Spring rains, extremes, and risks in northern Morocco: fluctuations and trends (March 2024)

Aissam Bouaiche[1*], *Hind* Fattah[2], *Bouchaib* Essalak[3]

[1] Hassan II University, (LCEAT), Faculty of Arts and Humanities Ben M'Sick – Casablanca, Morocco.
[2] Mohamed V University, Department of Geography, (STHP), Faculty of Arts and Humanities, Rabat, Morocco.
[3] Mohamed V University, Faculty of Education Sciences, Rabat, Morocco.

Abstract The objective of this study is to examine the climatic conditions during this short rainy period and analyze the various atmospheric conditions responsible for the extreme precipitation recorded. It also examines the risks they posed in terms of flooding and property damage. The focus is on total monthly precipitation and daily maximums, with March holding the record values. Finally, the positive and negative impacts of this exceptional period on water resource mobilization and the agricultural sector will be examined. The methodology adopted in this study aims to characterize extreme spring rainfall in the two cities of the Tangier region (Tangier and Chefchaouen) during the year 2024, particularly in March. The proposed approaches are divided into two categories: the dynamic approach to explain synoptic situations, weather types, and climatic conditions; and the analytical approach to analyze rainfall series for the year 2024 (March). In addition, the Gumbel method enabled us to determine the return periods of precipitation (1976-2024).

1 Introduction

Spring rainfall has several fairly specific characteristics, marking the end of the rainy season in Morocco, which follows the wet winter season typical of the Mediterranean region. Climate change in northern Morocco manifested itself in heavy rainfall between March 26 and 31, 2024, as a result of Storm Nelson. These extreme climatic phenomena have produced a range of impacts, especially those related to flooding.

Therefore, Among the natural hazards that often threaten the safety of human societies are flood risks. Today, these hydromorphological phenomena are becoming a hot topic around the world and in Morocco, due in particular to the dramatic and costly damage associated with them, which affects society, its property, and the environment [6,7]. In the past, extreme floods have caused flooding in many regions of Morocco. This was the case, for example, with the floods that devastated Sefrou on September 25, 1950, those that ravaged the Ziz Valley on November 5, 1965, and those of the Moulouya on May 23, 2000, and 2002, and the very recent floods in Tangier, Fez, Nador, Errachidia, Taza, Tetouan, and Missour.

* Corresponding author: Bouaiche.Aissam.UH2.Lceat@gmail.com

Since the beginning of this century, the Tangier-Tetouan region has experienced several episodes of torrential rainfall. These rains have caused catastrophic flooding, resulting in enormous material damage and loss of life (September 2008 and 2009, October 2010 and March 2024). Since then, several questions have continued to be asked [4]**:** *does the frequency of this phenomenon reflect an aspect of climate change*? *To what extent does human intervention in the natural cycle and water regime cause flooding to worsen*?

In fact, population growth and socioeconomic development in various regions of Morocco over the past five decades have certainly encouraged increasing human occupation of vulnerable river areas, which are often threatened by flooding. In addition to specific weather conditions, the occupation of river areas at risk of flooding largely explains the increase in flood-related damage in several regions of Morocco [4,7]**.**

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2 Data and method used

2.1 Presentation of the study area

Located in the extreme northwest of Morocco, the Tangier-Tetouan-Al Hoceima region is bordered to the north by the Strait of Gibraltar and the Mediterranean Sea, to the west by the Atlantic Ocean, to the southwest by the Rabat-Salé-Kenitra region, to the southeast by the Fez-Meknes region, and to the east by the Oriental region. Covering an area of 16,010 km², or 2.25% of the country's total area, the region is part of the Rif domain and consists of five homogeneous environmental units [13,15]. These are more or less extensive spatial areas with similar characteristics in terms of their natural conditions (see Figure. 1).

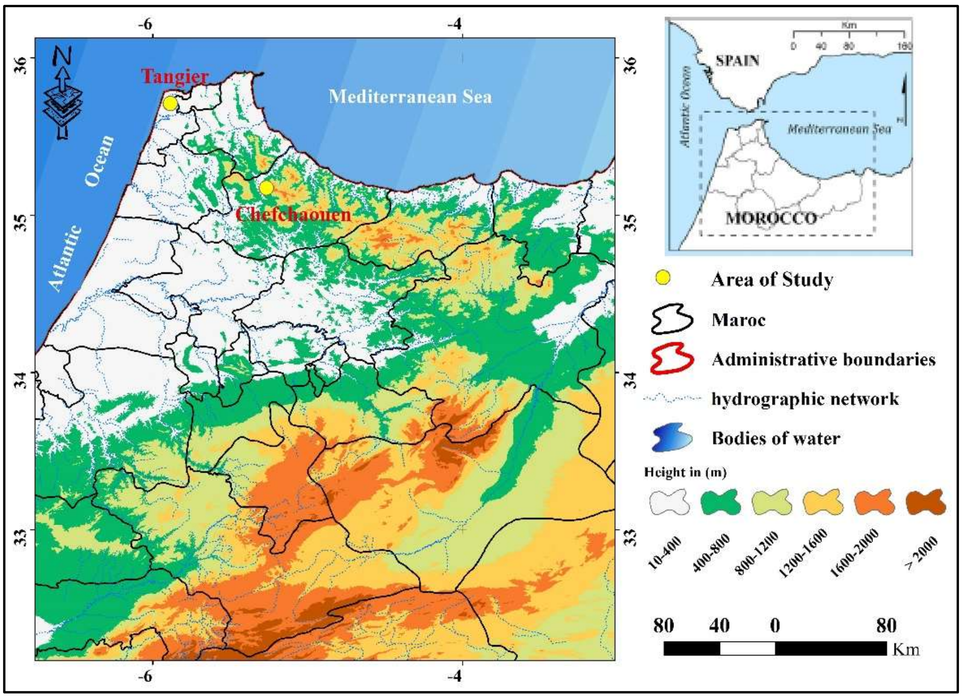


Fig. 1. location of the study area (two cities: Tangier and Chefchaouen)

