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Par: DJENAOUI Abdelouahed et HAMDANI Nour El Houda

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**Cartographie de la Susceptibilité aux  
inondations par la méthode de l'Analyse  
Multicritère et SIG dans le sous bassin versant  
de l'Oued Sahel (Soummam)**

Soutenu devant le jury composé de:

MEZALI Farouk	Université de M'sila	Président
MOKHTARI Elhadj	Université de M'sila	Encadreur
ABDELKEBIR Brahim	Université de Guelma	Co-Encadreur
MERZOUK Belkacem	Université de M'sila	Examineur

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**Flood Susceptibility Mapping by the method of  
Multi-criteria Analysis and GIS in the sub-  
watershed of the Sahel Wadi (Soummam)**

**Defended in front of the jury composed of:**

MEZALI Farouk	University of M'sila	President
MOKHTARI Elhadj	University of M'sila	Supervisor
ABDELKEBIR Brahim	University of Guelma	Co- Supervisor
MERZOUK Belkacem	University of M'sila	Examiner

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بِسْمِ اللَّهِ الرَّحْمَنِ الرَّحِيمِ



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# *Dedication*

*Alhamdulillah, first and foremost.*

*To my mother, my father, my brothers Abdelmadjid, Tofik, and Aboubaker, my sisters, and my little sister Inas.*

*,To my friend Omar Leboukh*

*رحمة الله و أسكنه فسيح جنانه.*

*To all my close friends, Hossein, AbdelGhani, AbdelSabour.*

*To my friend Iyad from Egypt and to all my friends here and from abroad.*

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*To my graduation teammate, Ms. Hamdani*

*To all my classmates*

*Here I am at the end of my studies.*

*جزاكم الله عني خيراً كثيراً*

*DJENAOUI Abdelouahed*

# *Dedication*

*To the man who had put me right back at my feet when I fell for the first time and for countless times after, the first person who supported and believed in me with all the love in my heart to my father*

*رحمة الله وجمعنا به في جنات النعيم .*

*To the heart that loves me like no one else does, the light of my life that surrounded my path with her prayers and eased my difficulties with her presence my mother.*

*To my greatest blessing my lovely sisters, my brothers, my sweet cutie pie Zakaria, my brother-in-law, and all of my adorable nephews and family.*

*To my precious friends, this lifetime would have been colorless without your company., your love is my treasure.*

*To my classmates and professors, your acquaintance was my honor.*

*To everyone who contributed to my education and enlightened my path from the first letters of the alphabet until the end of this research,*

*جزاكم الله عني خيراً كثيراً و أحسن الجزاء.*

*To each and every one reading this epitome of our diligence, I hope it will be informational and beneficial for you.*

*Hamdani Nour el houda*

# Abstract

Specialists have been urged to search for efficient methods with more accurate and timely results in flood forecasting, this urgency arises from the realization that several factors contribute to flood susceptibility, impacting both urban and rural areas and leading to far-reaching and extensive repercussions. Among the well-known approaches to address this challenge are the Geographic Information System-based Multicriteria Analysis methods.

In our study, we will discover flood forecasting and flood risk assessment, particularly in the area of the sub-watershed of Wadi El Sahel, through the use of the Geographic Information System (GIS)-based Analytical Hierarchy Process (AHP) and Fuzzy Analytical Hierarchy Process (FAHP). These methods obtained very accurate results when validated with the Area Under the ROC Curve (AUC) curve, achieving an accuracy of 88.40% and 92.00% in AHP and FAHP results successively. For future flood risk management, we highly recommend the use of multicriteria methods while improving data quality and availability is essential for informed decision-making, refining criteria selection ensures a holistic assessment of flood management strategies, and it ought to incorporate and monitor real-time data for enabling more timely responses and adaptive decision-making, then for assessing the effective strategies enhancing modeling capabilities is a must, lastly promoting stakeholder collaboration and public awareness fosters inclusive and resilient decision-making.

Using Geographic Information System-based Multicriteria Analysis methods (GIS-MCA) for long-term planning and continuous evaluation helps optimize water resource allocation and address emerging challenges.

