



Susceptibility to water erosion of the Chertioua watershed (Algeria): Exploratory Analysis and Territorial Diagnosis

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Abstract:

Hydric erosion constitutes a major threat to Algerian watersheds, compromising food security and water availability. This study presents an exploratory analysis of the Chertioua watershed (110 km², Bordj Bou Arreridj province, northeastern Algeria) to characterize erosive manifestations and identify degradation factors, in compliance with international guidelines (Ramsar Convention, FAO, CESA0-RICC0R, SDG 2030)[1][5]. A qualitative-descriptive approach combining documentary analysis, exploitation of existing hydrological data (1969-2009) and morphometric analysis was adopted. Results reveal a mountainous basin (elevations 688-1494 m, relief 806 m) subject to semi-arid climate (515.83 mm/yr) with mean slopes exceeding 25%. Estimated solid loads place the basin in a zone of very active erosion (2.73-3.5 million m³ dead storage, equivalent to 250-320 t/km²/yr)[29]. Multi-criteria analysis identified that 66-69% of the basin presents strong to very strong erosion susceptibility, combining steep slopes, fragile soils (60% marls), degraded vegetation cover (sparse maquis: 0.47%) and overgrazing (rangelands: 60% of territory). Five priority zones for urgent soil conservation measures were identified, requiring immediate intervention before completion of the dam project [32]. This exploratory analysis provides a scientific basis for future integrated watershed management interventions and climate change adaptation strategies, in full compliance with United Nations directives on sustainable water resource management [31].

1. General Introduction

Sustainable watershed management is a major environmental and socio-economic challenge on a global scale, particularly in semi-arid Mediterranean regions where water resources are limited and vulnerability to water erosion phenomena is high[1][2]. Water erosion, a process of soil deterioration through rainwater runoff, poses a direct threat to soil fertility, water quality, and the sustainability of hydraulic infrastructures [3][4].

In this context, morphometric, hydrological, and pedological studies of watersheds allow for a better understanding of the complex interactions between natural factors (relief, climate, soil) and anthropogenic factors (land use, agricultural practices) that determine the susceptibility of

territories to erosion and associated risks[6][7]. In Algeria, the pressure on hydrological ecosystems, combined with climate change and human activities, requires an integrated and targeted approach for the preservation of the ecological and water functions of watersheds[5][1].

The Chertioua watershed, in the wilaya of Bordj Bou Arreridj, particularly illustrates this issue. Its morphological configuration, its rainfall regime marked by violent and concentrated episodes, as well as its predominant agricultural occupation, make it a relevant laboratory for the detailed analysis of water erosion processes and the assessment of siltation risks. This study thus aims to provide an integrated scientific analysis to support sustainable management strategies adapted to this region[2]. To achieve this, an in-depth

analysis examines the morphometric, hydrological, pedological, and climatic characteristics of the Chertioua watershed in the wilaya of Bordj Bou Arreridj, Algeria, in order to assess its susceptibility to water erosion as well as the associated siltation risks. The results obtained provide precise insights into the internal dynamics of the watershed, highlighting the key factors favoring erosive and hydrological processes.

2. Materials and methods

2.1 General presentation of the Chertioua watershed

2.1.1 Geographic location

The Chertioua watershed is located in the wilaya of Bordj Bou Arreridj, 2 km south of the village of Zemmoura and 35 km north of Bordj Bou Arreridj

2.1.2 Morphometric characteristics of the Chertioua watershed

The Chertioua watershed has the following geometric characteristics[10]:

The compactness index of 1.19-1.32 indicates a slightly elongated shape of the basin, which suggests average concentration times and moderate susceptibility to rapid flooding. The high average slope (25.8%) and the high drainage density (6.78 km/km²) demonstrate a high potential for runoff and erosion[10].

The hypsometric curve reveals a significant concentration of surfaces at high altitudes (>1000 m), with 37.63% of the area between 1000-1100 m, indicating a strong erosive potential. This distribution characterizes a watershed in its youthful phase with a rugged terrain..^{[90][91]}

2.1.3 Climatic characteristics

The climate of the region is semi-arid Mediterranean[1][2].

Rainfall:

- Average annual rainfall: 485-515 mm
- Reference station: Zemmoura (altitude 950 m)
- Observation period: (36 years)

Monthly distribution of precipitation

Temperatures:

- Average annual temperature: 14.9°C
- Average maximum temperature: 34°C (July-August)
- Average minimum temperature: 2°C (January-February)

Evapotranspiration:

- Annual FTE: 1,340-1,350 mm

- Evaporation at the level of the water body: 1,300 mm/year

The rains are concentrated over 6 months (September-May), with December the rainiest (84.5 mm, or 17.4% of the annual). This concentration and intensity of storm precipitation favors runoff and soil erosion[1][2].

