Hydro-meteorological characteristics and occurrence probability of extreme flood events in Moroccan High Atlas

Mohamed El Mehdi Saidi, Tarik Saouabe, Abdelhafid El Alaoui El Fels, El Mahdi El Khalki and Abdessamad Hadri

ABSTRACT

Flood frequency analysis could be a tool to help decision-makers to size hydraulic structures. To this end, this article aims to compare two analysis methods to see how rare an extreme hydrometeorological event is, and what could be its return period. This event caused many deadly floods in southwestern Morocco. It was the result of unusual atmospheric conditions, characterized by a very low atmospheric pressure off the Moroccan coast and the passage of the jet stream further south. Assessment of frequency and return period of this extreme event is performed in a High Atlas watershed (the Ghdat Wadi) using historical floods. We took into account, on the one hand, flood peak flows and, on the other hand, flood water volumes. Statistically, both parameters are better adjusted respectively to Gamma and Log Normal distributions. However, the peak flow approach underestimates the return period of long-duration hydrographs that do not have a high peak flow, like the 2014 event. The latter is indeed better evaluated, as a rare event, by taking into account the flood water volumes. Therefore, this parameter should not be omitted in the calculation of flood probabilities for watershed management and the sizing of flood protection infrastructure.

Key words | flood, frequency analysis, Ghdat watershed, Morocco, peak flow, water volume

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HIGHLIGHTS

- The paper compares two analysis methods to see how rare an extreme hydro-meteorological event is, and what could be its return-period.
- Assessment of frequency and return period of the 2014 flood is performed using a frequency analysis of historical floods. We took into account, on the one hand, flood peak flows and on the other hand, flood water volumes.
- The flood peak flows and the flood water volumes are not correlated and no significant linkage appears from their linear regression. The peak flow approach underestimates the return period of long-duration hydrographs that do not have a high peak flow.
- The 2014 event was better evaluated, as a rare event, taking into account the flood water volumes.
- For watershed management, the paper shows that to avoid the construction of undersized hydraulic structures, the flood water volumes should not be omitted in the calculation of flood probabilities.

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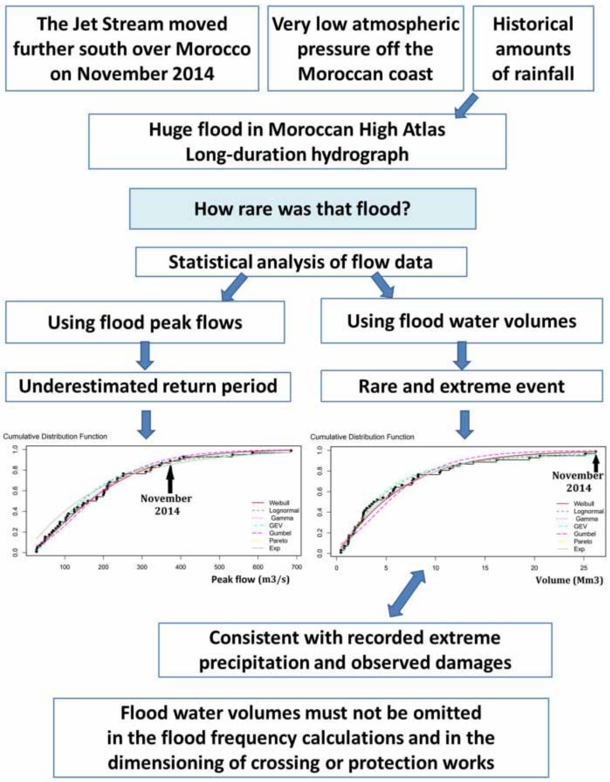
GRAPHICAL ABSTRACT