This geographical context is responsible for the region's significant microclimates. This variant of the Mediterranean climate is highly heterogeneous and results from three factors: altitude, latitude, and the ocean (see Figure. 1). Altitude influences rainfall distribution. Under the influence of disturbances caused by the Azores High, slopes exposed to westerly or southwesterly winds, as well as high peaks, receive ample rainfall, while those facing east or southeast form semi-arid areas (400 mm/year). The entire coastline is classified as humid or subhumid. In the subhumid region, areas below 500 m altitude experience a pronounced meso-Mediterranean climate, with less than five dry months and more than 700 mm of rainfall.

2.2 Data source and method

This study was developed based on daily precipitation measurements collected during 2024 for two synoptic and hydrometric stations (Tangier and Chefchaouen) from the General Directorate of Meteorology (DGM) in Casablanca and the Lkouss Water Basin Agency [4]. (see Table. 1). For the study of atmospheric circulation, our study is based on an analysis of Moroccan and European weather maps. These maps are available on several websites, including: www.wetterzentarale.de and www.wether3.de (see Table. 2).

Table 1. Geographical locations and characteristics of the rainfall stations studied.

Station	Longi tude	Latitude	Altitude (m)	study period	Annual average (mm)	Standard deviation σ (mm)	Coefficient of Variation (%)
Tangier	**-5,91**	**35,67**	**21**	**2024**	**769**	**249**	**31**
Chafchaouen	**-5,3**	**35,08**	**630**		**998**	**350**	**30**

Table 2. The characteristics of the synoptic charts used in this study

Map type	pressure level (hPa)	The characteristics	Map source
Isobaric at altitude	500 hPa	to determine the atmospheric conditions for cyclogenesis	www.wetterzentarale.de
Ground-level Isobaric	1015 hPa		www.wether3.de

The methodology adopted in this study aims to characterize extreme spring rainfall in two cities in the Tangier-Tetouan-Al Hoceima region (Tangier and Chefchaouen) during the year 2024, particularly in March. The proposed approaches are subdivided into two categories:

- The synthetic or dynamic approach to explaining synoptic situations, weather types and climatic conditions.
- The analytical or separate approach to analyzing rainfall series for the year 2024 (March) at the synoptic stations in Tangier and Chefchaouen.

Secondly, frequency analysis is a statistical prediction method that involves studying past events characteristic of a given process in order to define the probabilities of their future occurrence [14]. This prediction is based on the definition and implementation of a frequency model, which is an equation describing the statistical behaviour of a process, with these models describing the probability of occurrence of an event of a given value [4,9].
Gumbel postulates the double exponential law, or Gumbel's law, is the limiting form of the distribution of the maximum value of a sample of ŋ values. Since the annual maximum of a variable is considered to be the maximum of 365 daily values, this law must therefore be capable of describing the annual maximum series [9,12].

The distribution function of Gumbel's law [9]. is expressed as follows:

$$f(x) = \exp\left[-\exp\left(-\frac{x-a}{b}\right)\right] \quad (1)$$

Let us set the following reduced variable $u = \frac{x-a}{b}$ (2)

The advantage of using the reduced variable is that the expression of a quantile is then linear. Indeed, to find the value x of a quantile corresponding to the distribution $f(xq) = q$ based on the two parameters a and b, simply use the following relationship:

$$xq = a + bu\, q \quad (3)$$

3. Results and discussion

3.1. The atmospheric factors responsible for the catastrophic floods of March 30 in Tangier and Chefchaouen

During the spring, the second half of March was the period that posed the greatest threat to the population due to the heavy rainfall that hit the north and northwest of the country and the Mediterranean coast. Analysis of the situations relating to this period is necessary to understand the origin of these extreme rainfall patterns.

In spring, the barometric field at 500 hPa was, on average, close to climatological normal in Morocco, with pressures around 1015 hPa in the center and south, and between 1015 and 1020 hPa in the north (see Figure. 2).