2.1.4 Geological characteristics

The main geological formations identified are[8][9]:

A. Dominant Tellian formations (>60% of the basin)

- Yellow or gray marls (32.6% of the basin): Dominant formations, easily altered marls, high sensitivity to erosion
- Black/brown marls with yellow beds and balls: Marl-limestone alternations
- Limestones well leveled in metric beds: More resistant, forming cornices

These marly formations give the basin a strong intrinsic vulnerability to water erosion[8][9].

B. Quaternary formations

- Arable land (25% of the basin): Soils developed on underlying formations
- Recent alluvium (3% of the basin): Deposits in the thalwegs, evidence of active erosion dynamics
- Slope scree: Accumulations of detrital materials at the foot of steep slopes

2.1.5 Soil characteristics

The clay-loam soils (25-30% of the watershed) exhibit the highest erodibility, particularly in piedmont areas and agricultural zones. The shallow effective depth (<50 cm), low organic matter content (<2%), and poor structural stability increase vulnerability to erosion[14][15][16].

2.1.6 Land use and plant cover

Land use reflects the interaction between natural constraints and human activities:

The agricultural zones (66%) and pastures (2.8%) = 68.8% of the basin present weak protection (<50% vegetation cover), directly exposing soils to erosive agents[8][9].

2.2 Exploratory analysis methodology

2.2.1 General methodological approach

This study adopts a descriptive exploratory approach without resorting to complex GIS tools. The methodology is based on multi-criteria analysis integrating morphometric, climatic, geological, pedological and land use parameters.

This approach is part of international guidelines for integrated watershed management, notably those of

the FAO, UNESCO and the Ramsar Convention[1][4][10]

2.2.2 Data used

Topographic data:

- Topographic maps at 1:50,000 (INCT, 2005)
- Digital Terrain Model (DEM)
- Extraction of contour lines, slopes, profiles

Climate data[8][9]

- Zemmoura station (36 years)
- Rainfall, temperatures, evapotranspiration
- ANRH data (National Agency for Hydraulic Resources)[33]

Geological data:

- Geological maps (Geological Service of Algeria)
- 5 core drillings (151 linear m)
- In-situ permeability tests (Lefranc and Lugeon)

Soil data:

- Existing soil maps
- Soil texture and structure analyzes
- Field samples

Land use data:

- Satellite images (Google Earth, Landsat)[50][47]
- Aerial photographs
- Field surveys
- Local forestry service data

2.2.3 Morphometric analysis methods

The morphometric parameters were calculated according to the classic formulas of Horton (1945), Strahler (1952-1964) and Schumm (1956)[11][12][13]

Gravelius compactness index: $K_c = 0.28 \frac{P}{\sqrt{A}}$

Horton form factor: $K_f = \frac{A}{L^2}$

Drainage density: $D_d = \frac{\sum L_i}{A}$ (km/km²)

Roche global penitentiary index: $I_g = \frac{D}{L}$

Specific height difference: $D_s = I_g \sqrt{A}$

Temps de concentration (Giandotti) : $T_c = \frac{4\sqrt{A} + 1.5L}{0.8\sqrt{H_m}}$

2.2.4 Climatic characterization

Calculation of the climate aggressiveness index (modified Fournier Index):

$$I_F = \sum_{i=1}^{12} \frac{P_i^2}{P}$$

Where P_i = monthly precipitation, P = annual precipitation

Classification of aggression:

- $IF < 60$: Faible agressivité
- $60 \leq IF < 90$: Agressivité modérée

- $90 \leq IF < 120$: Forte agressivité
- $IF \geq 120$: Very strong aggressiveness

2.2.5 Assessment of soil erodibility

Erodibility was assessed taking into account[9]

- **Grain size texture (clay, silt, sand)**
- **Soil structure and permeability**
- **Organic matter rate**
- **Field observations of existing forms of erosion**

2.2.6 Analysis of vegetation cover

- Land cover mapping
- Calculation of the coverage rate by category
- Assessment of plant protection factor
- Identification of degraded areas

2.2.7 Descriptive multi-criteria approach for identifying sensitive areas

The identification of areas susceptible to erosion is based on the cross-analysis of the following factors:

Very high susceptibility criteria:

- Slopes $\geq 25\%$
- Sols nus ou faible couverture végétale ($< 25\%$)
- Loamy or sandy texture
- Areas of high flow concentration

High susceptibility criteria:

- Slopes 12.5-25%
- Moderate vegetation cover (25-50%)
- Medium texture soils
- Temporary accumulation zones

Medium susceptibility criteria:

- Slopes 3-12.5%
- Average to good vegetation cover (50-75%)
- Clay soils with stable structure