INTRODUCTION

Many studies currently consider floods as the deadliest natural disasters in the world with around 20,000 victims per year and very high economic costs (Ahern *et al.* 2005). The Mediterranean region is no exception to the rule; it regularly endures intense and recurring hydrological events following extreme weather events. As a transitional zone between tropical and temperate climates, this area is considered by an IPCC report to be a climatic hot spot (IPCC 2013). The precipitation can reach several millimeters in a few minutes or exceed 200 millimeters in 24 hours (Tolika *et al.* 2007). Autumn 2014 was marked there by many intense rainfall events. In France, for example, on 29 September, in the Herault department, the commune of Plaissan recorded 343 mm of rainfall and 452 mm at Saint-Gervais sur Mare from 17 to 19 September 2014 and even 500 mm in Corsica on 28 and 29 November. In Italy, from 9 to 12 November, Lake Maggiore overflowed causing loss of lives (Raymond *et al.* 2016). Moreover, the people of the Mediterranean region remember painful events that have been reported in the literature (e.g., Vinet 2003; Barnolas & Llasat 2007; Barredo 2007; Menad 2012; Llasat *et al.* 2013, 2014; Barrera-Escoda & Llasat 2015; Vannier *et al.* 2016). During the last decades, Morocco has also experienced floods caused by stormy rainfall (Bouaicha & Benabdelfadel 2010; Saidi *et al.* 2010; Reynard *et al.* 2013; Karmaoui *et al.* 2016). These floods caused significant human and economic damage in many regions of the country: the Ourika Valley in 1995 (Saidi *et al.* 2003), El Hajeb, Taza, and Khenifra cities in 1997, Mohammedia, Berchid, and Beni Mellal in 2002 (El Khalki & Benyoucef 2005), Oued Guir valley in 2008 (Aït

Hssaine 2008), Casablanca and Fès in 2010 (Lasri *et al.* 2011), and recently in the south-west of Morocco in November 2014 (Theilen-Willige *et al.* 2015).

The High Atlas of Marrakech is a mountainous environment characterized by a semi-arid climate with high temperatures in summer and a strong seasonal and interannual irregularity of precipitation (Zkhiri *et al.* 2016). This morpho-climatic environment regularly experiences severe floods that affect populations and infrastructure. In addition to the cause of demographic pressure on the land and climate change, the vulnerability of watersheds to floods is increasingly important. The frequency of these floods is also alarming, and any year may witness a major one. The most infamous was that of 17 August, 1995 (Saidi *et al.* 2003). In an unprecedented time (a few tens of minutes), the flood claimed hundreds of lives and caused huge material damage (State Secretariat at the Moroccan Ministry of Energy Mines Water and Environment 2008). For this purpose, this work aims to study a recent extreme event that occurred in November 2014 and which made headlines by causing a great deal of damage. No less than 47 people were swept away by turbulent wadis or buried under the rubble of collapsed houses. Roads were cut out and many localities were landlocked. The High Atlas of Marrakech had its share of damage. The flow rates of rivers such as Ourika, Zat, and Ghdat (Figure 1) reached very high values (respectively, 347, 442, and 340 m^3/s). Moreover, for the main stream that collects these Atlas rivers (Tensift Wadi), the flood was historic with a record of 1,597 m^3/s at Abadla station downstream of Marrakech. To this end, our goal is to analyze this exceptional flood and its excessive rains as well as the disturbance responsible for the Ghdat watershed. We also carry out a frequency analysis of the river floods and seek, through two different approaches, how rare this extreme hydrometeorological event of November 2014 is, and what could be its return period. This would allow a better judgment of exceptional events in order to better manage them and fight against their impacts.

MATERIALS AND METHODS

The physical environment

In the east of the High Atlas of Marrakesh, and upstream of the Tensift basin, the Ghdat watershed (Figure 1) occupies an area of 552 km² and has a mountain range that culminates at 3,542 m. 82% of the lands are situated between 1,000 and 2,600 m (Figure 1) and the mean altitude is 1,730 m. Slopes are also important in some places and their average, measured from a digital elevation model, is about 30.7%. The hydrometric station of Sidi Rahal (690 m) also serves as a rainfall measurement station. Rainfall and discharge data cover a period of 47 years from the hydrological year 1970/1971–2016/2017. These data come

