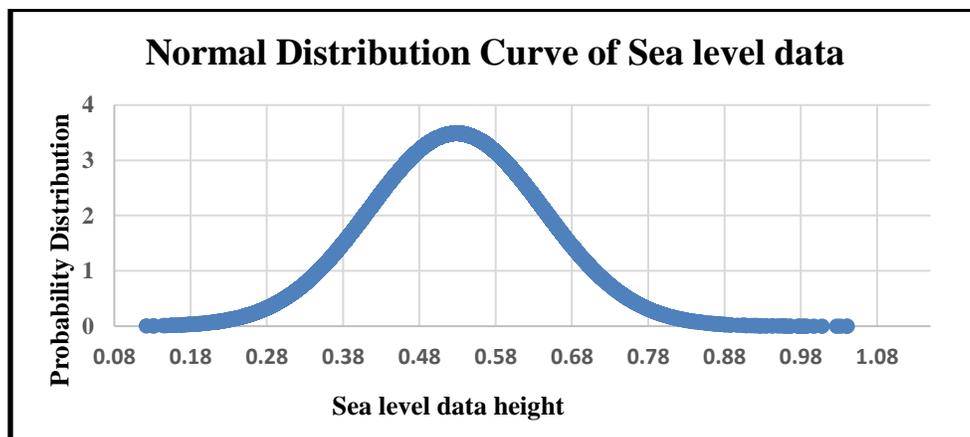
CDF method Provides a comprehensive representation of the probability distribution, capturing the entire range of values, it requires fitting a statistical model to the data, which may introduce errors if the model assumptions include errors.

### **Data and Methods of Analysis**

The study adopts a quantitative analytical approach, utilizing observed sea level heights referenced to the chart datum of Alexandria Western Harbor (AWH). Sea level measurements were obtained using a CS475A radar sensor installed inside the Harbor at coordinates (31°11'55.55"N, 029°52'22.10"E) as shown in Figure (3). The dataset is of high quality and reliability, with negligible observation gaps, Figure (4) illustrates the standard deviation graph for the observed sea level data collected in AWH. Any missing data, which amounted to only a few hours over the entire period, were mathematically interpolated.



**Figure (3) Alexandria coastline with Sea level Radar position in AWH Plan (Google Earth)**



**Figure (4) Normal Distribution Curve of Sea level data**

The calculation of return periods is a crucial aspect of risk assessment and prediction, however the estimation of the likelihood of recurrence of extreme sea level relies on the best fit method for data distribution and the related parameters to this distribution (Wolski, et al.,2025). Traditional methods for estimating long return periods often involve significant uncertainties, particularly when large portions of data are excluded from calculations (Pugh and Woodworth, 2014).

The analysis of wave heights along the Estonian coast using the Gumbel distribution resulted in a satisfactory alignment with theoretical models and is effectively utilized for accurate predictions of extreme values (Wolski et al., 2025).

The average recurrence interval (ARI) for extreme sea levels can be calculated for different thresholds, with higher sea levels corresponding to longer ARIs through the following formulae (Pugh and Woodworth, 2014).

For a given extreme sea level with a specific (ARI) at any coastline, there is a 37% probability of no occurrences ( $1/e = 0.367$ ), a 37% probability of one occurrence, 18% probability of two occurrences, and 6% probability of three occurrences during the design period (Pugh and Woodworth, 2014).

The probability of no exceedance ( $x=0$ ) within a specified design period is determined using the formula:  $F=1-\exp(-N)$  ..... (1)

While Direct Exceedance Probability is one of the most widely used return period methods that measures the possibility of a storm surge could be exceeded within a given time frame. This method applies direct exceedance probability (P) for different extreme sea levels, and the return period T in years calculated using the equation as inverse of exceedance probabilities (Coles, 2001). It calculates probabilities conservatively, assuming independence for each division of time (e.g., year or month). The probability Q(z) represents the likelihood of sea level exceeding a threshold value z (Pugh, 2004).

$$\text{Return period} = \frac{1}{Q(z)} \text{ ..... (2)}$$

The recurrence probability of a specific sea level, z, denoted as Q(z), corresponds to the annual exceedance probability for that threshold. The return period, also known as the Average Recurrence Interval (ARI), and calculated as the inverse of the exceedance probability (Vogel, 2015). However, this approach relies on precise estimates of the exceedance probability, which can be difficult to obtain in cases of limited data or non-consistent conditions. Recurrence interval or return period calculates the probability of exceedance (P) by applying the equation (Paugh, et al. 2014):

$$T = \frac{1}{P} \text{ ..... (3)}$$

The Cumulative Distribution Function (CDF) utilizes cumulative probabilities F(x) to provide a more comprehensive view of the data, especially when there are variations in extreme sea levels, used for calculating the probabilities of extreme sea levels involves distinguishing between tidal frequency and surge frequency (Abdelhamed, 2024 ; Goda, 2010). The CDF describes the probability that a variable will take a value less than or equal threshold, the return period is calculated based on the calculation of the CDF.

