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FLOW-DURATION-FREQUENCY CURVES IN HIGH-FLOW CONDITIONS
A STRATEGIC DECISION-MAKING TOOL FOR SELECTED STREAMS IN THE CONSTANTINOIS COASTAL BASIN, NORTHEASTERN ALGERIA

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ABSTRACT

Effective management of surface water resources in the Constantinois Coastal Watershed (northeastern Algeria) is challenged by strong climatic variability and complex geomorphological conditions. This semi-arid Mediterranean basin (11,509 km^2) is characterized by highly variable and intermittent flow regimes driven mainly by episodic runoff. Conventional hydrological approaches, such as descriptive statistics and rating curves, are inadequate as they do not simultaneously account for flow duration and frequency. This study develops a frequency-based approach using hydrometric discharge series, whose observation periods vary between stations and extend approximately from 1946/1947 to 2006/2007, to construct Discharge-Duration-Frequency (QdF) curves. Mean discharges calculated over successive durations were associated with their occurrence frequencies, following a framework analogous to Intensity–Duration–Frequency (IDF) curves used in rainfall analysis.

Results indicate an average annual runoff of approximately 3,250 hm^3. In the Kebir-East wadi, 30-day accumulated runoff volumes are estimated at about 160 and 196 hm^3 for return periods of 10 and 20 years, respectively, with uncertainties below 20% based on the Generalized Extreme Value (GEV) distribution.

This work offers an original contribution by extending the QdF approach to intermittent Mediterranean hydro-systems, where hydrological variability and data limitations remain critical constraints. By integrating duration and frequency within a unified probabilistic framework and applying GEV-based synthetic data generation, the proposed method enhances the robustness of flow characterization. It provides a transferable and decision-support tool for water resources management, flood risk mitigation, and hydraulic infrastructure design in semi-arid regions facing increasing hydroclimatic variability

Keywords: Surface Runoff, Frequency Analysis, Discharge-Duration-Frequency Curves (QdF), Constantinois Coastal Basin, Water Resources Management.

INTRODUCTION

Understanding surface flow regimes of rivers is a major challenge for sustainable water resources management (Benslimane et al., 2011; Boutebba et al., 2014; Faye, 2016; Bouly et al., 2019; Pandey et al., 2022; Berrezel et al., 2023). Classical statistical approaches, based on global indicators such as annual means, standard deviations, extreme values, and quantiles, as well as traditional analyses including flow-duration curves and characteristic discharges, provide only a partial description of river hydrological behavior (Saidi et al., 2012; Nassa et al., 2021; Benkaci et al., 2020; Mah et al., 2023; Ezz, 2025). In particular, these methods remain limited in their ability to distinguish between perennial and intermittent flow conditions over observation periods (Smakhtin, 2001).

To overcome these limitations, Smakhtin (2001) emphasized the importance of explicitly incorporating the concept of duration into hydrological analyses, especially for a better characterization of low-flow regimes and flow permanence. Building on this concept, S.t-Hilaire (2005a) formalized the Discharge-Duration-Frequency (QdF) curves, which simultaneously integrate flow magnitude, duration, and probability of occurrence, following an approach analogous to the Intensity-Duration-Frequency (IDF) curves widely used in rainfall analysis (Houichi, 2017).

Since then, QdF relationships have been widely applied in various hydrological contexts. Several studies have demonstrated their relevance for the construction of synthetic hydrographs and flood forecasting (Oancea et al., 1992; Bessenasse et al., 2006; Cherki, 2019; Baudhanwala et al., 2023), as well as for the regional characterization of hydrological regimes across basins of different sizes and climatic conditions (Yahiaoui et al., 2011; Ketrouci and Meddi, 2015; Onyutha and Willems, 2015; Hachemi and Benkhaled, 2016; Grairi et al., 2017; Renima et al., 2018). Other research has highlighted their key role in the design and management of hydraulic structures (Ouattara et al., 2022; Long et al., 2023; Kouloughli and Telli, 2023), particularly dams (Shaikh et al., 2024), reservoirs (Mezenner et al., 2022; Zegait and Pizzo, 2023; Verma et al., 2023; Trivedi and Suryanarayana, 2023; Mehta et al., 2023c; Panchal and Suryanarayana, 2025), and flood protection systems (Boulghobra, 2013; Hountondji et al., 2019; Aroua, 2020; Orta and Aksoy, 2022; Wang et al., 2023; Ben Said et al., 2024).

Moreover, the application of QdF curves to low-flow conditions has contributed to improved drought management by providing more reliable estimates of allowable water withdrawals, supporting the maintenance of environmental flows, and assessing the dilution capacity of rivers for pollutant discharges, thus reducing the impact on public health (Smakhtin, 2001; Sung and Chung, 2014; Amitouche et al., 2017; Baba Hamed, 2021; Awang et al., 2023; Chabokpour et al., 2025).

Despite these advances, the application of QdF curves remains limited in the coastal basins of northeastern Algeria, particularly for the analysis of high-flow conditions using daily discharge time series (Bong et al., 2023). Furthermore, few studies have addressed the spatial transferability of these relationships to neighboring or smaller basins, although these regions are characterized by pronounced hydrological variability and increasing pressure on water resources, due especially to climate change (Nichane and Khelil, 2015; Argaz, 2018; Aroua, 2018; Assemian et al., 2021; Nakou et al., 2023; Qureshi et al., 2024).

Within this context, the present study aims to develop Discharge-Duration-Frequency (QdF) curves for the high-flow period of several coastal wadis in the Constantinois Coastal basin (northeastern Algeria), using available daily discharge data and appropriate frequency analysis methods. The objectives are twofold: to improve the understanding of surface flow regimes in these basins, and to provide operational tools for streamflow forecasting, optimization of water storage, and flood risk management (Ayari et al., 2016; Bekhira et al., 2019; Benslimane et al., 2020; Athmani et al., 2025). In addition, the derived QdF curves may be extrapolated to adjacent or ungauged basins using spatial regionalization techniques such as the drainage-area ratio method, thereby contributing to an integrated and coherent regional water resources management framework.