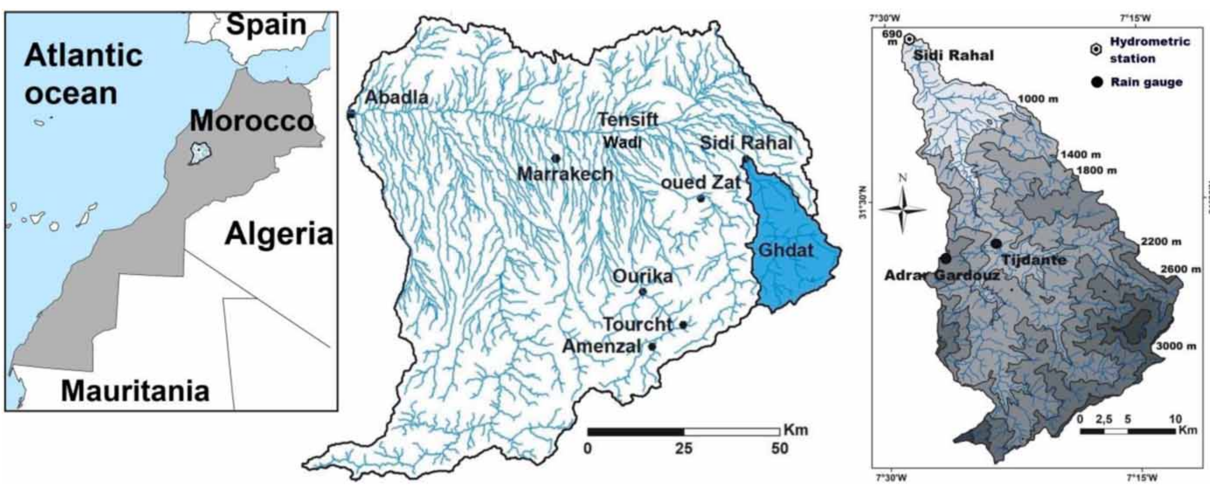


Figure 1 | Location, hypsometry, and hydrography of Ghdat watershed upstream of Tensift basin.

from measurements made by the Tensift Hydraulic Basin Agency at Marrakech. In 2012, this agency installed two other rainfall stations upstream of the basin: Tijdante station at 1,122 m altitude and Adrar Gardouz station at 2,285 m altitude (Figure 1).

The November 2014 downpours and hydrograph typology

The month of November 2014 witnessed heavy and intense rains that affected the Ghdat watershed particularly from the 20th to 23rd of the month. Significant rainfall amounts were recorded at two upstream stations: 83.3 mm at Tijdante and 325 mm at Adrar Gardouz (Figure 2). This latter value is equivalent to the annual average of Sidi Rahal station. According to the Tensift Hydraulic Basin Agency, historical amounts of rainfall were also recorded during the four days in neighboring stations (Figure 1) such as Amenzal station (251 mm) and Tourcht station (410 mm).

This period was particularly rainy throughout the western Mediterranean. Heavy rains were noted in southern France (Paquier 2015), in Italy (Faccini *et al.* 2015; Giordan *et al.* 2017), and in the Maghreb (Zeineddine & Murărescu 2016). The jet stream, which usually flows from west to east across the Atlantic Ocean, around latitudes 50 and 60 north, abnormally passed further south during autumn 2014, especially in the last 10 days of November (Figure 3).

The southern branch of the jet stream caused a flow of sea air towards North Africa and then to southern Europe and thus contributed to abnormally wet conditions in the western Mediterranean. Parts of central and southern Morocco, therefore, experienced one of the rainiest months in their modern history. The Azores anticyclone, which usually maintains dry weather over the country, shifted westwards, giving way to the intrusion of an atmospheric depression off the Moroccan coast. This depression was unusually deep with a central pressure of 985 hPa (Figure 4) and even 975 hPa at one time off the Portuguese coast in the Xandra depression (Karrouk 2015; Roman & Ait Hssaine 2016).

Frequency analysis of Ghdat floods

In order to estimate the occurrence probability and the return period of the 2014 flood, we performed a frequency analysis of all Ghdat floods. We used a flood sample measured over 51 years from 1964/1965 to 2014/2015. The sample is composed of annual maximum instantaneous flows recorded at Sidi Rahal station by the Hydraulic Basin Agency of Marrakech. Different statistical distributions may

