الجمهوريـــــة الجزائريـــــة الديمقراطيـــــة الشعبيـــــة
République Algérienne Démocratique et Populaire
وزارة التعليم العالي و البحث العلمي
Ministère de l'Enseignement Supérieur et de la Recherche Scientifique
جامعة حسيبة بن بوعلي- الشلف
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كلية الهندسة المدنية و المعمارية
Faculté de Génie Civil et d'Architecture
قسم الهندسة المدنية
Département de Génie-civil

END OF STUDY DISSERTATION

To obtain the diploma of

MASTER

Field : Hydraulics

Speciality : Urban Hydraulics

by

BADANI SAID

Thème

FLOOD RISK MAPPING IN ARID REGIONS BASED ON MORPHOMETRIC ANALYSIS AND GIS – CASE STUDY OF CHELLIF WATERSHED

Soutenue le 29/06/2025, devant le jury composé de :

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Univesity year : 2024/2025

Acknowledgement

First, I express my fully gratitude to Allah the almighty for protecting me and for giving me the ability to do this work

My sincere gratitude my supervisor, Doctor, ZEROUALI Bilel , who not only encouraged me but also guided me through the journey , my doctors ,professors, lecturers, librarians, and other faculty Members at the Department of Hydraulic for their hard work ,guidance and dedication. I will always remember your encouragement to go ahead, when I was hesitant to move forward during writing due to certain immature ideas.

I am also so thankful to the technical hydraucal controle members who supported me during the year their names cannot be disclosed, but I want to acknowledge them a lot

I would like to thank Mr. BENOUDA Hamid, the head of the hydraulic department, for his encouragement, support, and guidance throughout the development of this work.

Words cannot express the feelings I have for my parents, my Mother and my Father , who formed part of my vision and taught me good things that really matter in life. Their infallible love and support has always been my strength

Finally, I thank all my brother and friends for their support and help.

Dedication

This work is dedicated to my mother and my father and further more my brothers and my friends

Said

Abstract

الملخص:

تقدم هذه الدراسة تقييماً شاملاً للخصائص المورفومترية وخطر الفيضانات في 36 حوضاً فرعياً ضمن حوض وادي الشلف الواقع في شمال وسط الجزائر. تم استخدام تقنيات نظم المعلومات الجغرافية (GIS) ونماذج الارتفاعات الرقمية (DEM) لاستخلاص وتحليل أهم المعاملات المورفومترية مثل المساحة، والانحدار ،وكثافة التصريف، ومعامل الشكل، ومعامل الالتواء، ونسبة الدائرية، وعدد المنحنيات. وتهدف هذه التحاليل إلى تقييم درجة خطورة الفيضانات عبر الأحواض الفرعية وتحديد المناطق الأكثر عرضة للخطر. أظهرت النتائج تبايناً مكانياً كبيراً، حيث أظهرت بعض الأحواض، وخاصة **وادي طويل السفلي، ضاية الفرانية، واد الوسال الأوسط، ووادي الجديوعية**، خصائص مورفومترية مرتبطة بارتفاع قابلية التعرض للفيضانات مثل الانحدارات الشديدة، والأشكال المدمجة، والكثافة العالية للتصريف ،وضعف القدرة على الامتصاص. تم إعداد خرائط تصنيف الخطورة لكل معامل ودمجها في خريطة نهائية لخطر الفيضانات. وتشير النتائج إلى أن أكثر من نصف الأحواض الفرعية تقع ضمن فئات الخطورة العالية أو العالية جداً، مما يؤكد الحاجة إلى اعتماد استراتيجيات موجهة لإدارة الأحواض، تشمل التحكم في التعرية، وتخطيط استخدام الأراضي ،وتدابير التخفيف من الفيضانات، لتعزيز القدرة على الصمود في مواجهة التغيرات الهيدرولوجية المتزايدة في المنطقة. **الكلمات المفتاحية:** خطر الفيضانات؛ التحليل المورفومتري؛ نظم المعلومات الجغرافية؛ إدارة أحواض التصريف؛ حوض الشلف؛ خصائص التصريف؛ نموذج الارتفاع الرقمي؛ المخاطر الهيدرولوجية

Abstract:

This study presents a comprehensive morphometric and flood hazard assessment of 36 sub-basins within the Cheliff watershed, located in north-central Algeria. Utilizing Geographic Information System (GIS) techniques and Digital Elevation Model (DEM) data, key morphometric parameters—such as area, slope, drainage density, shape factor, sinuosity index, circularity ratio, and Curve Number—were extracted and analyzed to evaluate their influence on hydrological behavior and flood susceptibility. The aim of the analysis was to evaluate the flood hazard degree across the watershed and identify basins with the highest vulnerability. The results reveal significant spatial variability, with several sub-basins—particularly **O. Touil Aval, Daia el Firania, O. Ouassel Moyen, and O. Djidiouia**—exhibiting morphometric characteristics associated with high flood susceptibility, such as steep slopes, compact forms, high drainage density, and limited infiltration capacity. Hazard classification maps were developed for each parameter and integrated into a final flood hazard map. The analysis indicates that more than 50% of the sub-basins fall into high or very high flood risk categories. These findings underscore the necessity of targeted watershed management strategies, including erosion control, land use planning, and flood mitigation measures, to reduce vulnerability and enhance resilience in the face of increasing hydrological extremes in the region.

Keywords : Flood hazard; Morphometric analysis; GIS; Watershed management; Cheliff basin; Drainage characteristics; DEM; Hydrological risk

Résumé

Cette étude présente une évaluation morphométrique approfondie et une cartographie du risque d'inondation pour 36 sous-bassins du bassin versant du Cheliff, situé au nord-centre de l'Algérie. En utilisant les techniques des Systèmes d'Information Géographique (SIG) et les Modèles Numériques de Terrain (MNT), les principaux paramètres morphométriques — tels que la superficie, la pente, la densité de drainage, le facteur de forme, l'indice de sinuosité, le rapport de circularité et le numéro de courbe — ont été extraits et analysés afin d'évaluer leur influence sur le comportement hydrologique et la sensibilité aux inondations. L'objectif principal de cette analyse est d'évaluer le degré de danger d'inondation à l'échelle du bassin et d'identifier les sousbassins les plus vulnérables. Les résultats mettent en évidence une variabilité spatiale marquée, certains sousbassins — notamment O. Touil Aval, Daïa el Firania, O. Ouassel Moyen et O. Djidiouia — présentant des caractéristiques morphométriques associées à une forte susceptibilité aux inondations, telles que des pentes abruptes, des formes compactes, une forte densité de drainage et une faible capacité d'infiltration. Des cartes de classement du risque ont été élaborées pour chaque paramètre, puis intégrées dans une carte finale du risque d'inondation. L'analyse montre que plus de 50 % des sous-bassins sont exposés à un risque élevé ou très élevé d'inondation, soulignant la nécessité d'adopter des stratégies ciblées de gestion des bassins versants, incluant le contrôle de l'érosion, l'aménagement du territoire et des mesures de réduction des inondations afin de renforcer la résilience face aux extrêmes hydrologiques croissants dans la région.

Mots clés : Risque d'inondation ; Analyse morphométrique ; SIG ; Gestion des bassins versants ; Bassin du Cheliff ; Caractéristiques de drainage ; MNT ; Risque hydrologique

Table of contents

Chapter 1: General information and statistics on Floods

Chapter 2: Presentation of the study area and data

Chapter 3: Flood susceptibility Methodology and GIS

Chapter IV:Results and discussion

Introduction

Introduction

General Context

Floods are among the most recurrent and destructive hydrometeorological disasters globally, with devastating impacts on human lives, ecosystems, and infrastructure. In recent years, the frequency and intensity of extreme weather events, including flash floods, have increased significantly due to anthropogenic climate change. According to the Intergovernmental Panel on Climate Change (IPCC, 2021), global warming is intensifying the hydrological cycle, leading to more intense and irregular rainfall events, increased evapotranspiration, and shifts in regional precipitation patterns. These changes are particularly critical in semi-arid and arid regions, where even short, intense rainfall episodes can trigger flash floods with catastrophic consequences.

At the same time, rapid and often unregulated urban development exacerbates flood risks by altering natural drainage systems. The expansion of impervious surfaces, such as roads, rooftops, and paved areas, reduces the land's ability to absorb rainfall, increasing surface runoff and elevating flood peaks. In many regions, especially in the Global South, this urban growth occurs without adequate flood control infrastructure or land use planning, further increasing exposure and vulnerability to floods (Douben, 2006).

The Mediterranean basin, and North Africa in particular, is identified as one of the most climate-sensitive regions in the world. Algeria, situated at the interface of the Mediterranean and the Saharan climatic systems, faces a dual challenge: water scarcity on one hand and an increased risk of flash floods on the other. This paradox is particularly evident in the Chellif Basin, the largest watershed in Algeria, which spans a wide range of topographical and climatic zones from the High Plateaus to the Tell Atlas and the coastal plains. Although classified as a semi-arid region, the Chellif Basin is regularly exposed to intense and localized rainfall events that generate destructive flash floods, especially in the northern and central parts of the basin.

Historical records and recent events underscore the basin's flood vulnerability. For instance, flash floods in the cities of Chlef, Oued Fodda, and El Karimia have repeatedly caused loss of life and damage to roads, bridges, and agricultural lands. The increasing intensity of these events, compounded by land degradation, deforestation, and inadequate urban planning, highlights the urgent need for effective flood hazard assessment and management tools.

Introduction

In many parts of Algeria, including the Chellif Basin, a major obstacle to flood risk analysis lies in the lack of consistent and high-resolution hydrological and meteorological data. Traditional flood prediction models often rely on long-term time series of rainfall, discharge, and soil moisture data, which are either unavailable or incomplete in many regions of the country. This challenge necessitates the adoption of alternative approaches that do not depend heavily on extensive historical datasets.

Rationale and Alternative Approaches

In this context, GIS-based morphometric analysis has emerged as a reliable and efficient method for assessing flood susceptibility, especially in data-scarce regions. Morphometric parameters—such as basin area, slope, drainage density, elongation ratio, and circularity—reflect the geomorphological structure of a watershed and influence its hydrological response to rainfall events. When analyzed in a GIS environment, these parameters can be quantified from freely available Digital Elevation Models (DEMs) and spatial datasets, enabling rapid and large-scale assessment of flood-prone areas.

This approach is particularly relevant for the Chellif Basin, where the complex interplay of terrain, geology, and land cover generates varied hydrological behaviors across subwatersheds. By integrating morphometric analysis with land use data and flood hazard classification criteria, a spatially explicit flood risk map can be developed to support policy decisions, infrastructure planning, and disaster preparedness.

Furthermore, the flexibility and scalability of GIS-based methods allow for continuous updates and refinements as new data become available. This adaptability makes it an ideal tool for dynamic and multi-hazard environments like the Chellif Basin, where both urban and rural communities face growing exposure to climate-related hazards.

Objectives of the Study

The overall aim of this study is to conduct a comprehensive flood hazard assessment of the Chellif Basin using a morphometric-GIS framework. This research seeks to address the pressing need for spatially resolved flood risk information in a region where hydrological data are limited but vulnerability to flooding is high.

The specific objectives of the study are:

- **Morphometric delineation of watersheds**

  To identify and delineate sub-watersheds within the Chellif Basin using high-resolution DEMs and hydrological tools in a GIS environment, forming the spatial foundation for subsequent analysis.

- **Analysis of morphometric parameters**

To compute key morphometric indices—such as area, perimeter, stream order, stream length, slope, drainage density, shape factor, circularity ratio, and relief ratio—that determine watershed hydrological behavior.

- **Flood hazard assessment**

To evaluate the susceptibility of each sub-watershed to flooding based on a multi-criteria analysis that incorporates morphometric indicators and physiographic attributes.

- **Thematic mapping**:

To produce high-resolution maps that visualize watershed boundaries, morphometric parameters, and flood hazard intensities, thus enabling spatial prioritization of risk mitigation interventions.

- **Support for sustainable development and disaster risk reduction**:

To provide actionable information for regional planners, engineers, and decision-makers to design flood-resilient infrastructure and implement targeted land use policies in line with Algeria’s climate adaptation strategies.

Chapter 1: General information and statistics on Floods

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Introduction

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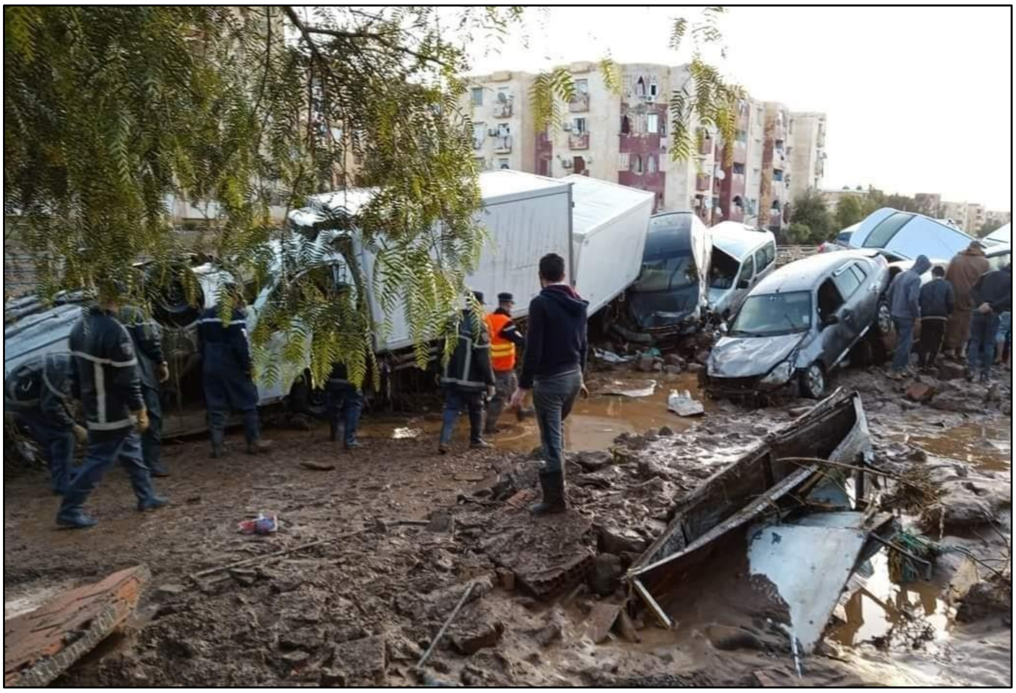


Photo I. 1: Flood of Beni-Slimane Médéa.

1. Floods and Their Types

Floods are among the most widespread and destructive natural hazards globally, occurring when water temporarily submerges land that is usually dry. They result from an imbalance between water input—typically due to intense or prolonged precipitation—and the capacity of the natural or built environment to absorb, channel, or store that water. In both humid and arid environments, floods can significantly disrupt ecosystems, infrastructure, and human livelihoods. However, in arid and semi-arid regions, such as much of Northern Algeria, the geomorphological and climatic conditions—characterized by sparse vegetation, impervious soils, and intense but irregular rainfall—make the landscape particularly prone to flash flooding.

Chapter 1: General information and statistics on Floods

The severity and nature of a flood are governed by multiple factors including rainfall intensity and duration, drainage network characteristics, topography, land use patterns, and soil saturation levels. Human-induced factors such as deforestation, urban expansion, and poor land management practices further aggravate flood risks. Depending on their origin, dynamics, and spatial scale, floods are generally categorized into several main types, each with specific characteristics and implications.

1.1 Riverine Floods

Also known as fluvial floods, riverine floods occur when the water level in a river or stream exceeds its banks and inundates the adjacent floodplain. These floods typically result from prolonged rainfall, snowmelt, or a combination of both, and they can last from days to weeks depending on the catchment size and the extent of precipitation. Riverine floods are common in temperate and tropical zones with well-developed drainage systems but can also affect arid basins when large upstream rainfall events occur. In the Chellif Basin, for instance, intense rainfall events in the upstream mountainous areas can lead to downstream flooding along the main river course.

Photo I. 2: River flood

1.2 Flash Floods

Flash floods are sudden, short-duration floods characterized by rapid runoff and high discharge rates, often occurring within a few minutes to hours of the triggering event. They are usually caused by intense, localized rainfall over impervious or steep terrains, where infiltration is minimal. Arid and semi-arid regions, such as those in Northern Algeria, are particularly vulnerable to flash floods due to sparse vegetation, thin soils, and a lack of natural or artificial retention systems. These floods are extremely dangerous because of their abrupt onset, high velocities, and ability to cause significant damage in a short time, especially in urban settings or narrow valleys (wadis).

Photo I. 3: Flash flood in Algeria

1.3 Pluvial (Surface Water) Floods

Pluvial floods occur when rainfall exceeds the absorption capacity of the soil and the drainage capacity of the urban infrastructure, leading to water accumulation on the surface. Unlike riverine floods, pluvial floods can happen far from rivers and streams and are commonly observed in densely built environments with low infiltration potential. These floods are increasingly common in cities where impervious surfaces dominate, and drainage networks are either undersized or poorly maintained. In towns within rapid urbanization without adequate stormwater infrastructure has increased pluvial flood risk during heavy rain events.

Photo I. 4: Pluvial (Surface Water) Floods

1.4 Coastal Floods

Although not relevant to inland areas like the Chellif Basin, coastal floods are important to mention in a general flood classification. These occur when storm surges, high tides, or tsunamis push seawater onto the land, often exacerbated by rising sea levels and coastal subsidence. Coastal flooding poses a severe threat to low-lying deltaic regions and is usually associated with tropical cyclones or seismic activity.

Photo I. 5: Coastal Floods

1.5 Dam Break and Reservoir-Induced Floods

These floods occur due to the sudden release of a large volume of water following the structural failure of a dam or the deliberate discharge from reservoirs to avoid overtopping. In semi-arid regions where dams are constructed for irrigation, drinking water, or flood control, the risk of dam failure due to poor maintenance, extreme rainfall, or seismic activity can lead to catastrophic downstream flooding. Although rare, the consequences are often devastating due to the high velocity and volume of released water.

Overall, floods manifest in various forms depending on climatic, hydrological, and topographical conditions. Understanding these different types is essential for accurate hazard assessment, especially in regions such as the Chellif Basin, where the interplay between natural vulnerability and anthropogenic factors increases flood risk. Identifying the dominant flood type—such as flash floods in arid catchments—helps guide appropriate mapping, early warning systems, and mitigation strategies.

Photo I. 6: Dam Floods, Failures and Disasters in 2022

(https://sandrp.in/2022/12/17/dam-floods-failures-and-disasters-in-2022/)

1. 6. Groundwater Flood

This type of flooding happens when the underground water table rises due to extended periods of rain, and the water seeps up to the surface. It usually appears slowly and may persist for a long time. Groundwater floods can be difficult to manage because they affect foundations, basements, and underground infrastructure, and they may not be visible until after the ground becomes saturated.

Photo I. 7: Groundwater Flood

Chapter 1: General information and statistics on Floods

Summary of Major Flood Events

Pakistan Flood (2022):

During the summer monsoon of 2022, Pakistan faced one of its most devastating floods, caused by prolonged and intense rainfall. This disaster affected nearly one-third of the country's population, displacing 32 million people and resulting in 1,486 deaths, including 530 children. Economic losses were estimated at over $30 billion. The most affected regions included the southern provinces of Balochistan, Sindh, and Punjab, covering a land area of approximately 85,617 km². A notable expansion of flood coverage was observed between August 18 and 31, prompting a 14-day simulation (1,209,600 seconds) focused on this critical period. The Indus River Basin played a key role in the hydrological dynamics of the event.

UK Flood (2015):

In December 2015, northwest England experienced severe flooding, especially along the River Eden and its tributaries—Caldew, Petteril, Eamont, and Irthing. The steep topography of the catchment contributes to frequent fluvial floods. Carlisle, located downstream, suffered extensive damage during this event, which lasted from December 4 to 7. The affected area covers approximately 135.5 km².

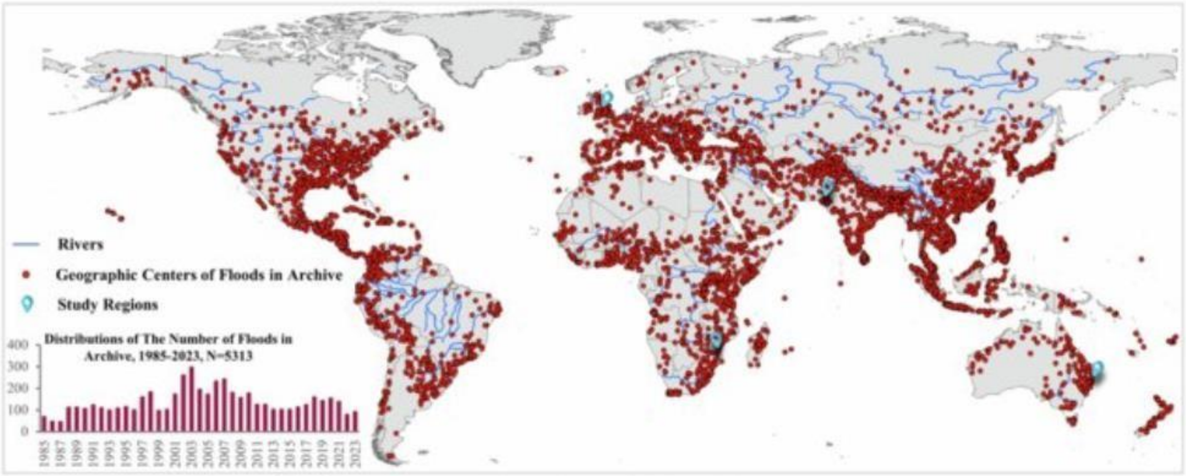
Australia Flood (2022):

Eastern Australia was struck by major flooding beginning in February 2022, intensified by successive heavy rains. Widespread inundation was reported in Queensland and New South Wales, prompting mass evacuations and damage to residential properties. The Richmond River Basin was central to the hydrological behavior of the event. The study area, focused on the Ballina region, spans 1,361.3 km². The simulation period covered February 20 to March 2, 2022.

Mozambique Flood (2019):

On March 14, 2019, Tropical Cyclone Idai made landfall in Beira, Mozambique, triggering devastating floods due to prolonged rainfall and strong winds. Overflowing of the Pungwe and Buzi Rivers led to widespread inundation of low-lying areas. The disaster damaged over

4,000 homes, injured around 1,600 people, and claimed 603 lives across Mozambique, Zimbabwe, and Malawi. The flood-affected area in Beira spans 6,190.9 km², with the event lasting from March 14 to 20, 2019.



(a) Global Flood Database, 1985-2023

Figure I. 1: Global flood databases (Xu et al. 2025)

Floods in Algeria

According to Boutaghen et al. (2022), the information presented in this chapter on floods was gathered from a variety of sources, including technical reports, scientific studies, and institutional databases. Several investigations have been conducted to compile an inventory of historical flood events and their impacts across Algeria. These sources provide data on casualties, descriptions of the resulting damage, as well as other flood-related parameters such as rainfall intensity, discharge, and water depth. Sardou et al. (2016) developed a comprehensive catalogue of floods in northwestern Algeria, covering the period from 1847 to 2014. Their study documented 127 events, of which 62.20% were classified as flash floods. The most extensive and complete record of flood events since 1921 is maintained by the Civil Protection (CP), with key statistics summarized in Figure 3.1.. Additionally, the Algerian National Agency for Water Resources (ANRH) compiled an inventory of flood events that occurred between 1970 and 2000 (Lahlah, 2000).