MATERIAL AND METHODS

Study area

Located in northeastern Algeria, the Constantinois Coastal basin (03) lies approximately between latitudes 36.30° and 37.10° N and longitudes 4.98° and 8.68° E (Fig. 1). The basin extends administratively from the Wilaya of Béjaïa in the west to the Tunisian border in the east. It is bounded by the Mediterranean Sea to the north and by the Wilayas of Souk Ahras, Guelma, Constantine, and Mila to the south.

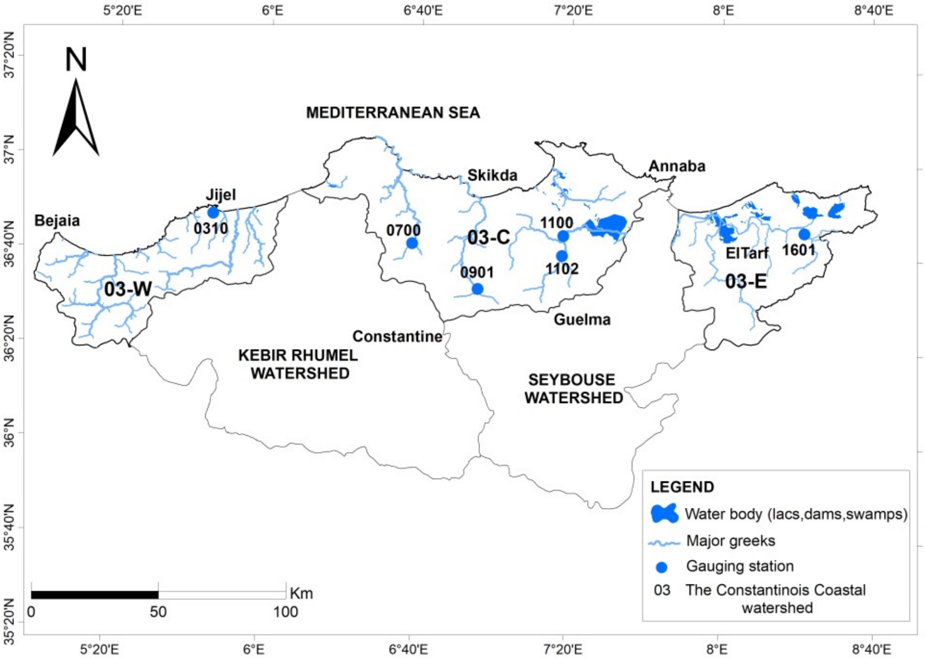

Figure 1: Localization of the study area and hydrographic basins

Covering an area of approximately 11,509 km² (Agence des Bassins Hydrographiques Constantinois-Seybouse-Mellegue, ABH-CSM 2000), the basin spans ten Wilayas, with Skikda being the principal administrative division. The region exhibits significant hydro-climatological and geomorphological variability, which directly influences streamflow regimes and hydrological balances (Chow et al., 1988). According to Mebarki (1999), the basin's average annual runoff contribution is estimated at around 3250 hm³ at its outlet.

The Constantinois Coastal basin experiences a Mediterranean climate characterized by wet, cool winters and hot, dry summers. Climate projections suggest a trend toward increasingly drier conditions across the Mediterranean region as a result of greenhouse gas emissions (Lange, 2020; Avithrapriya et al., 2022; Pastagia et al., 2025). Precipitation shows high spatial and temporal variability, ranging from 650 mm annually in the basin's upstream areas to 1800 mm in the wettest zones, notably the Collo-Jijel region.

This high variability in precipitation directly influences runoff generation and contributes to the irregular and intermittent flow regimes observed across the basin (Mehta et al., 2023b; Mehta et al., 2025; Adil et al., 2025).

Hydrologically, streamflow in the basin is characterized by strong temporal irregularity, with predominantly intermittent regimes, especially in upstream and semi-arid zones, where flows are mainly driven by episodic rainfall and surface runoff.

Geologically, the basin is distinguished by successive tectonic formations extending from north to south (Vila, 1980; Wildi, 1983). The internal domain comprises a crystalline basement overlain by Paleozoic sedimentary rocks, which are tectonically overthrust onto southern units. The flysch domain features Cretaceous sandstone-pelitic sequences and Oligocene sandstones, while the outer domain consists of Lower Cretaceous marly-limestone formations (Boudoukha and Messaid, 2014). The basin's tectonic complexity has given rise to a dense network of rivers and streams.

The main watercourses, from east to west, include the El Mafragh (formed by the Kebir-East and Bounamoussa wadis), Kebir-West (and its Hammam tributary), Saf-Saf, Guebli (with its Fessa tributary), Djendjen, and Agrioun wadis. Hydrologically, the basin is subdivided into three coastal sub-basins: Eastern (03-E), Central (03-C), and Western (03-W).

- The Eastern Constantinois Coastal (03-E) basin covers 3203 km² with a hydrographic network extending approximately 1760 km. Its main river, the Kebir-East, is over 35 km long, draining an area of 680 km² at the Ain Assel gauging station. The Kebir-East merges with the Bounamoussa wadi in the Mekhada marshes to form the El Mafragh River. Flow is monitored at stations including Kebir-East at Ain Assel, Zitoun at Gue-Zitoun, Kebir-West at Ain Charchar, and Hammam at Zit Emba.

- The Central Constantinois Coastal (03-C) basin spans 5582 km², almost half of the total basin area, and is mainly situated within the Wilaya of Skikda. Its 4200 km hydrographic network is dominated by the Saf-Saf (over 50 km) and Guebli (over 40 km) wadis. Key monitoring stations include Saf-Saf at Khemakhem, Guebli at Sidi Mezghich, and Fessa at Guenitra.