**Key words:** Flood susceptibility, AHP, Fuzzy AHP, Flood hazard, GIS-MCA.

# Résumé

Les spécialistes ont été invités à rechercher des méthodes efficaces avec des résultats plus précis et opportuns dans la prévision des inondations, cette urgence découle de la prise de conscience que plusieurs facteurs contribuent à la susceptibilité aux inondations, affectant à la fois les zones urbaines et rurales et entraînant des répercussions profondes et étendues. Parmi les approches bien connues pour relever ce défi figurent les méthodes d'analyse multicritères basées sur le système d'information géographique.

Dans notre étude, nous découvrirons la prévision des inondations et l'évaluation des risques d'inondation, en particulier dans la zone du sous-bassin versant de l'Oued El Sahel, à travers l'utilisation du Processus de Hiérarchie Analytique (AHP) basé sur le Système d'Information Géographique (SIG) et de l'Analytique Fuzzy. Processus hiérarchique (FAHP). Ces méthodes ont obtenu des résultats très précis lorsqu'elles ont été validées avec la courbe Area Under the ROC Curve (AUC), atteignant une précision de 88,40 % et 92,00 % dans les résultats AHP et FAHP successivement. Pour la gestion future des risques d'inondation, nous recommandons fortement l'utilisation de méthodes multicritères, tandis que l'amélioration de la qualité et de la disponibilité des données est essentielle pour une prise de décision éclairée, l'affinement de la sélection des critères garantit une évaluation holistique des stratégies de gestion des inondations et doit intégrer et surveiller en temps réel des données pour permettre des réponses plus rapides et une prise de décision adaptative, puis pour évaluer les stratégies efficaces, l'amélioration des capacités de modélisation est indispensable, enfin la promotion de la collaboration des parties prenantes et la sensibilisation du public favorisent une prise de décision inclusive et résiliente. L'utilisation des méthodes d'analyse multicritère basée sur le système d'information géographique (GIS-MCA) pour la planification à long terme et l'évaluation continue permet d'optimiser l'allocation des ressources en eau et de relever les défis émergents.

**Mots clés:** Susceptibilité aux inondations, AHP flou, AHP, Risques d'inondation, GIS-MCA.

## ملخص

تم حث المتخصصين على البحث عن طرق فعالة ذات نتائج أكثر دقة وفي حينها للتنبؤ بالفيضانات، وبنشأ هذا الحض من إدراك أن العديد من العوامل تساهم في التعرض للفيضانات، مما يؤثر على كل من المناطق الحضرية والريفية ويؤدي إلى تداعيات بعيدة المدى وواسعة النطاق. من بين الأساليب المعروفة لمواجهة هذا التحدي طرق التحليل متعدد المعايير المستندة على نظم المعلومات الجغرافية.

في دراستنا، سنستكشف توقع الفيضانات وتقييم مخاطرها، ولا سيما في منطقة مستجمعات المياه لنهر وادي الساحل، باستخدام طرق التحليل التسلسلي الهرمي المعتمدة على نظم المعلومات الجغرافية وطرق التحليل التسلسلي الهرمي الضبابي، قد حققت هذه الطرق نتائج دقيقة جداً عند التحقق منها باستخدام منحى AUC وتم تحقيق دقة بنسبة 88.40% و 92.00% على التوالي في نتائج تحليل التسلسل الهرمي وتحليل التسلسل الهرمي الضبابي. لإدارة مخاطر الفيضانات في المستقبل، نوصي بشدة باستخدام طرق متعددة المعايير بينما يعد تحسين جودة البيانات وتوافرها أمراً ضرورياً لاتخاذ قرارات مستنيرة، ويضمن اختيار معايير التحسين تقييمًا شاملاً لاستراتيجيات إدارة الفيضانات، ويجب أن يدمج ويرصد في الوقت الفعلي البيانات لتمكين الاستجابات في الوقت المناسب واتخاذ القرار الملائم، ثم أن تقييم الاستراتيجيات الفعالة التي تعزز قدرات النمذجة أمر لا بد منه، وأخيراً تعزيز تعاون أصحاب المصلحة وتعزيز الوعي العام لصنع القرار الشامل والمناسب.

يساعد استخدام أساليب التحليل متعدد المعايير المستندة إلى نظم المعلومات الجغرافية (GIS-MCA) للتخطيط طويل الأجل والتقييم المستمر على تحسين تخصيص موارد المياه ومعالجة التحديات الناشئة.

**الكلمات الرئيسية:** تعرض للفيضانات، تحليل التسلسل الهرمي الضبابي، تحليل التسلسل الهرمي، مخاطر الفيضانات، التحليل المتعدد المعايير المعتمدة على نظم المعلومات الجغرافية.