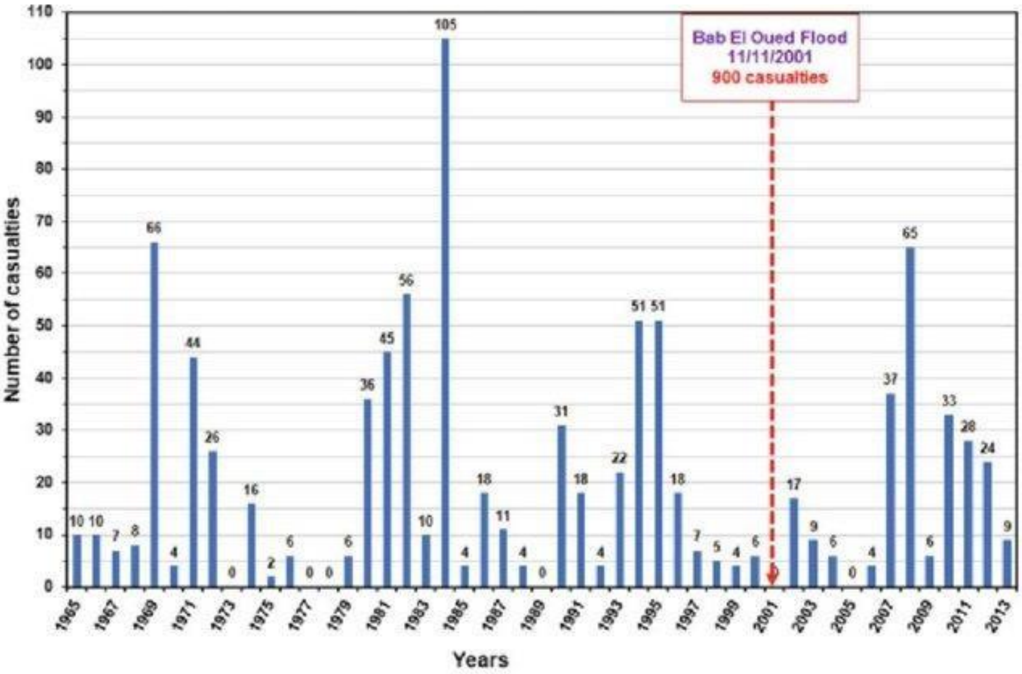


Figure I. 2: Evolution of the number of flood-related casualties in Algeria (CP database, period 1965-2013)

According to Hafnaoui et al. (2023), the annual average number of flood-related deaths in Algeria has decreased to 22 in recent years. However, since 2010, this average has been exceeded in several years. The period between 1969 and 2009 was marked by particularly destructive floods that resulted in a high number of casualties. In contrast, the years from 2010 to 2022 were characterized by a greater number of flood events, but with comparatively fewer fatalities.

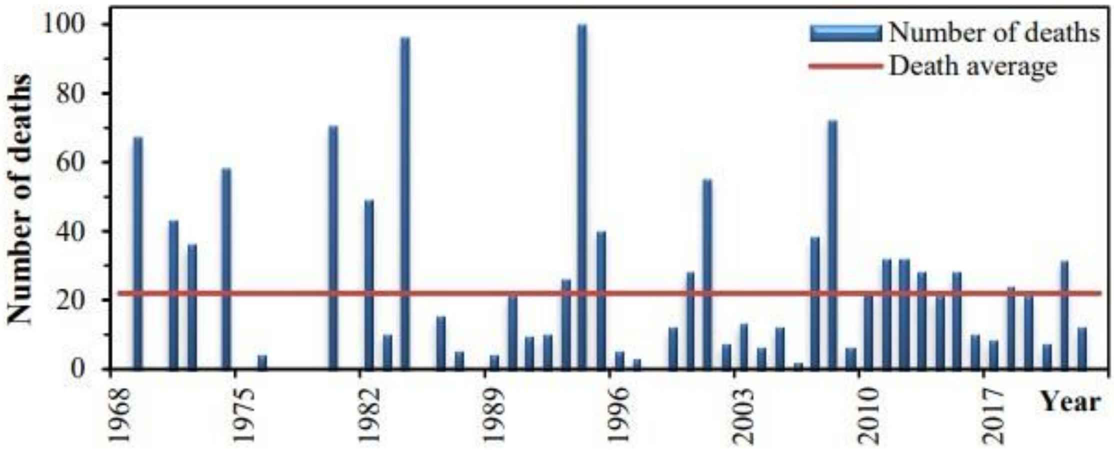


Figure I. 3: Number of deaths during 1969-2022 without the flood of Bab El Oued (Hafnaoui. Et al. (2023)

Flash floods, particularly in Saharan regions, are known for their sudden onset and violent nature. These extreme events are characterized by intense tractive forces capable of sweeping away both natural elements—such as vegetation and soil—and human-made structures like pipelines, bridges, and dams. Several recent floods illustrate the destructive power of these phenomena (Remini et al 2023).

- **Oued M’Zi (September 30, 2016):** Originating in the Saharan Atlas, the M’Zi wadi is prone to flash floods. The 2016 event caused significant damage, including the rupture of a pipeline, with water depths exceeding 2 meters and a tractive force estimated at 100 N/m^2. Though the discharge was not recorded, large volumes of mud were transported.
- **Ittel River (September 3, 2020):** A violent flood in El Baadj sheared an oil pipeline where it crossed the river, leading to a substantial oil spill.
- **Labiod River (October 28–31, 2011):** A prolonged flood with a discharge of 1600 m^3/s destroyed a bridge downstream from a narrow canyon section, demonstrating the power of accelerated flow through confined spaces.
- **Tiout River (May 30, 2020):** A historic flood destroyed the ancient Tiout dam, which had stood for over seven centuries, underscoring the exceptional strength of recent flash floods.
- **Saoura Oases (October 2008):** A widespread but underreported flood event affected many oases in southern Algeria, including Ghardaïa, Ain Sefra, Tiout, and Béchar. Rapid water level rises in local wadis caused significant material damage across these vulnerable settlements.

These floods often carry not only sediment but also large floating debris such as uprooted palm trunks. When obstructed by narrow channels or bridge structures, these materials form temporary dams, worsening flood impacts downstream.

Chapter 2:
Presentation of the study area and data

1. Overview of the Cheliff Catchment Area

1.1. Geographical Location and Boundaries

The Cheliff basin (code 01) spans an area of approximately 43,500 km² and is divided into two main regions:

- Upper Cheliff Region: This area, covering about 20,500 km², is bordered to the south by the Djebel Amour mountain range and to the north by the Ouarsenis mountains.
- Lower Cheliff Region: Extending over 2,250 km², this part is bounded by the Tiaret, Saïda, and Ouarsenis massifs to the south and the Dahra and Beni Menacer ranges to the north.

Geographically, the Cheliff basin lies between longitudes 0° 7' and 3° 31' East and latitudes 33° 53' and 36° 26' North. It shares borders with:

- The coastal regions of Algérois and Oranais to the north,
- The Isser, Hodna, Zahrez, and Constantinois High Plateaus basins to the east,
- The Macta basin and the Oran High Plateaus to the west, And the Saharan Atlas to the south.

Basin Structure and Subdivision

The Cheliff basin is composed of three main hydrological sub-units:

- Upper Oued Cheliff Basin (upstream of Boughezoul), covering 19,710 km²;
- Middle and Upper Cheliff Sub-Basin, with an area of 13,870 km²; Lower Cheliff and Oued Mina Sub-Basin, spanning 10,170 km².

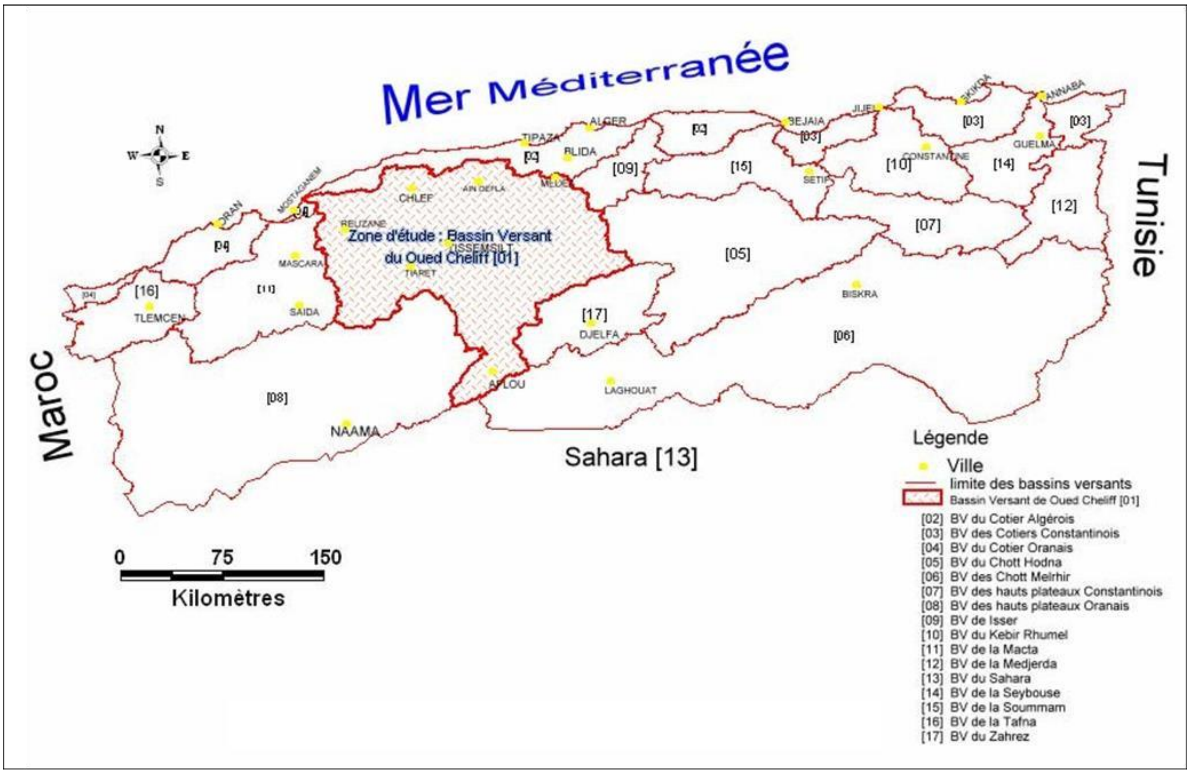


Figure II. 1: Location map of the study area – Cheliff basin–

2.Physical Characteristics of the Cheliff Watershed

2.1. Hydrography of the Basin

The Oued Cheliff is a unique river among North African waterways. It is the only river that drains part of the High Plateaus and is one of the longest and most voluminous rivers in the region. These features are primarily due to the deep structural characteristics of the landscapes it traverses.

The river's thalweg (main riverbed) extends over 759 km, beginning with the Nahr Oussel and Nahr Touil streams. Its source lies in the Saharan Atlas, in the Djebel Amour mountains near Aflou. From there, it flows approximately 700 km through the High Plateaus and the Cheliff Valley before reaching the Mediterranean Sea near Mostaganem, passing through nine provinces (wilayas) along its course.

It receives inflows from several tributaries, including:

- Western tributaries: Laghouat, Djelfa, Oued Touil, Tiaret, and Tissemsilt
- Eastern tributaries: Nahr Oussel, Oued Mina, upper Médéa, Aïn Defla, Chlef, Oued Fodda, Oued Sly, Relizane, Oued Rhiou, lower Mina, and Mostaganem

With significant water potential, the main river drains an area of 43,700 km² at the Sidi Bel Attar hydrometric station.

The main tributaries of the Oued Cheliff are primarily on its left bank, flowing northward and forming the basins of Oued Mina, Rhiou, Sly, Fodda, Deurdeur, Djidiouia, and Zeddine. On the right bank, the main tributaries include Oued Ras, Ouahrane, Ebda, and Harbil.

The Oued Touil Basin is the largest in the upper section of the Cheliff watershed. It originates on the northern slopes of Djebel Amour and is drained by Oued Touil, which flows in a southto-north direction. The drainage area is approximately 9,500 km² at Bir Kheitar. Downstream, until it joins with Nahr Oussel, Oued Touil becomes Oued Ouerk. The Nahr Oussel Basin originates in the Ouarsenis mountains and the Sersou Plateau. After the confluence with Oued Ouerk, it becomes the Oued Cheliff, as illustrated in Figure 2.10.

The distribution of surface water resources across the basin is characterized by the following average specific discharges (Lo) and annual water contributions (Ao):

- Upper Cheliff (upstream of Boughezoul) – Area: 19,516 km² ○ Low surface runoff: *Lo = 6 mm/year*, *Ao = 117 million m³/year*
- Upper Cheliff (downstream of Boughezoul) – Area: 5,004 km² ○ *Lo = 74 mm/year*, *Ao = 372 million m³/year*
- Middle Cheliff – Area: 5,030 km² ○ *Lo = 90 mm/year*, *Ao = 485 million m³/year* ○ *This is the most productive area in the Cheliff basin*
- Mina and Lower Cheliff – Area: 14,200 km² ○ These basins include the major left-bank tributaries of the Cheliff ○ *Lo = 39 mm/year*, *Ao = 551 million m³/year*

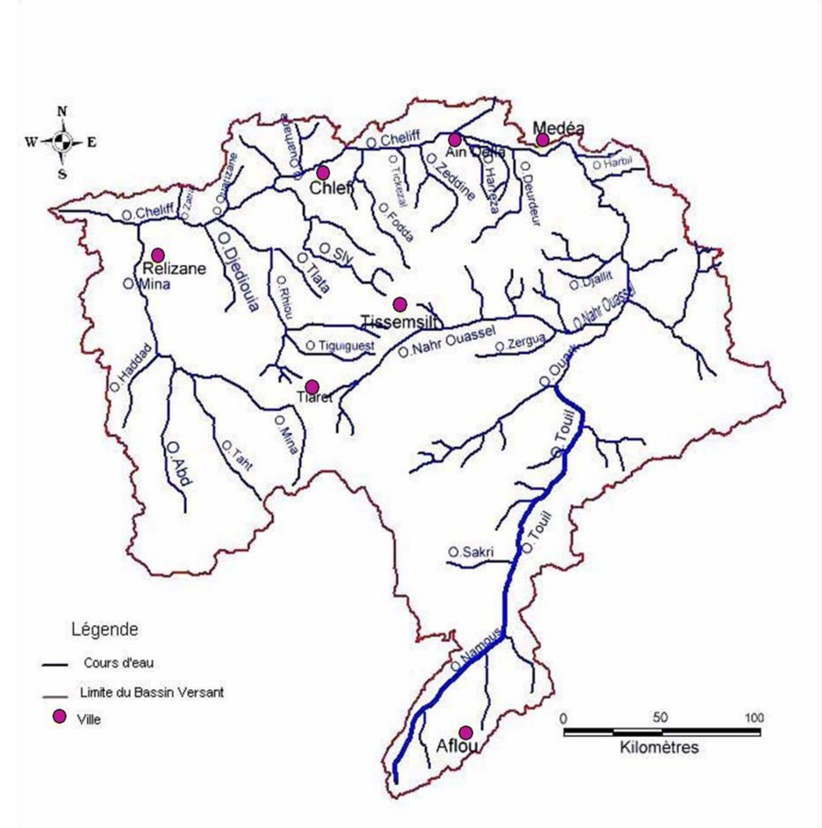


Figure II. 2: Map of Oued Cheliff and its main tributaries

2.2. Climatic Characteristics

The upstream region of the Cheliff basin experiences a semi-arid climate with relatively significant temperature gradients. In contrast, the downstream area is marked by a semi-humid to humid climate from October to April and a semi-arid climate during the rest of the year.

2.2.1 Temperature

Temperature is a climatic parameter with much lower variability compared to precipitation. Measurement errors are generally minimal in both magnitude and frequency, which usually eliminates the need for data correction or series extension.

Over a 23-year observation period (1925–1948), the average monthly temperatures ranged from 3 °C in the coldest months to 27 °C in the hottest months in the upstream area of Cheliff, and from 5 °C to 31 °C in the downstream area. The hottest months are July and August, during which average maximum temperatures range from 31 °C to 40 °C. The coldest months are recorded between December and February, with average minimum temperatures ranging from –1 °C to 6 °C \.

Using temperature data from 13 meteorological stations covering the period 1913–1960 and an additional 5 stations from 1975–1997, the data were grouped into geographically homogeneous regions. These groupings are presented in Table 2.3. The southern region includes data from Aflou and Laghouat stations (located outside the basin boundaries). The central region comprises Tissemsilt, Tiaret, Theneit El Had, and Boughar stations. The stations in Relizane, Cheliff, Ain Defla, Miliana, and Médéa represent the middle and lower parts of the Cheliff basin. Since no station exists in the Dahra region, the stations of Oran and Mostaganem Port were included to compensate.

Temperature variability increases toward the south due to progressively more arid conditions. The areas within the Middle Cheliff region record the highest temperature values. Specifically, the hottest stations in the available dataset are Ain Defla and Cheliff, both showing a similar average annual temperature of 18.7 °C. In Ain Defla, average monthly temperatures exceed 30 °C during July and August \[138].

Here is the English translation and rephrased version of the paragraph:

2.3. Geology and Lithology

The Cheliff Basin is part of the sub-littoral sedimentary basins that extend in an East– West direction and were formed after the final Alpine phase of tangential tectonics. This geological structure is illustrated in the following geological cross-section:

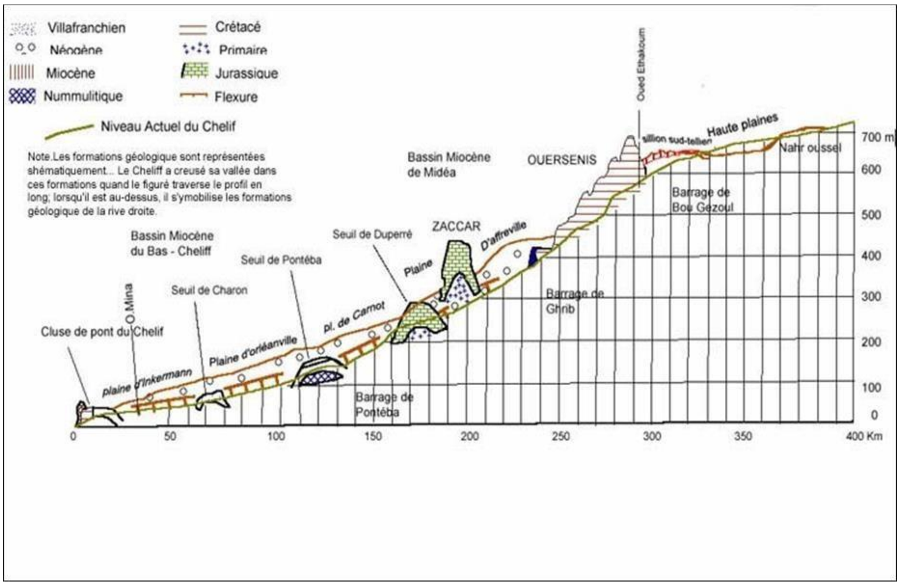


Figure II. 3: East–West Geological Cross-Section

To the north, the Cheliff depression is separated from the sea by the Northern Tell, which is composed of a series of parallel landforms primarily made up of Jurassic–Cretaceous geological formations. These formations are also present in the plain, particularly in the Dahra region and in the epi-metamorphic massifs with schistosity found in Doui, Rouina, and Témoulga.

To the south, the Cheliff Basin is bounded by the Southern Tell, a mountainous region where the bedrock consists mainly of marly-limestone formations. This area corresponds to the Tellian allochthon, made up of various tectonic nappes. Both Tellian structures were formed during the Mesozoic era, shaped by multiple tectonic events:

A pre-Cretaceous compressive phase generated northeast–southwest (NE–SW) folds; A phase with a tangential tectonic component occurred after the Senonian and Paleocene, and is thought to be partially responsible for the observed epimetamorphism;

A deep compressive phase, dated to the Aquitanian–Burdigalian (early Miocene), led to the development of a new phase of epimetamorphism.

This structural configuration is illustrated in the following geological cross-section:

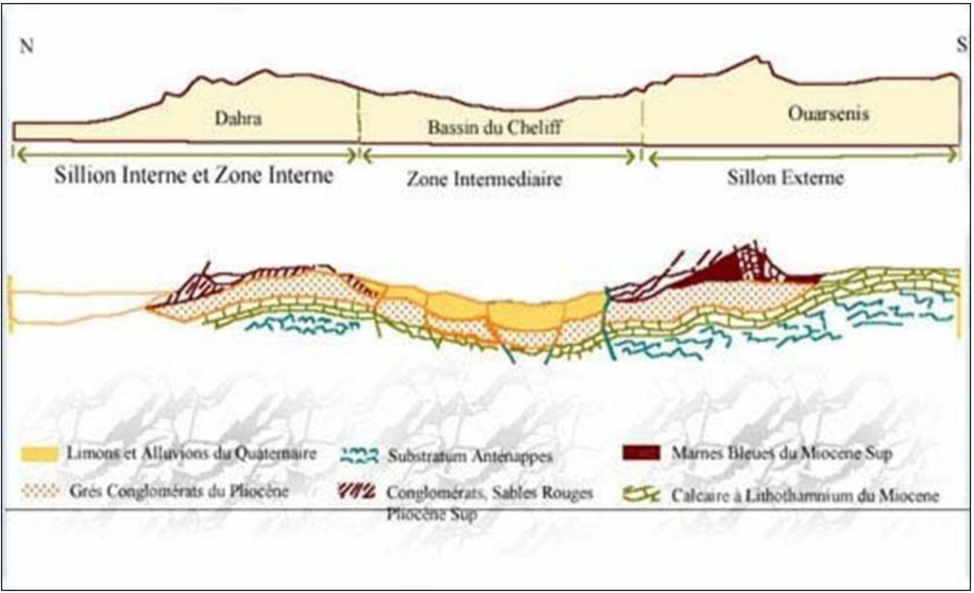


Figure II. 4: North–South Geological Cross-Section

As the Tellian nappes completed their emplacement, a new sedimentary cycle began, marked by a marine transgression that gradually flooded the basin and led to the deposition of a thick Mio–Plio–Quaternary sedimentary cover. At the same time, the Cheliff Basin was affected throughout the Neogene period by significant tectonic activity. Some researchers (Y. Gourinard, A. Perrodon, B. Fenet) describe these tectonics as mainly extensional, while others, like G. Thomas, consider it polyphased. This tectonic activity continues to the present day, as evidenced by the region's strong seismic activity.

Due to highly variable paleogeographic conditions, aquifer formations are limited in extent. For instance, Gontass sandstones are only found in the El Khemis plain (Upper Cheliff), and Lithothamnion-bearing limestones are confined to the left bank of the Cheliff River, between Oum Drou and Zemmoura.