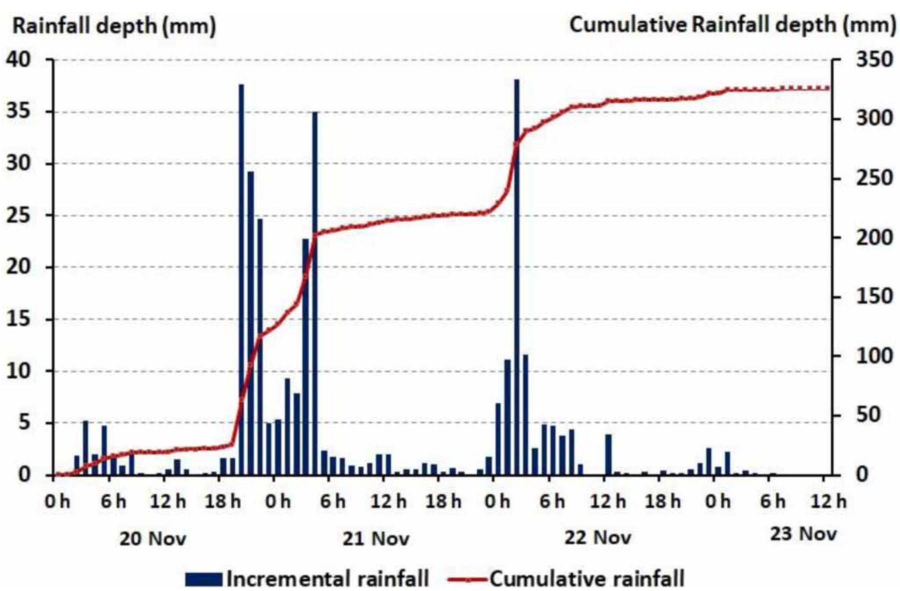


Figure 2 | Incremental and cumulative rainfall at Adrar Gardouz from 20th to 23rd November 2014.

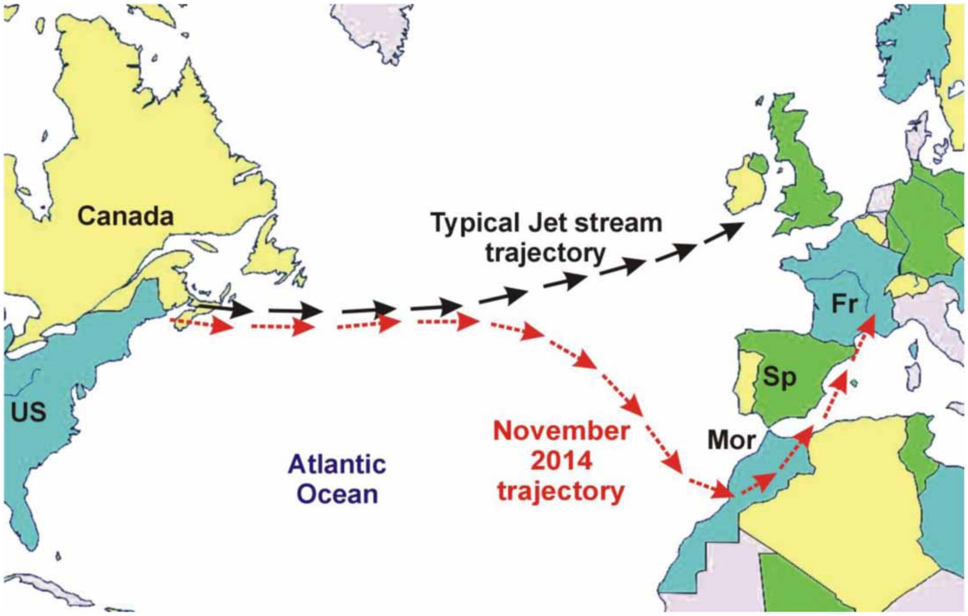


Figure 3 | Typical trajectory and southward deviation of the jet stream in November 2014.

