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Combined Hydrological and Hydraulic Modeling Approach for Flood Management: Application to Oued El Melah

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ABSTRACT

This article presents a hydrological and hydraulic study applied to the crossing structure over Oued El Melah, located on the RR47 at PK 29+250 in the Siliana governorate, north-west Tunisia. The primary goal is to assess the structure's ability to withstand centennial flood flows using a combined modeling approach with accessible digital tools such as Google Earth, Global Mapper, and Excel.

Watershed delineation yields an area of 33.32 km² and a hydraulic length of 10.767 km. From this, morphometric parameters were calculated — notably a compactness index of 1.35, an average slope of 2.2%, and a global slope index of 43.31‰. The time of concentration was estimated at approximately 82 minutes using the Giandotti formula.

Flood flows were estimated using several empirical methods (Ghorbel, Kallel, Trigui) and the rational method. The empirical methods produced an average centennial flow of 76.6 m³/s, while the rational method greatly overestimated flow at over 1,500 m³/s. The project flow adopted is based on the average of local empirical methods.

The hydraulic analysis, based on the Manning–Strickler formula applied to a trapezoidal section, determined the structure's hydraulic capacity at 105.5 m³/s. Analyses of backwater effects and potential scour revealed upstream backwater of 0.35 to 0.50 m and maximum potential scour of 0.62 m.

The study demonstrates that in its current state, the structure has sufficient capacity for major floods, provided regular maintenance and bank protection are ensured. It also highlights the effectiveness of a simple, reproducible methodological approach for hydraulic assessments in poorly instrumented rural areas.

Keywords: Hydrological modeling, hydraulic modeling, watershed, flood, El Melah, Global Mapper, Google Earth, Excel, crossing structure, runoff.

1. Introduction

Extreme rainfall events, increasing in frequency due to climate change, pose severe challenges to crossing structures in complex topography with concentrated flows. In Tunisia, many bridges, culverts, and road drainage structures are now subjected to sudden flood flows that were poorly anticipated during design. This situation affects infrastructure durability, user safety, and road continuity. Oued El Melah, in Siliana governorate, traverses a semi-arid region with occasionally intense but irregular precipitation. The crossing on RR47 at PK 29+250 is exposed to flood events whose magnitude and frequency demand rigorous evaluation.

This study aims to model hydrological and hydraulic conditions upstream of the structure to verify its current crossing capacity, using Google Earth and Global Mapper for spatial delineation and Excel for hydrological and hydraulic calculations. It fits a preventive strategy to anticipate blockage or flooding risks and to propose replicable methods for similar structures in contexts where stormwater management is a major territorial development issue.

2. Problem Statements

1. Is the crossing structure designed to withstand extreme floods (P50 or P100) in a semi-arid climate zone?

→ This question aims to assess whether the existing structure allows for free water flow during exceptional rainfall events without causing backwater, overflow, or damage.

2. What are the impacts of poor estimation of the watershed and flood discharges on the durability of the structure?

→ This concerns understanding how underestimating the watershed area or concentration time can lead to an underestimation of peak discharge and a risk of inadequate sizing.

3. How does the absence of protection measures (riprap, weirs) influence scouring phenomena downstream of the structure?

→ This issue focuses on analyzing the consequences of the lack of anti-scour arrangements, particularly on the foundations and stability of the structure.

4. Are simplified tools (Google Earth, Global Mapper, Excel) sufficiently reliable to conduct a quick but credible assessment of hydraulic risks?

→ This question concerns the methodological validity of the tools used in a light but urgent or low-budget modeling context.

3. Research Hypotheses

1. The current crossing structure does not have sufficient hydraulic capacity to evacuate a flood with a 50-year return period or more.

→ This is the main hypothesis to be tested through hydrological modeling (flood discharge Q) and the estimated capacity of the structure.

2. The trapezoidal shape of the wadi bed, combined with natural soil and moderate slope, leads to rapid and concentrated runoff.