- The Western Constantinois Coastal (03-W) basin covers 2724 km² and includes a dense hydrographic network (over 2000 km), primarily drained by the Djendjen (70 km), Djemaa, and El Berd (40 km) wadis. Monitoring stations include El Kantara and El Agrem at El M'Kaceb and Chdia, respectively.

Overall, streamflow monitoring across the basin relies on nine water level recording stations, with data provided by the Hydrological Service of the National Agency for Hydraulic Resources (ANRH) across its Annaba, Constantine, Tébessa, and Jijel offices.

For each gauging station, daily mean discharge values are archived across multi-year observation periods. Based on data availability and study objectives, six hydrometric stations were selected (Table 1).

The hydrometric datasets cover a long observation period ranging approximately from 1946/1947 to 2006/2007 depending on the station (Table 1).

Table 1: Hydrometric stations with geographic coordinates and operating periods

Water course	Station	ANRH code	Latitude (°N)	Longitude (°E)	Recording period
Kebir-East	Ain Assel	031601	36.767521	8.364658	1946/47-2003/04
Kebir-West	Ain Charchar	031100	36.751686	7.304324	1952/53-1998/99
Hammam	Zit Emba	031102	36,681002	7,299818	1969/70-1986/87
Saf-Saf	Khemakhem	030901	36.558734	6.932782	1973/74-2001/02
Fessa	Guenitra	030700	36.715266	6.640419	1991/92-2006/07
El Kantara	El M'kaceb	030310	36.802454	5.763385	1972/73-1991/92

Morphometric characteristics of the selected catchments were analyzed using GIS tools (ArcMap 10.3) and high-resolution (30 m × 30 m) satellite imagery (Mehta et al., 2023b). Parameters related to basin geometry, relief, and drainage patterns were derived from the RSTM-1 Arc-Second Global DEM datasets available through the USGS EarthExplorer platform (Gangani et al., 2023).

The key morphometric indices are summarized in Table 2. For a detailed description of the formulas and methodologies used to calculate these indices, the reader is referred to Soni (2016), Ikbal et al. (2017), Sukristiyanti et al. (2018), and Markad et al. (2020).

Table 2: Watershed morphometric characteristics of selected rivers

Morphometric indices	Drainage basin (main water course or wadi)					
	Kebir-East	Kebir-West	Hammam	Saf -Saf	Fessa	El Kantara
Drainage Area (km^2)	680	1144	486	319	204	22
Perimeter (km)	157	189	120	109	69	22
Shape index (circularity ratio)	0.35	0. 40	0.43	0.34	0.54	0.57
Maximum elevation (m)	1192	1210	1210	1209	1363	556
Minimum elevation (m)	24	18	71	190	110	14
Total land elevation drop (m)	1168	1192	1139	1019	1253	542
Mean slope index (m/km)	63	66	70	75	78	60
Mean slope aspect (°/N)	189	174	173	183	162	152
Drainage density (km/km^2)	3	2	2	3	2	2
Water course slope (m/km)	24	19	26	25	55	44
Time of concentration (h)	8	10	7	5	4	2

Morphometric indices reported on table 2 give a clear picture of the elongated type of the watersheds ($0.34 \leq$ Circularity ratio ≤ 0.57); the shape index being less than 0.785. As a result, such basins are supposed to have high infiltration capacity and low runoff. In the largest part of the study area, the relief is quiet remarkable ($542 \leq$ Total land elevation drop ≤ 1253 m) and the land surface slopes are moderately inclined ($60 \leq$ Mean slope index ≤ 78 m/km) and south-facing ($152 \leq$ mean aspect ≤ 189 °/N).

The branched type hydrographic network is relatively dense with regularly branching drains ($2 \leq$ Drainage density ≤ 3 km/km^2) and the main rivers are distinguished by fairly slight gradients ($19 \leq$ main water course slope ≤ 55 m/km). These different geomorphological features confer to the studied watersheds a concentration time (T_c), estimated by the Giandotti II formula as described by Grimaldi (2012), variable according to size and elongation, between 2 hours for El-Kantara and 10 hours for Kebir -West wadis, respectively.

Selection of relevant variables and database construction

For each hydrometric station, the development of *Flow-Duration-Frequency* (QdF) curves is based on continuous daily flow recordings collected over an extended observation period (Mehta et al., 2023a; Lang et al., 1999). For each hydrological year (spanning from September of year i to August of year i+1), the procedure involves calculating the average flow rate (Q), typically expressed as volume, passing through the gauging section over a specified consecutive d-day period.

This process begins by organizing the 365 daily observations into a single column, where the first and last entries correspond to September 1 of year i and August 31 of year i+1, respectively. To smooth out random fluctuations, a one-day interval moving average filter is applied. Subsequently, the average flow and the maximum average volume over 1, 7, 15, 30, 90, and 365 consecutive days are computed. The values expressed in Hm^3 correspond to volumes derived from mean discharges over the considered duration, obtained by converting the averaged flow rates into equivalent water volumes. For purposes related to water storage planning, only the maximum values are retained, as they represent the potential water availability during high-flow periods.

The same procedure is repeated for all station-year combinations considered in the study. Thus, for each hydrometric station, a matrix is generated, consisting of L rows (extreme flow values, Q) and C columns (corresponding to the reference durations, d), for both high-flow periods.

However, it should be emphasized that the low-flow data were found to be too incomplete and irregular for reliable frequency analysis. As a result, only the high-flow time series were retained and used for the construction of the QdF curves for the selected rivers.

It is also important to note that the database includes variables with missing values. Depending on the nature and extent of the missing data, appropriate imputation methods were employed, including the use of the arithmetic mean and linear regression based on the double cumulative curve method.

Frequency analysis

One of the fundamental tools for analyzing the occurrence of extreme events is Frequency Analysis (FA). This statistical method utilizes measurements of past and observed events to estimate the probabilities of future occurrences. Specifically, frequency analysis is employed to estimate the magnitude of the T-year event, x(T), where T represents the return period (Salas JD and Obeysekera J 2020), defined as the inverse of the exceedance probability ($P = 1/T$) (Villarini et al., 2021; Kim H et al.,2024; Verma et al., 2024; Coles, 2001).