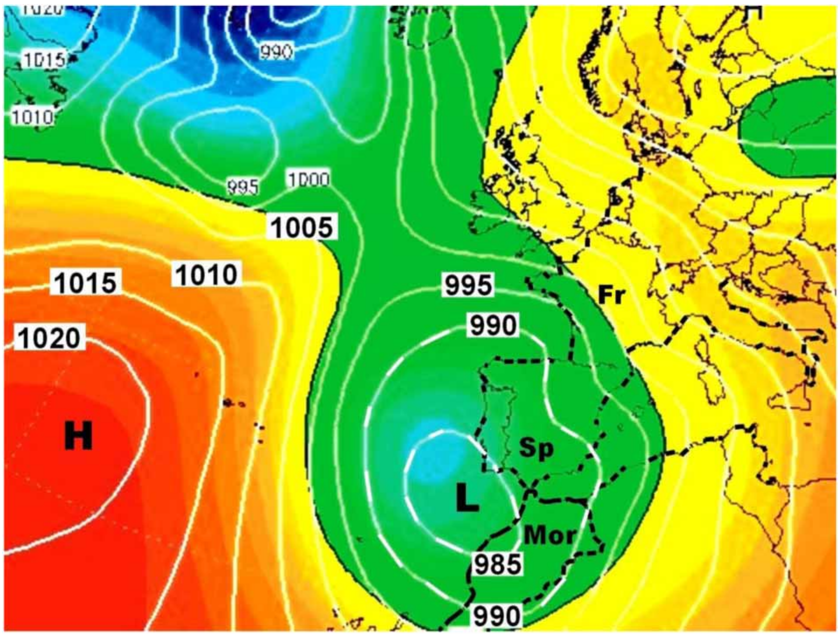


Figure 4 | Atmospheric pressure map at 500 hPa at the end of November 2014 (wetterzentrale.de).

be appropriate to adjust flood flows. In 1932, Gibrat demonstrated that they are well-adjusted by the three-parameter Log-Normal distribution (Gibrat 1932). Other authors have proposed the Gamma and generalized extreme value distributions (GEV) (Leboutillier & Waylen 1993; Cheng *et al.* 2012) or Gumbel law (Mujere 2011; Bhagat 2017). That is why it would be wise to use a tool that allows testing a multitude of distribution functions and choosing the best adjusted one, according to quantitative criteria. Akaike information criterion (AIC) (Akaike 1973) estimates the adjustment model quality. It attempts to address the tradeoff between parsimony and goodness-of-fit and to indicate which hypothesis should be considered first (Vandekerckhove *et al.* 2014). Another criterion derived from AIC is the Bayesian information criterion (BIC) (Schwarz 1978). Contrary to AIC, the assessment of the goodness-of-fit depends on the size of the sample and not just the number of parameters. For both criteria, we should choose the distribution function that would minimize the loss of information; that is, with the smallest information criteria (Cameron & Trivedi 2005).

RESULTS AND DISCUSSION

The flood hydrograph

The intense rains from 20 to 23 November 2014 fell on a soil already saturated by previous downpours, especially by a rainy sequence from 2 to 9 November. This later sequence brought 73 mm of rainfall to Sidi Rahal, 62 mm to Tijdante and 41 mm to Adrar Gardouz. This wet situation, combined with geomorphology that is favorable to runoff, caused a torrential flow of the Ghdat Wadi. The hydrograph produced (Figure 5) shows several pulsations exceeding 150 m^3/s and a peak of 373 m^3/s on 22 November at 8 a.m. The flood spanned over 3 days, derogating from habitual local flash floods (Saidi *et al.* 2012). This flood duration allowed the routing of water volumes exceeding the usual norms. No less than 26 million cubic meters swept away homes and damaged agricultural fields and roads, especially causing the submersion of the regional road R210 connecting Sidi Rahal to Marrakech (Figure 6) and the destruction of a bridge near Marrakech (Figure 7).

Frequency analysis of flood peak flows

Figure 8 illustrates the result of the frequency test using several frequency models.

According to its lowest AIC and BIC values, the Gamma distribution seems to be the most appropriate to estimate the occurrence probability of Ghdat floods and their return periods (Table 1). The decennial flood reached 383 m^3/s and that of the 100-year flood was 672 m^3/s (Table 2).

These quantiles are very high compared to the mean discharge (2 m^3/s). This area is a semi-arid environment that can experience intense rainy periods and excessive downpours, as was the case in November 2014. Paradoxically, the peak discharge resulting from this rainy period (373 m^3/s) is believed to be comparable only with the ten-year flood, despite the enormous damage observed (Ait Mlouk *et al.* 2016; Bennani *et al.* 2016). This frequency