Similarly, Lias limestones (Zaccar, Rouina, and Témoulga) are also very limited in extent, meaning no large, continuous aquifers exist. However, a single area can still contain multiple stacked reservoirs.

The southern part of the region consists of the Zahrez Basin, a closed basin made up of high plains. It contains Cretaceous formations, an incomplete continental Tertiary, and Quaternary deposits composed mainly of slope debris, dunes, torrential alluvium, and crusts.

Based on lithology, the region's geological formations can be classified as follows:

- Limestones, sometimes dolomitized, where water flow is enhanced by fractures or karstic erosion, such as the highly permeable Lias limestones of Zaccar (with nearly a third of precipitation infiltrating), as well as those of Rouina and Témoulga. Similarly, Turonian limestones, when fractured (e.g., Zahrez), form good reservoirs.
- Lithothamnion-bearing limestones from the Upper Miocene.
- Sandstones, with varying degrees of consolidation, from the Barremian and Albian periods in regions like Ain Oussera Plain, Sersou Plateau, and the Djelfa and Slim syncline, as well as Calabrian deposits on the Mostaganem Plateau.
- Detrital deposits with variable permeability, including Miocene sandstones and conglomerates, and Pliocene–Quaternary sands, gravels, pebbles, and conglomerates.
- Recent Quaternary alluvium, often clayey–silty, which are generally poor for infiltration.
- Coarse alluvium carried from certain areas of the Upper, Middle, and Lower Cheliff.
- Impermeable or nearly impermeable formations, which represent the majority of the region's deposits, including Cretaceous and Tertiary series from Dahra, Ouarsenis, and Zahrez.

2.4. Land Use

The study area's land use is categorized into several distinct classes, each contributing differently in terms of both surface area and percentage coverage. Forested areas (trees) cover approximately 872 km², accounting for 1.72% of the total area and offering vital green cover. Shrubland is the most extensive category, occupying 17,916 km² or 34.96% of the landscape. Grassland follows with 9,325 km², representing 27.16% of the area. Cropland is slightly more prominent, spanning 11,039 km² and comprising 35.31% of the total land. Wetlands are scarcely represented, covering just 0.0018% of the area. Barren land accounts for 4,326 km² or 0.24%, while water bodies occupy 40 km², equivalent to 0.09%. Built-up areas, reflecting urban infrastructure, cover 231 km², making up 0.52% of the region (Fig. 4d).

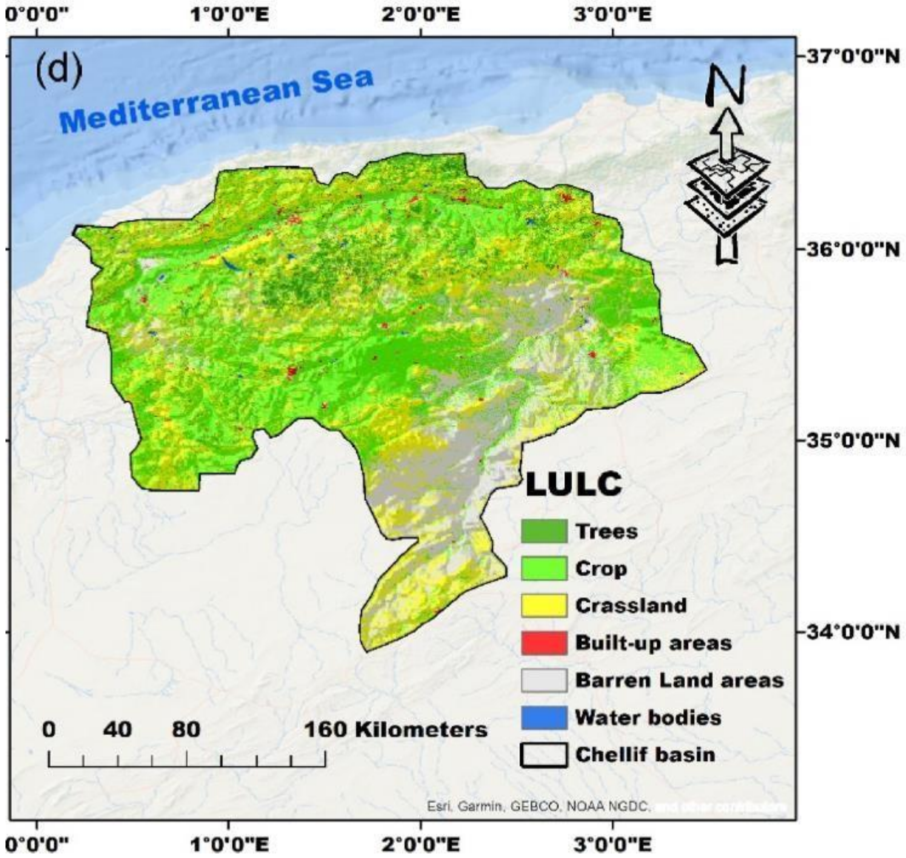


Figure II. 6: Geology map of the Cheliff Watershed (Zerouali et al. 2024)

2.6. Rainfall

The Cheliff River basin, a key hydrological zone in Algeria, displays significant spatial variation in its annual mean rainfall. In the northeastern region, rainfall ranges from 300 to 550 mm/year, creating relatively favorable conditions for vegetation growth and agricultural activities. In contrast, the northwestern part receives considerably less rainfall, averaging between 180 and 240 mm/year, which presents challenges for both agriculture and water resource management. The southern regions, both eastern and western, experience moderate rainfall levels between 180 and 300 mm/year (Fig. 4c). This variability in precipitation highlights the critical need to understand the spatial distribution of rainfall within the Cheliff basin, as it directly affects local ecosystems and water availability. Consequently, tailored strategies are essential to ensure sustainable development and climate resilience across the basin's diverse sub-regions.

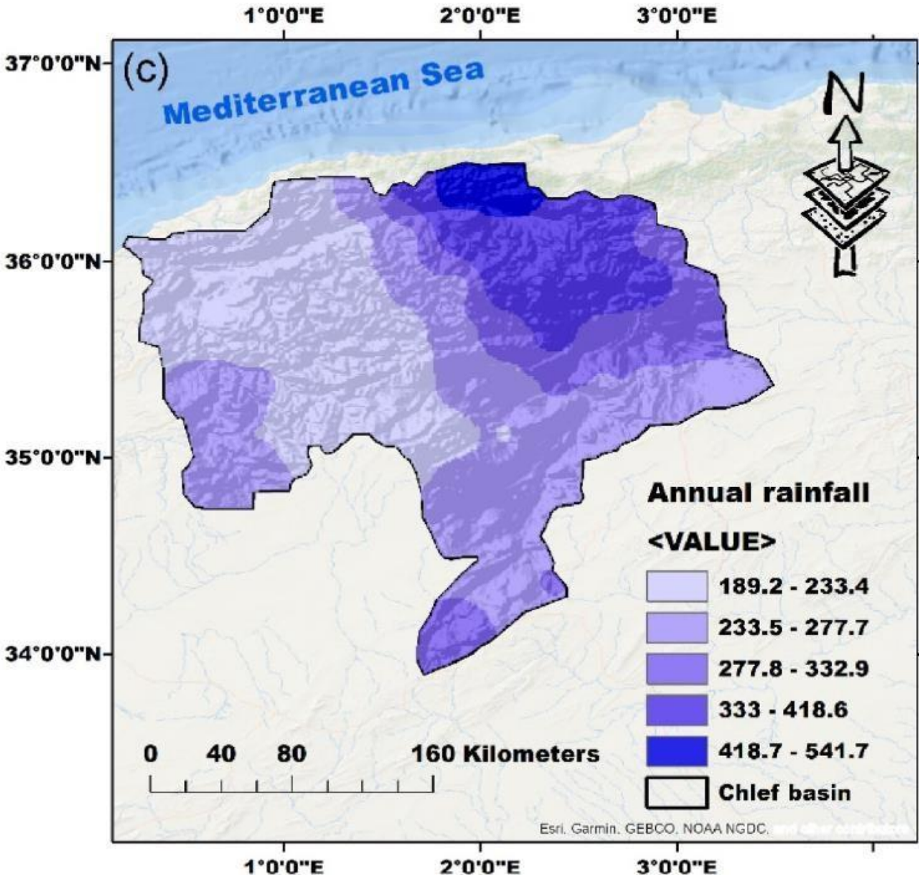


Figure II. 7: Rainfall map of the Cheliff Watershed (Zerouali et al. 2024)

2.7. Soil type

The soil distribution map of the study basin reveals distinct types across different regions. In the northern and eastern parts, Calcareous Cambisols dominate—these are soils that exhibit horizon differentiation due to mineral illuviation and transformation, with the "calcareous" designation indicating a notable presence of calcium carbonate. Such soils are generally favorable for agricultural use. In the southern region, two or more soil types are present, notably Xerosols (sandy) and Calcareous Yermosols. These soils are typically found in arid to semi-arid climates, characterized by low moisture availability and sparse vegetation. Yermosols, in particular, are indicative of dry conditions, and the presence of calcium carbonate further defines their chemical composition. Additionally, a smaller area of clayey soils, extending from Ghilizane in the west to Medea in the east, covers around 3,842 km²—approximately 9% of the total area (Fig. 3d).

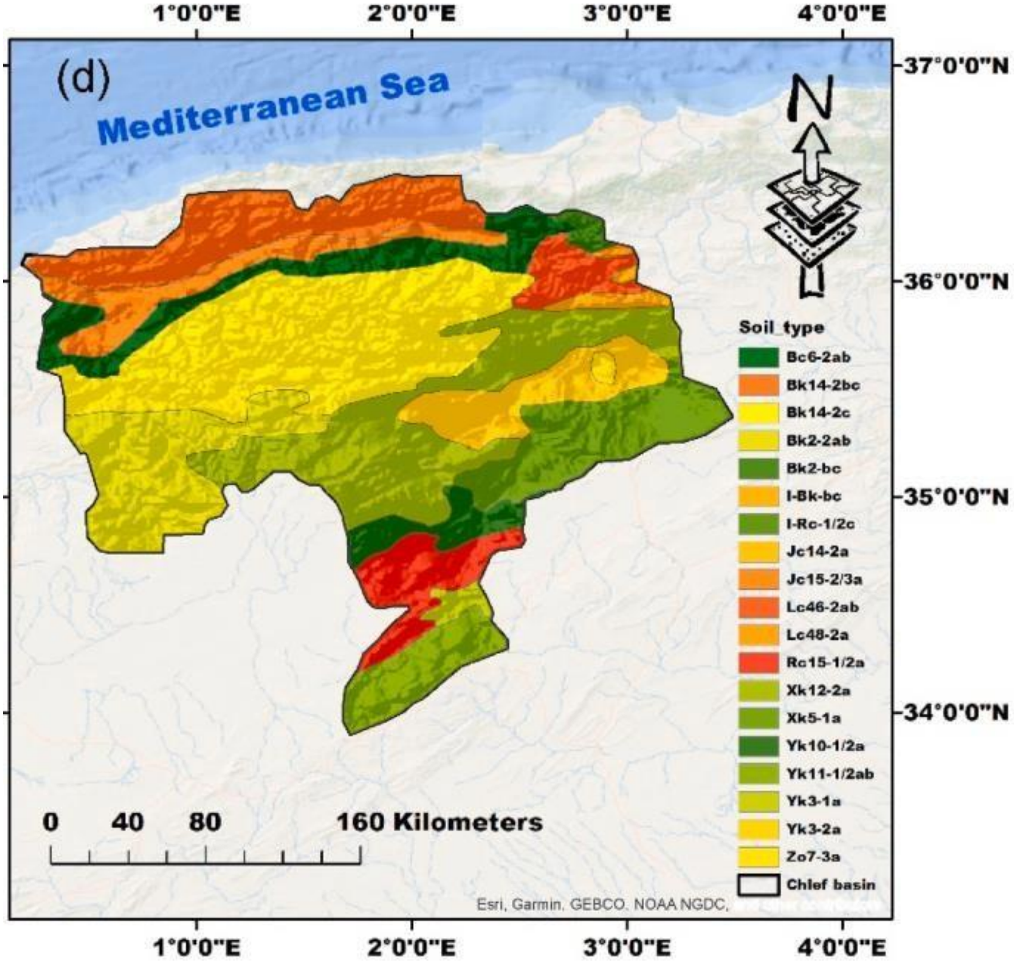


Figure II. 8: Soil map of the Cheliff Watershed (Zerouali et al. 2024)

Conclusion

The Chellif Basin, located in north-central Algeria, presents a complex and diverse study area characterized by its strategic geographical position between the Tell Atlas and the Saharan Atlas. Geologically, it is composed of sedimentary formations with structural features shaped by tectonic activity, which contribute to varied topography and drainage patterns. The region experiences a semi-arid to sub-humid Mediterranean climate, with irregular and seasonal rainfall that plays a key role in shaping hydrological responses and flood dynamics. Land use and land cover (LULC) are dominated by agricultural activities, urban expansion, and natural vegetation, all of which influence surface runoff and water infiltration processes. These diverse physical and environmental characteristics make the Chellif Basin a critical zone for hydrological and environmental studies, particularly in the context of flood risk assessment and water resource management.

Chapter 3:
Flood susceptibility Methodology and GIS

Chapter 3: Flood susceptibility Methodology and GIS

Introduction

Satellite data refers to information collected by satellites orbiting the Earth. This data is widely used in various fields such as geography, meteorology, earth sciences, environmental monitoring, navigation, natural resource management, weather forecasting, climate studies, scientific research, national security, communication, defense, and many others. It includes images, videos, and measurements of phenomena such as temperature, vegetation, elevation, pollution levels, air and ocean currents, precipitation, and mapping.

Satellite data can be processed and analyzed using image processing software, Geographic Information Systems (GIS), and data modeling tools to extract valuable insights. It serves as a critical resource for scientists, businesses, and governments, helping them make informed decisions and effectively plan a wide range of activities and projects.

ArcGIS 10.8 Software

ArcGIS Desktop (commonly referred to as ArcMap) is a Geographic Information System (GIS) software used for visualizing, managing, creating, and analyzing spatial data. With ArcGIS, users can explore the geographic context of their data, allowing them to uncover patterns, relationships, and trends in innovative ways.

ArcGIS Desktop is composed of three key applications:

- ArcMap – the core application for map-based tasks such as creating maps, performing spatial analysis, and editing geographic data.
- ArcCatalog – used for managing GIS data, organizing files, and accessing metadata.
- ArcToolbox – provides access to a wide range of geoprocessing tools for data processing and spatial analysis.

Together, these components support the full range of GIS operations—from simple data visualization to complex spatial modeling and data management.

In ArcMap, users interact primarily with maps. A typical map layout includes a geographic display area along with map elements such as layers, legends, scale bars, north arrows, and other cartographic components. This interface allows users to analyze spatial relationships, update data, and produce high-quality maps for decision-making and communication.

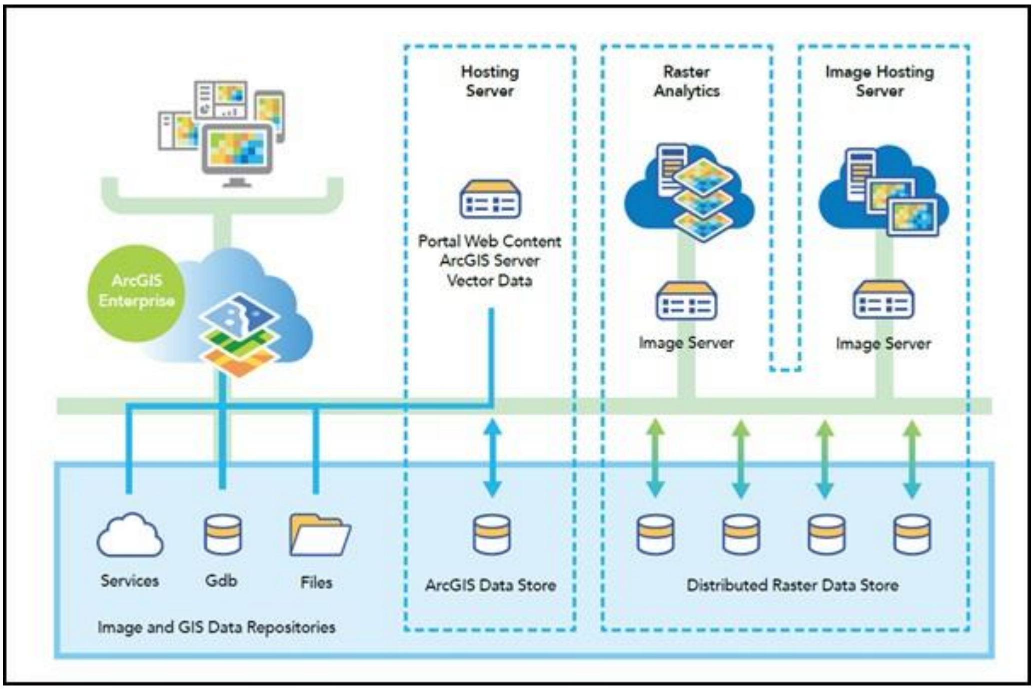


Figure III. 1: what it is the ArcGIS?

Methods

1. Import and prepare the DEM

- Begin by importing a Digital Elevation Model (DEM) for your study area.
- Ensure that the DEM is projected using a hydrologically appropriate coordinate system (e.g., Universal Transverse Mercator (UTM) or a local system like *Egypt 1907 / Red Belt*).
- A proper projection ensures accurate surface area and distance calculations.

Digital Elevation Models (DEM)

A Digital Elevation Model (DEM) is a digital representation of the Earth's terrain, typically in the form of a regular raster grid where each cell holds an elevation value. It depicts the bare-earth surface, excluding vegetation and man-made structures. According to the USGS, a DEM is *"a representation of the bare topographic surface of the Earth, excluding trees, buildings, and other objects"* (USGS.gov).

DEMs can be generated from various sources, including:

- Radar data (e.g., SRTM, TanDEM-X),

- Stereoscopic imagery (e.g., ASTER, WorldView missions),
- Airborne LiDAR surveys,
- Digitization of topographic maps.

In hydro-geomorphometric analysis, DEMs serve as a fundamental input for:

- Calculating slope and aspect,
- Determining flow direction and flow accumulation,
- Extracting drainage networks and watershed boundaries,
- Deriving morphometric indices such as maximum and average elevation, relief, drainage density, and channel length.

Tools like Spatial Analyst and ArcHydro in ArcGIS, as well as GRASS and SAGA modules in QGIS, facilitate these analyses. They offer capabilities such as:

- Sink filling (to correct depression errors),
- Flow accumulation computation,
- Drainage line extraction,
- Automatic sub-watershed delineation.

As noted in the QGIS documentation:
"From a DEM, it is possible to extract a channel network, delineate watersheds, and compute geomorphological statistics."

In summary, the DEM is a core geospatial dataset essential for any morphometric analysis. When integrated into a GIS, it enables accurate quantification of the structure and spatial dynamics of a watershed.

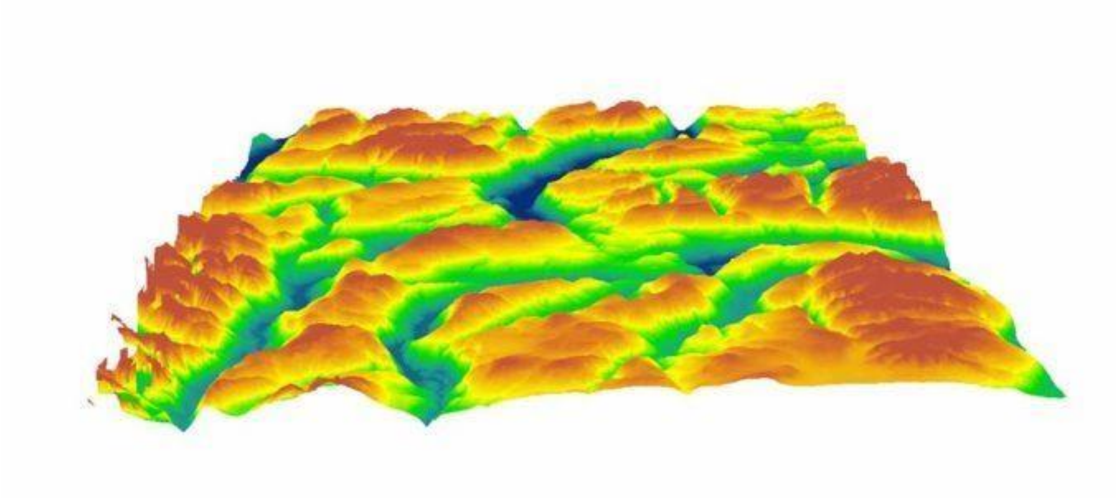


Figure III. 2: The Digital Elevation Model (DEM)

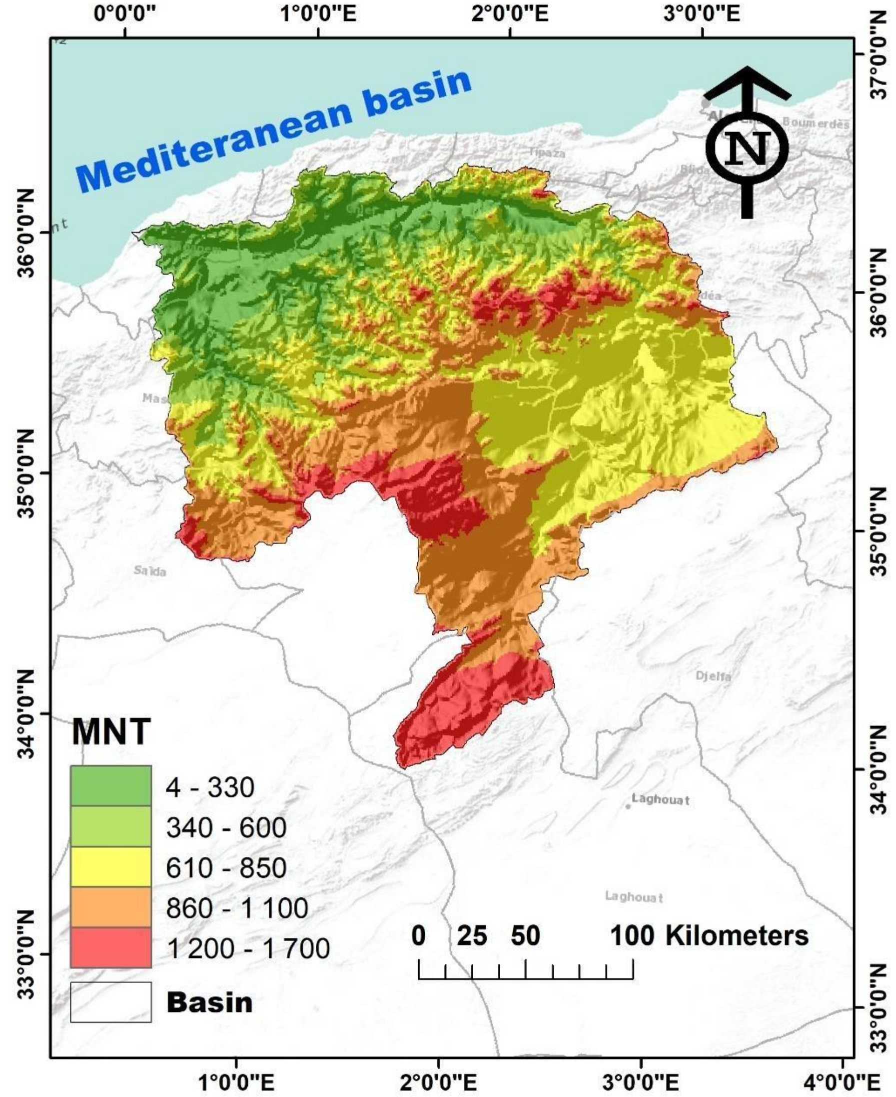
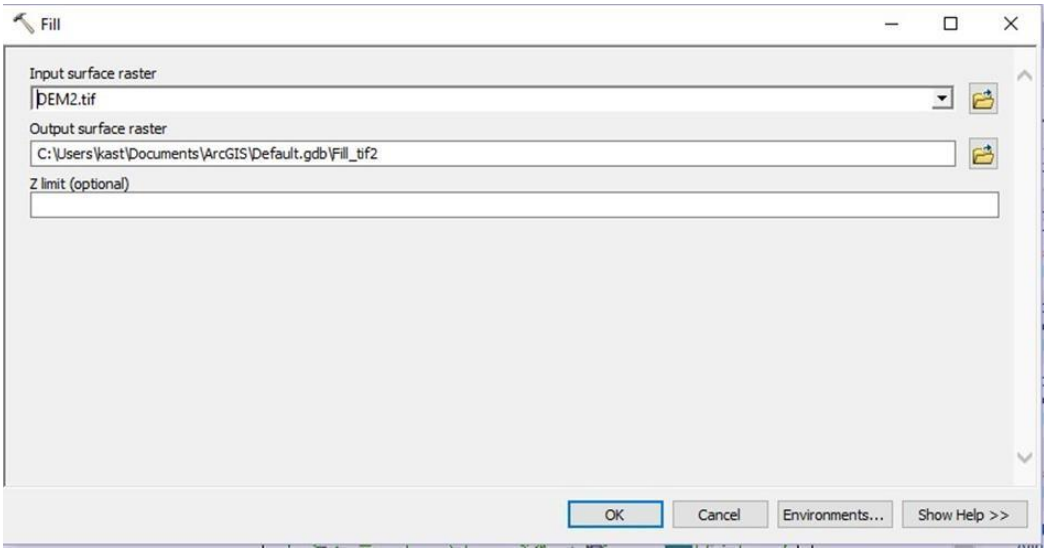


Figure III. 3: Digital Elevation Model (DEM) map of Chellif bassin

To correct any imperfections in the DEM, such as internal drainage areas (sinks), the data underwent a preprocessing step. This involved detecting and statistically analyzing the sinks before applying the "Fill" tool in ArcGIS, which eliminates all depressions by filling them. This tool is also capable of removing peaks—isolated cells with unusually high elevation values that do not conform to the general terrain pattern.