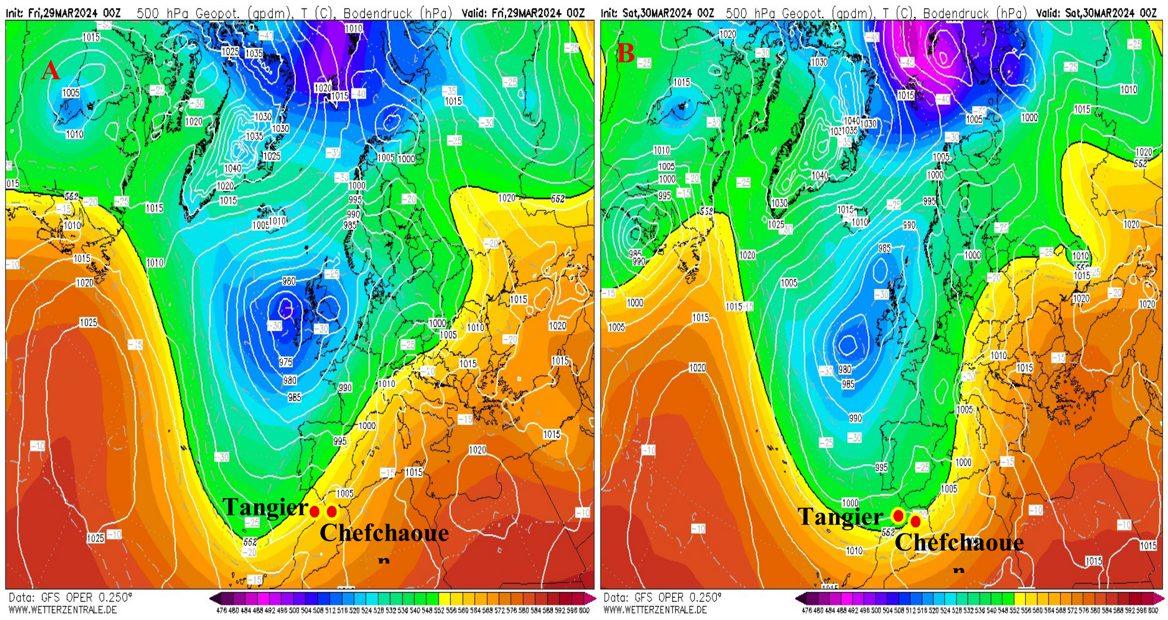


Fig. 2. from left to right, isobaric situation at altitude on March 29 (A) and 30 (B), 2024, 0 UTC. Data Source: www.wetterzentrale.de

This situation favored spring rainfall close to normal, reflected in a slight surplus in the north, normal conditions in the center, and a slight deficit in the south. This situation favored spring rainfall close to normal, resulting in a slight surplus in the north, normal conditions in the center, and a slight deficit in the south. On the other hand, in terms of timing, March saw significantly higher than normal precipitation, particularly in the far northwest of the country (see Figure. 3).

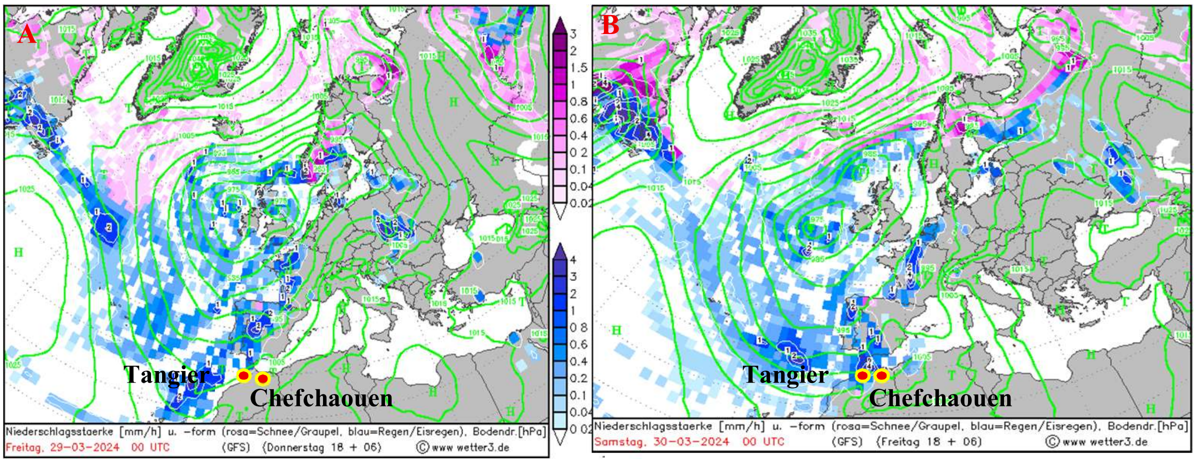


Fig. 3. from left to right, isobaric situation on the ground on March 29 (A) and 30 (B) 2024 0 UTC Data Source: www.wetter3.de

Northern Morocco will be affected at the end of March by the extension of a fairly deep depression, known as Storm Nelson, associated with cold air masses at high altitude. The phenomenon will also affect Western Europe, bringing severe weather conditions to these regions.

The instability intensified and the storms became more threatening. The unstable clouds developed mainly over the western and central Rif and the Middle Atlas, as can be seen from satellite figure 4 [4, 15].

During the period from March 24 to 30, the cities of Tangier and Chefchaouen stood out with a very remarkable accumulation of extreme rainfall. In contrast, relatively low amounts were recorded in southern cities. The cold, humid air mass that affected northern Morocco caused heavy snowfall in the Atlas and Rif mountains, as shown in a satellite image from March 29 and 30, 2024 (see Figure.4).