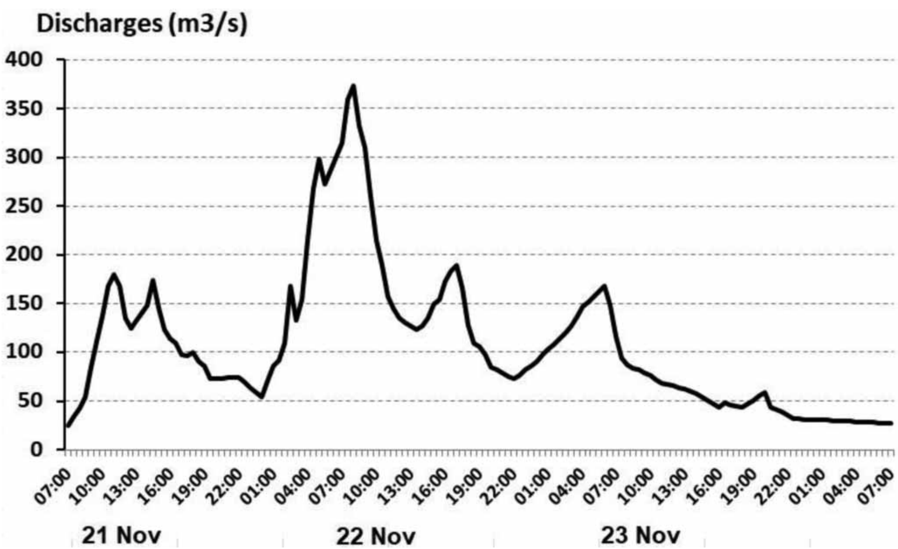


Figure 5 | The flood hydrograph of Ghdat Wadi between 21 and 23 November 2014.

Figure 6 | Road cut off between Sidi Rahal and Marrakech due to 2014 Ghdat flood (source: Tensift Hydraulic Basin Agency).

Figure 7 | Part of Zat bridge washed away by the November 2014 flood (source: Tensift Hydraulic Basin Agency).

analysis seems to underestimate the return period because, although the flood event spanned 3 days and produced a huge volume of water, it did not have a very high peak flow. Indeed, this analysis uses only the peak flows without taking into account the shape of the hydrograph. Peak flows and flood water volumes are not linked by linear regression and the correlation between the two parameters is not significant (Figure 9). A typology analysis of flood hydrographs shows, on the one hand, sharp hydrographs with high peak flows but a short duration and low water volumes (Figure 10(a)) and, on the other hand, hydrographs more spread over time without necessarily a high peak flow (Figure 10(b)). The latter are as devastating as the first and should be estimated at their fair value. For this purpose, in the following approach, we will re-analyze the flood occurrence probabilities using their water volumes instead of instantaneous maximum flow rates.

Frequency analysis of flood water volumes

The above frequency test is applied to floods using their water volumes (Figure 11). According to AIC and BIC criteria (Table 3), Log Normal function is most appropriate to represent the flood water volumes' distribution. The decennial water volume would amount to 14.58 million cubic meters and the volume of the centennial flood would reach 42.12 million cubic meters. But the crucial information is that the return period of the November 2014 flood, estimated at nine years with the first analysis, would be 32 years using water volumes instead of maximum instantaneous flow rates (Table 4). The new occurrence

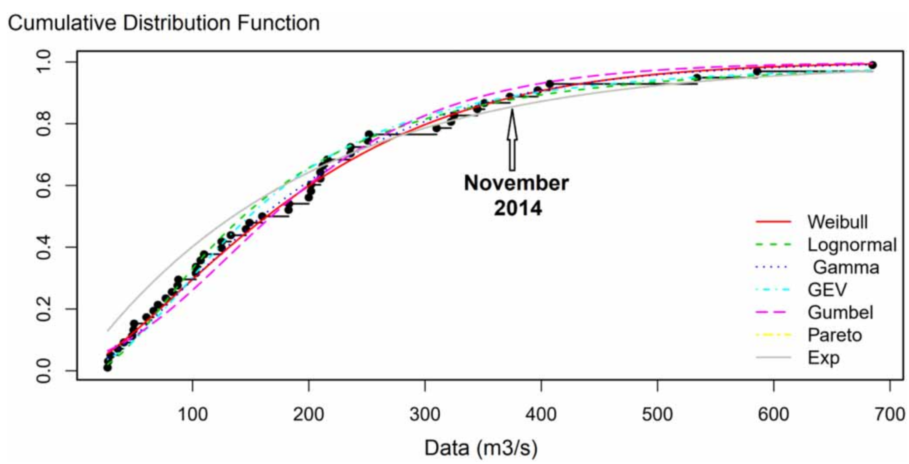


Figure 8 | Adjustment of probability laws to peak discharges of Ghdat floods from 1964/1965 to 2014/2015.

Table 1 | AIC and BIC criteria of the frequency analysis of flood peak flows

Criterion	Weibull	Log Normal	Gamma	GEV	Gumbel	Pareto	Exp
AIC	611.163	610.742	**610.123**	615.289	617.152	618.480	616.480
BIC	614.946	614.525	**613.907**	620.964	620.935	622.263	618.372

Bold numbers (the lowest values of AIC and BIC criteria) indicate the most appropriate distribution.

