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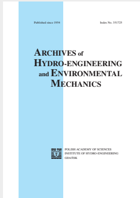

Enhancing Flood Protection Strategies in Algeria through the Assessment of Maximum Discharge in Wadis

Herizi Toufik[a*], Bensefia Sofiane[a], Tiaiba Imane[b]

[a]Environment and Health Laboratory Department of Agricultural Sciences, Faculty of Life and Natural Sciences and of Earth and Universe Sciences, Mohmed El-Bachir El-Ibrahimi University, El-Anasser, Bordj Bou Arreridj, Algeria, 34030, e-mails: toufik.harizi@univ- bba.dz, Sofiane.bensefia@univ-bba.dz; [b]Department of English, Faculty of Letters and Languages, Mohmed El-Bachir El-Ibrahimi University, El-Anasser, Bordj Bou Arreridj, Algeria, 34030, e-mail: imane.tiaiba@univ-bba.dz; *Corresponding author

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Abstract. For flood protection infrastructure to be designed effectively, it is essential to accurately assess the maximum discharge ($Q_{\max}$) in Algerian wadis and watercourses. In the absence of direct field measurements, reliance on foreign methodologies is common. However, these methods often overlook the specific characteristics of hydrological systems in Algeria leading to significant inconsistencies and complicating methods choice. Accordingly, the crucial question that arises is: which methodology provides the most reliable ($Q_{\max}$) estimates for the purpose of designing effective flood defenses? Therefore, this paper explores the estimation of maximum discharge in Wadis when direct flow rate data is unavailable. The proposed model, outlined in equation (3), is developed through statistical modeling and incorporates key factors such as watershed area (A) and rainfall intensity (P_{tc}). The model correlates with observed discharge values by utilizing data from Algeria's National Water Resources Agency, covering 60 Wadis across diverse regions. This approach outperforms existing models, achieving a notably low mean normalized error of 10%, signifying substantial improvements in accuracy.

Key words: Maximum discharge, Algeria's wadi, modeling, flooding, flood risk protection

Notations

A	–	catchment area (km^2),
C_v	–	coefficient of variation,
$H_{\max}$	–	maximum altitude (m),
$H_{\min}$	–	minimum altitude (m),
L	–	length of the waterway (km),
MNE	–	mean ± normalised error (%),
N_d	–	number of data,

NE	–	normalised error,
P_{tc}	–	rainfall intensity (mm),
$Q_{\max}$	–	maximum discharge (m^3/s),
R	–	correlation coefficient,
δ	–	standard deviation.

1. Introduction

The maximum discharge values in North Africa are exceptionally high and should not be underestimated. In countries like Morocco, Algeria, Tunisia, and Libya, the flow regime is torrential, often leading to devastating consequences. Recent floods in Libya, for instance, demonstrated the catastrophic impact of such events, including thousands of fatalities, widespread displacement, dam collapses, and the submergence of entire cities. These disasters are driven by a combination of climatic and geographical factors, creating flood conditions that are far more severe than those typically observed in Central Europe (Leivadiotis et al 2024, Tramblay et al 2024). Accurate estimation of the maximum flood discharge in Algeria is crucial due to the significant risks associated with flooding and the need to design infrastructure, such as bridges, dams, and flood protection systems (Fig. 1–2). Although much research has been conducted, there is still no widely recognized technique for determining the maximum discharge in hydraulic structure design (Wing et al 2020).This challenge is further complicated by the fact that Algeria's watercourses are primarily wadis rather

Fig. 1. Flood event on September 10, 2024, in Oued Bacher, located in the southwest of Algeria (photo by Melina Malek)