The estimation of x(T) values is achieved by fitting a probability distribution function,

F (x; m*)*, with *m* parameters to a sample of N observations. According to S.t-Hilaire (2005 b), the main steps involved in frequency analysis include:

- Homogeneity check: Ensuring that the data originates from a homogeneous sample.
- Randomness check: Verifying that the series does not exhibit autocorrelation.
- Representativeness check: Confirming the absence of outliers in the dataset, ensuring that it accurately reflects the population.

Once these assumptions are validated, the following steps are taken:

- Fitting a statistical distribution: A distribution F (x; m) is fitted to the sample data, and goodness-of-fit tests are conducted to determine the appropriateness of the model.
- Estimating expected quantiles: The expected quantiles x(T) or x(P) are calculated using the fitted theoretical model.

For the purposes of this study, these methodological steps were efficiently carried out using Statgraphics Centurion XV-II, Easyfit-Pro software, and Excel applications.

Results and discussion

From a mathematical perspective, the frequency analysis of a random variable requires, in addition to the relevance of data (absence of outliers), verification of some basic assumptions, particularly the stationary, random, and homogeneous nature of the values taken by the variable in question. Inflow records were subjected to exploratory data analysis and a series of hypothesis tests to evaluate the suitability of the time series for frequency analysis. Along with graphical tests (histograms, box plots, stem-and-leaf diagrams), non-parametric tests for randomness (Wald-Wolfowitz), homogeneity (Mann-Whitney), stationarity (Kendall), and the Grubbs and Beck (1972) test for outliers were applied.

The results from the exploratory analysis and statistical tests (Table S1 in supplementary material) demonstrate that the inflow time series are suitable for frequency analysis. However, some extremely large events (outliers) were identified in a few series. For instance, the 15-day inflow (Q-15d) sample data contains an outlier. These extreme events, along with similar ones, were omitted from forthcoming analyses (Mehta et al., 2023a).

From the descriptive statistics (Tables 3, 4, and 5), it is evident that, in most cases, the empirical distribution of water inflows in the studied wadis is right-skewed (Cs > 0). This characteristic is reflected in the exploratory data analysis diagrams such as frequency histograms, box plots, stem plots, and Q-Q plots. Furthermore, the moderately to strongly high coefficients of variation (Cv) suggest the application of tail probability models for fitting the empirical data series.

Table 3: Eastern Constantinois Coastal-Statistical summary of Inflow during high water periods

Statistic	Q_{-1d}	Q_{-7d}	Q_{-15d}	Q_{-30d}	Q_{-90d}	$Q_{-annual}$
Kebir-East wadi at Ain Assel (031601)						
N	42	42	42	42	42	42
$\overline{Q}$ (Hm^3)	16.72	48.74	67.38	88.78	156.33	199.00
Cv	0.51	0.63	0.62	0.66	0.65	0.65
Cs	1.79	1.08	1.90	2.17	1.50	1.46

Table 4: Central Constantinois Coastal-Statistical summary of Inflow during high water periods

Statistic	Q_{-1d}	Q_{-7d}	Q_{-15d}	Q_{-30d}	Q_{-90d}	$Q_{-annual}$
Kebir-West wadi at Ain Charchar (031100)						
N	36	36	36	36	36	36
$\overline{Q}$ (Hm^3)	14.89	40.07	54.38	67.60	123.54	149.98
Cv	0.68	0.82	0.84	0.86	0.84	0.86
Cs	0.52	1.25	1.23	1.32	1.23	1.10
Hammam wadi at Zit Emba (031102)						
N	18	18	18	18	18	18
$\overline{Q}$ (Hm^3)	7.28	13.92	17.51	21.17	36.24	46.14
Cv	0.85	0.74	0.66	0.64	0.70	0.69
Cs	1.105	0.934	0.487	0.297	0.826	0.666
Saf-Saf wadi at Khemakhem (030901)						
N	29	29	28	29	29	29
$\overline{Q}$ (Hm^3)	4.88	9.68	13.74	16.53	25.83	30.69
Cv	1.52	1.24	1.04	0.96	0.95	0.89
Cs	3.20	2.81	2.42	2.16	2.30	1.90
Fessa wadi at Guenitra (030701)						
N	16	16	16	16	16	16
$\overline{Q}$ (Hm^3)	2.90	7.51	10.31	13.70	29.73	37.77
Cv	0.69	0.58	0.59	0.70	0.44	0.63
Cs	0.53	0.89	1.26	2.94	0.46	2.48

Table 5: Western Constantinois Coastal-Statistical summary of Inflow during high water periods

Statistic	Q_{-1d}	Q_{-7d}	Q_{-15d}	Q_{-30d}	Q_{-90d}	$Q_{-annual}$
El Kantara wadi at El M'Kaceb (030310)						
N	19	20	20	20	20	20
$\overline{Q}$ (Hm^3)	0,642	1.688	2.179	2.941	5.07	6.63
Cv	0.56	0.56	0.53	0.53	0.50	0.44
Cs	1.36	0.83	0.74	0.61	0.52	0.45

Several probabilistic models have been developed to describe the distribution of hydrological variables. However, selecting an appropriate model is one of the major challenges in water engineering, as there is no universal consensus on which distribution should be used for frequency analysis of extreme flows. In this study, nine probability distribution models commonly applied in hydrology were evaluated to determine the best fit: the 2- and 3-parameter Log-normal, Gumbel (type 1), Generalized Extreme Value (GEV), Log-Pearson 3, 2- and 3-parameter Gamma, and 2- and 3-parameter Frechet distributions. The density and cumulative distribution functions of these models can be found in the Mathwave tutorial on data analysis and simulation (2021). The parameters for the various probability densities were determined using the method of moments, which is the only procedure implemented in the *Easyfit* Pro software by Mathwave Technology Company.