Table 2 | Quantiles of peak flows and their return periods in Ghdat watershed

Return period (years)	500	100	50	20	10	5	2
Probability	0.002	0.01	0.02	0.05	0.1	0.2	0.5
Discharge (m^3/s)	865	672	587	473	383	291	157

probability of this flood (3.12%) corresponds better to the exceptional downpours and better explains the considerable damage to infrastructure caused by the flood (Figures 6 and 7). Using only flood peaks' data in order to estimate flood frequencies, neglecting hydrographs' shape and water

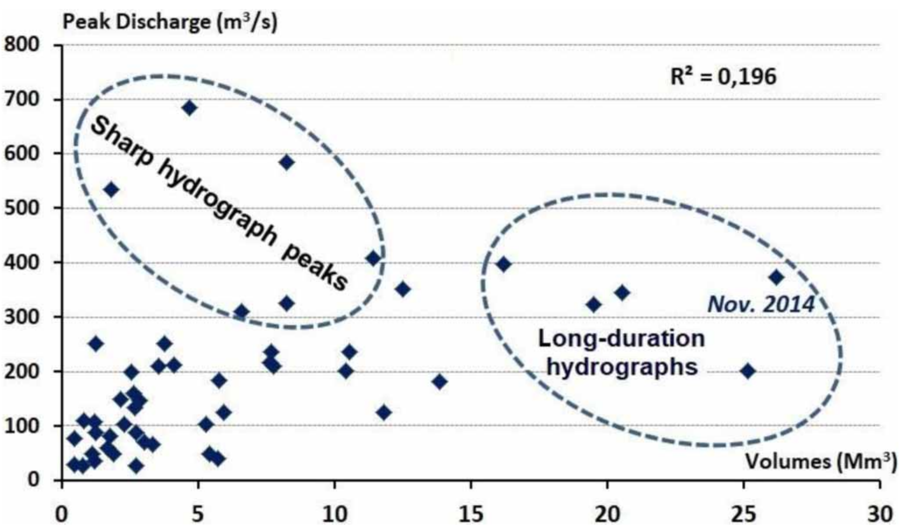


Figure 9 | Correlation between peak flows and water volumes of the Ghdat floods from 1964/65 to 2014/15.

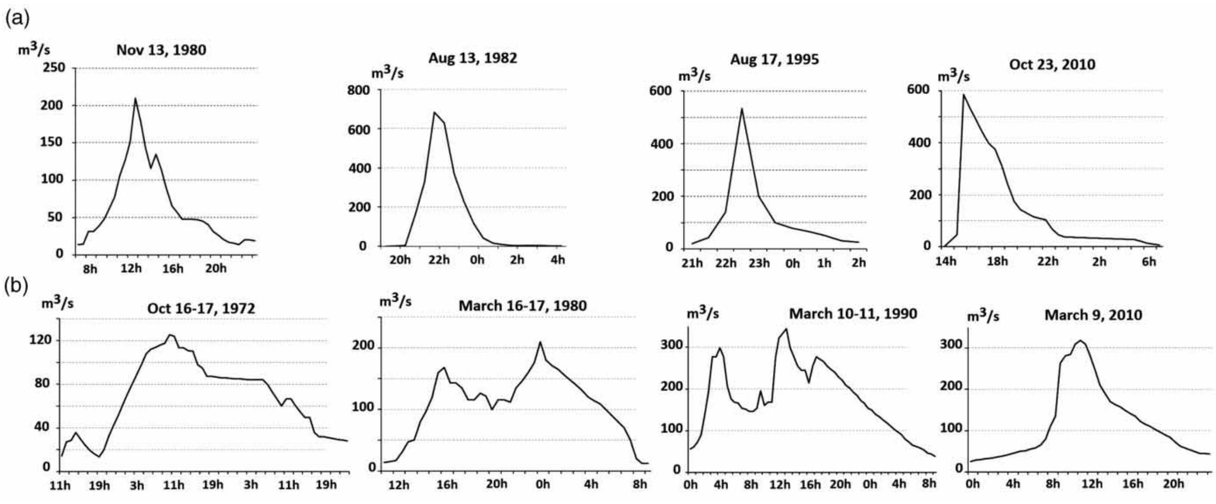


Figure 10 | Typology of Ghdat floods: (a) sharp hydrograph peaks and (b) long-duration hydrographs.