Fig. 2. The flood event on March 1st, 2024, in Oued Soummam, located in the Béjaïa Province in northeastern Algeria, documented by N. Bensalem

than permanent rivers. Wadis in Algeria and across North Africa are characterized by their intermittent flow, carrying water only during certain periods of the year (Remini 2023). However, during the flood season, they become extremely dangerous due to intense and sudden rainfall. The rapid water flow can lead to severe flash floods, submerging vast areas in a short time (Fig. 1 and 2). In the light of these considerations, the current research aims to develop a new strategy for improving the estimation of maximum discharge in wadis by introducing an alternative equation that accounts for the unique characteristics of local watersheds. By refining these calculations, the study seeks to enhance the accuracy of flood predictions and support the effective design of flood protection infrastructure, addressing the limitations of existing methods, which often produce inaccurate results. This strategy relies on catchment characteristics, such as basin area (A) and rainfall intensity (P_{tc}), to calculate maximum discharge ($Q_{\max}$). The selection of these two parameters, (A) and (P_{tc}), is based on the proportional relationship between maximum discharge ($Q_{\max}$) and watershed area (Moriasi et al 2007). Additionally, rainfall intensity is widely used to calculate maximum discharge in many countries worldwide (Benabdelouahab et al 2020, Keef et al 2009). Hydrological models have been developed to predict and analyze flooding caused by intense rainfall events (Beven et al 1984, Crawford and Linsley 1966, Todini 1996, Tramblay et al 2012, Zhao 1992, Athmani et al 2025). Some researchers have formu-

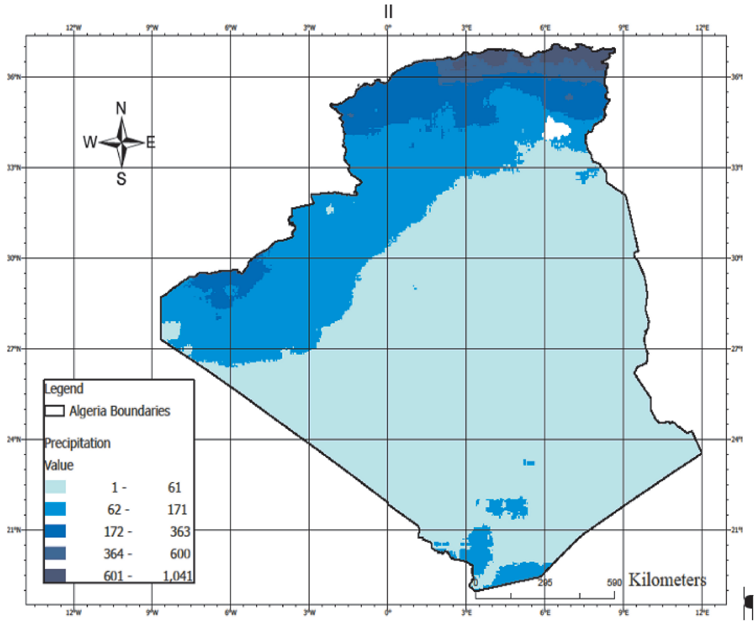

Fig. 3. Precipitation Distribution in Algeria (Climate Hazards Group. CHIRPS Daily Precipitation Data, 2023. Accessed via Google Earth Engine. Consulted on 2024. https://developers.google.com/earth-engine/datasets/catalog/ UCSB_CHG_CHIRPS_DAILY.)

lated equations linking maximum discharge to basin rainfall patterns, suggesting that peak flood discharge may be correlated with rainfall intensity (Aqnouy et al 2018, Aziz et al 2020, Guta 2021, Jin et al 2015, Sampath et al 2015).

2. Material and Methods

Having established the rationale and aims of this study, we now turn to the methods used to achieve these objectives by referring, first to the study area.

2.1. Study Area

Algeria, situated in North Africa, covers an area of 2 381 741 km^2, with more than 80 per cent of that area desert. The country stretches about 2000 km from north to south and about 1800 km from east to west, and has a humid and semi-arid climate. The Mediterranean region, and in particular North Africa, is among the areas most vulnerable to climate change, according to reports by international bodies on climate change (Bensefia et al 2024, Mrad et al 2018).