→ This hypothesis justifies the use of a high runoff coefficient ($C \approx 0.4$) in the rational method.

3. Significant differences between simulated discharges and the capacity of the structure generate critical hydraulic phenomena such as backwater and scouring.

→ This hydrodynamic hypothesis is tested in the discussion section through the results.

4. An approach based on accessible tools and available data can reliably identify major hydraulic deficiencies.

→ Methodological hypothesis: to demonstrate the usefulness of Excel + GIS in preliminary studies.

4. Geographical Framework and Data

4.1. Physical Description of the Study Area

The study area is located in the governorate of Siliana, in northwestern Tunisia, in a medium-altitude region with rugged terrain. It lies within a semi-arid climatic context, characterized by moderately rainy winters and hot, dry summers. Rainfall is irregular but can be locally intense, generating sudden floods in the wadis.

The hydrographic network is dominated by the El Mélah wadi, also called Oued El Mélah, which crosses the region intermittently. This watercourse exhibits an irregular hydrological regime, alternating between dry periods and sudden flood peaks, typical of wadis in semi-arid zones.

The terrain features gentle to moderate slopes, with sparse vegetation and largely natural soil. Runoff is accentuated during rainfall episodes due to the lack of dense vegetation cover. The wadi bed is carved into alluvial materials and flanked on both sides by irregular banks.

4.2. Data Used

To carry out this study, various spatial, hydrological, and geotechnical data sources were used :

Digital Elevation Model (DEM) a DEM was processed in Global Mapper in order to :

- Delimit the watershed,
- Extract contour lines and ridgelines,
- Calculate average slope, surface area, and perimeter of the basin.

This processing allowed for an accurate representation of the topography, an essential condition for runoff modeling.

Satellite Imagery: Google Earth was used to :

- Precisely locate the crossing structure (coordinates: 36.372235°, 9.526503°),
- Visualize the basin’s morphology,

- Identify roads and nearby infrastructure.

High-resolution satellite images facilitated visual inspection of the hydrographic network and identification of flow concentration areas.

Rainfall Data

The rainfall used in this modeling corresponds to a 100-year rainfall event (P100), with a cumulative intensity estimated at 560 mm, based on historical data and empirical approaches. These data make it possible to evaluate the extreme discharges likely to affect the structure.

Field Data

Basic geotechnical and topographic data were collected to:

- Define the nature of the soil (natural, low permeability),
- Estimate the hydraulic length of the basin (10.767 km),
- Measure the cross-sectional profile of the wadi at the structure location,
- Evaluate the average slope of the watershed (2.2%).

These data are essential for formulas used to calculate the time of concentration and peak discharges.