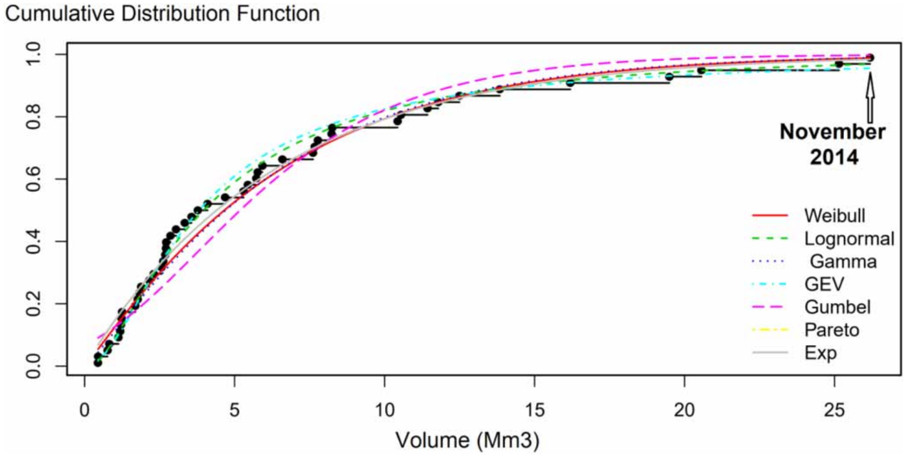


Figure 11 | Adjustment of probability laws to water volumes of Ghdat floods from 1964/1965 to 2014/2015.

Table 3 | AIC and BIC criteria of the frequency analysis of flood water volumes

Criterion	Weibull	Log Normal	Gamma	GEV	Gumbel	Pareto	Exp
AIC	282.763	**279.625**	282.222	284.730	299.109	283.202	281.202
BIC	286.546	**283.409**	286.006	290.406	302.892	286.985	283.093

The lowest values of AIC and BIC criteria (bold numbers) indicate the most appropriate distribution.

Table 4 | Quantiles of flood water volumes and their return periods in Ghdat watershed

Return period (years)	500	100	50	20	10	5	2
Probability	0,002	0.01	0.02	0.05	0.1	0.2	0.5
Volume (Mm^3)	73.77	42.12	31.94	21.08	14.58	9.33	3.97

volumes, would therefore underestimate some events with a wide hydrograph shape or with several peaks. The flood of 21–23 November 2014 on the High Atlas of Marrakech is an illustrative example.

CONCLUSION

The rainfall recorded in November 2014 in central and southern Morocco was exceptional in terms of amount, duration, and the geographical extent. Precipitation totals of 251, 325, or even 410 mm were recorded in a few days in the watersheds of Marrakech High Atlas. They correspond to regional rainfall records and caused memorable floods. The meteorological situation during this month was characterized by unusual weather conditions. A change in the jet stream trajectory was noticed. It abnormally followed a trajectory further south crossing Morocco and moving up to southern France. A deep atmospheric depression, named Xandra, was produced off the Moroccan coast and caused strong and rainy weather. In addition to its relatively high peak flow, the Ghdat flood resulting from this rainy episode was marked by a very large water volume, the largest ever observed in the basin. This was the result of the flow rate being maintained at higher than 100 m^3/s during 3 days. For this purpose, we performed the frequency analysis of this flood taking into account first the peak flow and then its water volume. The first approach attributes to this event only the decennial quantile, while with water volumes, its return period would be 32 years. That low probability of occurrence is better correlated with the flood damage and with the high rainfall intensities. This allows us to better highlight the flood water volumes in the calculation of their return periods and occurrence probabilities in the semi-arid Mediterranean environment. Dimensioning of crossing or protection structures would still be based only on the frequency analysis of peak flows, while the hydrograph shape and the flood duration are also important. In the current climate change context, more abundant and intense rainfall is expected in the future. That would lead to extreme hydrological events which could affect the proper functioning of the transportation routes and delay the resumption of economic activities. The November 2014 event is marked in the Moroccan public memory by the magnitude of the flood damage. This work would then be seen as a post-event survey in a valley of the High Atlas in order to preserve the memory of hazards and better manage future natural disasters.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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