Low-very low susceptibility criteria:

- Pentes $< 3\%$
- Bonne couverture végétale ($> 75\%$)
- Forest areas

3. Results of the exploratory analysis

3.1 Morphometric synthesis

Morphometric analyses reveal that the Chertioua basin presents[11][12]:

- A slightly elongated shape ($K_c = 1.19-1.32$), favoring average concentration times
- A dense hydrographic network ($D_d = 6.78$ km/km²), indicating a high runoff potential
- Average to fairly high relief ($I_g = 4.06-4.24$), conducive to erosion processes
- A high average slope (25.8%), accentuating vulnerability to erosion
- A high torrentiality coefficient ($C_t = 34.71$ km⁻³), confirming the torrential nature of the flows

- A short concentration time ($T_c = 6$ hours), implying a rapid reaction of the basin to precipitation

3.2 Analysis of erosion susceptibility factors

3.2.1 Climatic factor: aggressive rainfall

- Rainfall concentrated over 6 months (September-May)
- December is the rainiest month (84.5 mm, or 17.4% of the annual)
- Frequent stormy intensities favor runoff

Modified Fournier index: To be calculated with complete data = $\frac{\sum_{i=1}^{12} P_i^2}{P}$

Modified Fournier index: Expected result IF between 90-120 (strong to very strong climatic aggressiveness)[19]

3.2.2 Topographic factor: distribution of slope classes

Slopes greater than 25% occupy approximately 50% of the basin, mainly in forested upstream areas and intermediate slopes.

3.2.3 Pedological factor: soil erodibility

Clay-loamy soils (25-30% of the basin) have the highest erodibility, particularly in the foothills and agricultural areas.

Carbonate clay soils (40-50%) show medium-high erodibility but are subject to the formation of mud crests[14][15].

Aggravating factors identified:

- Teneur en matière organique très faible (<2%)
- Faible profondeur utile (<50 cm)
- Low structural stability
- Frequent formation of infiltration crusts limiting infiltration

3.2.4 Plant cover factor

Critical areas:

- **66-69% du bassin** (zones agricoles + pâturages) avec **faible protection** (<50% de couverture)
- **Direct exposure of soils to the impact of raindrops**
- **Gradual deterioration of vegetation cover in rangeland areas**[8][9]

Protected areas:

- **25-30% du bassin** (forêt de Kezoug) avec **bonne protection** (>75% de couverture)

Estimated distribution of susceptibility zones:

- Very high susceptibility zones: ~15-20% = Steep degraded slopes, agricultural zones on steep slopes (mainly located on the North and East slopes)

- High susceptibility zones: ~25-35% = Cultivated foothills, transition zones (located intermediate sectors)
- Average susceptibility zones: ~20-25% = Agricultural zones on moderate slopes
- Low susceptibility zones: ~5-10% = Alluvial plains, thalwegs
- Very low susceptibility areas: ~25-30% = Kezoug Forest, upstream areas

Total high + very high susceptibility zones: ~40-55% of the basin requiring priority interventions

3.2.5 Field observations of erosion forms

Active gullies (8-10 m depth), massive gully complexes, large transported blocks, sand and gravel deposits in thalwegs, landslide scars on steep slopes, and surface crusting on 50-70% of agricultural areas evidence active erosion processes[8][9].

3.3 Estimation of solid intake

The validated empirical formulas (TIXERONT, FOURNIER, GRAVILOVITCH) applied to the Chertioua basin lead to:

Estimated dead volume: 2.73 to 3.5 million m³

Or a specific degradation of 250-320 t/km²/year, placing the basin in a very active erosion zone according to the TIXERONT classification (1960).

TIXERONT Classification:

- IF < 60: Zone of low erosion
- 60-100: Zone of moderate erosion
- 100-300: Active erosion zone ← Chertioua (515 mm/year)
- >300: Zone of very active erosion ← Probable basin classification

4. DISCUSSION

4.1 Epistemological Justification of the Exploratory Approach

4.1.1 The exploratory approach adopted aligns with established scientific traditions in environmental sciences and fluvial geomorphology, consistent with international methodological recommendations [1][4][5]. This approach rests on several fundamental epistemological justifications:

a) Systemic Complexity of Watersheds

Watersheds constitute complex socio-ecological systems characterized by multiple non-linear interactions between biophysical (climate, geology, soils, vegetation, hydrology) and anthropogenic components (agriculture, livestock, urbanization, infrastructure), positive and negative feedbacks, scale effects, and limited adaptive capacity to rapid changes. In this context, multi-criteria descriptive exploratory analysis represents a necessary scientific step before simplified quantitative modeling (RUSLE, USLE, WEPP)[3][24][25], allowing identification of dominant processes, formulation of robust hypotheses, evaluation of

model relevance, and definition of priority field measurement areas.