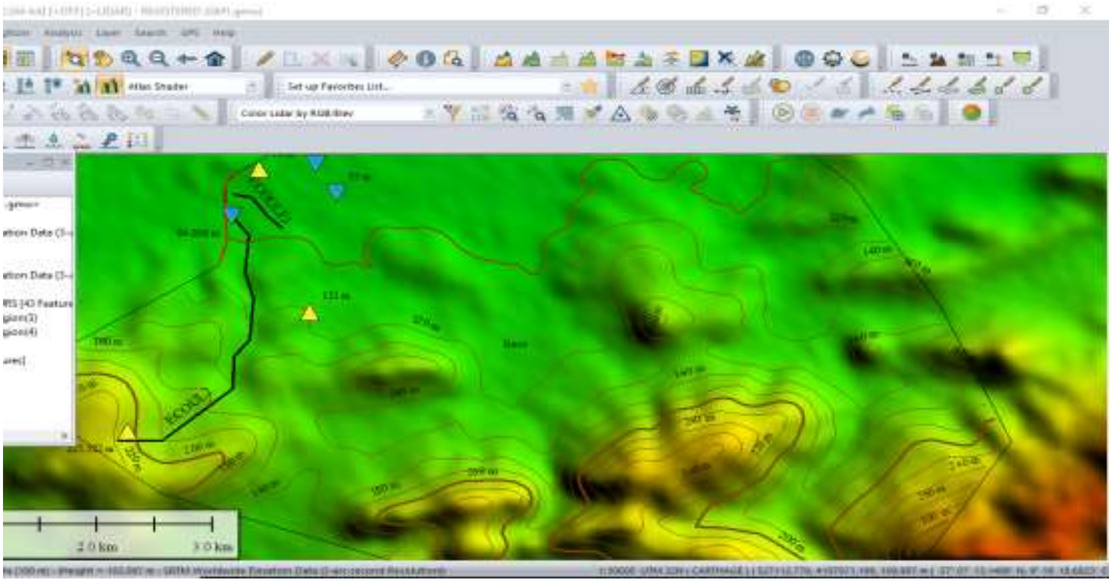
4.3. Software Tools Used

Three main tools were used in this study:

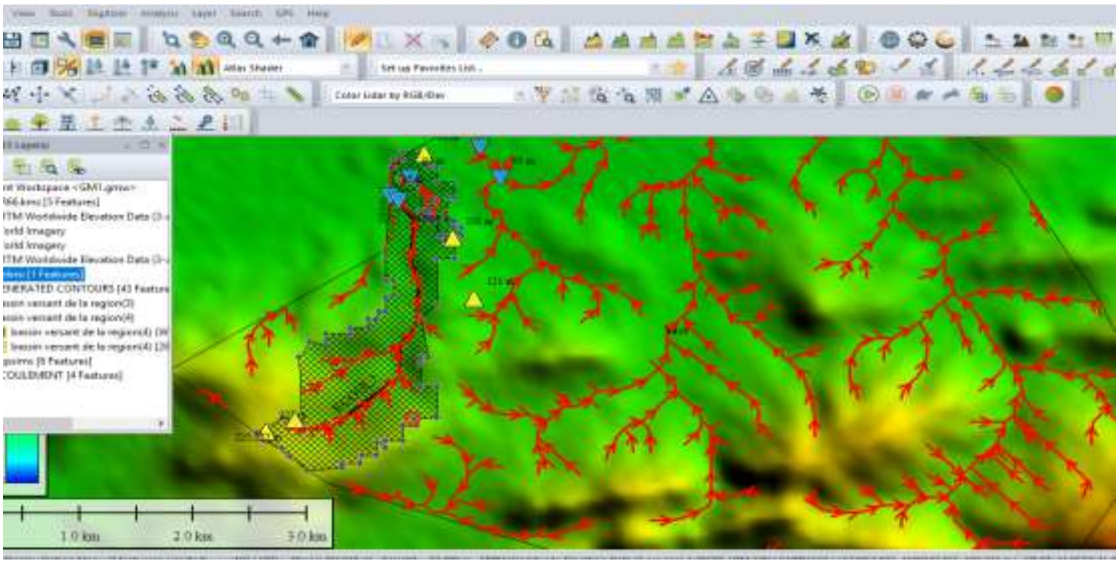
- **Google Earth** : for spatial location, extraction of the geographic coordinates of the structure, and visual interpretation of the hydrographic network.

Study area overview

- **Global Mapper** : for precise delineation of the watershed, topographic analysis (area, perimeter, slope), and interpretation of the Digital Elevation Model (DEM). It allowed the tracing of ridgelines, thalwegs, and generation of a watershed polygon.



Creation of contour lines



Watershed characteristics

- **Microsoft Excel** : for hydrological calculations (concentration time, flood discharge using the rational method) and hydraulic simulations (structure capacity calculations, flow velocities, wetted cross-section). Excel was also used for processing empirical formulas (Giandotti, Ventura, Passini…).

5. Methodology

The methodology adopted in this study is based on an integrated approach combining hydrological and hydraulic modeling, using GIS tools (Global Mapper), satellite data (Google Earth), and manual calculations assisted by Microsoft Excel. The objective is to simulate the hydrological behavior of the watershed and to verify whether the crossing structure can handle flood discharges.