Input surface raster: DEM2.tif

Output surface raster: C:\Users\kast\Documents\ArcGIS\Default.gdb\Fill_tif2

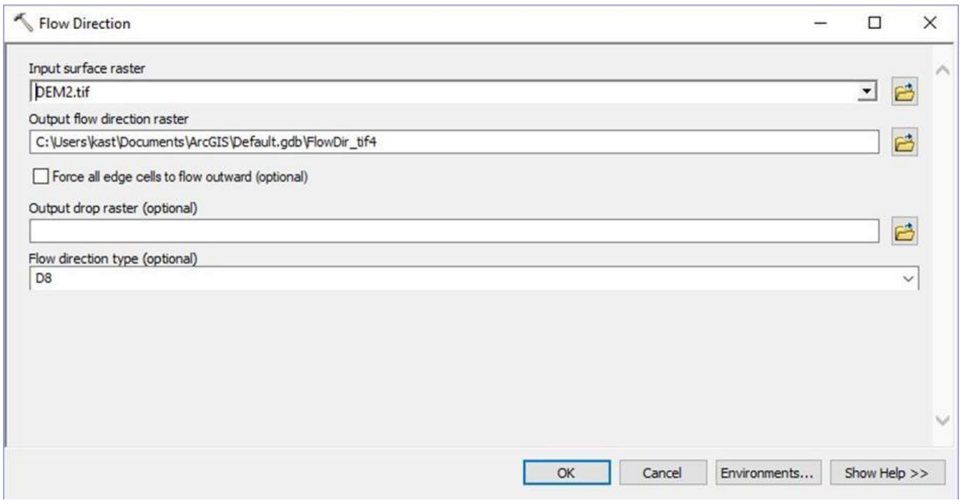
Z limit (optional):

Figure III. 4: ArcGIS window showing the hydrological correction of the DEM

2.Flow Direction

The Flow Direction tool generates a raster that defines the direction of water flow from each cell to its steepest downslope neighbor. This is done using one of several algorithms: D8 (Deterministic Eight), MFD (Multiple Flow Direction), or DINF (D-Infinity).

In the commonly used D8 method, each cell is allowed to flow into only one of its eight surrounding neighbors, based on the steepest descent. The output raster assigns a specific value corresponding to one of the eight possible directions. This method, known as the eightdirection flow model (D8), is based on the approach developed by Jensen and Domingue (1988).



Flow Direction

Input surface raster: DEM2.tif

Output flow direction raster: C:\Users\kast\Documents\ArcGIS\Default.gdb\FlowDir_tif4

☐ Force all edge cells to flow outward (optional)

Output drop raster (optional):

Flow direction type (optional): D8

Figure III. 5: ArcGIS window for flow direction calculation

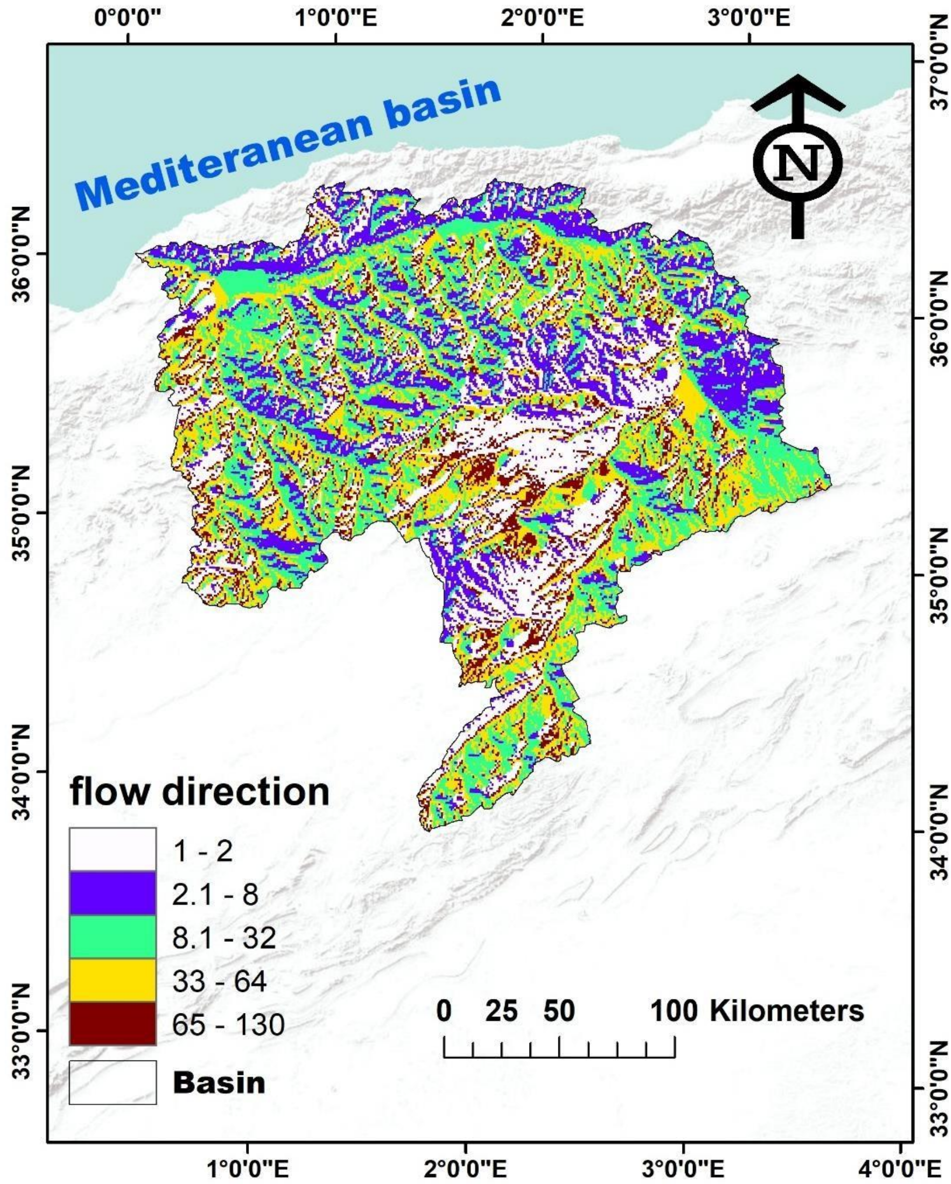


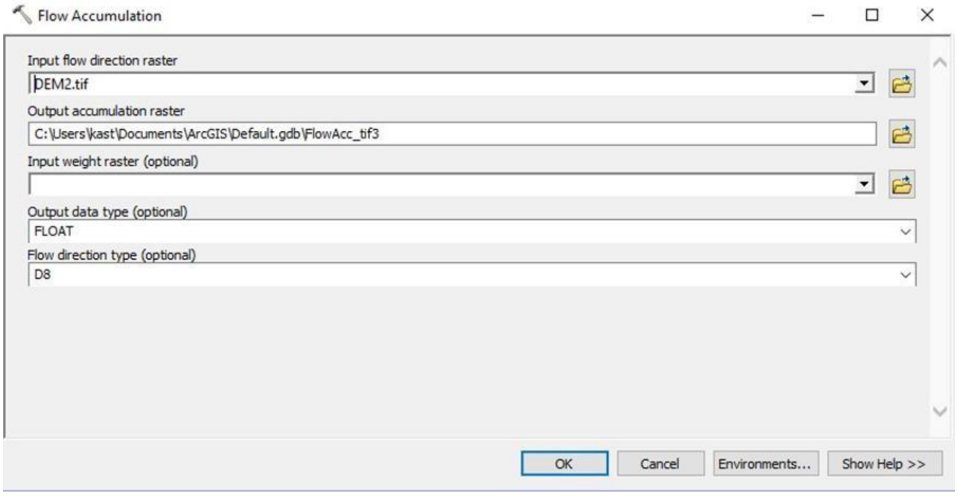
Figure III. 6: Flow direction map of Chellif bassin

3.Flow Accumulation

The Flow Accumulation tool calculates the accumulated flow as the total weight of all cells flowing into each downslope cell in the output raster.

If no weight raster is specified, each cell is assigned a default weight of 1, and the resulting values in the output raster represent the number of upstream cells that contribute flow to each cell.

In the diagram below, the top-left image illustrates the flow direction for each cell, while the top-right image shows the flow accumulation values, indicating how many cells drain into each individual cell.



Flow Accumulation

Input flow direction raster: DEM2.tif

Output accumulation raster: C:\Users\kast\Documents\ArcGIS\Default.gdb\FlowAcc_tif3

Input weight raster (optional):

Output data type (optional): FLOAT

Flow direction type (optional): D8

Figure III. 7: ArcGIS window for flow accumulation calculation

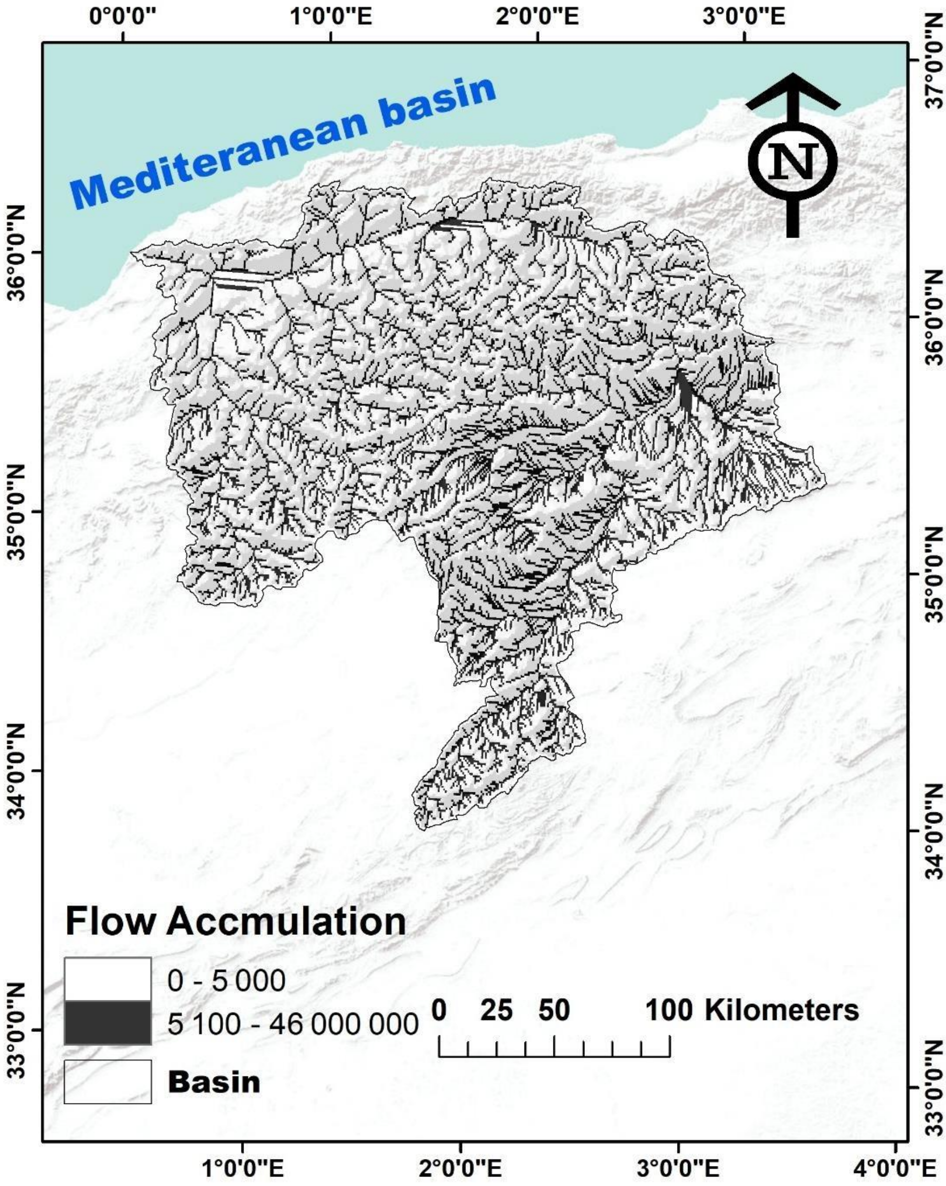


Figure III. 8: Flow accumulation map of Chellif bassin

4.Hydrographic Network Extraction:

Extracting a hydrographic (stream) network for mapping or spatial analysis can be done either manually or automatically. Many studies assessing the vulnerability to pollution rely on having access to a stream network. If no vector layer of the hydrographic network is available for your watershed, then network extraction becomes an essential step.

Key Steps for Hydrographic Network Extraction:

- **Dem preprocessing:**

  If your Digital Elevation Model (DEM) hasn't already been processed, you may need to perform several preprocessing steps, such as filling sinks, removing depressions, or correcting elevation errors. This ensures more accurate results when deriving the stream network.

- **Flow Direction Calculation:**

  Use the preprocessed DEM to compute flow direction. This step determines the direction water would flow based on elevation differences between cells. Common algorithms include D8, D-Infinity, or Multiple Flow Direction (MFD).

- **Flow Accumulation:**

  Apply a flow accumulation algorithm to the flow direction raster. This step calculates how much flow is accumulated in each cell, representing the upstream contributing area. Higher accumulation values usually indicate main rivers or streams.

- **Stream Network Extraction:**

  Define a threshold value for flow accumulation that distinguishes stream cells from non-stream areas. This threshold depends on the study area's characteristics and the desired level of detail. Tools like **"Stream to Feature"** or **"Stream Link"** in ArcGIS can then be used to convert the flow accumulation raster into a vector stream network.

- **Stream Network Refinement:**

  Depending on data quality and project goals, you may need to refine the extracted stream network. This may involve removing small or spurious streams, smoothing the network, or conducting network analyses to eliminate artifacts.

Note:

The specific steps and tools may vary depending on the ArcGIS version you're using and any extensions or plugins installed. Always refer to ArcGIS documentation and tutorials for detailed guidance and best practices when extracting stream networks.

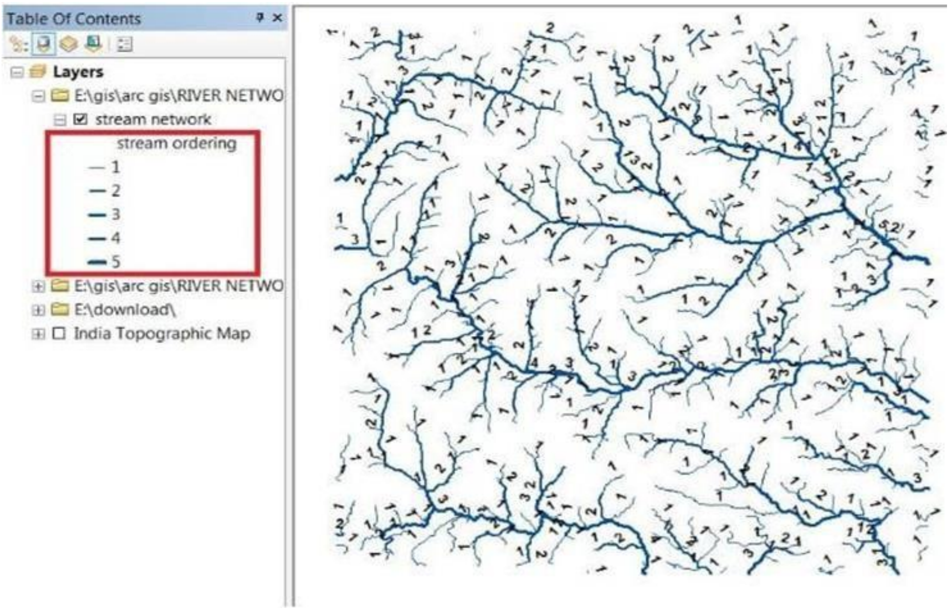


Figure III. 9: ArcGIS window displaying the hydrographic network

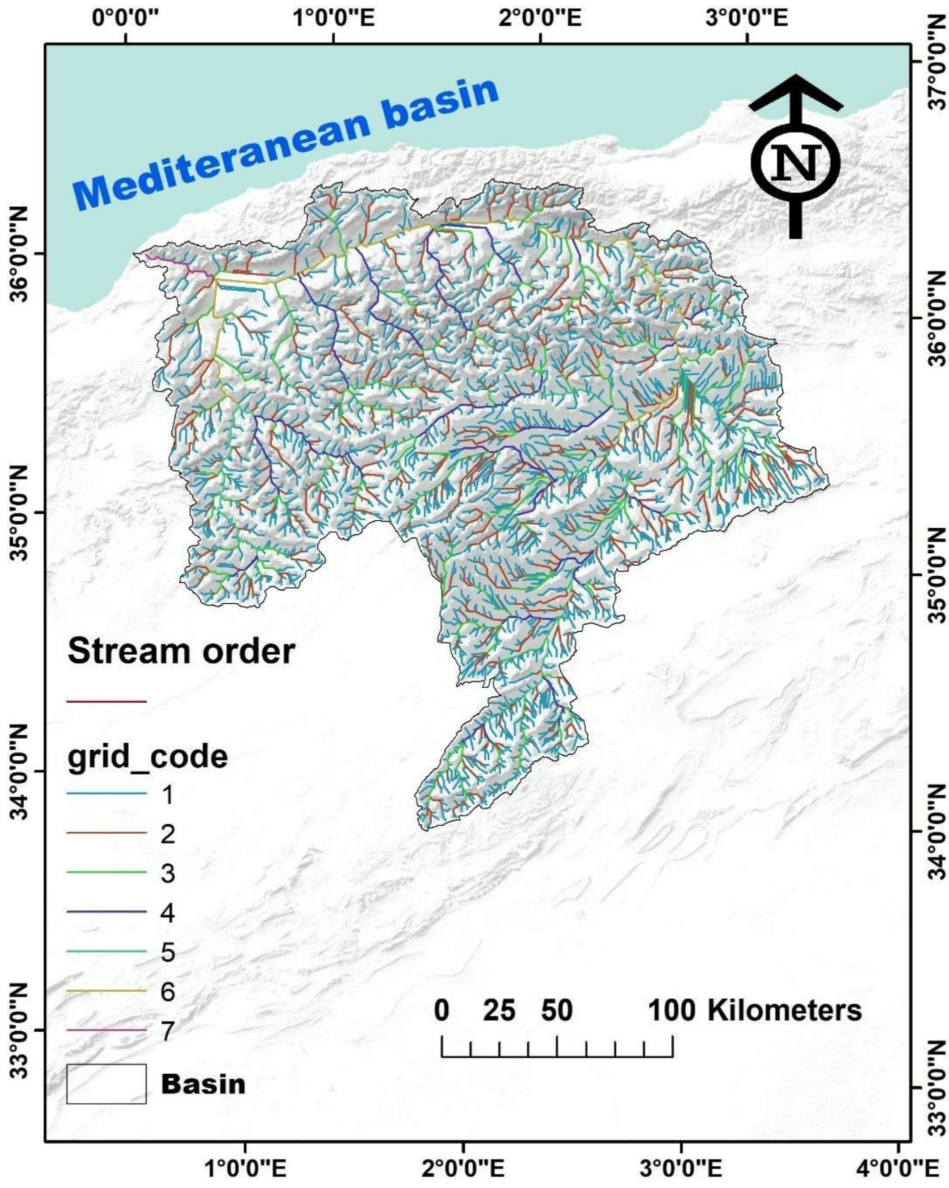


Figure III. 10: Stream order map of Chellif bassin

5.Slope Map

In ArcGIS, slope refers to the measure of the steepness or incline of the terrain at a specific location. It is typically expressed in degrees or percent, indicating the rate at which elevation changes over a given horizontal distance. Technically, slope is derived from a Digital Elevation Model (DEM) or other elevation data that represents the terrain's surface.

Slope analysis is widely used in fields such as urban planning, civil engineering, natural resource management, and hydrologic modeling to better understand terrain characteristics and support informed decision-making.

In ArcGIS, slope is calculated using the finite difference method, which estimates the change in elevation between neighboring cells to determine the local slope value. The result is commonly displayed as a slope map, where different colors or shades represent various slope classes.