QdF curves construction

The derivation of the QdF curves is based on frequency analysis of mean discharge series computed over multiple durations, using the Generalized Extreme Value (GEV) distribution selected through goodness-of-fit tests (Chi-square, Kolmogorov-Smirnov, and Anderson–Darling) among several candidate probability models.

Based on the results of the Karl Pearson (χ^2), Anderson-Darling (AD), and Kolmogorov-Smirnov (KS) goodness-of-fit tests, the Generalized Extreme Value (GEV) distribution, with the lowest sum of ranks, is the most suitable model for predicting inflows in the Constantinois Coastal wadis. Below is a brief explanation of how this choice was made.

The derivation of the Discharge-Duration-Frequency (QdF) curves follows a structured multi-step approach. First, mean discharges are calculated over predefined consecutive durations (e.g., 1, 7, 15, 30, and 90 days, as well as annual values) from the observed daily series. Second, for each duration, frequency analysis is carried out using the selected probability distribution (GEV) to estimate discharge quantiles associated with different return periods (2, 5, 10, 20, 50, and 100 years). Third, the estimated quantiles Q(T,d) are obtained for each duration and recurrence interval. Finally, the QdF curves are constructed by plotting these quantiles against return periods for each duration, providing a combined representation of discharge, duration, and frequency.

For each variable, test scores ranging from one to nine (1-9) are assigned to each probabilistic model based on the test criteria. The distribution with the lowest total score is chosen as the best fit. Specifically, the distribution best supported by a test is assigned a score of one (1), the next best gets a score of two (2), and so on, in ascending order. The overall ranks of each distribution are determined by summing the individual test ranks (Olofintoye et al., 2009). An example of the application of this ranking technique is provided for the Kebir-East wadi Q-90day inflows in Table S2 of the supplementary material.

Finally, any distribution is excluded if the test shows a significant difference between the predicted and observed discharge values at the 5% significance level. In this case, the Generalized Extreme Value distribution (GEV), with a minimum total score of 4, was considered the best-fitting model for estimating the T-year event. The same procedure was repeated for all 36-time series, and the overall minimum total score was calculated.

Thus, the expected percentiles Qd(T) corresponding to the 2, 5, 10, 20, 50, and 100-year recurrence periods for each reference duration d are summarized in Tables 6, 7, and 8.

Table 6: Eastern Constantinois Coastal-Water inflows for different durations and frequencies (Hm^3)

T (years)	Q_{-1d}	Q_{-7d}	Q_{-15d}	Q_{-30d}	Q_{-90d}	$Q_{-annual}$
Kebir East wadi at Ain Assel (code: 031601)						
2	15.83	44.32	60.56	78.62	137.79	171.52
5	23.33	70.14	94.71	125.35	223.37	282.35
10	28.2	87.95	119.35	159.79	286.23	362.57
20	32.78	105.62	144.61	195.71	351.62	445.08
50	38.61	129.33	179.85	246.83	444.36	560.6
100	42.9	147.76	208.3	288.86	520.39	654.12

Table 7: Central Constantinois Coastal- Water inflows (Hm^3) for different durations and frequencies

T (years)	Q_{-1d}	Q_{-7d}	Q_{-15d}	Q_{-30d}	Q_{-90d}	$Q_{-annual}$
Kebir-West wadi at Ain Charchar (code: 031100)						
2	13.5	33.01	43.62	53.13	98.44	118.06
5	23	62.12	83.71	103.25	188.52	231.44
10	28.94	83.02	113.55	141.59	256.5	317.34
20	34.38	104.39	144.93	182.76	328.77	408.92
50	41.06	134.1	189.97	243.31	433.78	542.44
100	45.82	157.98	227.33	294.73	521.93	654.9
Hammam wadi at Zit Emba (code: 031102)						
2	5.88	11.97	16.14	20.17	32.33	40.7
5	11.44	21.42	26.94	32.8	55.69	70.56
10	15.49	27.86	33.49	39.91	70.74	90.24
20	19.67	34.18	39.35	45.94	84.87	109.03
50	25.55	42.57	46.37	52.73	102.73	133.23
100	30.32	49.02	51.24	57.15	115.81	151.29
Saf-Saf wadi at Khemakhem (code: 030901)						
2	2.47	5.76	9.2	11.83	19.21	23.61
5	5.91	12.66	18.7	23.82	38.2	45.88
10	9.7	19.64	27.64	34.2	53.86	63.7
20	15.12	29.03	39.02	46.51	71.7	83.13
50	26.2	46.82	59.25	66.75	99.75	112.86
100	39.1	66.82	79.9	85.9	125.2	138.94
Fessa wadi at Guenitra (code: 030701)						
2	2.45	6.34	8.70	11.55	25.08	31.86
5	3.79	9.80	13.45	17.87	38.79	49.28
10	4.88	12.63	17.33	23.02	49.98	63.49
20	6.11	15.82	21.71	28.84	62.61	79.54
50	8.03	20.80	28.53	37.90	82.28	104.53
100	9.75	25.26	34.65	46.03	99.94	126.96

Table 8: Western Constantinois Coastal-Water inflows for different durations and frequencies (Hm^3)

T (years)	Q_{-1d}	Q_{-7d}	Q_{-15d}	Q_{-30d}	Q_{-90d}	$Q_{-annual}$
El Kantara wadi at El M'Kaceb (code: 030310)						
2	0.54	1.5	1.97	2.67	4.67	6.22
5	0.85	2.39	3.05	4.12	7.05	8.98
10	1.09	2.99	3.77	5.08	8.57	10.7
20	1.37	3.58	4.46	6	10	12.28
50	1.79	4.37	5.37	7.19	11.81	14.22
100	2.17	4.98	6.05	8.08	13.12	15.6

For instance, during high water periods, the expected 10-year and 20-year water inflows at the Kebir-West wadi at Ain Charchar for a 30-day duration are approximately 140 Hm^3 and 180 Hm^3, respectively. For the Guenitra recording station (Fessa wadi), these would be around 23 Hm^3 and 29 Hm^3, respectively.