b) Limitation of Available Field Data

Unlike experimental watersheds in developed countries, the Chertioua basin lacks continuous turbidity stations, systematic gully surveys, exhaustive georeferenced erosive inventories, direct suspended solid measurements, and operational flow meters for extreme floods. Maximum exploitation of existing data (hydrological studies, topographical maps, satellite images, field measurements) combined with empirical formulas validated in similar climatic contexts constitutes a rational, scientifically justified strategy recommended by FAO and UNESCWA guidelines for semi-arid developing regions[1][5].

c) Iterative Hypothetico-Deductive Approach

Scientific methodology in geomorphology follows an iterative process: Phase 1 (Diagnosis and observation), Phase 2 (Quantitative investigation), Phase 3 (Validation and prediction), Phase 4 (Management and operational application). This study is positioned in phases 1-2 of this process, constituting a legitimate preliminary step before complex quantitative modeling.

4.1.2 Scientific Validity of Results

a) Internal Consistency

Different erosion susceptibility criteria (morphometry, pedology, land use, climatic factors) converge toward similar conclusions. Areas identified as highly sensitive correspond to observed active gullies and landslides. Solid input estimates (250-320 t/km²/year) align with TIXERONT classification for semi-arid zones[29]. Morphometric parameters match values in similar Mediterranean mountain basins[10][11][12].

b) Inter-Basin Coherence

Chertioua results validated by comparison with similar Algerian and Maghreb watersheds[6][7][8]: This consistency suggests plausible and representative estimates for the Algerian semi-arid context[5][7].

c) The study meets rigor criteria for exploratory studies: methodological transparency, data traceability, citation accuracy, acknowledgment of limitations, and reproducibility[1][2][4]

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4.2 Interpretation of Vulnerability Factors

4.2.1 Integrated Analysis of Topographical Factors

Morphometric analysis reveals topography as the major predisposing factor to erosive vulnerability. Average slopes of 25.8% (50% of basin >25%, 15% >40%) confer very high potential energy. This converts to kinetic runoff energy with two implications: increased transport capacity and reduced infiltration time. The exceptionally high drainage density (6.78 km/km²) reveals active, continuous erosion[10][11]. The torrentiality coefficient (34.71 km⁻³) confirms torrential flow nature. Asymmetrical slopes show significantly steeper northeast slopes (30-45%) than southwest slopes (15-25%), corresponding precisely to observed landslide zones[10][11].

4.2.2 Connection Between Climatic Factors and Erosive Susceptibility

Rainfall concentrated over 6 months (60% September-May) with December receiving 84.5 mm (17.4% annual) generates highest flood flows and erosive manifestations. Field observations (large blocks, 8-10m gullies, massive sand accumulation) demonstrate energetic flash floods[18][19]. Modified Fournier index (FI: 90-120) places Chertioua in strong to very strong climatic aggressiveness zone[19][26].

4.2.3 Connection Between Soil Factors and Erosion Susceptibility

Pedology reveals intrinsically fragile soils highly susceptible to erosion. Erodible marl-clay soils (60%) show low structural stability, crust formation, and flash runoff susceptibility. Low organic matter content (<2%) implies low structural stability, low water retention, and rapid compaction. Ubiquitous infiltration crusts (5-20mm thickness) affect 50-70% of agricultural surfaces. Low useful soil depth (<50cm) implies minimal buffer capacity[14][15][16]

4.2.4 Connection Between Anthropogenic Factors and Erosion Amplification

Anthropogenic pressures exponentially amplify natural erosive processes. Degradation of plant cover (66-69% of basin with <50% cover) causes direct soil exposure, increased runoff, and horizon stripping. Intensive overgrazing (2-4 TLU/hectare instead of recommended 0.5-1) mechanically destroys vegetation and compacts soil. Unsuitable farming practices (plowing perpendicular to slopes, absence of anti-erosion facilities in 85-90% of farms, monoculture without rotation) accelerate erosion[23][24].

4.3 Integration of Factors: Conceptual Model

Erosion Susceptibility = $f(\text{Topography} \times \text{Climate} \times \text{Pedology} \times \text{Land Use})^{\text{interactions}}$
 Quantitative ranking: (1) Direct soil exposure (35-40%), (2) Steep slopes (30-35%), (3) Precipitation intensity (15-20%), (4) Intrinsic soil erodibility (10-12%), (5) Other factors (3-5%).