The calculation of the return period for extreme sea levels using Gumbel equations relies on significant statistical parameters, such as the spread of the data distribution, location parameter, standard deviation, and the observed sea level extremes. These parameters depicts the characteristics of sea level extremes. The return period parameters of the Gumbel equations precisely calculate the mean and standard deviation of monthly extreme values over the total 20 months of sea level observations.

## Results And Discussion

Sea level data, represented graphically as a normal distribution curve (Figure 5), shows that the most frequently occurring sea level values are centered around the mean sea level. This mean sea level has been accurately calculated using T-Tide software. The data indicates that the most common sea level values fall within the range of 0.5 to 0.55 meters, with these levels recorded 2,445 times during the observation period.

The data set consists of 13,986 hourly sea level records collected over a span of 20 months, providing a comprehensive basis for analysis. To analyze the data statistically, the mean of the monthly extreme sea levels, represented as  $\bar{x}$

$$\bar{x} = \frac{1}{M} \sum_{i=1}^M xi \dots\dots\dots (4)$$

Where M is the total number of months

$xi$  represents the extreme sea level value for month  $i$ .

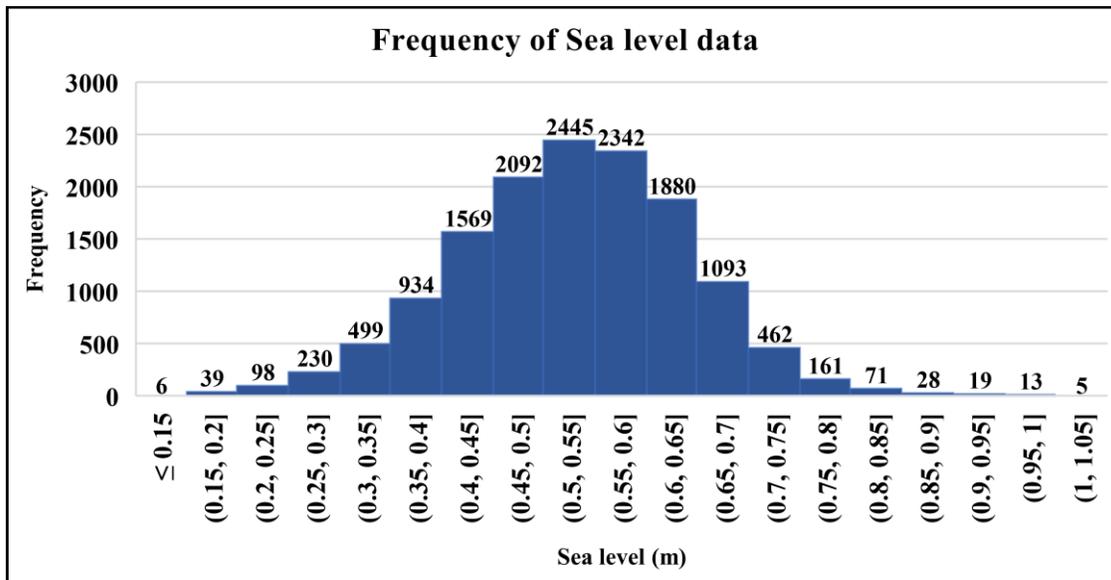


Figure (5) Sea level data represented as normal distribution curve

Using this formula, the mean extreme sea levels ( $\bar{x}$ ) was found to be 0.771 meters, which indicates the average extreme sea level during the observation period. Additionally, the standard deviation ( $s$ ) of the extreme sea level data was calculated to be 0.09798. The standard deviation measures how much the extreme sea level values deviate from the mean. A relatively small standard

deviation like this suggests that the extreme values are relatively close to the mean, indicating consistency in the observed extremes over the 20 months.