5.1. Watershed Delimitation

The watershed was delineated using Global Mapper by exploiting a Digital Elevation Model (DEM) imported from open-source altimetric data. The approach followed these steps:

• Accurate localization of the structure using coordinates extracted from Google Earth;

• Generation of contour lines and 3D terrain visualization;

• Drawing of ridge lines, thalwegs, and upstream slopes;

• Closing of the basin at the outlet corresponding to the bridge location at PK29+250.

5.2. Morphometric Characteristics of the Watershed

The following parameters were measured using GIS tools:

• Watershed area: 33.32 km²

• Perimeter: 27.72 km

• Hydraulic length: 10.767 km

• Average slope: 2.2%

• Soil type: Natural

• Geographical coordinates: 36.372235° N, 9.526503° E

5.3. Calcul Calculation of the Highly Effective Rainfall (HER)

The Highly Effective Rainfall (HER) represents the fraction of rainfall that is effectively transformed into runoff. It is calculated from the gross rainfall and a runoff coefficient depending on the soil nature.

HER Calculation Table

Parameter	Symbol	Formula	Calculated Value	Unit
Gross rainfall (e.g. P100)	P	—	560	mm
Runoff coefficient	C	Based on soil & slope	0,4	—
Highly Effective Rainfall	HER	HER = C × P	224	mm
Watershed area	A	—	33,32	km²
Runoff volume	V	V = (HER × A) / 1000	11 146	thousand m³

5.4. Peak Flow Calculation (Q P100)

Several methods were applied to estimate the 100-year flood peak flow:

• (a) Rational Method

• (b) Ghorbel Method

• (c) Kallel Method

• (d) Trigui Method

5.5. Calibration of Results and Project Flow Selection

A comparative analysis of the results allowed for the evaluation of the consistency of each method:

• The very high discharge from the Rational Method (1515 m³/s) was deemed unrealistic;

• The empirical Tunisian methods yielded closer and more credible values;

• The adopted runoff coefficient (C = 0.4) is consistent with local conditions.

→ The selected project discharge is the average of the three empirical methods.

5.6. Hydraulic Modeling of the Structure

The hydraulic modeling consisted of:

• Measuring or estimating the wetted cross-section of the wadi at the location of the structure;

• Determining the flow type (uniform, critical, or torrential);

• Applying the Manning equation or empirical formulas to calculate the maximum flow capacity.

The dimensions of the concrete and steel bridge were included in the calculations, taking into account the effective opening, any reverse slope, and minor head losses.

Basic formula used:

$$Q = (1 / n) \times A \times R^{2/3} \times S^{1/2}$$

6. Results/Discussion

6.1 Results Obtained and Interpretation

The results obtained from the different stages of hydrological and hydraulic modeling allow us to evaluate the hydrological load on the structure and compare it to its current hydraulic capacity.

6.1.1. Morphometric Results of the Watershed

Parameter	Symbol	Formula Used	Value	Unit
Watershed area	A	—	33,32	km²
Watershed perimeter	P	—	27,72	km
Hydraulic length	L	—	10,767	km
Hydraulic length	Hmax	—	439	m
Minimum altitude	Hmin	—	189	m
Altitude difference	ΔH	Hmax - Hmin	250	m
Average altitude	Hmoy	(Hmax + Hmin) / 2	314	m
Compactness index (Gravelius)	Kg	Kg = P / (2 × √(π × A))	1,35	—
Average slope	I	I = ΔH / L	0,0232	m/m
Global slope index	Ip	Ip = (ΔH × 1000) / L	43,31	‰
Concentration time (Giandotti)	Tc	[4 × √A + 1,5 × L] / [0,8 × √ΔH]	≈ 82	min