Given Algeria's location within the climate change-vulnerable Mediterranean region, understanding the spatial distribution of extreme rainfall across various regions of Algeria (Fig. 3 and 4) over the past four decades is vital, as it provides essential insights for infrastructure development, flood and drought risk assessment, agricultural planning, and resource management. Findings from several studies indicate a clear spatial pattern of extreme rainfall events across Algeria, with the northern region receiving the highest amounts, followed by decreasing levels in the northeast, northwest, and central areas. In contrast, the southern region generally experiences lower extreme rainfall levels, with few exceptions in areas like Adrar. Topography, water systems, prevailing winds, and climate change likely influence this distribution. Gaining a deeper understanding of these factors is crucial for effectively managing and mitigating the impacts of extreme rainfall events across Algeria (Salhi et al 2024).

Fig. 4. Geographical Distribution of Major Wadis in Algeria; Accessed via Google Earth Engine

2.2. Statistical Modeling Data

To develop an equation for estimating maximum discharge, this study utilized data obtained from Algeria's National Water Resources Agency (NWRA, known as ANRH in French). The dataset includes several key variables: the catchment area (A), ranging from 1 to 8735 km^2, and rainfall intensity (P_{tc}), which varies between 29 to 201 mm. Maximum discharge values recorded at different stations span from 10 to 12700 m^3/s. These measurements were taken at hydrometric stations set up along the wadis, where water levels and discharges were continuously monitored. As illustrated in Figure 5, these stations employ sensors to measure water height, a crucial parameter for

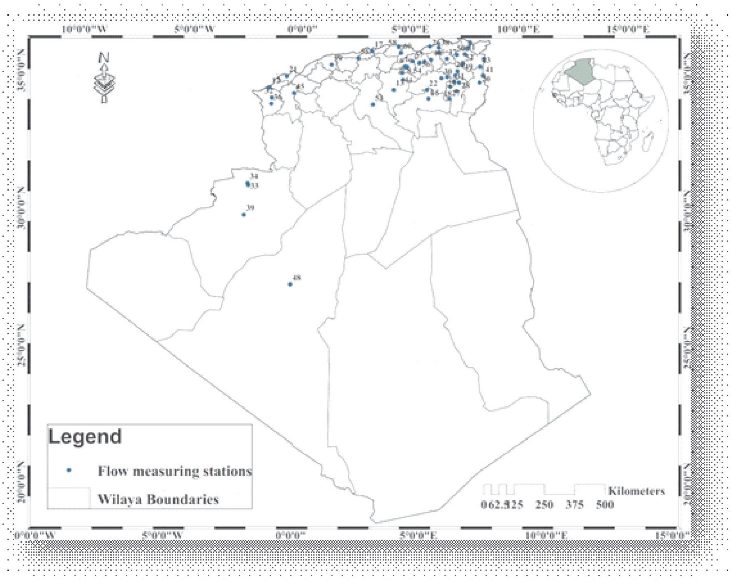

Fig. 5. Spatial distribution map of discharge measuring stations across the study area

determining maximum discharge, particularly during significant flood events. Further details regarding additional parameters included in the dataset are provided in Table 1.

Table 1. Statistical properties of the data utilized

Setting	N_d	Average	Standard deviation	C_v	Ranges
Q_{max}	60	1827 m^3/s	2829	1.55	10–12700
A	60	1101 km^2	1865	1.69	1.02–8735
L	60	50.54 km	54.89	1.09	0.85–236
H_{max}	60	1468 m	440.77	0.30	520–2350
H_{min}	60	897 m	336.39	0.37	167–1980
P_{tc}	60	88 mm	38.09	0.43	29–201

where N_d is the number of data, C_v is the coefficient of variation

Recognizing the limitations of purely theoretical models in complex systems, statistical modeling plays a crucial role (Yamazaki et al 2011). The process generally involves data collection, equation selection, parameter estimation, forecasting, and performance evaluation (Winsemius et al 2013). This is especially important in hydrology, where datasets often contain noise or missing values (Wing et al 2020). Statistical methods allow for meaningful analysis and reliable predictions (Küpferle et al 2009).