The Gumbel equations used to estimate the return period for monthly extreme sea levels as follows: (Zaiontz, 2025)

The spread of data distribution calculated by formulas

$$\beta = \text{Scale parameter (Zaiontz, 2025)}$$

a) Scale parameter ( $\beta$ )

$$\beta = \frac{s\sqrt{6}}{\pi} \dots\dots\dots (5)$$

$$\beta = 0.0764$$

b) Location parameter ( $\mu$ )

$$\mu = \text{mean}(x) - \gamma \beta \dots\dots\dots (6)$$

where:

$\gamma$  = The limiting difference between the harmonic series and the natural logarithm (Euler – Maschioni) constant (approx. 0.5772)

$$\mu = 0.72645$$

The probability of recurrence of extreme sea level is calculated by

$$F(x) = \exp\left(-\exp\left(-\frac{x-\mu}{\beta}\right)\right) \dots\dots\dots (7)$$

$$\text{Return period (T)} = \frac{1}{(1-F(x))} \dots\dots\dots (8)$$

**Table (1) Return period for maximum monthly Sea level in Alexandria**

Date	Max. Sea level	$(x - \bar{x})^2$	Probability F(x)	Return Period (T) (Months)
<b>Jun-18</b>	0.715	0.00309	0.313	1.455
<b>Jul-18</b>	0.803	0.00105	0.693	3.254
<b>Aug-18</b>	0.74	0.00093	0.433	1.763
<b>Sep-18</b>	0.81	0.00156	0.715	3.513
<b>Oct-18</b>	0.706	0.00417	0.271	1.371
<b>Nov-18</b>	0.755	0.00024	0.502	2.010
<b>Dec-18</b>	0.819	0.00235	0.742	3.883
<b>Jan-19</b>	0.873	0.01050	0.863	7.321
<b>Feb-19</b>	0.753	0.00031	0.493	1.974
<b>Mar-19</b>	0.609	0.02610	0.010	1.010
<b>Apr-19</b>	0.651	0.01429	0.068	1.073
<b>May-19</b>	0.603	0.02807	0.007	1.007
<b>Jun-19</b>	0.734	0.00134	0.007	1.007
<b>Jul-19</b>	0.802	0.00099	0.689	3.219
<b>Aug-19</b>	0.791	0.00042	0.651	2.863

Sep-19	0.752	0.00034	0.489	1.956
Oct-19	0.824	0.00286	0.757	4.108
Nov-19	0.873	0.01050	0.863	7.321
Dec-19	1.041	0.07314	0.984	61.888
Jan-20	0.757	0.00018	0.511	2.047

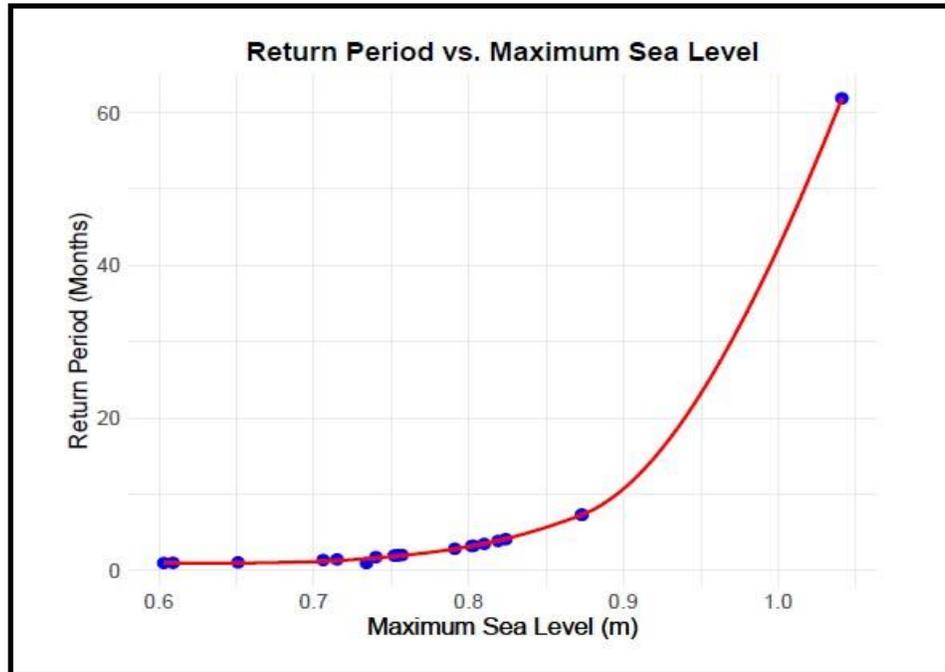


Figure (6) Return Period of Alexandria Harbor using Cumulative Distribution Function