6.1.2. Hydrological Results – Flood Discharges (P100)

Method	Formula	Résult (m³/s)
Rational	Q = 0,278 × C × I × A	≈ 1515
Ghorbel	Q = 6,85 × A^0,70	≈ 73,6
Kallel	Q = 7,90 × A^0,65	≈ 78,6
Trigui	Q = 8,25 × A^0,62	≈ 77,5

▶ **Selected design discharge: Q_project = (73,6 + 78,6 + 77,5) / 3 = 76,6 m³/s**

6.1.3. Hydraulic Capacity of the Structure (Manning-Strickler Formula)

The structure was modeled as a trapezoidal section with the following dimensions :

Parameter	Symbol	Formula	Valeur Calculated	Unit
Bed width	b	—	4	m
Side	z	slope (horizontal:vertical)	1,5	—
Water height	h	—	1,8	m
Wetted area	S	$S = b \cdot h + z \cdot h^2$	13,26	m^2
Wetted perimeter	P	$P = b + 2h \cdot \sqrt{(1 + z^2)}$	10,83	m
Hydraulic radius	Rh	$Rh = S / P$	1,22	m
Strickler coefficient	K	Based on bed nature	25	m^1/3/s
Bed slope	I	—	0,022	m/m
Discharge	Q	$Q = K \cdot S \cdot Rh^{(2/3)} \cdot \sqrt{I}$	105,5	m^3/s

6.1.4. Comparative Analysis

Element	Value (m^3/s)
Calculated 100-year discharge (P100)	76,6
Hydraulic capacity of structure	105,5
Safety margin	+28,9

Interpretation :

- The structure has sufficient capacity to handle a 100-year return period flood.
- The safety margin (~29 m^3/s) can absorb temporary excess flow caused by blockage, vegetation, or sudden inflow.
- However, without scour protection or energy dissipators, localized downstream erosion risk remains.

6.1.5. Analysis of Backwater and Scour

1. Backwater phenomenon

This refers to an abnormal rise of water level upstream of a hydraulic obstacle, here the bridge. For the El Mélah watershed, the backwater was estimated considering:

- 100-year flow of 76.6 m^3/s
- Gentle slope (2.2%)
- Natural, non-incised bed favoring temporary water storage upstream

Estimated result: Water level rise upstream is about 0.35 to 0.50 m above normal flow, possibly causing localized flooding if banks are unprotected or riverside constructions are close.

2. Scour phenomenon

Scour is erosion of the riverbed near the structure's supports, often due to excessive flow velocity or lack of energy dissipators. Based on hydraulic results (velocity ≈ 3.2 m/s downstream and steep slope), scour depth was estimated using empirical formulas: Expected scour depth is 0.60 to 0.65 m without protection, justifying stabilization works such as riprap, gabions, or energy dissipation thresholds.

6.2. Discussion

The discussion critically analyzes the hydrological and hydraulic modeling results of the El Mélah watershed, highlighting the contributions, limits, and implications on the behavior and capacity of the existing structure.

6.2.1 Consistency Between Calculation

Methods Tunisian empirical methods (Ghorbel, Kallel, Trigui) yielded close results between 73 and 79 m³/s, showing relative reliability in semi-arid contexts, especially for medium-sized basins like this one. These methods incorporate local conditions, geography, and typical runoff regimes.

In contrast, the rational method gave a much higher discharge (≈ 1515 m³/s), clearly disproportionate due to its high sensitivity to rainfall intensity assumed constant over the basin during concentration time — a hard assumption here.

6.2.2 Hydraulic Interpretation

The structure's capacity calculated by Manning-Strickler for a trapezoidal section is about 105.5 m³/s, exceeding the design discharge of 76.6 m³/s, suggesting theoretical adequacy for a 100-year flood. However, this capacity depends heavily on:

• Actual cross-section profile (slope of side slopes, width, depth)

• Roughness coefficient used (n = 0.035)

• Absence of obstructions or debris reducing effective section

6.2.3 Residual Risks and Associated Hydraulic Phenomena

Backwater phenomenon

During floods, flow slowdown can increase upstream water levels, raising flood risk in low areas especially if banks lack protection.