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# ***GENERAL INTRODUCTION***

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# General Introduction

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Natural phenomena proved without doubt our lack of control over their occurrence, triggers, and destructive consequences. While material losses can be recovered and life forms restored, human losses are unrecoverable. Floods are one of the most common natural destructive phenomena that threaten every form of life in the area.

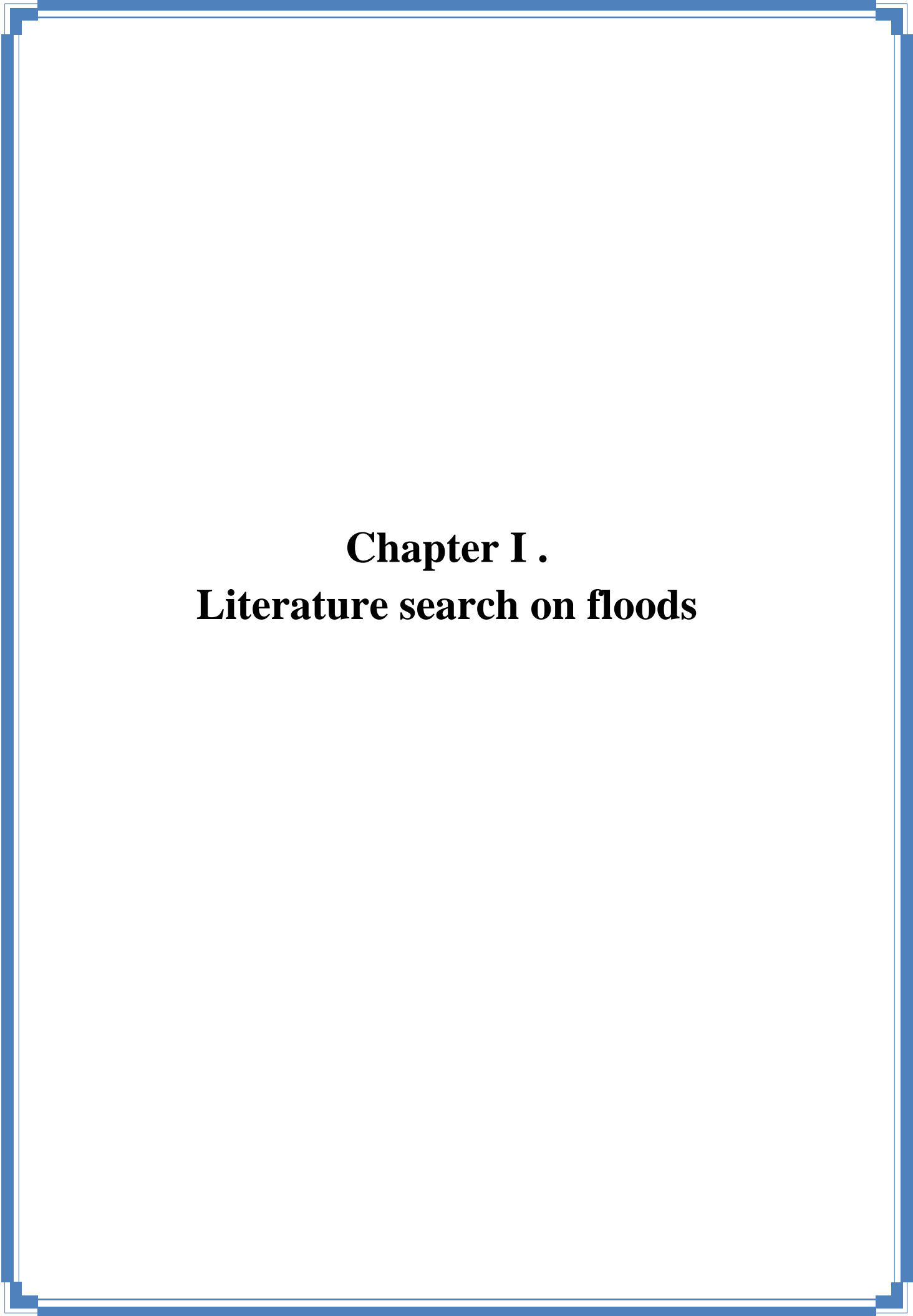
To better understand floods, a comprehensive study of the watercourse catchment area is essential. This includes conducting digital modeling and studying the phenomenon itself. The purpose of studying the watercourse catchment area, particularly the sub-watershed of Wadi El Sahel within the Soummam watershed, is to gain a general understanding of its characteristics. This information provides valuable insights into the behavior and potential impacts of flooding in the region.