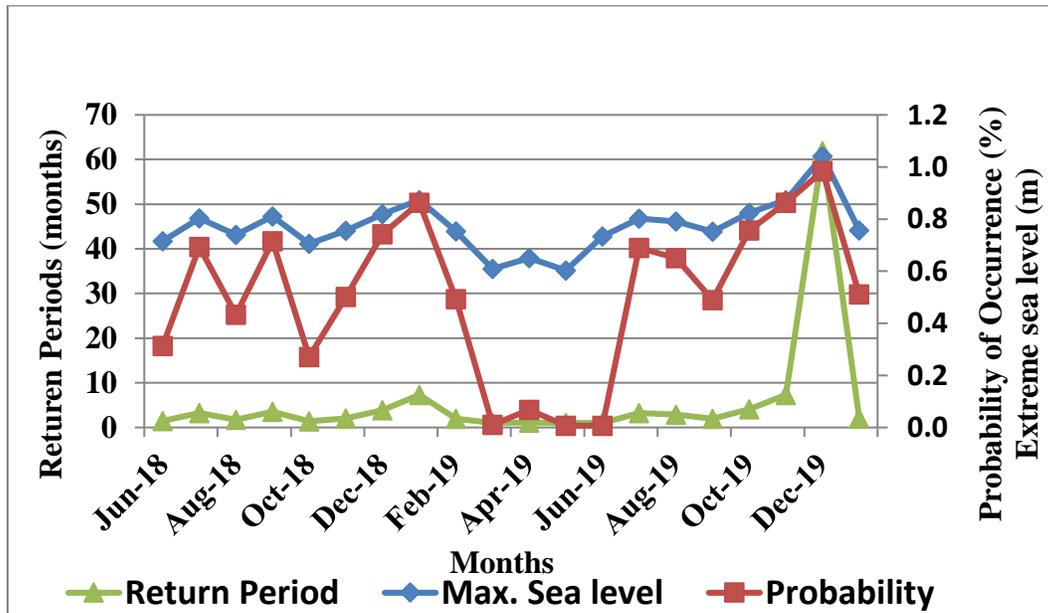


Figure (7) Extreme Sea Level Analysis: Probability of Occurrence and Return Period

The results highlight a critical relationship between extreme sea level events, their probabilities of recurrence, and return periods in months. The findings suggest that the highest extreme sea level, measured at 1.04 m, is associated with a very high probability of recurrence (98.4%) and a relatively long return period of 61.88 months.

The results revealed that extreme events may occur with moderate frequency. Typically, the highest value (1.04 m) is associated with the lowest probability and the longest recurrence period. However, in this study, applying the CDF method resulted in a high probability of 98.4%, corresponding to a return period of 61.88 months for extreme sea levels of 1.04 m or less. This indicates that the probability  $F(x)$  represents the proportion of observed values that fall below or equal to the specific threshold of 1.04 meters.

On the other hand, the lowest extreme sea level, at 0.609 m, is associated with a low probability of 1% and a short return period of 1.01 months. This indicates that while such low levels are rare in probability terms, they occur frequently over time.

## **Conclusions**

This study emphasizes the calculation of return periods in short-term intervals measured in months, contrasting with most return period studies, which typically use years.

The analysis of extreme sea levels in Alexandria, performed using the cumulative distribution function (CDF) with Gumbel distribution equations, is a non – traditional approach for return period calculations. However, this method present an appropriate fit for extreme statistical datasets. The results revealed consistent and precise return periods ranging from 1 to 61.9 months, and the potential for achieving high-accuracy results despite the short duration of data observations.

Predictions of extreme sea level heights and their frequency of reoccurrence, as highlighted in the 2023 IPCC report, suggest an increase by 20 to 30 times. The mean extreme sea level during the 20-month study period, calculated at 0.77 meters, exceeds the mean sea level in Alexandria by more than 0.25 meters. This underscores the significant impacts on coastal areas during storms and gusty winds associated with extreme sea levels, highlighting the importance of resilience planning for the anticipated increase in both frequency and recurrence of extreme events.

The findings stress the necessity of continuous sea level data observations to enable comprehensive analysis and precise predictions, which are critical for effective coastal management and risk assessment in Alexandria's near future.

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