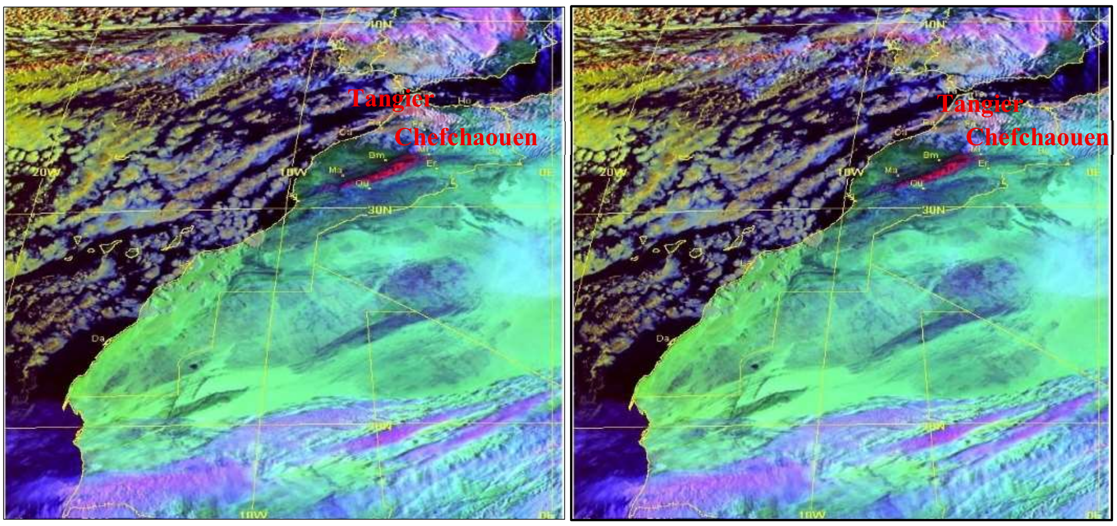


Fig. 4. Satellite situation on March 29 and 30, 2024, at 9 a.m.

3.2. Rainfall amounts for March 2024 and extent of flooding

During the 2023-2024 hydrological year (from September 1, 2023 to August 31, 2024), despite a pronounced drought during the first months of the year (September, October, and

November), the period from early March to the end of the same month was marked by heavy rainfall with a succession of stormy weather [13].

Heavy rainfall was recorded on the Mediterranean coast, the Rif, the Middle Atlas, and the northwest of the country. Daily rainfall reached historic levels. In 24 hours, rain gauges recorded 110 mm in Chefchaouen (see Figure. 5), 120.9 mm at Tangier airport (Figure. 6), 89 mm in Al Hoceima, and 98 mm in Tetouan on March 30. The same situation also caused exceptional rainfall in M'diq, which received 83 mm on March 30.

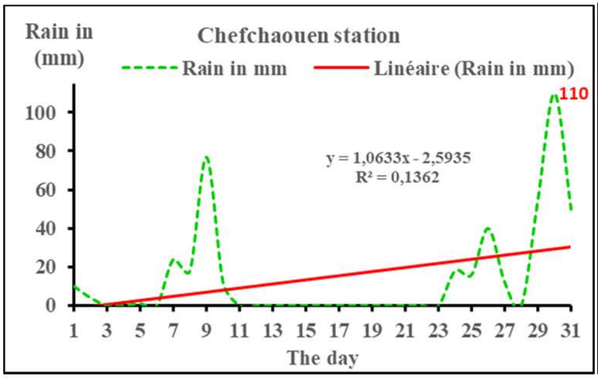


Fig. 5. Daily rainfall recorded at the Chafchaouen station during the month of March 2024.

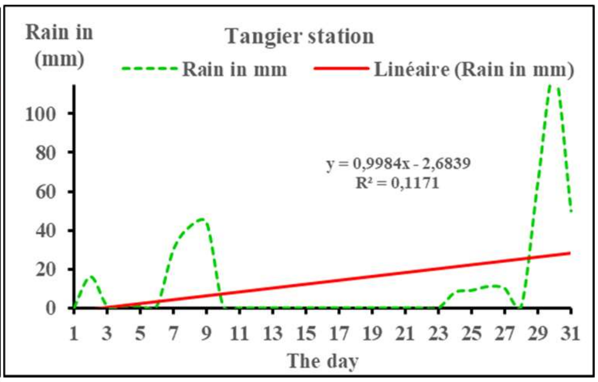


Fig. 6. Daily rainfall recorded at the Tangier station during the month of March 2024.

In addition, locally strong gusts of wind exceeding speeds of between 100 and 115 km/h from midnight on Saturday, March 9, to 6 p.m. on Sunday, March 10, in M'diq-Fnideq, Tangier, and Chefchaouen caused significant material damage (see Figure. 7& 8).

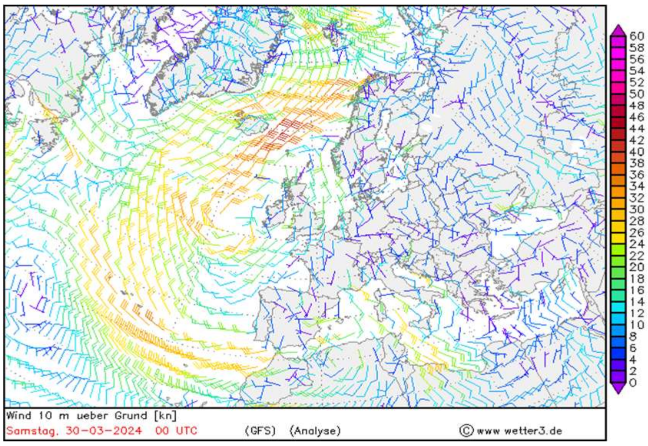


Fig. 7. Wind speed at a height of 10 meters above ground level on March 30, 2024, at 00 UTC

Fig. 8. The effects of high winds in the city of Tangier on March 30, 2024

In March 2024, the Mediterranean coast and northwestern regions of Morocco experienced exceptionally high rainfall [4]. Record daily rainfall figures contributed significantly to the monthly total, which reached levels never before seen during this time of year. The monthly total for March exceeded 100 mm: Tangier 150 mm (Figure.9), Tetouan 98 mm, and Chefchaouen 139 mm (Figure. 9). These exceptional values are in fact equivalent to annual totals for many regions and years in Morocco. As a result, it should be noted that this month's rainfall represents more than 20% of the annual total: 21.7% at Tangier airport, which had an annual total of 600 mm, 55.2% in Tetouan, which received 721.4 mm of rainfall for the year, and 62.6% in Al Hoceima, which recorded a total of 230 mm.