One of the approaches used for flood forecasting is the multi-criteria analysis methods (MCA) and geographic information systems (GIS), which are important tools to flood risk management. MCAs integrate criteria to prioritize strategies, considering economic, environmental, and social factors. GIS provides a spatial framework for analyzing flood-related data, identifying susceptible areas, and planning emergency responses. MCAs and GIS combined enhance flood risk assessment, floodplain management, and emergency planning. This approach strengthens overall flood management strategies.

the objective of this study is to map the flood-prone areas in the sub-watershed of Wadi El Sahel with the use of GIS-based multicriteria decision analysis for flood risk assessments in the study area and will be useful tools in defining the degree of flood risk in different areas within the sub-watershed of Wadi El Sahel.

The thesis consists of three chapters:

- The first chapter is literature search on floods.
- The second chapter is description of the watershed of Wadi El Sahel.
- The study concludes with the flood susceptibility maps and results validations produced by the methods used, then the global conclusion about the efficiency of these methods in the study area.



**Chapter I .**  
**Literature search on floods**

## **I.1 Introduction :**

Natural phenomena perpetually confronts us with our lack of control over their occurrence, causing deadly and destructive consequences. While material losses can be recovered and life forms restored, human losses are unrecoverable. since the damage caused cannot be reversed, therefore more effective prevention methods must be sought.

Floods are one of the most common natural destructive phenomena that threaten every form of life in the area causing extensive damages that impact various aspects of life in the affected regions.

## **I.2 Flood definition :**

A flood is defined as “a temporary condition of surface water (river, lake, sea), in which the water level and/or discharge exceeds a certain value, thereby escaping from its normal confines”.<sup>[1]</sup>

It is the event when normally dry land gets submerged in water. Flooding occurs usually when an area receives excessive rainfall or rapid snowmelt, or encounters a failure of man-made structures such as dams or reservoirs with the inability of the soil to absorb it. The overflowing concentrates and flows towards lower lands inundating roads, buildings, and agricultural fields. Flooding can cause considerable damage to infrastructure, obstruct transportation services, contaminate water sources, and menace lives and properties. The severity of a flood can vary from minor localized flooding to large-scale catastrophic events affecting entire regions.