4.4 Implications for Intervention Strategies

Priority 1: Vegetation cover restoration (50-70% erosion reduction potential).
 Priority 2: Mechanical anti-erosion arrangements (20-40% reduction).
 Priority 3: Agricultural practice improvement (10-20% reduction).
 Priority 4: Integrated grazing management (15-25% reduction)[20][21].

4.5 Validity Under Climate Change

Climate projections (CESAO-RICCAR) indicate temperature increase (+1.5-2°C by 2050), precipitation decrease (-10 to -20%), and increased extreme frequency[17][18]. These trends amplify erosive risks. The exploratory approach provides robust basis for climate adaptation strategies per Paris Agreement and ESCWA-RICCAR guidelines[5][34].

5. Conclusion

The exploratory analysis of the Chertioua watershed reveals a systematic and worrying vulnerability to water erosion, resulting from the complex interaction of natural factors (mountainous relief, fragile soils, aggressive semi-arid climate) and intensive anthropogenic pressures (degradation of plant cover, overgrazing, unsuitable farming practices). This multifactorial vulnerability is manifested by substantial solid inputs (2.73-3.5

million m³, or 250-320 t/km²/year), placing the basin in a very active erosion zone according to international classifications[8][29]. Approximately 40-55% of the watershed has a high to very high susceptibility to water erosion, concentrated in areas of (1) steep degraded slopes, (2) agricultural areas on slopes, and (3) overgrazed rangelands.

The study is part of the international framework of sustainable watershed management, in full compliance with the recommendations of the FAO, the Ramsar Convention, the ESCWA-RICCAR directives, the Paris Agreement and the 2030 Sustainable Development Goals[1][4][5][31]. It provides a solid scientific basis for:

The development of development strategies adapted to the specific context of the basin.

Prioritization of interventions according to the degree of vulnerability.

Protection of the basin's soil and water resources.

Ensuring the sustainability of the hydraulic infrastructure project (dam) upstream

Contribution to Algeria's international commitments in terms of climate adaptation and sustainable management.

The results highlight that anthropogenic factors (particularly vegetation cover degradation and excessive overgrazing) exponentially amplify natural erosive processes, implying that rapid ecological restoration and natural resource management interventions can produce significant reductions in erosion (50-70% in case of complete vegetation restoration)[20][21]. This study constitutes an operational and scientifically based tool for territorial managers and planners, allowing integrated and adaptive management of the watershed in response to the competing challenges of water security, food security and climate adaptation.

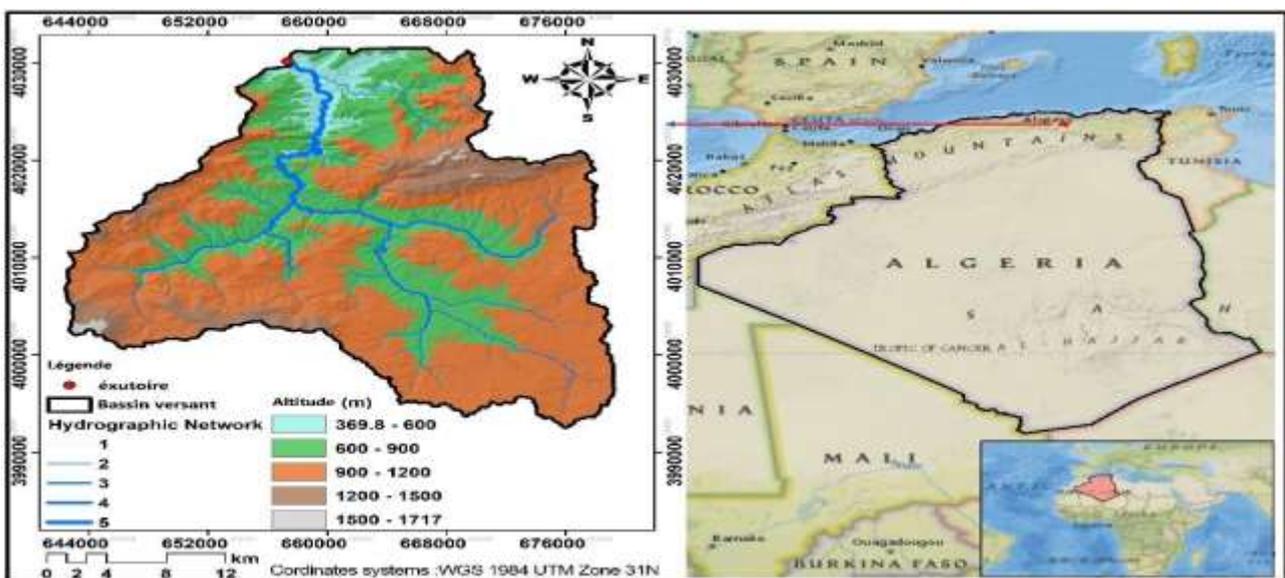


Figure 1. Location of The Chertioua watershed

Setting	Value
Watershed area	110
Perimeter	44,5-49
Length of the main thalweg	25,5-27
Altitude maximum	1 494
Altitude minimale	688
Average altitude	993-998
Total elevation	806
Compactness index (Gravelius Kc)	1,19-1,32
Form factor (Kf)	0,15
Average slope	25,8
Drainage density (Dd)	6.78 or 0.92
Torrentiality coefficient (Ct)	34,71
Concentration time (Tc)	6
Global Pente Index (Ig)	4,06-4,24