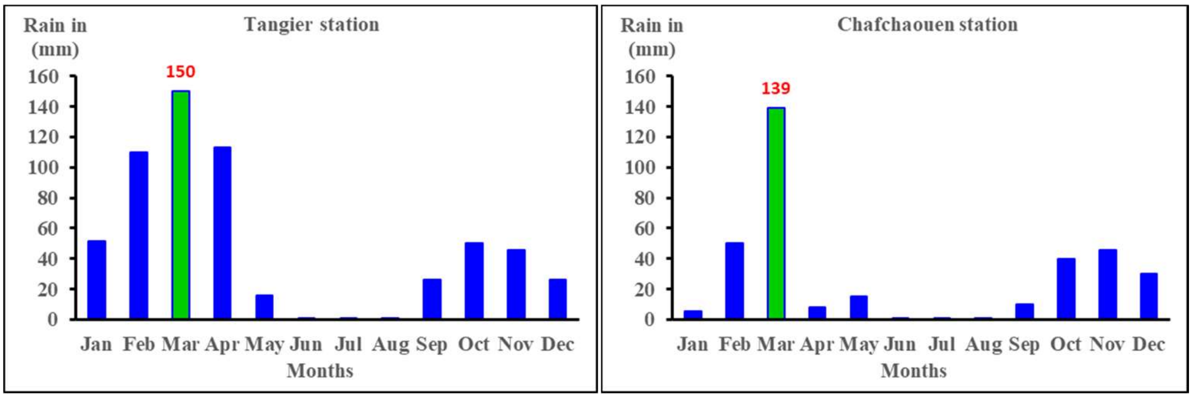


Fig. 9. From left to right, monthly rainfall distribution in the city of Tangier (left) and Chefchaouen (right) during the year 2024.

For the other stations (Martil, Asilah, Fahs-Anjra, Fnidaq, Larach, Taza, Ouezzane, Taounate), precipitation was well distributed during this period, with March totals below 15%. The cities located on the Mediterranean coast received the most rainfall this month, which can be explained by the proximity of the sea, which is warmer at this time of year, increasing the hygrometric capacity of the air masses, whose underlying surface layers were heavily saturated with water. The presence of cold valleys on the ground also created significant instability, leading to very intense daily precipitation [4, 5, 14].

The extreme rainfalls are the weather hazards that cause much damage and many casualties. The evaluation and the estimation of rainfall is therefore of great interest to anticipate disasters such as floods and allow thoughtful planning of the territory. Therefore, we worked on using an indicator R10 mm (Days with heavy rainfall ≥10mm), at the Tangier and Chefchaouen stations, but for only twenty-four years (24 years), from 2000 to 2024.

What distinguishes this index at the two stations (Tangier and Chefchaouen) is the fluctuation between years that recorded a number of days greater than or equal to 5 mm. At the Tangier station, this index remained relatively stable during the period studied, with a slight decrease (see Figure. 10 left). In contrast, the Chefchaouen station recorded 13 days more than the average, so that the number of years above the average remains 11 years compared to only 14 years. The increases vary from 0.09 mm/day to 0.50 mm/day per decade at both stations. On the other hand, the decreases are relatively small (not exceeding 0.01 mm/day per decade) (Figure. 10 right). In general, the index shows a downward trend at the Tangier station and upward trend at the Chefchaouen station over the period 2000-2024, as the latter is characterized by an increase in precipitation levels over the years.

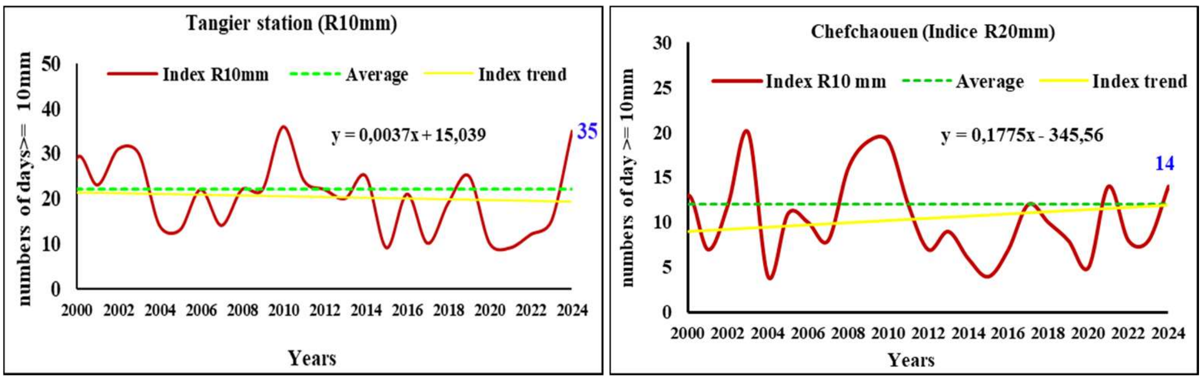
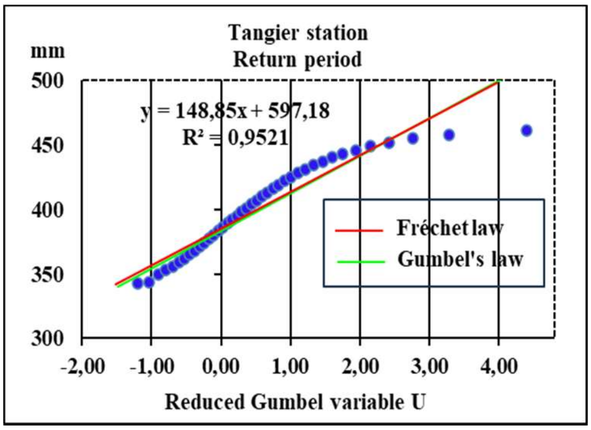