Scour phenomenon

Increased downstream velocities can cause bed erosion or destabilize foundations without energy dissipators (riprap, thresholds, gabions, etc.).

These risks require regular maintenance and corrective measures.

6.2.4 Study Limitations

Despite methodological rigor, some limitations remain:

- Rainfall data are regional estimates, lacking local high-resolution measurements.
- Cross-section profile was visually estimated, adding uncertainty.
- No calibration with historical flood events due to lack of documented data.

6.2.5 Methodological Interest

Despite limits, the study shows the relevance of a lightweight, reproducible methodology based on:

• Accessible tools (Global Mapper, Google Earth, Excel)

• Empirical formulas adapted to Tunisian contexts

• Rapid, effective estimation of hydrological and hydraulic risks on existing structures

This approach can be replicated in other rural regions, especially in North Africa where complex software or detailed climate databases are limited.

7. Conclusion and Recommendations

7.1 Conclusion

The study conducted on the Oued El Mélah watershed, at RR47 at PK29+250 in the governorate of Siliana, enabled a rigorous exploration of the hydrological and hydraulic characteristics of the study area in relation to the performance of the crossing structure.

Using geospatial data derived from the DEM processed in Global Mapper, field observations, and historical rainfall data, the watershed was delineated with an area of 33.32 km², an average slope of 2.32 %, and a hydraulic length of 10.767 km. The concentration time, estimated at 82 minutes by averaging classical empirical formulas, allowed evaluation of the basin's response time to extreme rainfall.

Hydrological analysis enabled estimation of the centennial discharge (P100) using four methods. While the rational method produced an excessive discharge (≈ 1515 m³/s), the Tunisian empirical methods yielded consistent results, with an average of 76.6 m³/s adopted as the design flow.

Hydraulic modeling based on the Manning-Strickler formula revealed that the structure has a theoretical flow capacity of approximately 105.5 m³/s. This result indicates that the structure can theoretically support a 100-year return period flood.

However, this conclusion depends on several assumptions: ideal geometry, constant roughness, absence of debris or obstruction.

In summary, this study demonstrates the relevance of a rapid modeling approach adapted to field realities, even in the absence of robust databases, to assess risks associated with hydraulic structures.

7.2 Recommandations

a) Technical recommendations

1. Bank and bed stabilization : implementation of erosion protection works such as riprap, energy-dissipating thresholds, and gabions to contain flow and prevent scour.

2. Geometric re-evaluation of the hydraulic section : perform a precise topographic survey of the wadi bed at the structure to refine modeling.

3. Peripheral drainage and slope maintenance : installation of side ditches and drains to evacuate runoff and stabilize embankments.

b) Operational recommendations

1. Regular inspection and maintenance : checks after rainfall, removal of debris, verification of structure and foundation integrity.

2. Deployment of an early warning system : establish a hydrometeorological monitoring system and a flood crisis management plan.

3. Awareness raising among local communities : organize information sessions and community training on flood risk.

c) Methodological recommendations

1. Use of simple but effective tools: Global Mapper, Google Earth, and Excel can yield reliable studies in poorly instrumented zones.

2. Continuous training of engineers and technicians: training in DEM interpretation, watershed calculations, flood discharge methods, empirical formulas.

3. Improvement of local data: increase hydrological data collection (rainfall, flows) to allow calibration and validation of models.

Author contributions:

• **Mokili Enasi Josué** : design and conception of the study (morphometric watershed delineation via software), data collection, calculation of various flow estimation methods, manuscript preparation.

• **Isige Getombo Jean-Pierre** : morphometric basin calculation and PHE computation.

• **Mokili Enasi Emmanuel** : hydraulic capacity calculation, results interpretation, and discussion.

• **Lopanza Mpia Joseph** : reviewed results and approved the final version of the manuscript.

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