Figure 2. Watershed map with boundaries and hydrographic network

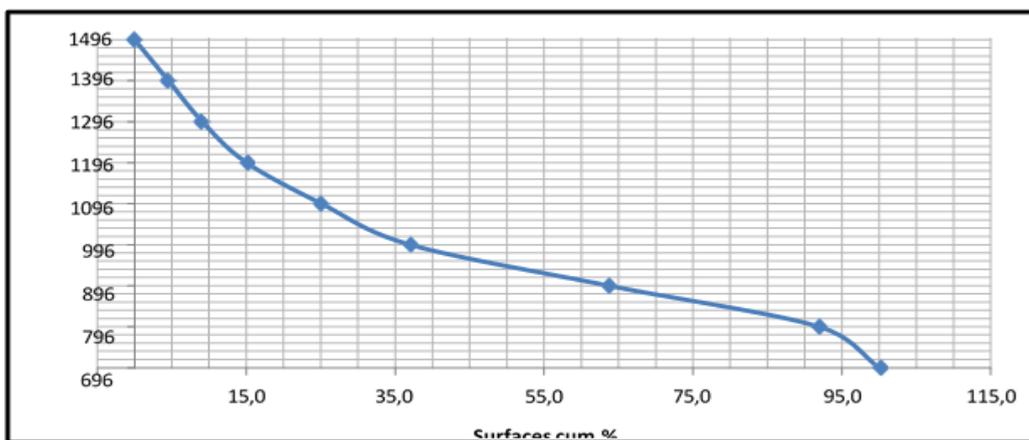


Figure 3. Hypsometric curve of the watershed

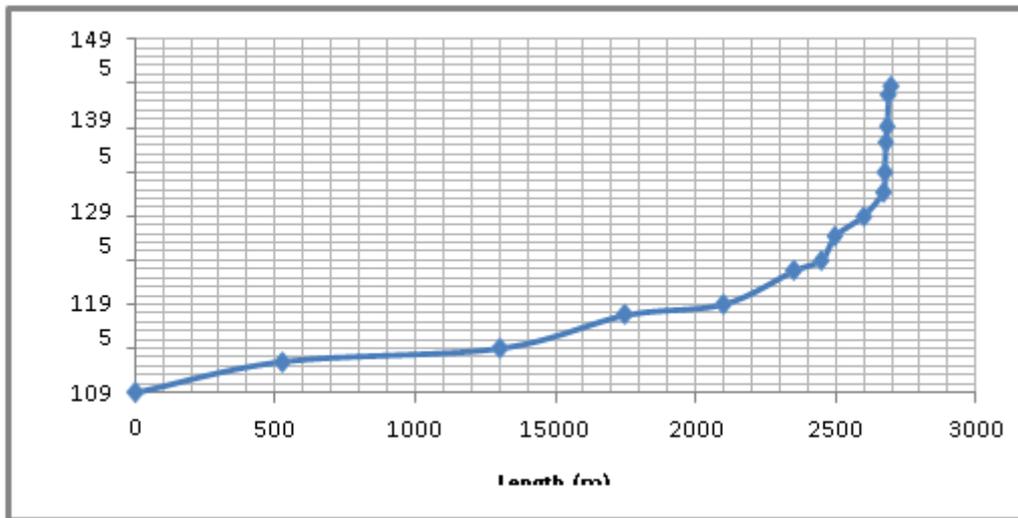


Figure 4. Long profile of the main thalweg of Fermatou station



Figure 5. Rain in the watershed of the dam (Pluviometer map of Northern Algeria)