Slope is a critical parameter in many GIS applications, including:

- Identifying areas at high risk of erosion
- Supporting land-use planning
- Watershed mapping
- Accessibility analysis
- Water flow estimation, among others

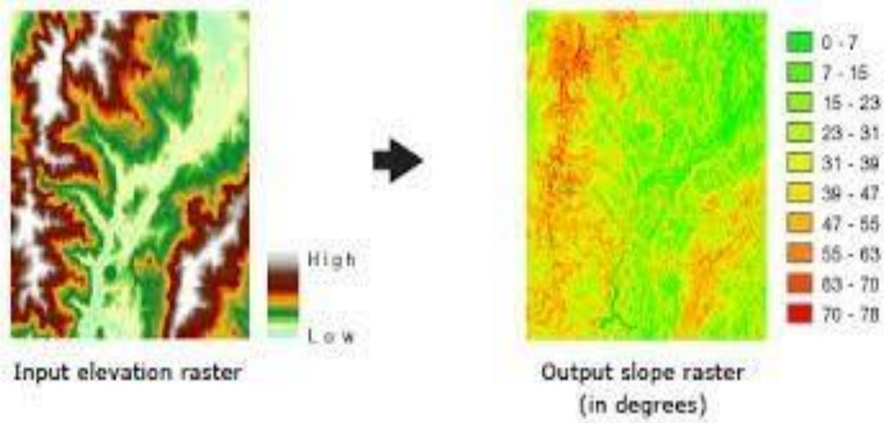
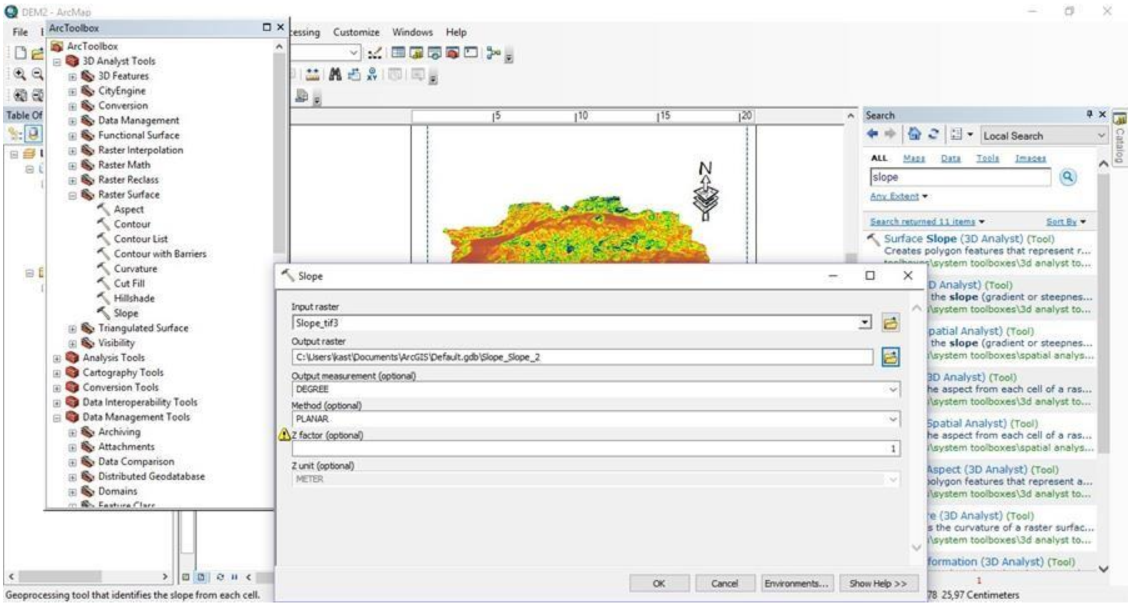


Figure III. 11: how the slope tool works in ArcGIS



Slope

Input raster: Slope_tif3

Output raster: C:\Users\kast\Documents\ArcGIS\Default.gdb\Slope_Slope_2

Output measurement (optional): DEGREE

Method (optional): PLANAR

Z factor (optional): 1

Z unit (optional): METER

Figure III. 12: ArcGIS window for slope calculation

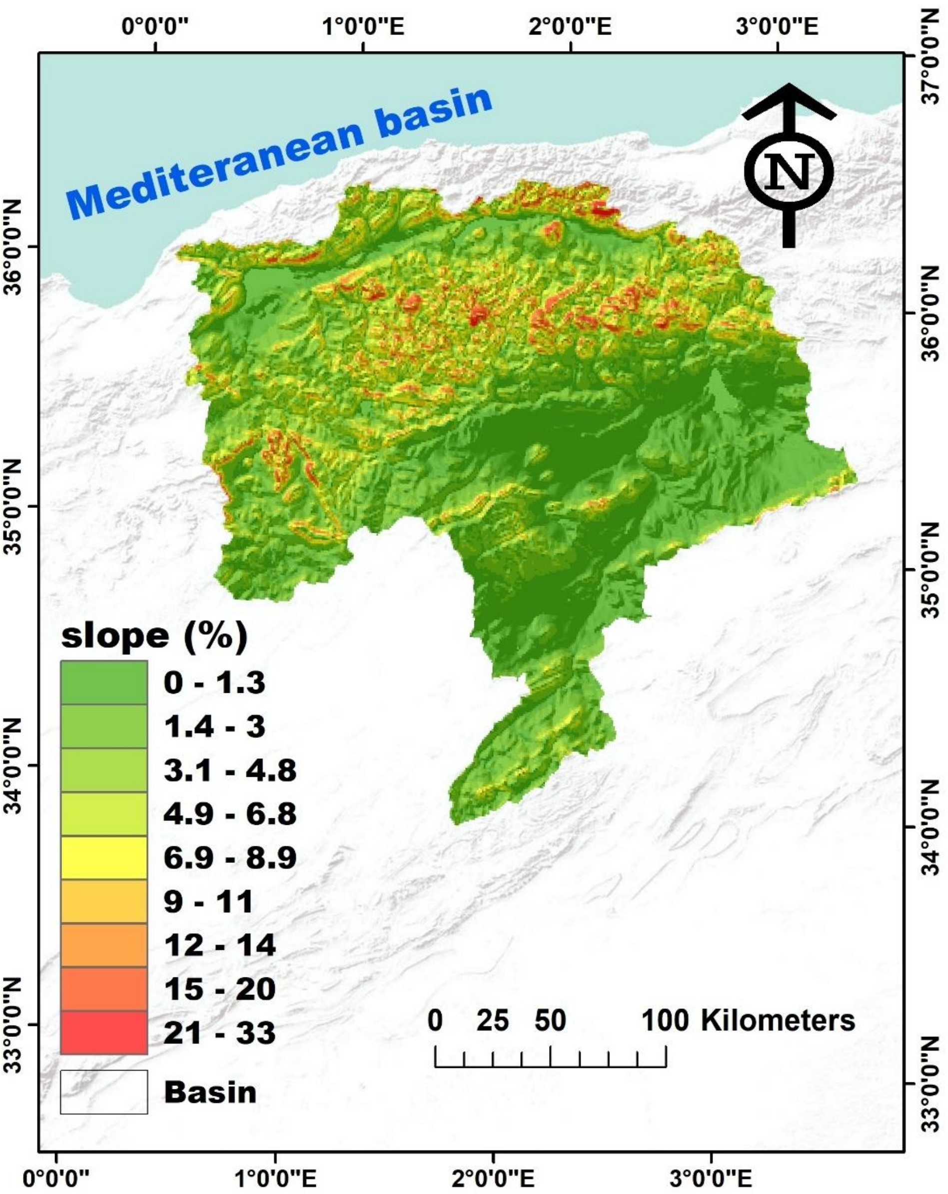


Figure III. 13: Slope map of Chellif bassin

6.Hillshade Map:

The hillshade technique is commonly used in ArcGIS to visually represent variations in elevation or terrain relief within a specific area. It is frequently applied in the creation of topographic maps or digital elevation models (DEMs). Hillshading is a visualization method based on a simulated light source, and it takes into account both the slope and the orientation (aspect) of the terrain surface. This technique provides a qualitative view of the landscape, without producing actual elevation values.

ArcGIS offers two main methods for generating hillshades**:** traditional **and** multidirectional**.**

- The traditional method uses a single light source, with user-defined altitude and azimuth values to simulate sunlight from a specific direction.
- The multidirectional method, on the other hand, combines illumination from multiple directions, producing a more detailed and balanced shaded relief.

The advantage of the multidirectional hillshade is its ability to reveal more terrain detail in areas that would otherwise suffer from overexposure or deep shadows using the traditional approach.

The azimuth **and** altitude properties both define the sun's relative position used to create 3D models such as hillshades or shaded relief maps.

- The altitude represents the sun's angle above the horizon and ranges from **0 to 90** degrees.
  - A value of 0 degrees means the sun is on the horizon, aligned with the horizontal reference plane.
  - A value of 90 degrees indicates the sun is positioned directly overhead.

These settings influence the way light and shadow are applied to the terrain, enhancing the perception of depth and elevation in the visual representation.

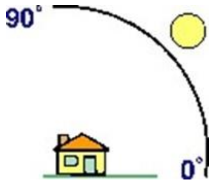
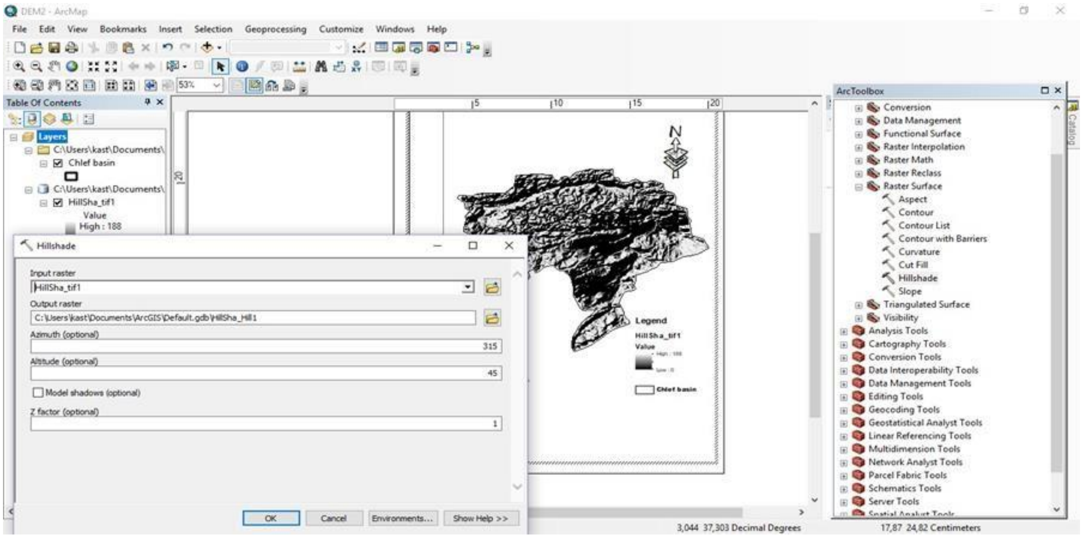


Figure III. 14: The azimuth and altitude

https://desktop.arcgis.com/fr/arcmap/latest/manage- data/raster-and-images/hillshade-function.htm)



Hillshade

Input raster: HillSha_tif1

Output raster: C:\Users\kast\Documents\ArcGIS\Default.gdb\HillSha_Hill1

Azimuth (optional): 315

Altitude (optional): 45

☐ Model shadows (optional)

Z factor (optional): 1

Figure III. 15: ArcGIS window for hillshade calculation

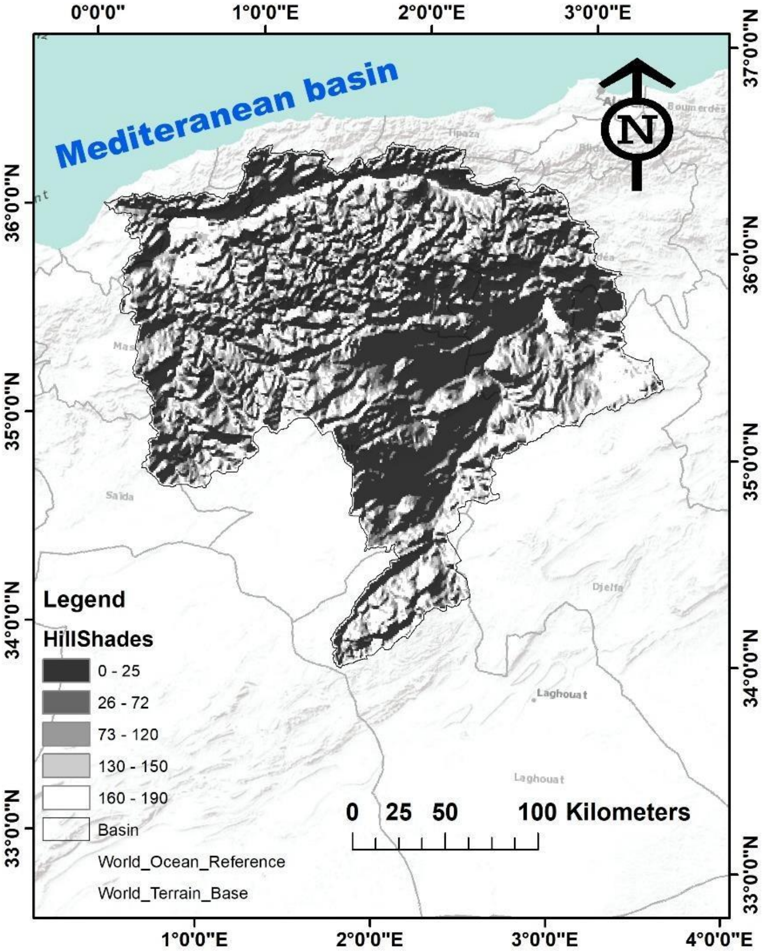


Figure III. 16: Hillshade map of Chellif bassin

7. Methods and Materials

7.1. Significance of SRTM Data in Flood Hazard Mapping

The use of SRTM DEM in this study provided the foundational data required for morphometric modeling and spatial flood hazard classification. Its 30-meter resolution allowed for the accurate calculation of slope, elevation, and hydrological flow variables, which are key inputs for identifying flood-prone sub-basins. The elevation gradient observed within the Chellif Basin—from the southern highlands to the northern plains—significantly affects runoff concentration, flow velocity, and accumulation, all of which are central to the basin's flood dynamics. Furthermore, the combination of remote sensing data with GIS processing enabled a robust and reproducible method for evaluating terrain-related flood risk in a semi-arid context, where in situ hydrological data are often sparse or unavailable. As such, the integration of SRTM-based elevation modeling within a geospatial analysis framework proved to be a highly effective approach for supporting flood hazard assessment and management in the region.

7.2. Input used for flood susceptibility

7.2.1. Elevation Map

Elevation represents the height of the land surface above a reference datum, typically sea level, and is one of the most fundamental parameters in geomorphological and hydrological studies. In the context of watershed morphometry and flood hazard mapping, elevation data are critical for understanding the vertical configuration of the terrain and for deriving other parameters such as slope, relief, flow direction, and stream network patterns. In this study, the elevation map was generated using Digital Elevation Models (DEMs) with a 30-meter spatial resolution, obtained from sources such as the Shuttle Radar Topography Mission (SRTM) and the Advanced Land Observing Satellite (ALOS). The elevation map was produced using ArcGIS software, where the raw DEM was processed and visualized through graduated color symbology to display elevation ranges across the Chellif Basin.

Relationship to Flood Susceptibility: Elevation has a direct influence on the hydrological behavior of a basin. Low-elevation areas, particularly those near stream confluences and valley bottoms, tend to accumulate runoff and are more susceptible to flooding. These zones serve as natural collection points for overland flow, especially during high-intensity rainfall events. Conversely, high-elevation zones typically act as runoff generators, contributing to flow acceleration due to gravity. Therefore, elevation mapping helps identify downstream flood-prone zones and upstream runoff contributors. In the Chellif Basin, many urban and agricultural areas are situated in low-lying floodplains, reinforcing the importance of elevation in spatial flood risk assessment.

7.2.2. Slope Map

Slope is a measure of the steepness or incline of the land surface, expressed either in degrees or as a percentage. It is derived from the elevation map using spatial analysis tools in GIS, particularly the Slope tool in ArcGIS, which calculates the maximum rate of elevation change between each cell and its neighbors in the DEM. The resulting slope map was classified into thematic intervals—flat (<5%), gentle (5–15%), moderate (15–30%), and steep (>30%)—to reflect terrain variability across the Chellif Basin.

Relationship to Flood Susceptibility: Slope strongly affects both the velocity and volume of surface runoff. Steeper slopes accelerate runoff, reducing infiltration time and increasing the risk of downstream flash flooding. They are also more prone to erosion, contributing to sediment transport that can clog drainage channels. Conversely, gentle and flat slopes facilitate water accumulation and longer retention times, making them susceptible to inundation or waterlogging. In semi-arid environments like the Chellif Basin, the interplay between steep upper catchments and flat alluvial plains creates a dual risk: rapid flow generation upstream and accumulation downstream. Mapping slope gradients, therefore, allows for the identification of both runoff source zones and runoff impact zones, which is essential for designing structural (e.g., retention basins) and non-structural (e.g., zoning) flood mitigation measures.

7.2.3. Shape Factor (SF)

$$SF = \frac{L_b^2}{A}$$

Where:

- L_b = Basin length (km)
- A = Basin area (km^2)

The Shape Factor (SF) is a dimensionless ratio that characterizes the overall geometry of a drainage basin. Specifically, it compares the square of the basin's length to its area, indicating how stretched or compact a watershed is. A low shape factor (close to 1) implies a more circular or compact basin, while higher values indicate an elongated basin.

Relationship to Flood Susceptibility: The shape of a watershed strongly influences the concentration time of runoff. In compact basins, rainfall reaches the outlet faster and more uniformly, resulting in higher and sharper flood peaks. Conversely, elongated basins have a delayed runoff response, often leading to lower peak discharge. Therefore, basins with low shape factor values are more flood-prone due to their faster and more synchronized runoff contributions.

7.2.4. Circularity Ratio (CR)

$$CR = \frac{4\pi A}{P^2}$$

Where:

- A = Basin area (km²)
- P = Basin perimeter (km)

The Circularity Ratio (CR) quantifies how closely the shape of a basin approximates a perfect circle. A value close to 1 indicates a nearly circular basin, whereas lower values reflect an elongated or irregularly shaped watershed. This index is influenced by lithology, structure, and geomorphology.

Relationship to Flood Susceptibility: Circular basins tend to have shorter runoff paths and shorter lag times, resulting in sudden and high peak discharges during intense rainfall events. This makes them more susceptible to flash floods, especially when combined with steep slopes or high drainage density. In contrast, more elongated basins spread the runoff over a longer time, which helps reduce flood risk. Hence, higher circularity ratios are typically associated with greater flood susceptibility.

7.2.5. Drainage Intensity (DI)

$$DI = \frac{F}{D_d} = \frac{N/A}{L_u/A} = \frac{N}{L_u}$$

Where:

- F = Stream frequency = $\frac{N}{A}$(number of streams per km^2)
- D_d = Drainage density = $\frac{L_u}{A}$(km^{-1})
- N = Total number of stream segments
- L_u = Total length of stream channels (km)

The Drainage Intensity (DI) relates the number of stream channels to the total length of the drainage network. It is a combined measure of drainage texture (via stream frequency) and drainage efficiency (via density), and offers insight into how dissected the terrain is.

Relationship to Flood Susceptibility: High drainage intensity typically indicates a densely dissected terrain with high runoff potential. When both stream frequency and density are high, it reflects a rapid hydrological response system where water is conveyed quickly to the main outlet. This leads to short concentration times and a greater risk of flooding, especially under heavy rainfall. Hence, higher DI values correlate with higher flood susceptibility, particularly in regions with low vegetation cover and impermeable soils.

7.2.6. Hydrologic Soil Groups (HSGs) and Curve Number Assignment

Hydrologic Soil Groups (HSGs) are a fundamental input to the USDA Soil Conservation Service Curve Number (SCS-CN) runoff estimation method. They classify soils based on infiltration capacity and runoff potential under bare soil and fully saturated conditions. To apply this method in the Chellif Basin, we utilized the HYSOGs250m global dataset developed by Ross et al. (2018), which provides gridded HSG data at a spatial resolution of 250 meters. This raster dataset classifies global soils into four standard categories: Group A (low runoff potential), Group B (moderately low), Group C (moderately high), and Group D (high runoff potential). The classification is based on soil texture (sand/clay ratio) and hydraulic conductivity. Additionally, four dual classes (A/D, B/D, C/D, D/D) represent soils that are generally saturated or have a shallow water table, indicating high runoff unless drained.

Each pixel in the HYSOGs250m.tif raster is assigned a numeric value representing an HSG:

- 1 = HSG-A: >90% sand, <10% clay – soils with very high infiltration, very low runoff.
- 2 = HSG-B: 50–90% sand, 10–20% clay – moderately well-drained soils.
- 3 = HSG-C: <50% sand, 20–40% clay – moderately high runoff potential.

- 4 = HSG-D: <50% sand, >40% clay – very low infiltration, very high runoff.
- 11–14 = Dual Groups (A/D to D/D): Soils with drainage-dependent behaviour due to saturation or shallow water table.

To generate a Curve Number (CN) map, this HSG layer was combined with a land use/land cover (LULC) classification, derived from Sentinel-2 imagery, within a GIS environment (ArcGIS). Each LULC–HSG combination was assigned a CN value using the standard NRCS lookup tables. For instance, cultivated land on Group D soil receives a CN value around 89, while forest on Group A may have a CN as low as 30–50, depending on forest density. Urban areas on Group C or D soils often exceed 90, indicating near-total runoff.

Relationship to Flood Susceptibility: The hydrologic soil group controls the infiltration capacity of the landscape, which in turn affects the amount of surface runoff generated during rainfall events. In regions dominated by Group D or dual D soils, such as many floodplains and lower Chellif sub-basins, the potential for flooding is considerably higher due to the limited water absorption and rapid surface flow. These areas are also more prone to waterlogging when combined with flat slopes. By identifying zones with high CN values, driven by poor drainage capacity or impervious land cover, this analysis helps prioritize areas where structural flood control (e.g., retention basins, improved drainage) and non-structural measures (e.g., land use zoning) are urgently needed. The CN map derived from HYSOGs250m thus plays a critical role in the multi-criteria flood hazard assessment framework applied in this study.

7.2.7. Sinuosity Index (SI)

The Sinuosity Index (SI) is a dimensionless morphometric parameter used to quantify the degree of meandering or curvature in a river or stream channel. It is defined as the ratio between the actual channel length (Lc) and the straight-line distance (Lv) between the source and mouth of the stream. The formula is expressed as:

$$SI = \frac{L_c}{L_v}$$

Where:

- L_c = Length of the river along its channel (measured in kilometers)
- L_v = Straight-line valley length from the river’s origin to its outlet (km)

A river with SI = 1.0 is considered perfectly straight. Values between 1.0 and 1.5 indicate moderate sinuosity, while values greater than 1.5 signify high sinuosity and a strongly meandering channel.