In applied sciences, particularly in the field of hydrology, research often focuses on understanding the relationships between variables such as precipitation and discharge. Statistical modeling plays a vital role in identifying these correlations, which are typically represented using scatter plots like (A, $Q_{\max}$) and (P_{tc}, $Q_{\max}$). These visualizations help derive equations that describe either linear or non-linear relationships, enabling the prediction of one variable based on the others. In this study, ($Q_{\max}$) is considered the dependent variable, while (A) and (P_{tc}) act as the independent variables. The goal of completing these charts is to determine the correlation between variables, ensuring their validity for calculating the maximum discharge.

3. Results and Discussion

As a direct outcome of analytical procedures described previously, the results of this study are presented and then discussed.

There are four commonly applied empirical methods to estimate maximum discharge in Algerian wadis including those developed by Giandotti, Mallet-Gauthier, Sokolovsky, and Turazza (Bennis 2009, Tramblay et al 2024). These methods use basin characteristics such as area, watercourse length, and rainfall intensity to predict discharge values. However, despite their widespread use, they often produce inconsistent results, complicating the selection of appropriate discharge values for designing flood protection structures. This discrepancy is likely to exist as these methods were initially formulated based on the characteristics of water basins that differ from those of Algerian wadis.

The objective of this study is to establish a relationship between watershed characteristics, rainfall intensity, and maximum discharge in wadis. This issue is particularly important for two reasons: first, it facilitates the implementation of effective flood protection measures in both rural and urban areas; second, it helps address the lack of field measurements in Algerian wadis. By analyzing the measured discharge values ($Q_{\max}$) concerning the catchment area, we produce Figure 6 ($R = 0.98$), which illustrates a strong correlation between these two variables. Extreme values of rainfall intensity (P_{tc}) play a crucial role in designing protective structures against flood hazards. Comparing these values with the recorded maximum discharges ($Q_{\max}$) in our study areas yields satisfactory correlation results, as demonstrated in Figure 7

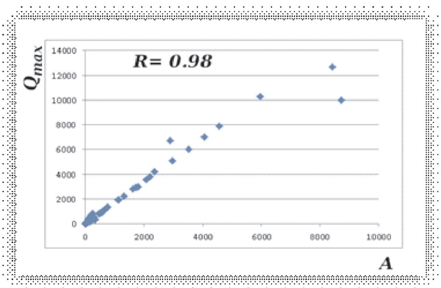

Fig. 6. Correlation between data of (A, $Q_{\max}$)

(R = 0.85). This highlights the significant relationship between rainfall intensity and peak discharge.

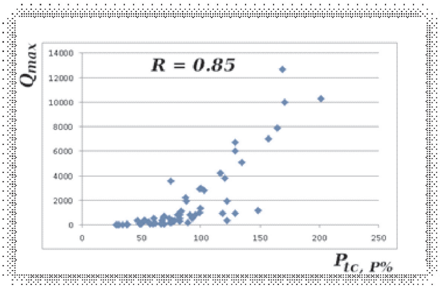

Fig. 7. Correlation between data of (P_{tc}, $Q_{\max}$)

Our findings emphasize the considerable impact of larger water surface areas on flood volume and peak discharge (Natarajan and Radhakrishnan 2019, Zhang et al 2014). Several studies (Beck et al 2020, Falcone et al 2010, Heffernan and Tawn 2004, McMillan et al 2011) that incorporate rainfall intensity into discharge models further validate the approach presented in this research. Figures 6 and 7 demonstrate the correlation between watershed area and rainfall intensity with maximum discharge in the wadi. This relationship allows for the formulation of a general equation that expresses maximum discharge as a function of these parameters:

$$Q_{\max} = f(A, P_{tc}). \tag{1}$$

This relationship can be detailed by writing it in this form:

$$Q_{\max} = a \cdot A + b \cdot P_{tc} + c. \tag{2}$$

To enhance the credibility of the research while acknowledging the diverse value ranges of all parameters, the dataset comprising 60 data points was deliberately divided into two groups: 30 for calibrating the proposed equation (Table 2) and the remaining 30 for validating it (Table 3). By utilizing computer tools like Origine software, we can determine the values of a, b, and c by inputting the data presented in Table 2. This enables us to express Equation 2 in the following form:

$$Q_{\max} = 1.17 \cdot A - 0.92 \cdot P_{tc} + 102. \tag{3}$$

Table 2. Characteristics of the parameters used for model calibration

Setting	N_d	Average	Standard deviation	C_v	Ranges
$Q_{\max}$	30	538 m^3/s	733.40	1.36	10–3589
A	30	291 km^2	429.18	1.47	1.02–2080
L	30	24.72 km	24.79	1.00	0.85–112
$H_{\max}$	30	1298 m	469.94	0.36	520–2326
$H_{\min}$	30	862 m	367.26	0.43	167–1980
P_{tc}	30	69.17 mm	29.34	0.42	29–148

Table 3. Characteristics of the parameters used for model validation (with another 30 data point)

Setting	N_d	Average	Standard deviation	C_v	Ranges
Q_{max}	30	3119 m^3/s	3483.51	1.12	85–12700
A	30	1911 km^2	2336.96	1.22	49–8735
L	30	76.36 km	63.87	0.84	10.20–236
H_{max}	30	1639 m	331.11	0.20	927- 2350
H_{min}	30	932 m	298.38	0.32	305–1546
P_{tc}	30	106.41 mm	37.35	0.34	56–201

Figure 8 depicts the relationship between the values calculated using Equation 3 and the actual measurements. The results indicate a strong correlation ($R = 0.95$), emphasizing the reliability of the proposed equation for calculating the maximum discharge. Any proposed model serves as a simulation of reality, making some degree of error inevitable during its application. This explains the presence of certain data points that deviate from the trend, which will be accounted for in the error calculation.

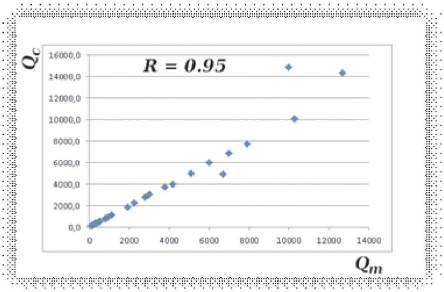

Fig. 8. Comparison of the calculated maximum discharge with the measured maximum discharge

To assess the accuracy of Equation 3 in calculating the maximum discharge, the dataset from Table 3 was used to compute the normalized error (NE) for each Wadi. The following relationship is applied to estimate the NE:

$$NE = \left| \frac{Q_c - Q_m}{Q_m} 100 \right|, \quad (4)$$

where:
Q_c – represents the maximum discharge computed using Equation (3),
Q_m – corresponds to the measured value.

For the validation dataset in Table 3, we define the mean normalized error (MNE) for the thirty values. In this comparison (Table 4), our equation consistently demonstrates a commendable (MNE) of 10%. We then compare the model proposed in this paper (Eq. 3) with other commonly used methods for calculating maximum discharge in Algerian Wadis, including the Giandotti, Mallet-Gauthier, Sokolovsky, and

Turazza methods, by evaluating their mean normalized error (MNE). The comparison of measured and calculated maximum discharge data revealed significant discrepancies. The average normalized errors (MNE) for the various equations were as follows: our model achieved 10%, while the Giandotti, Mallet-Gauthier, Sokolovsky, and Turazza methods had MNEs of 57.7%, 70.9%, 61.4%, and 60.5%, respectively. Notably, aside from Giandotti and Mallet-Gauthier, the errors exhibited a standard deviation (α) below 50%.