To make the results from Tables 6 to 8 more practical, the QdF curves were constructed by plotting the recurrence periods (in years) on the x-axis and the water inflows on the y-axis for each predefined reference duration. A chart summarizing the statistical relationships between the average water supply (Q), duration (d), and frequency (F), expressed in terms of the recurrence interval (T), was created for each studied wadi (Figs. 2 to 7).

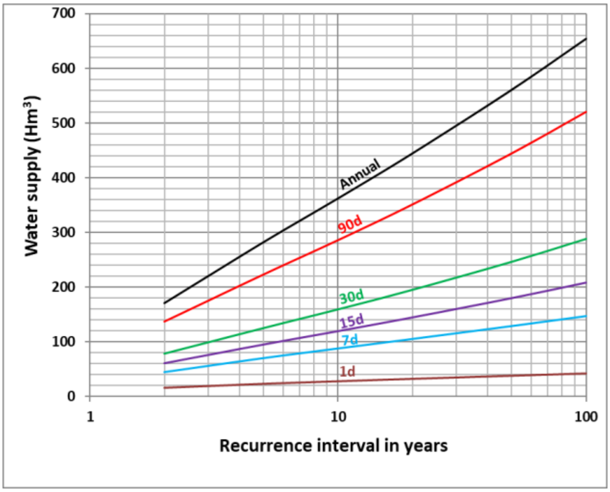

Figure 2: QdF Curves for the Kebir-East wadi at Ain Assel

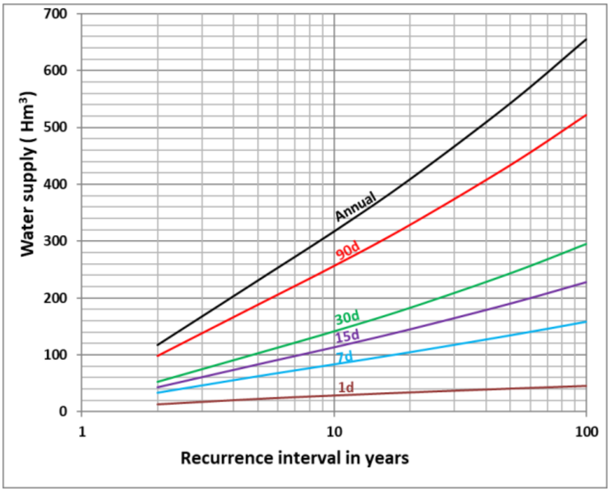

Figure 3: QdF Curves for the Kebir-West wadi at Ain Charchar

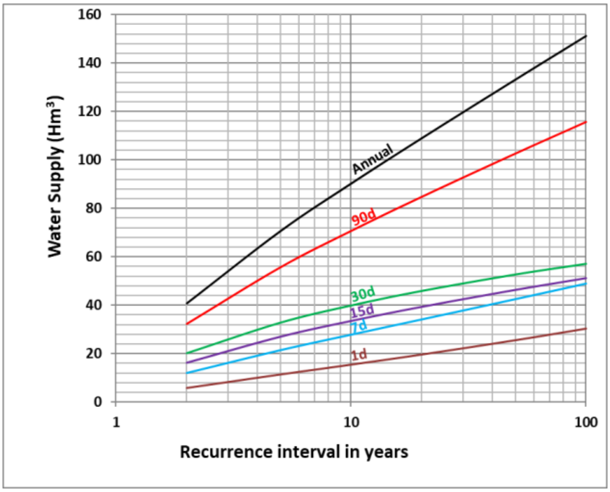

Figure 4: QdF Curves for the Hammam wadi at Zit Emba

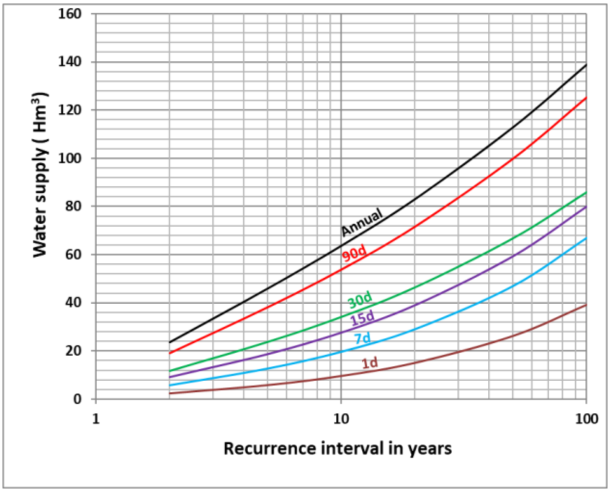

Figure 5: QdF Curves for the Safsaf wadi at Khemakhem

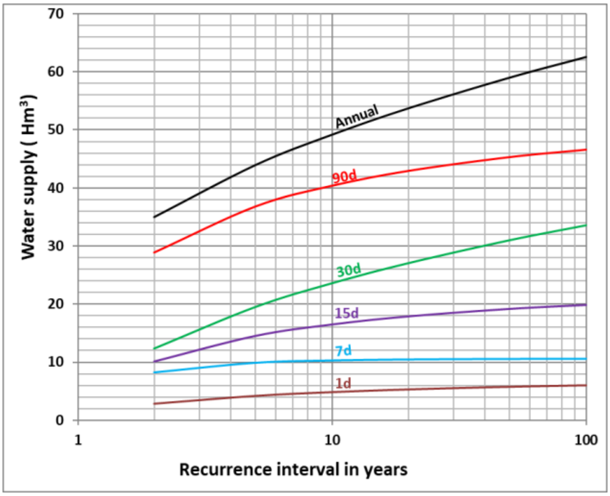

Figure 6: QdF Curves for the Fessa wadi at Guenitra

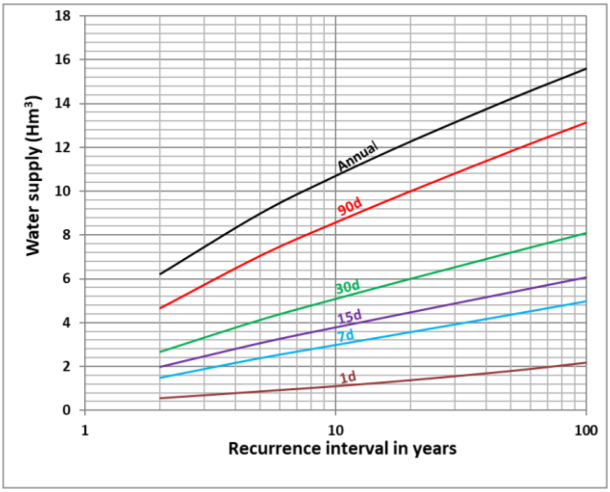

Figure 7: QdF Curves for the El kantara wadi at El M'kaceb

These curves are particularly suitable for intermittent rivers, as they explicitly account for the alternation between dry periods and short-duration flow events, which is a dominant feature of Mediterranean wadis.

Compared to traditional Flow Duration Curves (FDC), QdF curves provide an additional frequency dimension, allowing the joint analysis of flow magnitude, duration, and recurrence, which significantly improves decision-making in water resources management. (Mehta et al., 2023b).

Unlike traditional flood frequency analysis, which focuses on a single duration (often peak flow), QdF curves provide a multi-duration framework that allows simultaneous analysis of flow magnitude, duration, and recurrence, offering a more comprehensive characterization of hydrological regimes.

QdF (Discharge or Volume Duration Frequency) curves are vital tools in water resources planning and management. These curves offer valuable insights into the behavior of rivers or streams over time, particularly regarding flow rates, volumes, and their corresponding probabilities.

During high water periods, QdF curves are crucial for various purposes, including:

- Reservoir Design and Operation: Optimizing reservoir storage, releases, and spillway design to meet various operational objectives (Verma et al., 2024).
- Water Supply Planning: Estimating water availability for various uses and assessing the reliability of water supply under different demand scenarios, aiding in informed decision-making for water allocation.
- Environmental Impact Assessment: Evaluating the effects of altered flow regimes on aquatic ecosystems (Chadee et al., 2023b).

- Water Rights and Regulation: Assisting in determining water rights and permit conditions, providing a basis for evaluating water availability and managing competing water uses.
- Flood Risk Assessment: Supporting infrastructure design (e.g., bridges, dams, levees) to withstand different flood scenarios.

Furthermore, the QdF approach presented in this study can be directly integrated into water resources management and hydraulic infrastructure design in the study region. It provides a quantitative basis for sizing hydraulic structures (such as dams, spillways, culverts, and bridges), optimizing reservoir operation, and supporting flood risk mitigation strategies. In addition, QdF curves are particularly useful for decision-making in semi-arid regions where hydrological data are limited, as they synthesize complex flow information into a practical framework that accounts for both duration and frequency of flows.