Relationship to Flood Susceptibility: The sinuosity of a river affects how it stores, transports, and dissipates floodwaters. Highly sinuous rivers often develop in low-gradient terrains, where slower water velocities promote lateral erosion and sediment deposition. In these systems, water may overtop the banks more frequently, particularly during flood events, due to reduced flow efficiency. Furthermore, meandering channels can act as natural attenuation systems, dispersing flood energy over a wider area, but also increasing the risk of bank overflow and lateral flooding.

7.3 Evaluation of Flood Hazard Degrees for Sub-Basins

To evaluate the relative flood susceptibility of each sub-basin in the study area, a standardized hazard classification system was applied based on a set of selected morphometric parameters. These parameters include both linear (directly proportional) and inverse (negatively correlated) indicators of runoff potential and basin response. Each subbasin was assigned a flood hazard degree ranging from 1 to 5, corresponding to five categories of risk:

- **1**: Very Low Hazard
- **2**: Low Hazard
- **3**: Moderate Hazard
- **4**: High Hazard
- **5**: Very High Hazard

This classification enables a consistent, multi-criteria approach to assessing flood susceptibility using quantitative morphometric indices.

The hazard degree for each morphometric parameter was computed using normalization equations that scale the raw parameter values between 1 and 5. The process involves the following steps:

1. Determine the minimum (Y_{min}) and maximum (Y_{max}) values for each morphometric parameter across all sub-basins.

2. For each sub-basin, calculate the hazard degree ($H\ D$) for every parameter using one of the two formulas below, depending on the nature of the relationship between the parameter and flood risk.

For parameters with a linear (direct) relationship with flood susceptibility (e.g., drainage density, stream frequency, relief ratio, bifurcation ratio), the following equation is used:

$$HD = 4 \times \frac{Y - Y_{\min}}{Y_{\max} - Y_{\min}} + 1$$

For parameters with an inverse relationship (e.g., elongation ratio, circularity ratio, length of overland flow), where lower values indicate higher hazard, the formula is:

$$HD = 4 \times \frac{Y - Y_{\max}}{Y_{\min} - Y_{\max}} + 1$$

In both cases:

- Y is the morphometric parameter value for the sub-basin under analysis,
- Y_{min} and Y_{max} are the minimum and maximum values of that parameter across all subbasins.

This approach, adapted from Davis (1986), assumes a geometric linear transformation of parameter values onto a standardized 5-point scale, enabling fair comparisons and integration of diverse metrics.

Once the individual hazard degrees for each parameter are calculated, the total hazard score for each sub-basin is derived by summing the degrees of all contributing parameters. Finally, the overall flood hazard classification is obtained by averaging or re-scaling the total score back into the five-class system, thereby assigning each sub-basin a final hazard degree between 1 (very low) and 5 (very high).

Chapter IV:

Results and discussion

Results and discussion

1. Area map

The area of the drainage basins varies significantly, ranging from 496 km² (O. Mina Aval) to 3,005 km² (O. Sousselem). This wide range reflects the diversity in the size and extent of the sub-watersheds within the studied region (Figure IV.1). The average area is approximately 1,251 km², indicating that the catchments are generally large and capable of collecting and transporting substantial volumes of water. Larger basins tend to have more complex drainage networks and may exhibit varied hydrological responses compared to smaller ones.

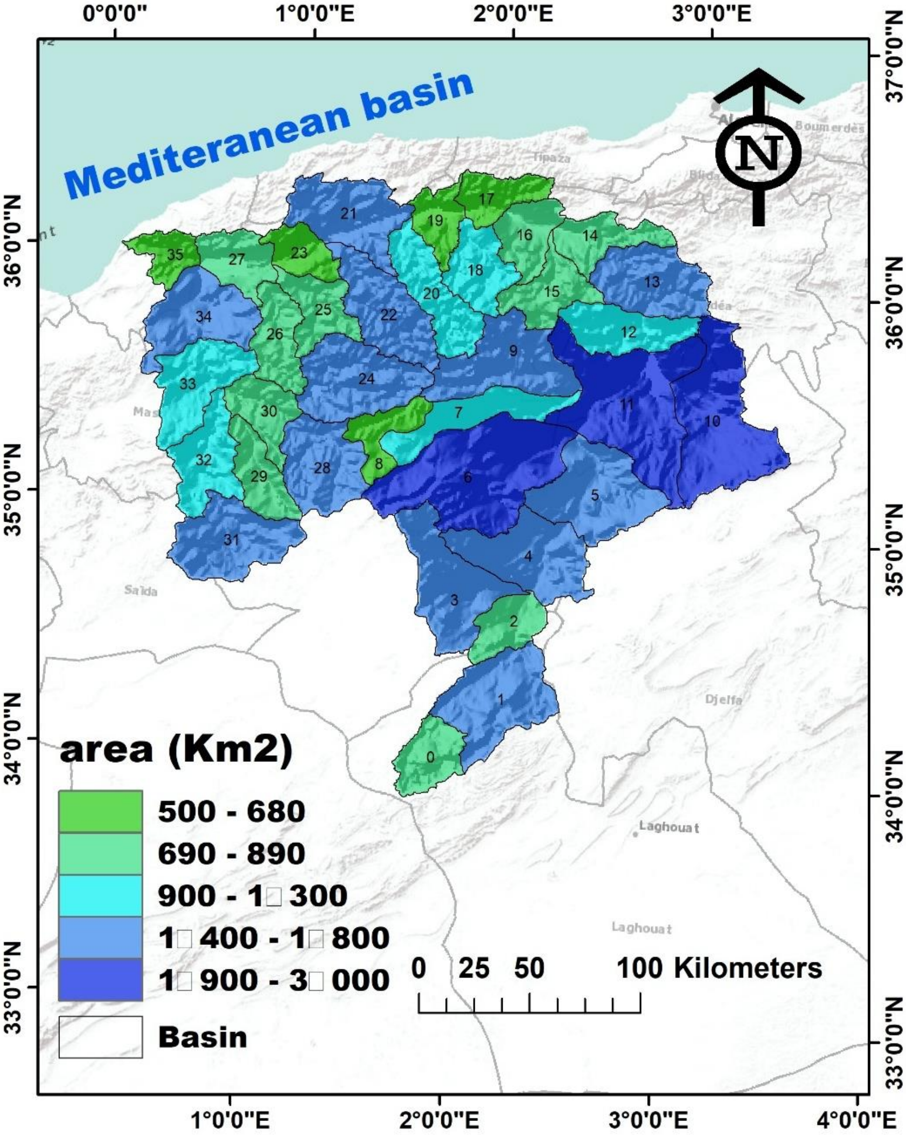


Figure IV. 1: Map of area of Chellif basin.

2. Slope map

The slope map of the Mediterranean basin region reveals variations in terrain steepness across 36 sub-basins, with values ranging from 1.0% to 3.2%. Basins with low slopes, such as Basins (O. Sakni, O. Touil Moyen, and O. Mechti Zerga), feature gentle terrain (1.0–1.3%), which slows water movement, enhances groundwater recharge, and promotes sediment deposition, making them less prone to flash floods (Figure IV.2). In contrast, basins with steeper slopes, such as Basins (O. Deurdeur, O. Ebda, and O. Cheliff Ouarizane), exhibit sharper terrain (up to 3.2%), leading to faster surface runoff, reduced infiltration, and increased erosion risk—factors that heighten their vulnerability to flooding. Therefore, slope analysis serves as a crucial indicator for assessing flood hazard levels and identifying the most vulnerable areas within the watershed.

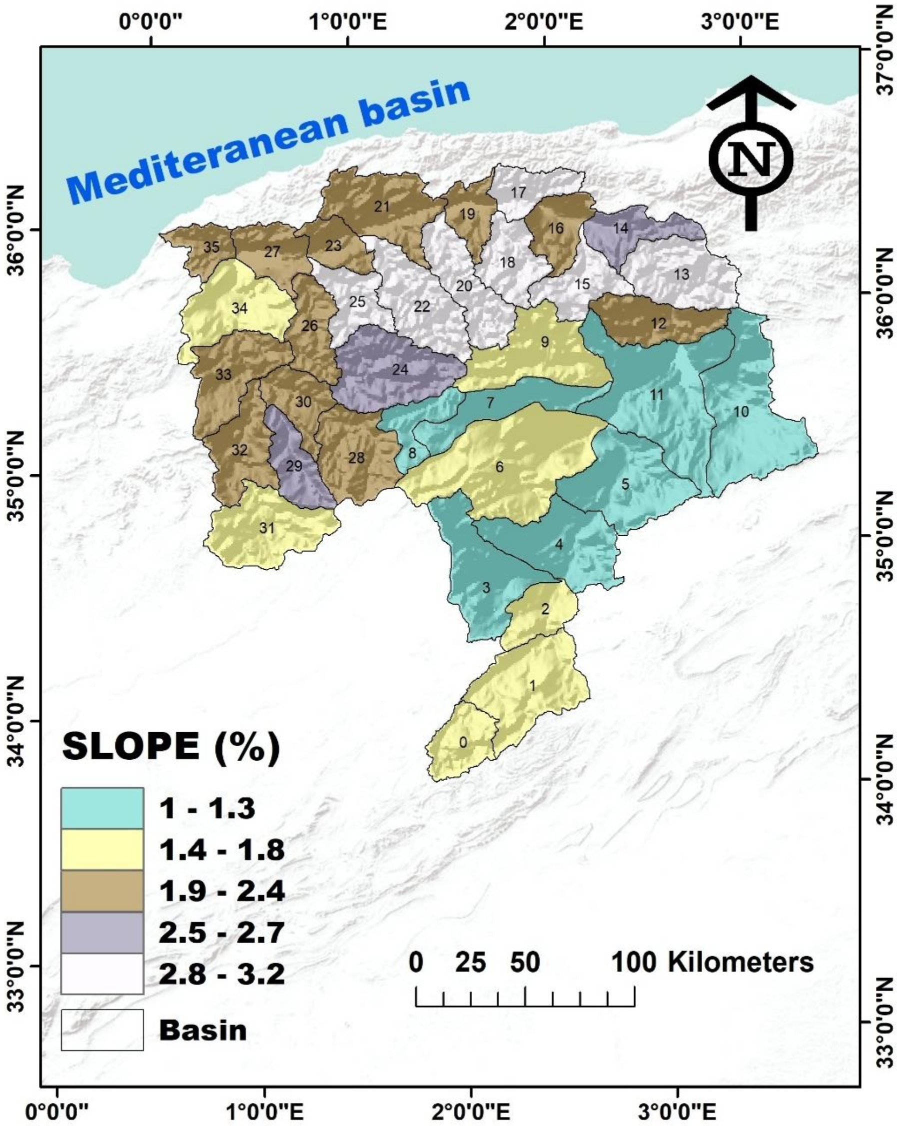


Figure IV. 2: Map slope of Chellif basin

3. Sinuosity Index

The sinuosity index, which measures the degree of meandering in stream channels, ranges from 0.15 (O. Sousselem) to 0.90 (O. Mina Aval) (Figure IV.3). A value closer to 1 indicates higher channel meandering. Most basins show relatively low sinuosity values, suggesting that the majority of stream courses are straight to moderately curved. Basins with higher sinuosity (e.g., O. Ouassel Amont, O. Mina Aval) may be influenced by lower slopes or geological controls that encourage meandering.

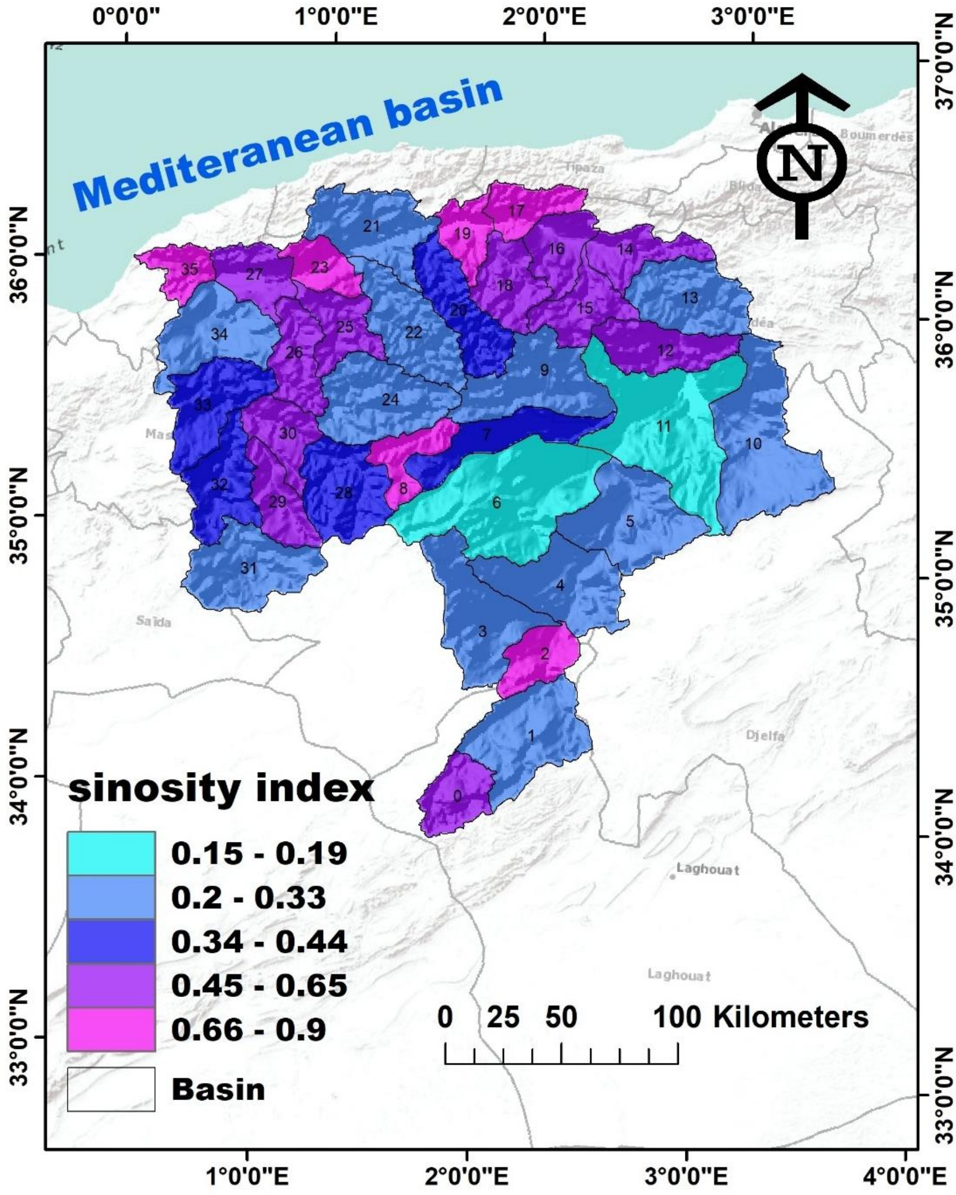


Figure IV. 3: Map sinuosity index of Chellif basin

4. Shape Factor

The shape factor values vary from 3.07 O. Sebgag Berkana to 9.90 O. Mechti Zerga. A higher shape factor usually denotes elongated basins, whereas lower values suggest more compact shapes (Figure IV.4). Elongated basins, such as O. Mechti Zerga and O. Riou Tleta, generally result in delayed peak flows, as water from distant parts takes longer to reach the outlet. Compact basins like O. Sebgag Berkana and O. Touil Amont tend to have more synchronized runoff, which can lead to quicker and potentially higher peak discharges.

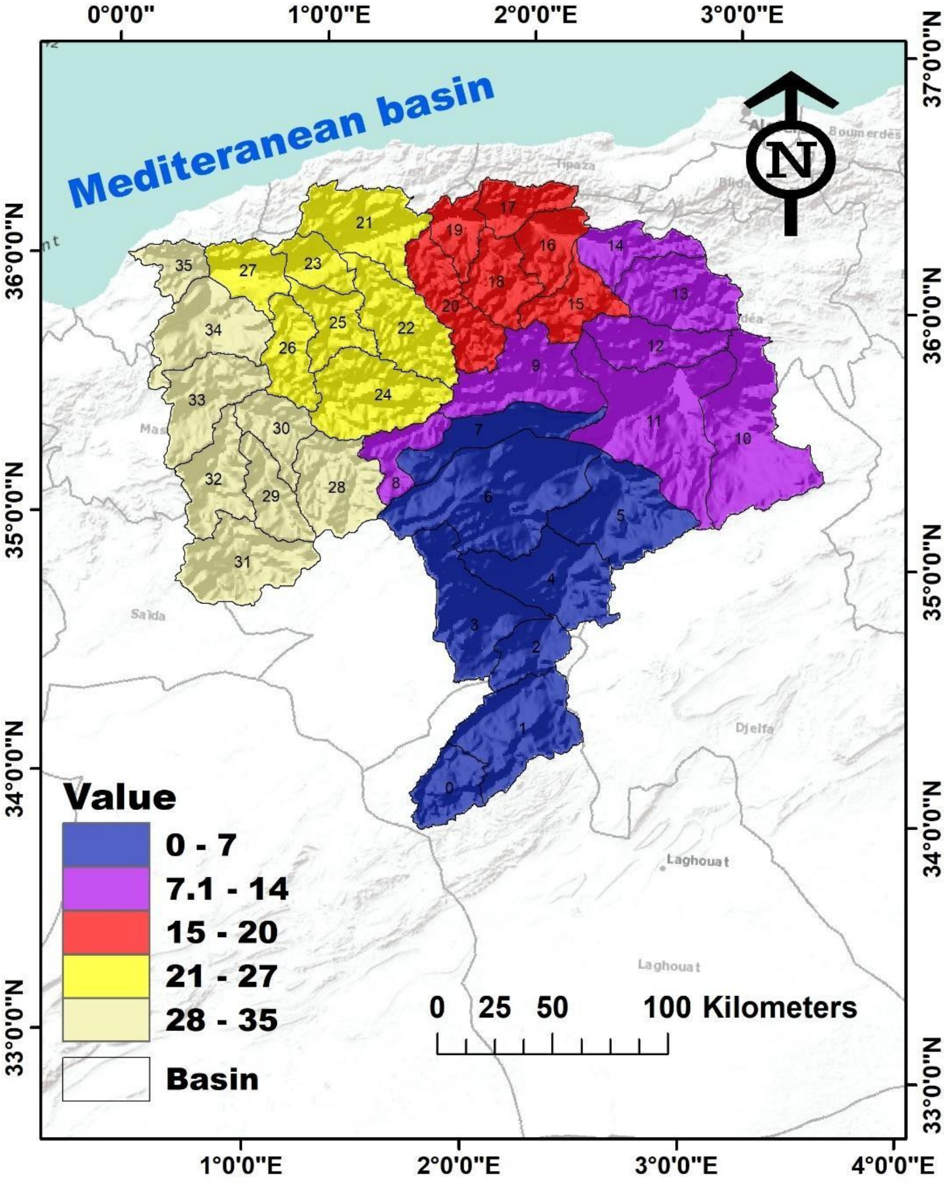


Figure IV. 4: shape factor of Chellif basin

5. Curve Number (CN)

The CN is a hydrologic parameter reflecting land use, soil type, and surface conditions, affecting the amount of runoff generated. Higher CN values (e.g., O. Cheliff Harrezzal and O. Mina Haddad) imply reduced infiltration and higher runoff potential, possibly due to impervious surfaces or less permeable soils (Figure IV.5). Lower CNs indicate areas with better infiltration and possibly more vegetation cover.

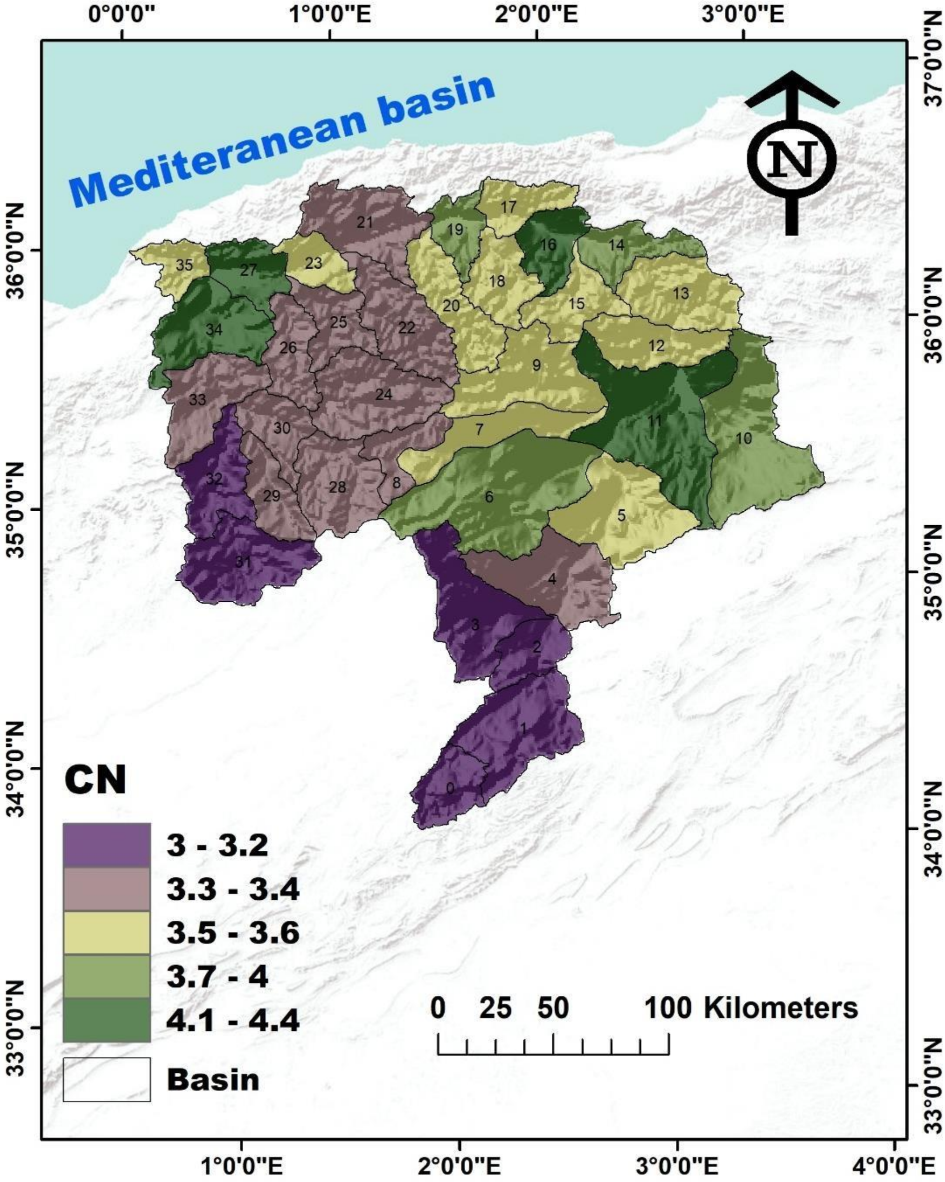


Figure IV. 5: map Curve number of Chellif basin

6. Drainage Density (Dd)

Drainage density values range from 0.34 Daia el Firania to 1.56 O. Cheliff Ouarizane km/km². Dd is the total length of streams per unit area and indicates how well or poorly a basin is drained (Figure IV.6). Higher values (e.g., O. Cheliff Ouarizane and O. Cheliff Tikazale) are characteristic of basins with closely spaced stream channels, possibly indicating less permeable surfaces, more runoff, and flashier hydrographs. Lower Dd values suggest either flatter terrain, permeable soils, or less rainfall.