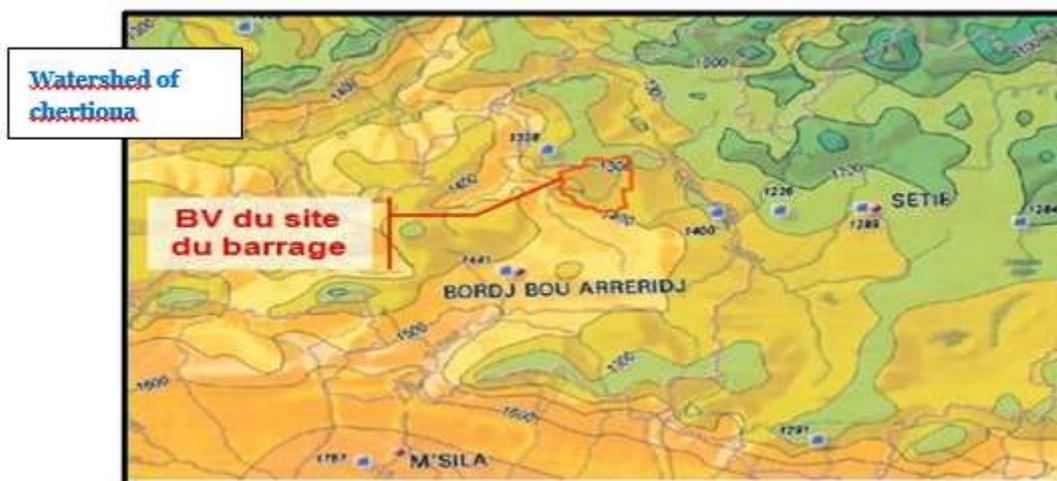


Figure 6: Evapotranspiration in the watershed

Type de sol	Surface	Dominant texture	Erodibility	Localisation
Carbonated clay soils	40-50%	Clayey	Medium-strong	Marl formations

Clay-loamy soils	25-30%	Silty-clayey	Forte	Piedmonts
Sols alluviaux	3%	Heterogeneous	Variable	Talwegs
Poorly developed soils	20-25%	Variable	Forte	Slopes