In summary, QdF curves are powerful tools that provide comprehensive insights into the behavior of rivers and streams. They enable water resources planners to address a wide range of challenges related to surface water management, helping ensure the sustainable use and management of surface water resources in the Constantinois Coastal Basin.

Synthetic data, confidence interval and errors (uncertainty)

The Generalized Extreme Value (GEV) distribution, along with other probabilistic models such as Galton, Gumbel, Frechet, and Log-Pearson III, is not a perfect tool for predicting the T-year flow with high accuracy. To better understand the expected water inflows during wet periods and assess the margin of error, confidence intervals (CI) are calculated (Koutsoyiannis D, 2020).

Generating synthetic data for confidence interval analysis

To quantify uncertainty, synthetic discharge series are generated using the GEV data generator integrated into Easyfit Pro 5.20 software, since the GEV distribution is considered the best fit for water inflows in the Constantinois Coastal Basin.

In practice, larger sample sizes are generally preferred for more accurate and reliable analyses.

For each duration, a matrix of 100 columns (representing variables) and 100 rows (representing maximum inflows) is generated. With 100 observations in each sample, this dataset is considered sufficiently large to provide meaningful insights while avoiding excessive computational requirements.

Ensuring accuracy in data simulation

To ensure the synthetic data accurately represents the characteristics of the underlying distribution, the Mann-Whitney test (also known as the Wilcoxon rank-sum test) is employed. This non-parametric test evaluates whether there are significant differences between two independent groups in terms of their distributions, particularly comparing the equality of medians between the observed and generated samples.

Since the observed sample sizes are relatively small, traditional techniques for model validation (such as the Nash-Sutcliffe Efficiency and Willmott Index of Agreement) are not feasible. Therefore, the Mann-Whitney test serves as an alternative method to evaluate the performance of the simulation.

For example, applying this test to the 15-day inflow data from El Kantara Wadi, Table S3 in the supplementary material shows the test results. For a sample with 20 observations and a median of 1.522 (observed data) and a second sample with 100 observations and a median of 1.773 (generated data), the test statistic W is 144.0. The p-value for this test is 0.3123, which is greater than the 0.05 significance level. Therefore, the null hypothesis (H0) cannot be rejected at the 95.0% confidence level, meaning that the two samples are drawn from the same distribution.

Validation was carried out using the Mann–Whitney test to verify that the synthetic data generated from the GEV distribution are statistically consistent with the observed data. In addition, the confidence intervals derived from the synthetic simulations were used to quantify the uncertainty and assess the relative error of the estimated T-year discharges.

Frequency analysis and confidence interval estimation

Once the synthetic data variables are validated, a frequency analysis is performed to estimate the 2, 5, 10, 20, 50, and 100-year inflows for the same duration using the GEV model. This results in 100 estimates for each T-year event, providing a range of predictions and allowing for the estimation of the confidence limits.

To estimate the 80% and 90% confidence intervals (CI), the first and ninth deciles and the 5 and 95% percentiles are used, respectively. These intervals provide a measure of the uncertainty in the flow estimates and are summarized in Table S4 in the supplementary material.