Fig. 10. From left to right, Trend in the number of days with rainfall exceeding R10 mm in Tangier (left) and R20 mm in Chefchaouen (right) from 2000 to 2024

3.3. Estimation of return periods for extreme rainfall events

The annual totals (1976-2024) recorded are shown in figure (11) according to the frequencies detected. There is a good distribution of points around the straight line. Including extreme years [8,14]. The maximum rainfall levels are at the top of the line (4.50 = 1,950 mm) for the Chefchaouen station, and 470 mm for the Tangier station. The wettest year for both stations was 2010.



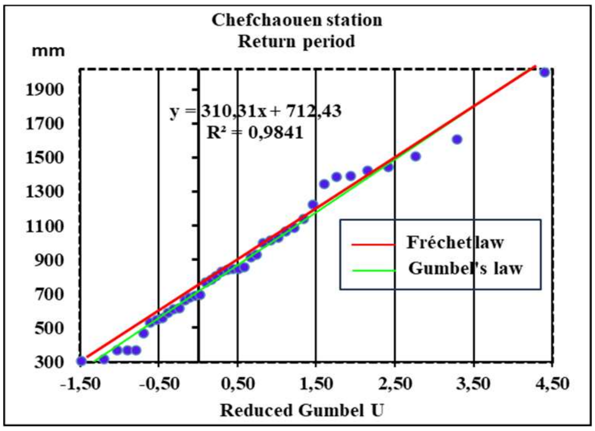


Fig. 11. Graphical representation for estimating return values for certain durations at the Tangier station (left) and Chefchaouen station (right).

The study of maximum rainfall frequency shows that the two stations studied receive more than 200 mm every two years and more than 500 mm every five years (Table. 3). However, the values can increase significantly if the period is extended. At the Chefchaouen station, rainfall can reach 1050.7 mm over 50 years. This is because this province combines three types of climates that are typical of mountainous regions, rainy and cold in winter and mild in summer. Rainfall is highest here, varying between 800 and 1400 mm/year, sometimes reaching 2000 mm/year with snowfall, although this remains rare at 600m. A semi-arid climate dominates the coastal area, with rainfall varying between 350 and 400 mm/year. The southern zone is characterized by a humid climate in winter and dry in summer, with rainfall ranging from 900 to 1300 mm/year [3,4, 9, 14].
But for the Tangier station, the quantities are also greater, due to its exposure to Atlantic and Mediterranean influences (proximity to the sea). It is possible to have 700 mm of rainfall once every 20 years, 850 mm in 25 years, 1080.8 mm in 75 years, and more than 1500 mm in 100 years (see Table. 3).

Table 3. maximum rainfall according to return periods for the two stations in Tangier and Chefchaouen

	years							
Return period	**2**	**5**	**15**	**20**	**25**	**50**	**75**	**100**
	mm							
Tangier	**367,7**	**580,9**	**670,8**	**700,2**	**850,9**	**900,3**	**1080,8**	**1500,3**
Chefchaouen	**287,2**	**510,9**	**630,6**	**794,4**	**875,9**	**1050,7**	**1600,3**	**1713,8**

The most commonly used distribution in modelling annual maxima is the tow-parameter GEV distribution. However, recent studies have called into question this systematic use of Gumbel distribution. Indeed, the Gumbel distribution tends to underestimate extreme values with long return. The consequences of the choice of distribution on quantiles are considerable. For a given frequency, the quantiles of a Fréchet distribution can be twice as large as the quantiles of a Gumbel distribution. However, our results show that the difference between the two distributions is minimal for our study area (see Table. 3).

3.4. Torrential rains causing exceptional flooding in march 2024

Torrential rains fell on the cities of Tangier and Chefchaouen during the night of March 29-30, 2024, causing severe flooding in several neighborhoods. The violence of the floods overwhelmed the fragile infrastructure, causing significant human and material losses in the neighborhoods (see Figure. 12). Many administrative and cultural buildings were seriously damaged.

The abundance of extreme rainfall, the geographical characteristics of two cities, particularly their mountainous terrain, and the natural or anthropogenic impermeability of most of the land mean that surface runoff is significant in the Rif River basins [1, 2, 3]. During storms, rivers experience sudden and violent flooding, causing material damage and loss of life, particularly in highly urbanized areas. This hazard is not new to the region, but due to demographic pressure and economic and tourist development, construction and concreting are increasing in the floodplain, increasing the risks with each flood. Built largely on the left bank of the El Kebir River, R'mel and Moghrane, at the level of a gorge, the cities of Tangier and Chefchaouen have experienced catastrophic flooding over the past 20 years.