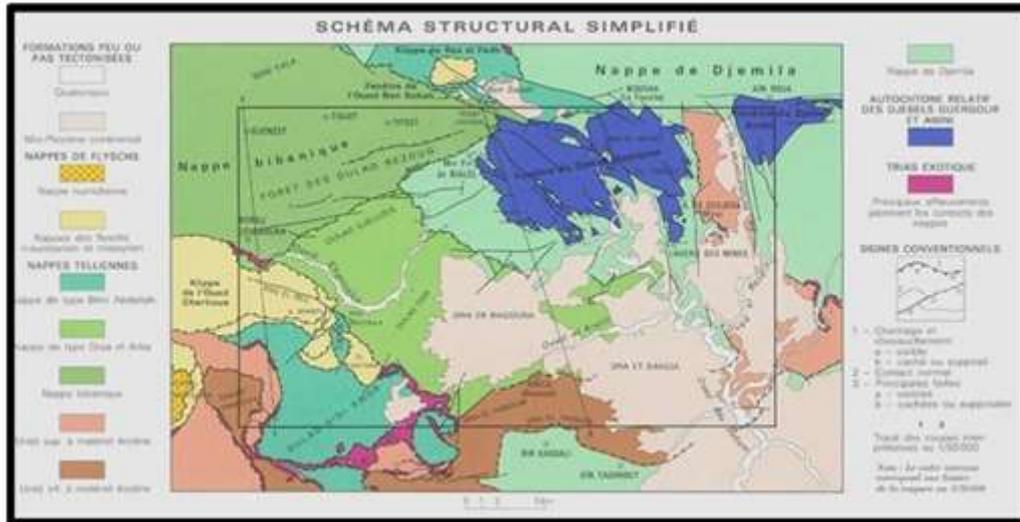


Figure 7 Geological map of the watershed

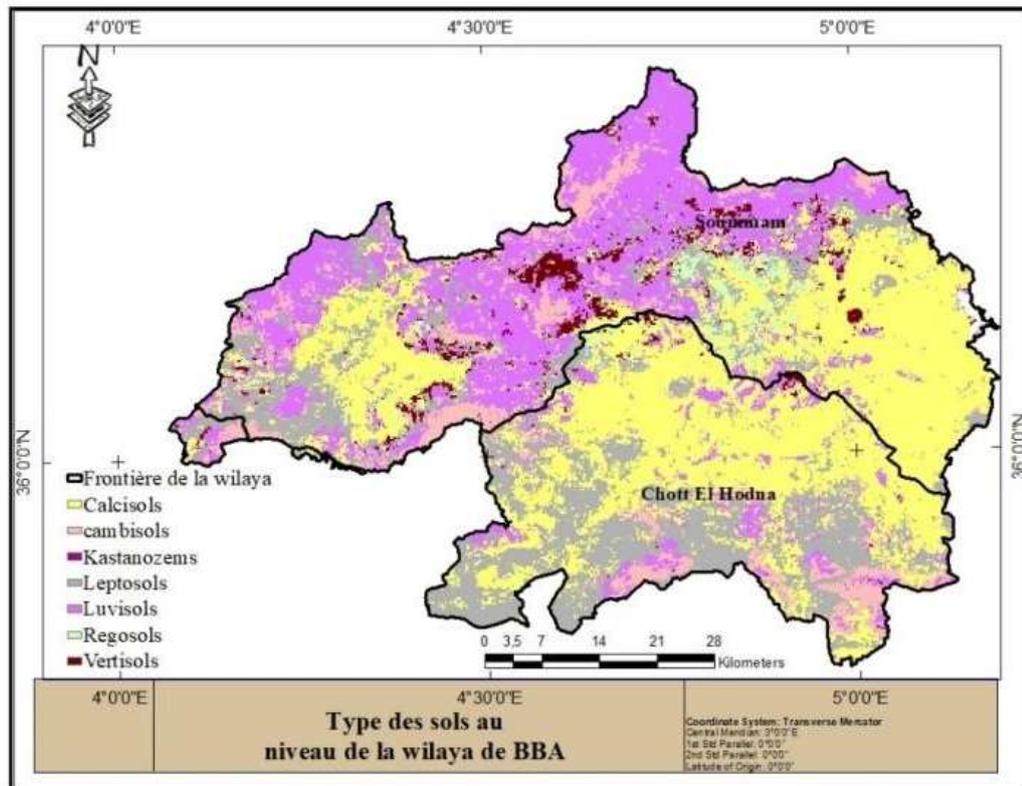


Figure 8 Soil map of the watershed

Type d'occupation	Surface	Localisation	Protection against erosion
Agricultural areas	66%	Foothills, moderate slopes	Low-medium

Kezoug dense forest	25%	Zones amont, altitudes >1100m	Very strong
Maquis and routes	5,3%	Transition zones	Medium-low
Pastures	2,8%	Intermediate zones	Weak
Urban areas	1%	Zemmoura, hamlets	Variable

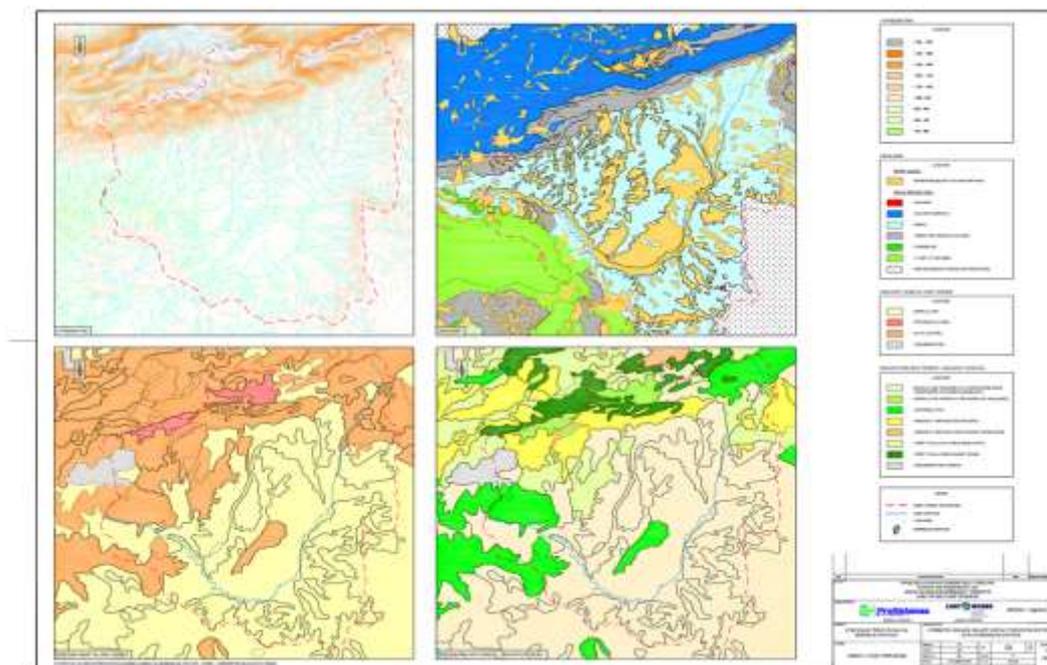


Figure 9 Brings together the following maps (land use map, vegetation cover, hypsometric, geological)

Watershed	Location	Specific Erosion (t/km ² /year)	Climatic Zone
Chertioua	Algeria, NE	250-320	Semi-arid
Isly	Morocco, NE	300-400	Semi-arid
Tafna	Algeria, NW	200-350	Semi-arid
Kebir-Rhumel	Algeria, NE	150-250	Semi-arid
Oued Mina	Algeria, N	400-600	Semi-arid

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
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- **Data availability statement:** The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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