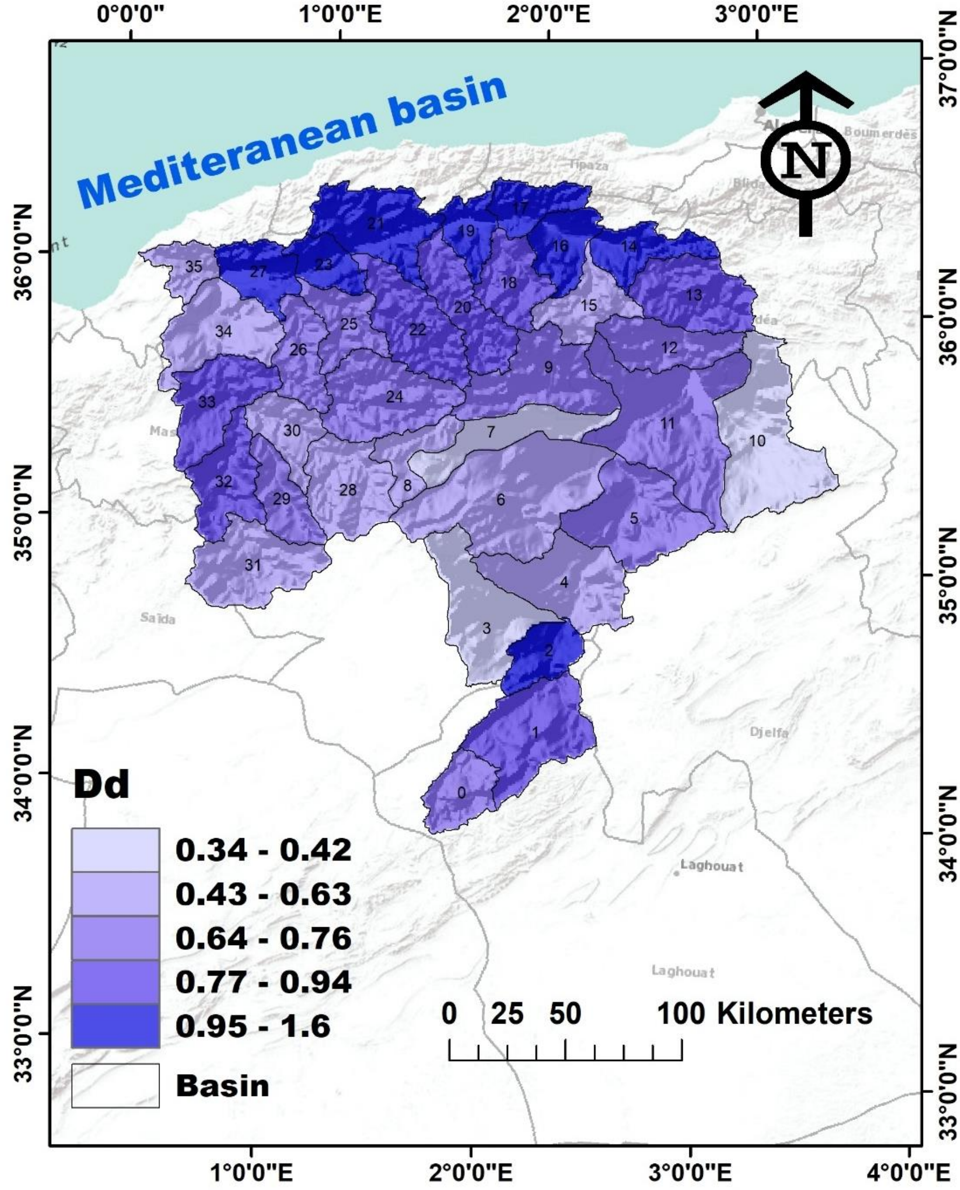


Figure IV. 6: Map Drainage density of Chellif basin

7. Circularity Ratio (CR)

Circularity Ratio values range between 3.88 O. Cheliff Tikazale and 10.71 O. Sousselem. CR measures how close a basin is to a perfect circle, where lower values (e.g., O. Cheliff Tikazale, O. Ouassel Amont) suggest compact basins, likely to produce more synchronized runoff and faster peak discharges (Figure IV.7). Higher values (e.g., O. Sousselem, O. Touil Aval) represent elongated basins, which typically delay runoff concentration, allowing more time for infiltration and reducing flood peaks.

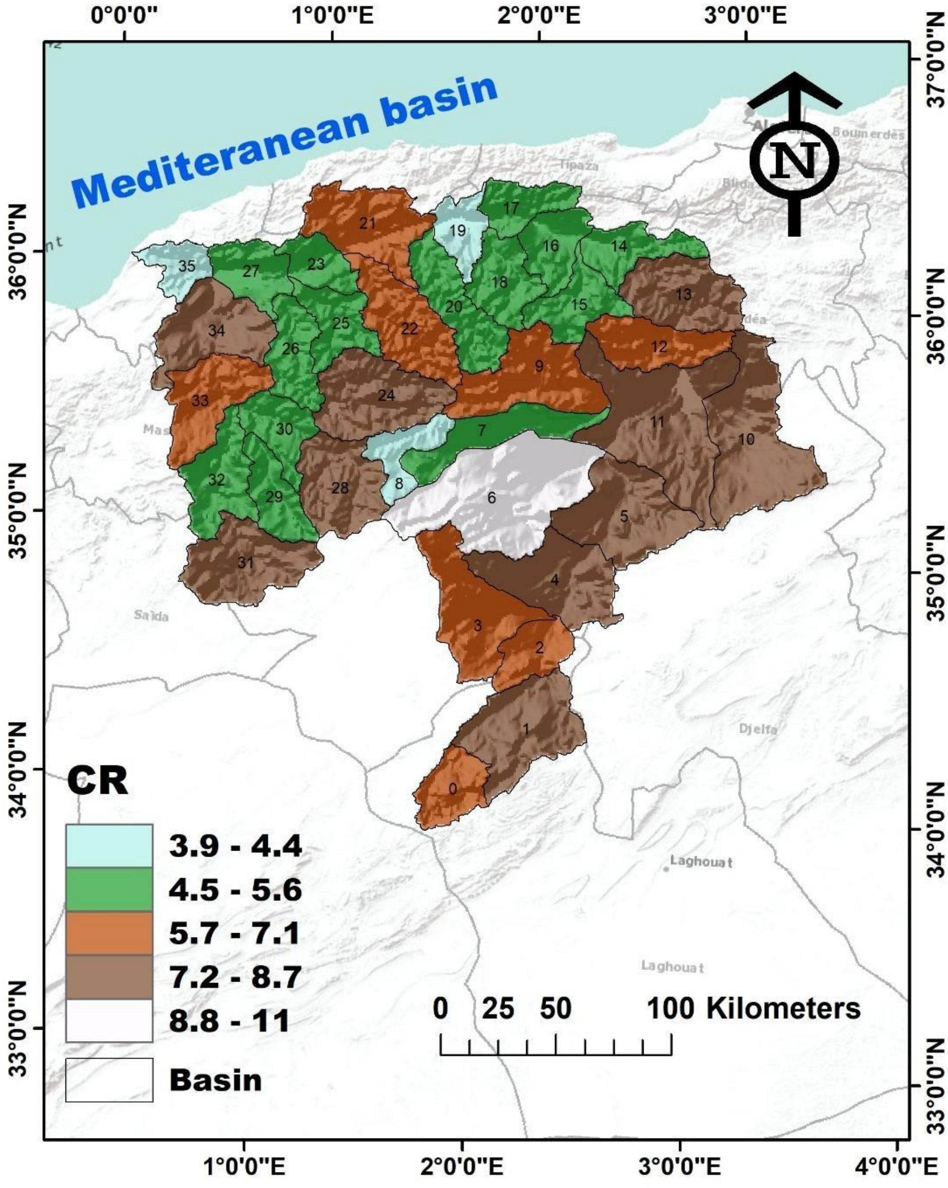


Figure IV. 7: Map Circularity Ratio of Chellif basin

The analysis of morphometric parameters across the sub-basins of the Cheliff watershed reveals (Table IV. 1) significant spatial variability that influences their hydrological behavior and flood susceptibility. The area of the sub-basins ranges widely from 496 km² to 3005 km², indicating a diversity of catchment sizes, where smaller basins tend to generate quicker runoff responses, while larger ones accumulate more flow over time. Slope values remain generally low, between 1.01% and 3.22%, typical of semi-arid regions with gently rolling topography, although steeper sub-basins such as O. Ebda and O. Deurdeur may exhibit faster runoff and higher erosion potential. The sinuosity index also varies significantly, from very straight channels (e.g., O. Sousselem) to more meandering courses (e.g., O. Mina Aval), influencing flow energy and sediment transport. Shape factors indicate that several basins, such as O. Mechti Zerga and Daia Boughzoul, are highly elongated, which tends to delay peak flows and reduce flash flood risk, unlike more compact sub-basins which can concentrate runoff more rapidly. Curve numbers, reflecting land cover and infiltration potential, range from 2.99 to 4.41, with higher values indicating greater runoff potential, especially in sub-basins with low permeability or more urbanized surfaces. Drainage density shows important contrasts as well, with values from 0.34 to 1.56 km/km²; lower values often point to permeable substrates and lower flood susceptibility, while higher values suggest rapid drainage and potential for quick flood responses. Finally, the circularity ratio varies from 3.88 to 10.71, showing that some sub-basins are quite round and compact—hence more prone to flash flooding—while others are more elongated and hydrologically stable. Altogether, this variability highlights the need for localized flood management strategies within the Cheliff basin, as each sub-basin exhibits unique morphological and hydrological characteristics.

Table IV. 1: mean values of morphometric parameters of the sub basin

Oued	ID	Area (km2)	slope %	sinosity index	SHAPE factor	Curve number	Drainage density	Circularity ratio
O. Sebgag Berkana	B1	778	1.53	0.57	3.07	2.99	0.70	6.00
O. Namous Chelal	B2	1734	1.43	0.26	4.12	3.04	0.83	8.25
O. Touil Amont	B3	690	1.31	0.65	3.18	3.20	0.94	5.60
O. Sakni	B4	1675	1.07	0.27	6.82	3.12	0.34	6.83
O. Touil Moyen	B5	1604	1.12	0.28	4.92	3.31	0.53	7.50
O. Touil Aval	B6	1751	1.21	0.25	3.54	3.54	0.63	8.67
O. Sousselem	B7	3005	1.48	0.15	4.32	3.82	0.58	10.71
O. Mechti Zerga	B8	1055	1.01	0.42	9.90	3.49	0.37	4.69
O. Ouassel Amont	B9	627	1.17	0.71	7.66	3.20	0.60	4.00
O. Ouassel Moyen	B10	1622	1.73	0.27	6.57	3.60	0.71	6.82
Daia el Firania	B11	2366	1.27	0.19	6.11	4.00	0.34	8.46
Daia Boughzoul	B12	2818	1.11	0.16	8.16	4.16	0.71	8.28
O. Cheliff Djelil	B13	1013	2.10	0.44	5.06	3.64	0.68	5.91
O. Cheliff Ghrib	B14	1379	2.82	0.32	3.29	3.48	0.90	7.85
O. Cheliff Harbil	B15	780	2.57	0.57	6.61	3.86	1.12	4.72
O. Deurdeur	B16	851	3.15	0.52	7.30	3.46	0.57	4.75
O. Cheliff Harrezzal	B17	757	2.31	0.59	4.48	4.41	1.13	5.31
O. Ebda	B18	661	3.22	0.67	5.11	3.59	1.39	4.76
O. Rouina Zeddine	B19	891	2.82	0.50	5.45	3.38	0.85	5.40
O. Cheliff Tikazale	B20	588	2.16	0.76	7.61	3.96	1.52	3.88
O. Fodda	B21	1154	2.82	0.39	7.44	3.38	0.89	5.49
O. Ras Ouahrane	B22	1438	2.25	0.31	6.69	3.34	1.15	6.38
O. Sly	B23	1404	3.01	0.32	6.56	3.28	0.86	6.35
O. Cheliff Ouarizane	B24	575	2.38	0.78	4.01	3.46	1.56	4.79
O. Riou Tiguiguest	B25	1618	2.66	0.28	3.74	3.25	0.72	8.21
O. Riou Tleta	B26	783	2.92	0.57	7.94	3.22	0.68	4.41
O. Djidiouia	B27	840	2.10	0.53	5.81	3.33	0.76	5.13
O. Cheliff Tarhia	B28	773	1.95	0.58	4.38	4.32	1.15	5.41
O. Mina Amont	B29	1327	1.77	0.34	3.26	3.29	0.60	7.72
O. Mina Amont	B30	772	2.64	0.58	4.87	3.23	0.67	5.22
O. Taht	B31	737	2.37	0.60	5.21	3.28	0.61	4.99
O. Mina Moyenne	B32	1499	1.42	0.30	4.05	3.16	0.48	7.71
O. Abd Amont	B33	1069	2.17	0.42	7.03	3.15	0.82	5.40
O. Abd Aval	B34	1240	2.14	0.36	4.85	3.26	0.84	6.63
O. Mina Haddad	B35	1425	1.68	0.31	4.92	4.22	0.55	7.07
O. Mina Aval	B36	496	2.21	0.90	5.36	3.47	0.42	4.05

Flood hazard assessment

1. Area hazard

The hazard analysis of the 36 drainage basins shows that most basins (41.7%) have a low hazard level, while 33.3% are classified as high hazard. Moderate and very high hazard levels account for 16.7% and 8.3% respectively (Figure IV.8). This indicates that although a large portion of the area is relatively stable, a significant number of basins are at risk and require focused management and mitigation efforts.

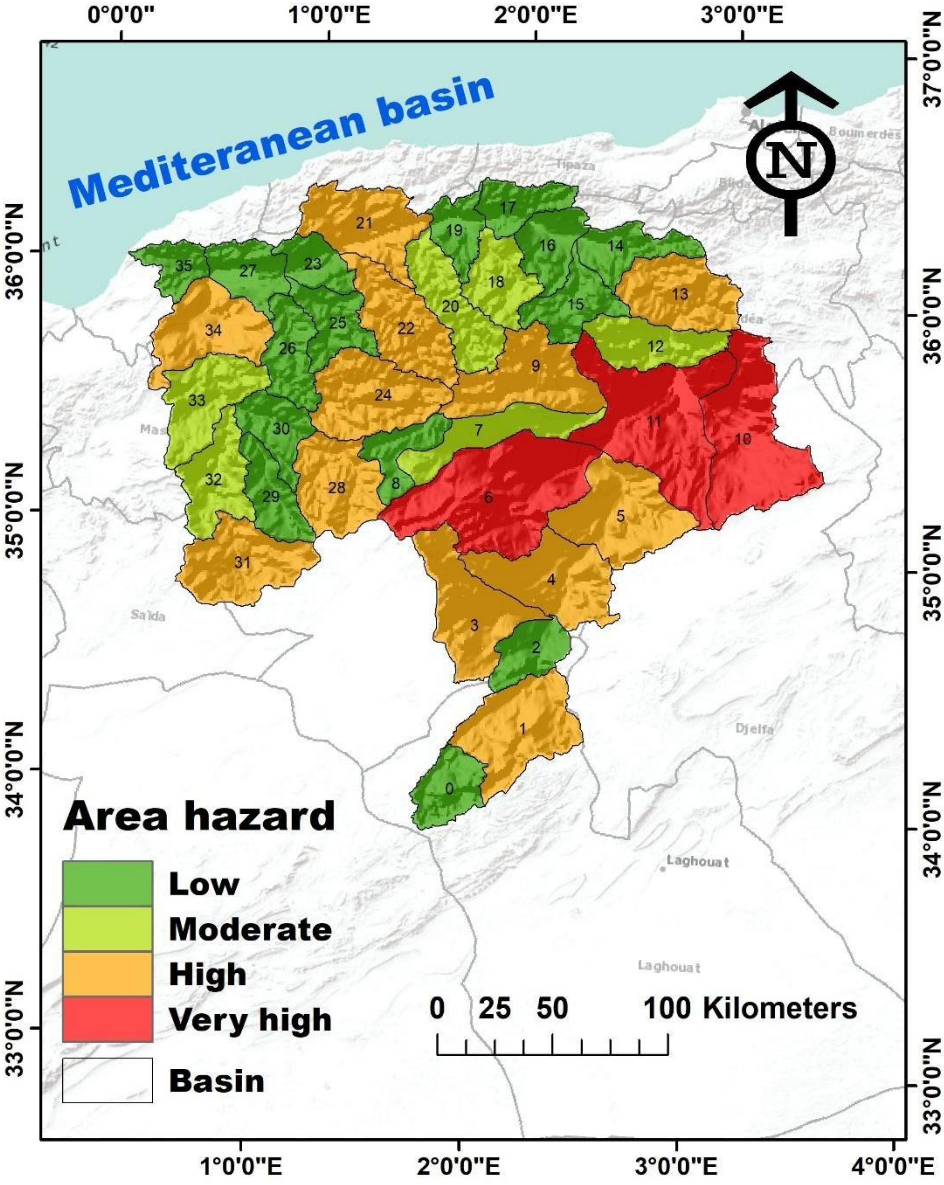


Figure IV. 8: Area hazard map of Chellif basin

2. Slope hazard

The analysis of the 36 drainage basins reveals a relatively balanced distribution across the four hazard levels. Moderate hazard is the most common, affecting 30.6% of the basins, followed closely by low hazard at 27.8% and very high hazard at 25.0% (Figure IV.9). High hazard represents the smallest share, with 16.7% of the basins. This distribution indicates that while a portion of the area remains relatively stable, a considerable number of basins fall under moderate to very high risk. Therefore, a combined strategy of continuous monitoring and targeted risk mitigation is essential to manage the varying levels of hazard effectively.

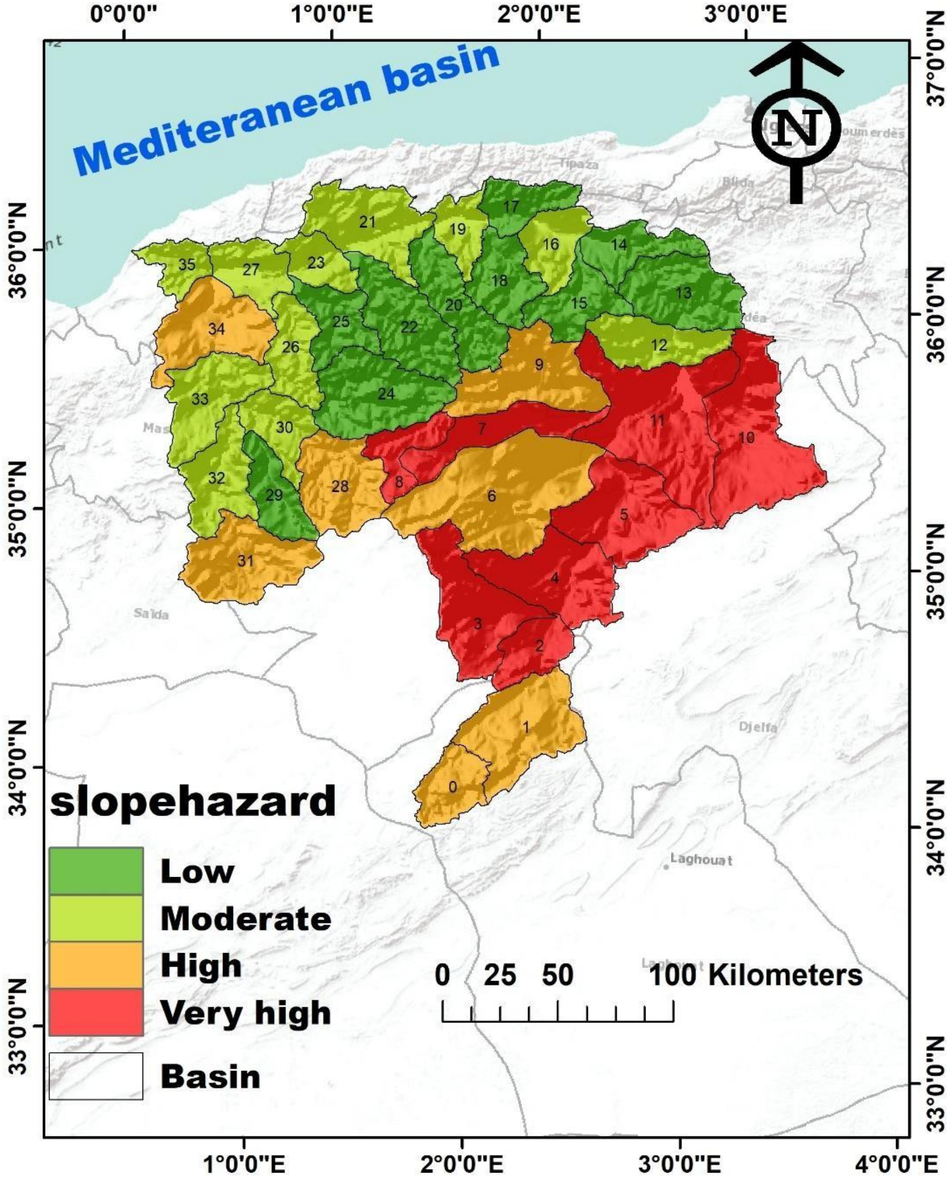


Figure IV. 9: Slope hazard map of Chellif basin

3. Sinuosity index hazard

The sinuosity-based hazard analysis of the 36 drainage basins shows that the majority fall under the moderate and high hazard categories. Specifically, 41.7% of the basins are classified as moderate hazard, while 33.3% are considered high hazard (Figure IV.10). Very high hazard accounts for 19.4% of the basins, and only a small fraction, 5.6%, are categorized as low hazard. This distribution indicates that most basins exhibit moderate to significant sinuosity, which may contribute to increased erosion or instability. As such, the findings highlight the need for targeted management in areas with elevated sinuosity to reduce potential risks.