The flooding of the Mghogha River, fed by heavy rainfall, caused flooding in a large part of the industrial zone. The water level reached between 0.10 and 0.80 meters for some units, with a total height of 1.50 meters above the road surface (see Fig. 12 left and right). Many factories had taken precautions, with most operators taking care to protect themselves by raising goods or isolating machinery. Roads submerged, industrial zone units buried under tons of mud, roads torn up, bridges destroyed, homes, businesses, and vehicles irreparably damaged; neighborhoods plunged into darkness for several weeks and thousands of people stranded. A city cut off from the rest of the Kingdom for several days [11].

Fig. 12. From left to right, flooding in the Mghougha neighborhood (left) and Boukhalef (right) of Tangier on March 30, 2024

The city of Chefchaouen awoke to torrential rain, with some 139 mm falling in the space of two hours, representing around 20% of the average annual rainfall (400 to 500 mm). These were the heaviest rains to hit northern Morocco in 35 years. The torrential rains that fell on Chefchaouen on December 30, 2024, have raised the specter of flooding in urban areas in northern Morocco, raising many questions about infrastructure and its ability to cope with such disasters.

Like other sectors, the road infrastructure in the city of Chefchaouen has been badly damaged by these disruptions. Several roads have been cut off, such as between Tetouan and Chefchaouen (Figure. 13), due to the collapse or deterioration of several bridges and protective walls, as well as the washing away or degradation of shoulders and roadways. Several schools were affected by the floods. The damage also affected the drinking water and electricity sectors.

In the electricity sector, the floods damaged the electrical infrastructure, causing power cuts in the municipality and neighborhoods within the urban area (Figure. 14).

Fig. 13. Damage to road infrastructure between Tetouan and Chefchaouen on March 30, 2024
Source : https://fr.le360.ma

Figure 14. Example of damage affecting establishments in the city of Chefchaouenon March 30, 2024
Source : https://fr.le360.ma

In 2024, rainfall played a crucial role in Morocco, providing significant relief from a persistent drought that has lasted for more than six consecutive years, with heavy rainfall in March partially filling the water deficit. The extreme rainfall significantly improved the water levels of several dams in northern Morocco, particularly in the cities of Tangier and Chefchaouen [1,2,13].
The rains recorded on Friday, March 29, and Saturday, March 30, helped improve the water levels of several dams, particularly in the northern region. Nationwide, the rate reached 28.94% compared to 34.63% on the same date last year. The latest rainfall has been beneficial for the Kingdom's main dams (Table.4). However, despite this improvement, the situation remains worrying. According to the latest data from the Directorate General of Hydraulics, the current reserves of all dams stand at 4.6 billion cubic meters (4,665.96 million m³) compared to 5.5 billion m³ (5,583.61 million m³) on March 31, 2023 (see Table. 4).
In terms of the fill rate per basin, loukous has a rate of 55.07%. The Chefchaouen, Nakhla, and Achraf El Idrissi dams are each 100% full. As for the others, the Oued El Maghazine dam is 82.01% full, Tangier-Mediterranean (77.26%), Ibn Battouta (63.21%), Neuf Avril 1947 (20.29%), Moulay Hassan Ben Al Mahdi (59.81%), Smir (83.59%), and Dar Khrofa (23.37%) (see Table.4).

Table 4. The fill rate and status of dams in northern Morocco following the extreme rainfall of March 29-30, 2024.

hydraulic dam	Normal volume (m³)	New water filling record 30 March 2024		Previous water filling record 30 March 2023	
		volume (m³)	(%)	volume (m³)	(%)
Chefchaouen	12,9 million/m³	12,2 million/m³	100%	12,1 million/m³	99,9%
Nakhla	4,2 million/m³	4,2 million/m³	100%	4,2 million/m³	99,9 %
Achrif El Idrissi	121,6 million/m³	121,6 million/m³	100%	121,4 million/m³	99,8 %
Wadi El Maghazine	672,9 million/m³	506,2 million/m³	82,01%	566,1 million/m³	84,1%
Tangier- Mediterranean	22 million/m³	16,7 million/m³	77,26%	22 million/m³	99,9 %
Ibn Battouta	29,1 million/m³	13,2 million/m³	59,21%	17,4 million/m³	63,21%
Neuf Avril 1947	300 million/m³	52,5 million/m³	20,29%	60 million/m³	22%
Hassan Ben Mahdi	23,4 million/m³	12,9 million/m³	59,81%	16,5 million/m³	70,3%
Smir	39 million/m³	31,6 million/m³	83,59%	38,4 million/m³	97,6 %
Dar Khrofa	480,2 million/m³	96,1 million/m³	23,37%	155,9 million/m³	32,5%

Data source: https://www.equipement.gov.ma/Actualites/Pages/Actualites.aspx?IdNews=4006

The issue of natural hazards, particularly flood risk, is a topical subject in Morocco and around the world, especially in light of the latest major catastrophic floods (1995, 2000, 2009, 2010, 2014, 2024), which left a lasting mark on the affected areas. Therefore, managing this risk is becoming increasingly necessary and must involve all stakeholders in order to identify the challenges to be addressed, the available resources, and possible alternatives to mitigate the human and material damage caused by this phenomenon.

While it is impossible to prevent these floods from occurring, which are mainly linked to the violence of extreme rainfall on the one hand, and geological and geomorphological conditions on the other, it is possible to mitigate their effects or reduce their frequency, primarily in the most sensitive and exposed areas. These protections can be divided into two groups: direct and indirect (see Figure. 15) [8, 10].