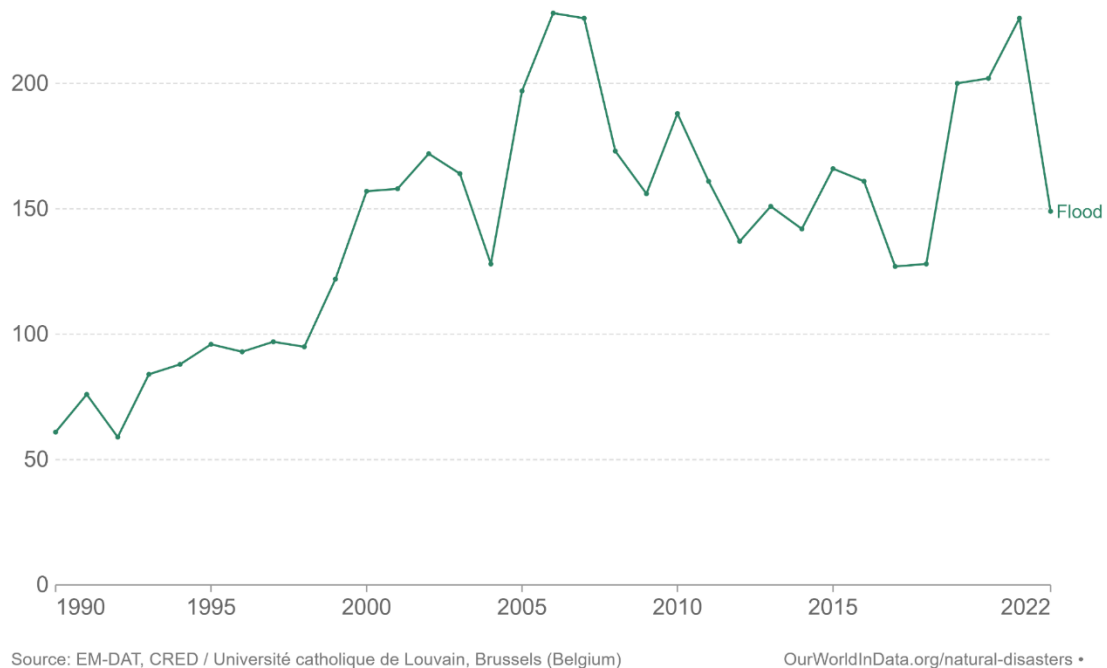
## **I.3 Floods history :**

### **I.3.1 In the world:**

Floods are among the most powerful forces on Earth. Human societies worldwide have lived and died with floods from the very beginning, spawning a prominent role for floods within legends, religions, and history. The history of floods can be traced back to the earliest civilizations, such as Mesopotamia and Egypt, where regular flooding of rivers like the Tigris, Euphrates, and Nile brought fertile soil for agriculture, but also posed threats to settlements. Inspired by such accounts, geologists, hydrologists, and historians have studied the role of floods on humanity and its supporting ecosystems, resulting in a new appreciation for the many-faceted role of floods in shaping our world.<sup>[2]</sup>

For the last half-century, the flood rate soared globally alarming governments, communities, and individuals, the following graph illustrates the flood inventory in the last 5 decades worldwide.

Number of recorded natural disaster events, 1990 to 2022



**Figure I.1.** Recorded floods in the last 50 years in the world <sup>[12]</sup>

It is crucial to stress that, while the global flood rate continues to rise, the specific impact of flooding events varies with their geographical location. Some areas may have more frequent or severe flooding, while others may see a reduction or remain relatively stable. Local variables such as topography, hydrology, and land management techniques may all have an impact on flood patterns and their effects on different areas.

Sample of major floods in the last two decades:

- 2022 Pakistan floods have affected at least 33 million people and killed at least 1,739 <sup>[3]</sup>
- January 2010 Haiti 230,000 died and in the same year in China floods 2,187 people were killed <sup>[4]</sup>
- September 23, 2008, Indian floods caused over 2,400 death and 22 million have been affected <sup>[5]</sup>
- 2007 South Asian floods affected Bangladesh, India, Myanmar, Nepal, Pakistan causing tens of millions of people to be affected and over 2000 people to get killed. <sup>[6]</sup>

### I.3.2 In Algeria :

Algeria, like other countries around the world, has experienced several floods in recent decades. These catastrophes have resulted in considerable casualties, significant material damage, and extensive economic and environmental losses. Here are some flood events that happened in Algeria in the last two decades:

- Algiers (Bab-El-Oued): November 10, 2001, which resulted in 710 deaths, 115 missing, and 30 billion dinars of economic losses.<sup>[35]</sup>
- Ghardaia in October 2008 Caused 100 death, 89 injured, and estimated material damage at 250 million euros.<sup>[34]</sup>



**Figure I.2.** Ghardaia flood in October 2008 <sup>[34]</sup>

- In 2009 the Wilayas of Elbayadh, Laghouat, and Naâma were submerged causing 15 deaths and huge losses of property .
- Elbayadh in 2011 resulted in 9 billion DA of economic losses and submerged many of the city's infrastructures under the water and 11 deaths.
- Tindouf in 2015 affected around 50.000 people and led to huge material losses.
- In 2023 the Wilayas of Tipaza, Boumerdes, Annaba, Setif, Skikda, Medea, Chlef, and Biskra each of these Wilayas suffered catastrophic flooding, that led to vast material losses in all flood-affected areas and 9 death tolls.<sup>[35]</sup>



**Figure I.3.** Severe floods in the north parts of the country(2023) <sup>[37][36]</sup>

## **I.4 Types of floods:**

different floods require different risk management and prevention plans so it is only plausible to classify floods depending on different characteristics, severity, and impact, As follows:

### **I.4.1 Flash flood:**

Flash floods are characterized as sudden and obstructive flooding that occurs within a short period, generally within six hours following heavy rainfall or other events that cause a water inundation. Due to the speed and intensity of the floodwaters, such type of flooding may be hazardous with a substantial probability of fatal consequences. Flash floods may occur in different geographic areas, (urban, rural, and coastal areas, etc.)

### **I.4.2 Urban flood :**

An urban flood is an inundation incident that develops within an urban area due to water overflowing onto streets, roads, buildings, and other urban infrastructure.