Table 4. Mean normalized error (MNE) when calculating the maximum discharge by various formulas

Model	Formula	δ	MNE %
Our model	$Q_{\max} = 1.71 \cdot A - 0.92 \cdot P_{tc} + 102$	0.15	10
Giandotti	$Q_{\max} = \dfrac{170 \cdot A \cdot (H_{moy} - H_{\min})^{1/2}}{4(A)^{1/2} + 1.5L} P_{tc}$	0.56	57.7
Mallet-Gauthier	$Q_{\max} = 2K(1 + \beta P_A) \dfrac{A}{\sqrt{L}} \sqrt{1 + 4 \log T - \log A}$	0.68	70.9
Sokolovsky	$Q_{\max} = \dfrac{0.28(P_{tc} - H_o)\alpha f A}{T_c}$	0.24	61.4
Turazza	$Q_{\max} = \dfrac{\alpha A P_{tc}}{3.6 T_c}$	0.24	60.5

Here:

k – constant that depends on the characteristics of the watershed and is set to 1.2,
β – is a regional coefficient set to 20,
PA – represents the average annual rainfall of the watershed in meters,
T – is a return period in year,
H_o – is the initial loss of water, which is 7 mm in Algeria,
α – is the runoff coefficient for a major flood, set to 0.9,
f – is the flood shape coefficient, set to 1.04; The value 0.28 is the unit conversion coefficient,
δ – is the standard deviation for the thirty errors,
T_c – concentration time in hours.

A key observation is that the Mallet-Gauthier method consistently overestimates discharge, which poses a potential risk. Equation 3 succinctly represents maximum discharge, enhancing clarity and reducing complexity. The advantages of Equation 3 lie in its alignment with the characteristics of Algerian basins, making it suitable for areas ranging from just over 1 km^2 to 8730 km^2, demonstrating significant flexibility.

Additionally, the average standard error is relatively low compared to other commonly used models in Algeria (Table 4). To highlight the superiority of the proposed model, we calculated error percentages, showing that over 66% of our model's errors fell within the ±10% range, while other models ranged from 3% to 13% (Table 5). In terms of discharge estimation accuracy, the Sokolovsky model proved to be the least reliable, with over 80% of its errors falling outside the specified comparison ranges (10%, 20%, 30%). The robust relationship between the discharges predicted by this model and the observed values highlights notable enhancements in performance compared to existing models.

Table 5. Percentage of calculated maximum discharge in error range

Model	Error range		
	±10%	±20%	±30%
The proposed equation	66.6%	76.6%	83.3%
Giandotti	13.3%	40%	40%
Mallet-Gauthier	6.67%	13.3%	26.7%
Sokolovsky	3.3%	10%	13.3%
Turazza	3.3%	6.67%	16.7%

4. Conclusion

In this study, we developed a model to estimate the maximum discharge in Algerian wadis, even in the absence of field data. The findings indicate that larger water surface areas (A) influence both flood volume and maximum discharge, a direct relationship validated by our model expressed in Equation 3. Additionally, incorporating rainfall intensity (P_{tc}) adds realism to the equation.

Designed around these two critical parameters, A and P_{tc}, our equation exhibits a low error rate of 10%, which is promising for its application in flood protection infrastructure design, significantly lower than that of commonly used methods in Algeria, such as Sokolovsky, Giandotti, Mallet-Gauthier, and Turazza. This error was calculated by comparing the measured discharge values in the 30 studied wadis with those predicted by Equation 3.

In Table 4, the mean normalized error (MNE) reflects the average error across these 30 discharge values. Notably, when comparing results from different models, the Mallet-Gauthier method tends to produce inflated discharge estimates, often resulting in the design of larger hydraulic structures. The key advantage of our proposed equation is its reliance on data specific to Algeria, coupled with its modest error rate. This may allow us to move away from other models that demonstrate higher error rates and are based on experimental data from different regions and contexts.

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The authors express sincere gratitude and appreciation to the National Water Resources Agency (NWRA – known as ANRH in French) for its generous provision of a comprehensive set of empirical data, which proved instrumental in the successful completion of this study.

4.1. Data Availability Statement

The authors confirm that the data supporting the results of this study are available at the level of the National Water Resources Agency (NWRA – known as ANRH in French) at its central headquarters, Bir Mourad Rais 16000, Algiers, or contact the agency via the email address Site web: http://www.anrh.dz.

ORCID
https://orcid.org/0009-0000-3809-8339
https://orcid.org/0000-0001-8040-2111
https://orcid.org/0000-0002-2540-3856

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