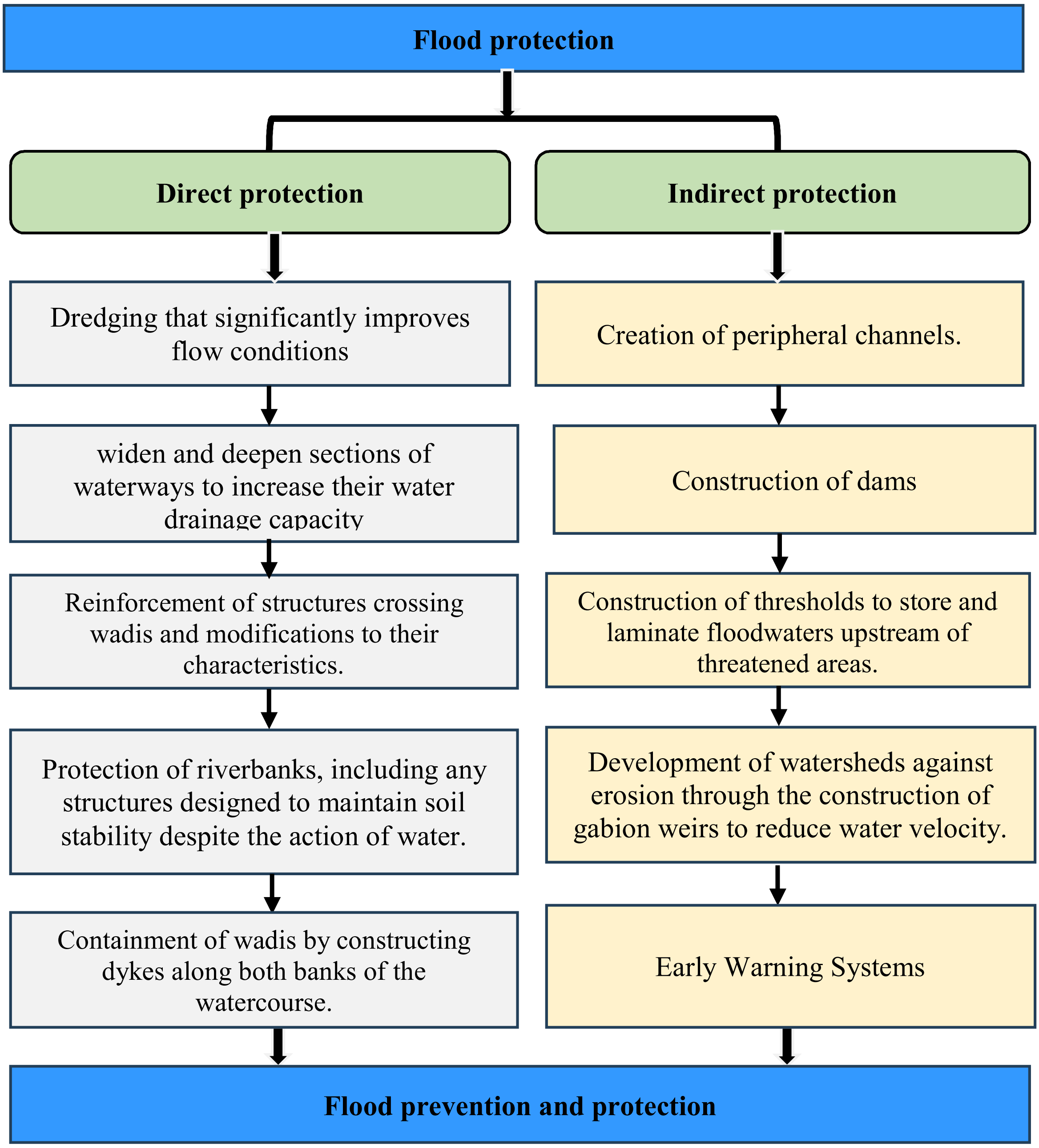


Fig. 15. The diagram shows direct and indirect flood protection.

Conclusion

The climate in northern Morocco during this short period experienced exceptional rainfall. In terms of seasonal rainfall, one would have to go back to 1995-96 or the 1960s to find similar conditions. However, in terms of daily rainfall intensity, records were broken on March 29 and 30, 2024, at certain stations, making it exceptional. Since the late 1970s, we have experienced a water deficit that has convinced us that climate change in Morocco primarily causes drought and water shortages. The effects of this abundance are obviously beneficial for the agricultural sector, but their intensity and temporal concentration can lead to major risks related to flooding, landslides and the collapse of old houses, followed by psychological consequences for the affected populations. Although the international scientific community is divided on estimates of the impact of climate change, there is certainly broad agreement that we are facing a new climate that is becoming more tropical due to global warming, resulting in high rainfall intensity.

Doesn't this indicate that these climate changes can also generate abundant rainfall? or is it simply part of a normal irregularity in the Mediterranean climate, which is self-evident? the last answer is, in my opinion, the most logical. However, the temperature contrasts between polar air and tropical ais masses have increased due to global warming, which causes heavy rainfall, especially during the spring season.

The risks posed by rainy events are detrimental to urban areas located near rivers, or those that run through the middle of them, as is the case for the cities of Tangier and Chefchaouen. The material and human damage weighs heavily on the economy and psychology, as it remains etched in the memories of the often-disadvantaged populations affected. Combating flooding caused by exceptional rainfall, such as that seen in the spring, requires increasing the resilience of cities to these types of risks by improving forecasting, information dissemination, watershed management, and drainage capacity in urbanized areas.

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