The relative error is computed based on the confidence interval bounds derived from the synthetic GEV-based simulations. Specifically, the upper and lower confidence limits are used to quantify the uncertainty around the estimated T-year discharge values. The relative error is then defined as the deviation between these bounds and the central estimated value, allowing a direct assessment of uncertainty in the frequency analysis results.

Relative error (RE) estimation

Using the confidence intervals, the Relative Error (R_E) of the expected T-year flows Q (T, d) can be roughly estimated. The relative error is given by the following relation:

$$R_E(\%) = 100\frac{L_{up} - L_{low}}{Q(T,d)} \tag{1}$$

This formula quantifies the uncertainty in the predicted inflow, allowing planners and engineers to understand the potential range of error in their flow predictions.

Summary of key concepts

- Synthetic Data Generation: Random discharge series are created using the GEV model to simulate potential inflow values.
- Mann-Whitney Test: A statistical test is used to ensure that the generated data reflects the observed data's distribution.
- Confidence Intervals (CI): The uncertainty of the predictions is quantified by estimating 80% and 90% confidence intervals.
- Relative Error (R_E): The margin of error is estimated as the relative difference between the upper and lower bounds of the confidence interval.

These approaches help in assessing the accuracy of the predicted T-year inflows and quantifying the uncertainty in hydrological predictions, thus providing a more robust understanding of water availability during wet periods.

Uncertainty and relative error in return period estimations

The estimated quantiles, particularly for return periods shorter than the observation period, are typically considered to be relatively accurate. However, larger uncertainties arise when estimating flows for rarer events, specifically for return periods greater than 2 or 3 times the observation period.

Relative error (RE) and confidence interval boundaries

In the analysis, L_{up} and L_{low} represent the upper and lower boundaries of the confidence interval, respectively. These values define the range within which the true value of the T-year flow is expected to fall. The margin of error, or relative error, is the difference between these boundaries divided by the expected value of the flow.

The results of the relative error estimations for the Eastern Constantinois Coastal region are shown in Table 9 (and in Table S5 in the supplementary material for the other regions).

Table 9: Eastern Constantinois Coastal- Relative error on predicted percentiles (%)

		Return period (T in years)					
		2	5	10	20	50	100
Duration	**Confidence interval**	**Kebir-East wadi at Ain Assel**					
7d	$CI_{80\%}$	8	7	7	8	10	12
	$CI_{90\%}$	10	10	10	11	14	18
15d	$CI_{80\%}$	7	10	7	2	7	15
	$CI_{90\%}$	9	13	9	2	9	19

30d	CI-$_{80\%}$	10	16	12	4	8	19
	CI-$_{90\%}$	13	21	15	5	11	30
90d	CI-$_{80\%}$	6	8	4	8	6	11
	CI-$_{90\%}$	8	10	6	10	8	15
Annual	CI-$_{80\%}$	9	9	11	13	17	20
	CI-$_{90\%}$	12	10	13	16	21	26

From these tables, you can observe the following trends:

Observations from relative error analysis

- For shorter return periods (such as 10-year flows), the relative error is generally lower, with most cases showing a 7% to 20% margin of error. This indicates a relatively higher confidence in estimating these flows accurately.
- For longer return periods (like the 20, 50, and 100-year flows), larger uncertainties appear.

However, in 80% of the cases, the maximum inflows observed over various durations still fall within acceptable error ranges:

- 20-year events: Relative error is less than 24%.
- 50-year events: Relative error is less than 32%.
- 100-year events: Relative error is less than 36%.

Interpreting the results

These findings suggest that, while the uncertainty increases for rarer events (i.e., those with longer return periods), the estimates for more frequent flows are generally quite reliable. This provides valuable information for decision-makers in the context of water resources planning, flood risk management, and infrastructure design, where high confidence is needed for more frequent events and more careful consideration is necessary for rare extreme events:

- Shorter return periods (e.g., 10-year events) have lower relative error (7-20%), making them more reliable.
- Longer return periods (e.g., 100-year events) have higher relative error (up to 36%), reflecting greater uncertainty in predicting rare extreme events.
- 80% of cases for the 20, 50, and 100-year events have relative errors within acceptable bounds, but the uncertainty increases as the return period grows.

CONCLUSION

The sustainable management of surface water resources in the Constantinois Coastal watershed (northeastern Algeria), an area characterized by climatic and geomorphological diversity, relies heavily on the understanding of probable water inflows and their spatial and temporal variability.

The QdF curves, especially those constructed for high water periods, are valuable tools that simplify complex hydrological data into a format that addresses key concerns related to flood protection and surface water storage. These curves are not merely theoretical constructs; they serve as practical decision support tools for regional and local authorities involved in hydro-technical projects and environmental management.

The constructed charts, summarizing the flow rate information at a station, provide a multi-duration frequency description of flow regimes during the wet period. The results can be readily extrapolated to estimate, with a satisfactory precision, the expected water volumes (Q) at a specified monitoring station during any period of d consecutive days and a given recurrence interval (T). Thus, providing actionable insights for water resources planning.

The applications of these results are broad and include:

- Flood protection and management.
- Surface water storage, particularly in the planning of dams and hill reservoirs.
- Urban, industrial, and agricultural drainage systems.
- Civil engineering projects, such as the design of bridges and culverts.
- Hydraulic engineering, especially in feasibility studies for water infrastructure and flood mitigation projects.

The QdF methodology developed in this study is transferable to Mediterranean and semi-arid basins characterized by intermittent flows and high hydrological variability (Mehta et al., 2023b; Ande et al., 2025a). Its application to other regions remains possible; however, it may require adjustments depending on data availability, record length, and specific basin characteristics such as climate, hydrological regime, and data quality. This highlights the potential of QdF curves as a flexible and robust decision-support tool for water resources management beyond the study area.

In summary, QdF curves are indispensable tools for water management in the Constantinois Coastal region, ensuring the efficient and sustainable use of water resources and helping mitigate the impact of extreme weather events.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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