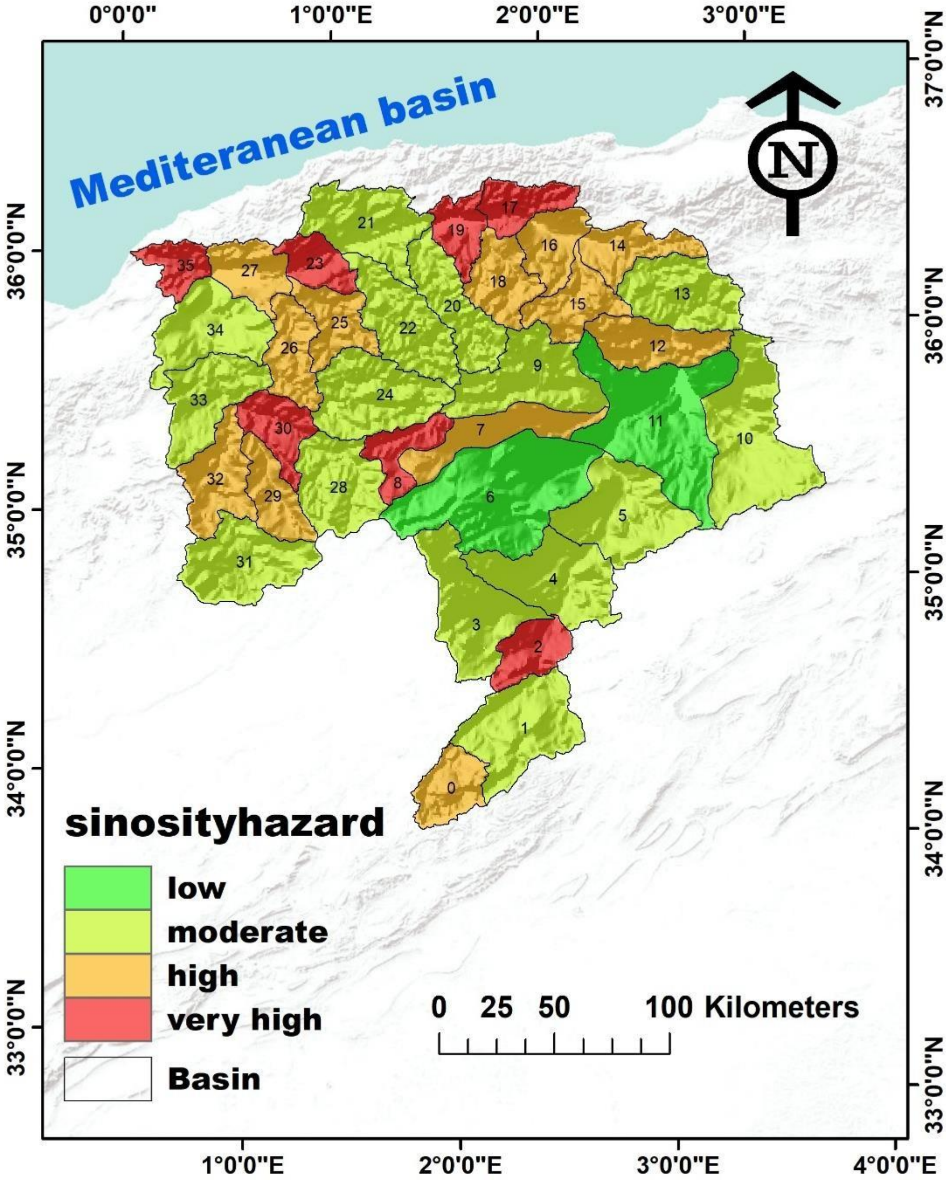


Figure IV. 10: Sinuosity index hazard map of Chellif basin

4. Shape factor Hazard

The analysis of hazard levels based on the shape factor of the 36 drainage basins reveals a relatively balanced distribution. The moderate hazard category is the most common, representing 13 basins (36.1%) (Figure IV.11), indicating that a significant portion of the basins have moderately elongated shapes that may influence runoff and flood behavior. Both the low and high hazard levels each account for 8 basins (22.2%), suggesting that variations in basin shape are fairly widespread across the region. The very high hazard level includes 7 basins (19.4%), highlighting a notable portion of basins that may have compact or highly irregular shapes, which can increase the risk of rapid runoff or concentrated flow. Overall, the shape factor data suggest a need for integrated watershed management that considers basin geometry in evaluating flood and erosion risks.

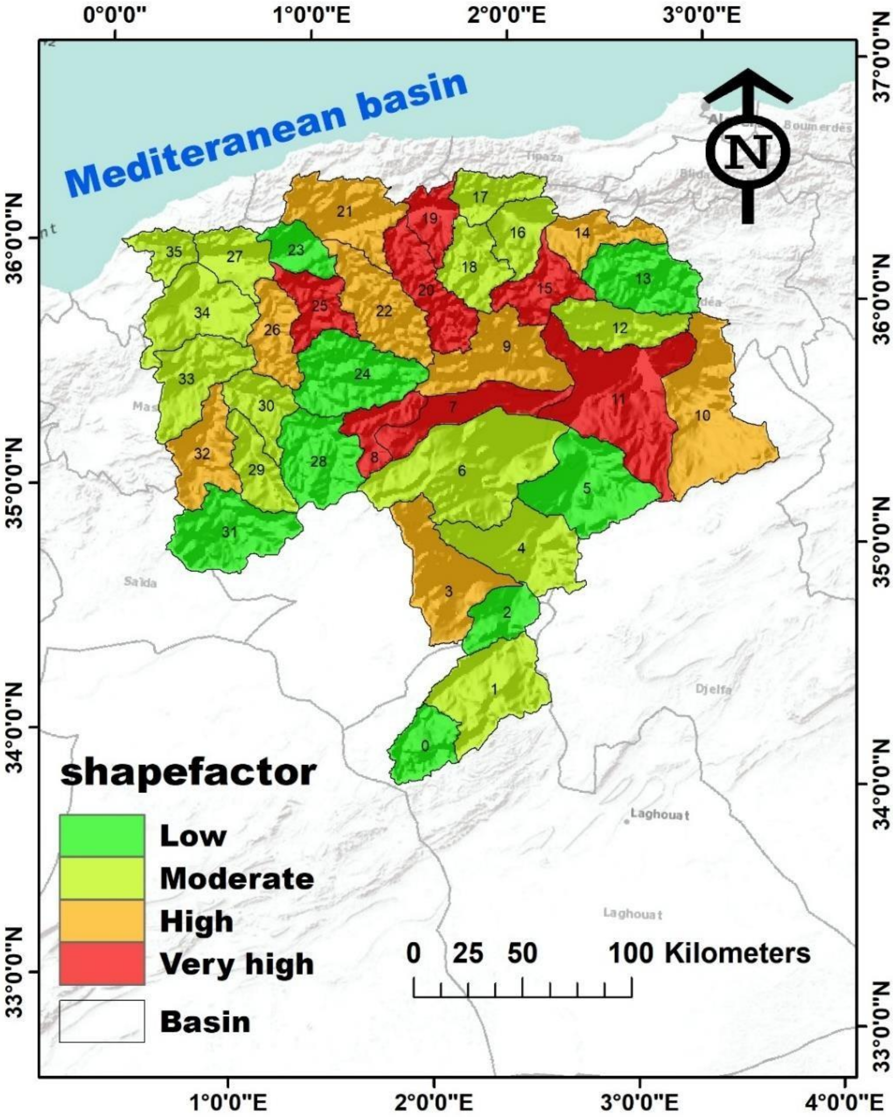


Figure IV. 11: Shape factor Hazard map of Chellif basin

5. Curve Number Hazard

The analysis of hazard levels based on the Curve Number (CN), which reflects surface runoff potential, shows that most of the 36 drainage basins fall within the lower hazard categories. Specifically, 15 basins (41.7%) are classified as low hazard, and 13 basins (36.1%) fall under moderate hazard (Figure IV.12). This indicates that the majority of the area has relatively low to moderate runoff potential, suggesting good infiltration capacity and lower risk of surface flooding. In contrast, only 4 basins (11.1%) are classified as high hazard, and another 4 basins (11.1%) as very high hazard, indicating that areas with high runoff risk are limited but still present. Overall, the data suggest a generally favorable hydrological condition, with a need for localized attention in basins with elevated curve number values.

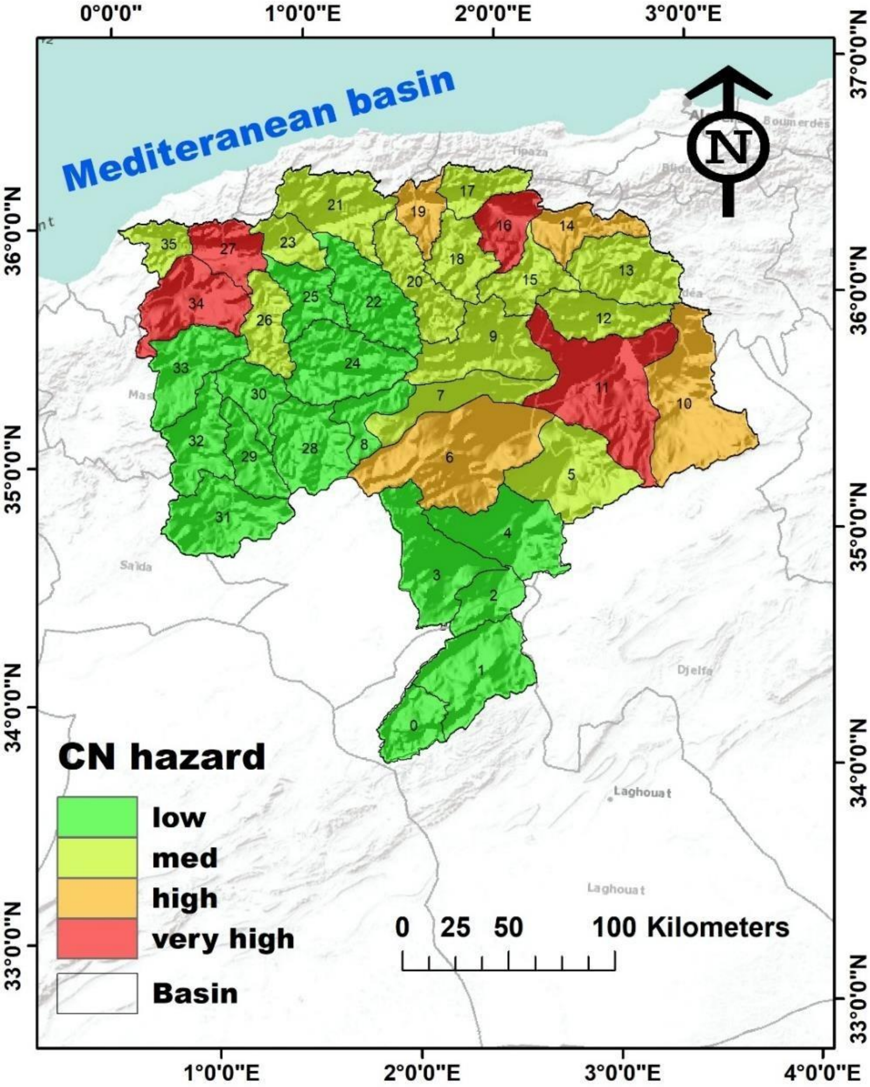


Figure IV. 12: Curve Number Hazard map of Chellif basin

6. Drainage density Hazard

The hazard analysis based on drainage density shows that the majority of the 36 basins fall into the moderate hazard category, with 15 basins (41.7%), indicating a balanced drainage network that may pose moderate flood or erosion risks. High and very high hazard levels together account for 47.2% of the basins (9 and 8 basins respectively), suggesting a significant portion of the area has dense drainage networks, which can lead to rapid surface runoff and increased vulnerability (Figure IV.13). Only 4 basins (11.1%) are classified as low hazard, reflecting limited areas with sparse drainage. Overall, the results point to a considerable number of basins where drainage density could contribute to higher hydrological risk, highlighting the importance of incorporating this factor into watershed management planning.

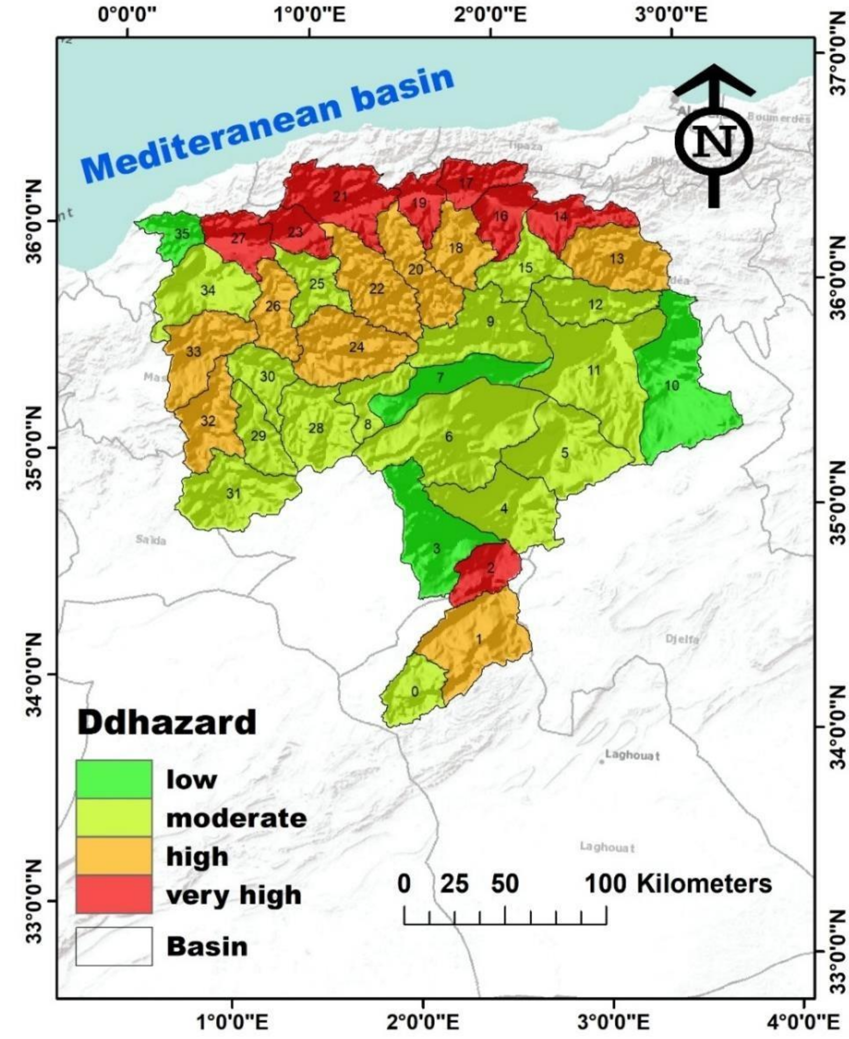


Figure IV. 13: Drainage density Hazard map of Chellif basin

7. Circularity Ratio (CR) Hazard

The hazard analysis based on the Circularity Ratio (CR) shows a fairly even distribution across the four hazard levels among the 36 drainage basins. Moderate and high hazard categories are the most represented, each with 10 basins (27.8%), indicating that many basins have intermediate shapes that could influence runoff concentration and flow speed (Figure IV.14). Low hazard accounts for 9 basins (25.0%), suggesting a good portion of the basins have more elongated or irregular forms, which tend to reduce flood risk. Meanwhile, 7 basins (19.4%) fall under the very high hazard category, reflecting more circular basins that typically generate faster and more concentrated runoff. This distribution suggests that while the risk associated with circularity varies, a significant number of basins may require closer hydrological monitoring.

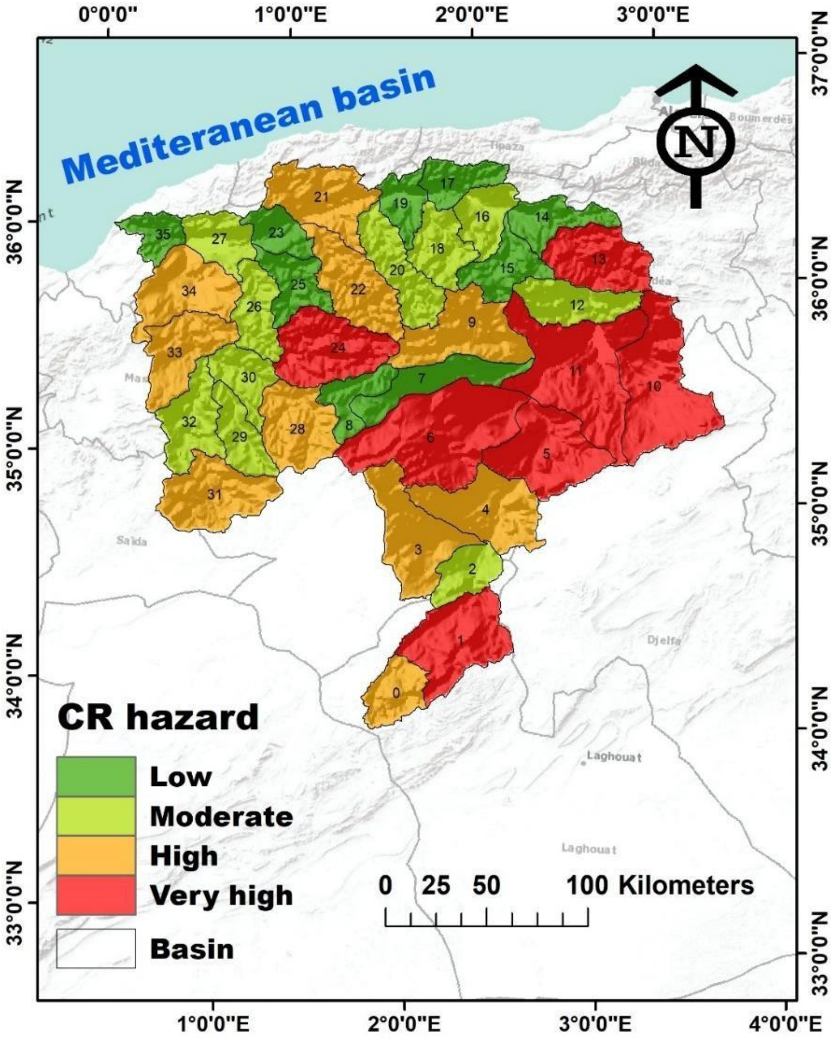


Figure IV. 14: Circularity Ratio hazard map of Chellif basin

8. Flood Hazard Map

The flood hazard analysis for the 36 drainage basins indicates that high hazard is the most prevalent category, with 13 basins (36.1%), suggesting a significant portion of the area is vulnerable to flooding. Moderate hazard includes 10 basins (27.8%), while low hazard accounts for 8 basins (22.2%), reflecting areas with relatively lower flood risk (Figure IV.15). The very high hazard category comprises 5 basins (13.9%), highlighting zones that may experience frequent or intense flooding. Overall, the distribution shows that over half of the basins fall into high or very high flood risk categories, emphasizing the need for targeted flood management and mitigation strategies.

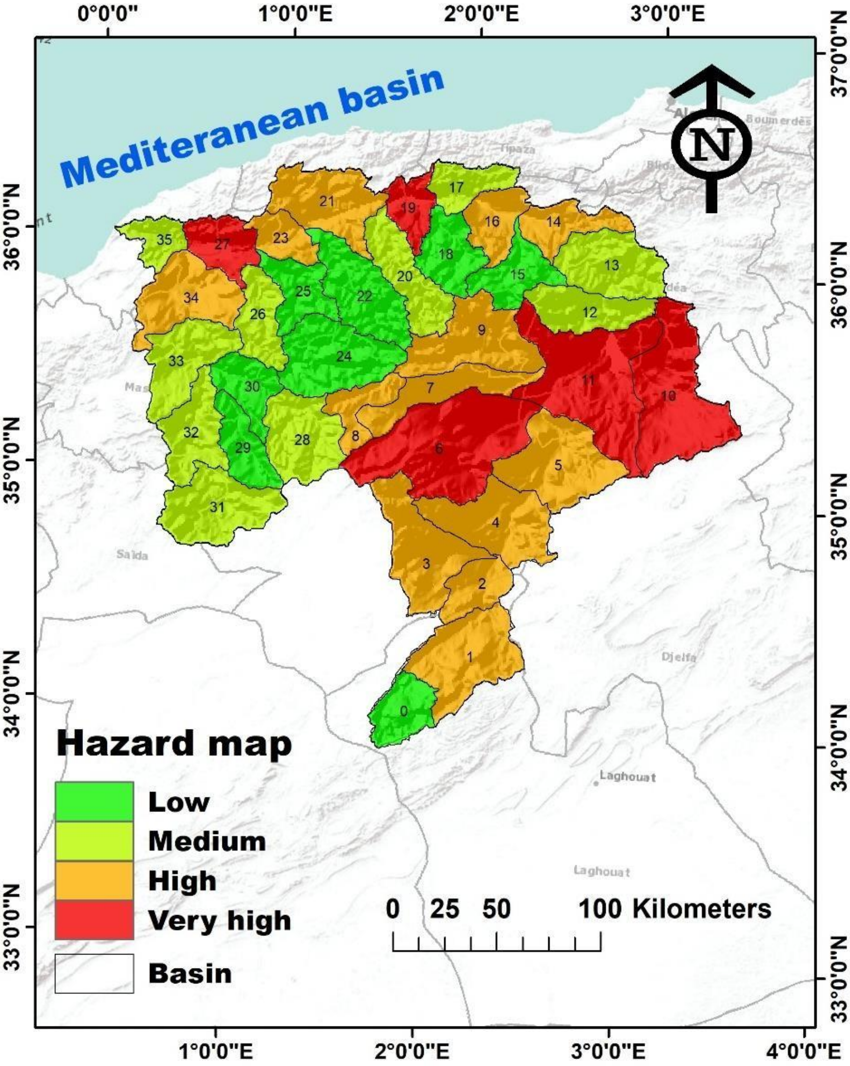


Figure IV. 15: Flood Hazard map of Chellif basin

Conclusion

The morphometric analysis of the Cheliff River Basin highlights significant spatial variability in basin characteristics such as slope, shape, drainage density, and runoff potential. These parameters directly influence the hydrological response and flood susceptibility of each sub-watershed. The study reveals that over half of the sub-basins are exposed to high or very high flood hazard levels, particularly those with steep slopes, compact shapes, high drainage densities, and elevated Curve Numbers. This underscores the urgent need for targeted watershed management, erosion control, and flood mitigation strategies to enhance resilience and ensure sustainable water resource planning in the region.

General Conclusion

General Conclusion

The morphometric and flood hazard analysis conducted across the 36 sub-basins of the Cheliff watershed highlights the significant spatial variability in terrain characteristics and their direct influence on hydrological behavior and flood risk. Key morphometric parameters such as slope, drainage density, shape factor, sinuosity index, circularity ratio, and Curve Number exhibit wide-ranging values, reflecting the geomorphological diversity of the region. These parameters have been instrumental in evaluating the susceptibility of each basin to surface runoff, erosion, and flooding.

The results reveal that a considerable number of sub-basins are characterized by conditions conducive to rapid runoff and high flood potential—particularly those with steep slopes, compact or circular shapes, high drainage densities, and elevated Curve Numbers. The flood hazard classification shows that over half of the sub-basins fall within high or very high flood risk categories, clearly underscoring the need for basin-specific risk reduction measures. This study emphasizes the importance of integrating morphometric analysis into watershed and flood management planning. The identification of high-risk zones enables decisionmakers to prioritize interventions such as reforestation, soil conservation, infrastructure adaptation, and early warning systems. Ultimately, this approach contributes to more resilient and sustainable flood risk management in the semi-arid context of the Cheliff basin.

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