Unlike natural bodies of water like rivers or lakes, urban environments have a significant number of paved surfaces, buildings, and other constructions that obstruct natural water infiltration through the soil. Instead, rainfall accumulates rapidly, overwhelming drainage systems, and causing localized floods. Urban flooding can happen in a variety of forms, from minor water accumulation on streets to more severe and disastrous flooding of buildings and properties.

### **I.4.3 River flood (fluvial ) :**

The situation in which there is an excessive and temporary overflow of water from a river, resulting in the flooding of adjacent areas beyond the typical limitations of the riverbanks, is referred to as a river flood. It is a natural phenomenon during which the river's water level expands over its average range, causing the river to spill over into neighboring land and potentially resulting in temporary or long-term flooding in the areas affected.

### **I.4.4 Coastal flood :**

The global rising sea level is leading to unforeseen flooding in coastal areas. A coastal flood is the occurrence of the temporary overflow of ocean or sea water over low-lying lands along the coast. Due to various factors, it can range from temporary localized events to large-scale and long-term catastrophes.

### **I.5 Flood duration:**

Flood duration is the amount of time that a flood event persists or continues in a particular area. It defines the time span from the beginning of the flooding until the reversion of water levels to normal ( non-flood levels).

Flood duration can vary widely depending on various parameters such as rainfall intensity, the volume of water reaching a river or basin, the geography of the area, and drainage system functionality. While Some floods extend a few hours or days, whereas other events could last for weeks or even months. The speed and duration of flooding can vary significantly:

- Flooding can occur slowly as rain continues to fall for many days. This type of flooding, sometimes called a slow-onset flood, can take a week to develop and can last for months before floodwaters recede. [7]
- Rapid-onset floods occur more quickly, typically developing within hours or days. These types of floods usually occur in smaller watersheds experiencing heavy rainfall, particularly in mountainous and urban areas, and the water usually recedes within a few days. [7]

### **I.6 Severity class and magnitude of floods: [1]**

The “severity class” in the DFO database represents an indicator for flood magnitude assessment purposes on a 1–3 scale :

- Class I: large flooding events, significant damage to structures and/or agriculture, casualties and/or a one to two decade-long reported interval since the last similar event;
- Class II: vast flooding events exceeding 20, but less than 100-year estimated recurrence interval and/or a local recurrence interval of around one to two decades affecting a large geographic region (>5000 km<sup>2</sup> );
- Class III: extreme flooding events; estimated recurrence interval >100 years.

## **I.7 Flood causes :**

### **I.7.1 Natural causes:**

- **Heavy rainfall or precipitation:** Depending on the temperature conditions in the atmosphere, heavy precipitation can downfall in the form of rain, snow, or hail. Heavy precipitation can be identified by the high rate of precipitation over a specified area and greater than or equal to 50 mm in 24 hours <sup>[8]</sup>.
- **Natural catastrophes:** Some other natural disasters may additionally trigger floods such as earthquakes, hurricanes, volcanic eruptions, tsunamis, or storm surges in coastal areas which can It may induce large-scale floods and disastrous outcomes.

### **I.7.2 Human-Induced causes:**

- **Urban land use:** Urban encroachment over floodplains and areas near watercourses and increased impervious surfaces. Which led to the channelization and modification of rivers, besides the deforestation of the forests for furthermore urban expansion.
- **Agricultural land use:** Initially, agricultural land use can have the same impact as vegetation cover, in that crops can intercept precipitation and reduce runoff. However, intensive agriculture where irrigation may be used, can cause waterlogged soils and therefore lead to runoff. Heavy use of agricultural machinery can compact the soil and reduce its infiltration capacity, making runoff more likely. <sup>[9]</sup>
- **Poor water management and structural failure:** While poor water management and unmaintained infrastructure take a significant role in causing floods and increasing their consequences, we encounter frequently structural failures that range from small-scale water management structures failures like canals and weirs to bigger- scales structure failures such as dams and large water tanks.
- **Climate change:** Floods are growing increasingly frequent and severe as a result of climate change. Rising global temperatures increase water evaporation, resulting in more precipitation occurrences. Furthermore, melting glaciers and ice caps are leading to rising sea levels, exposing coastal areas to an increased susceptibility to storm surges and tidal flooding. Changes in precipitation patterns may additionally impact river flows, increasing the hazards of floods.

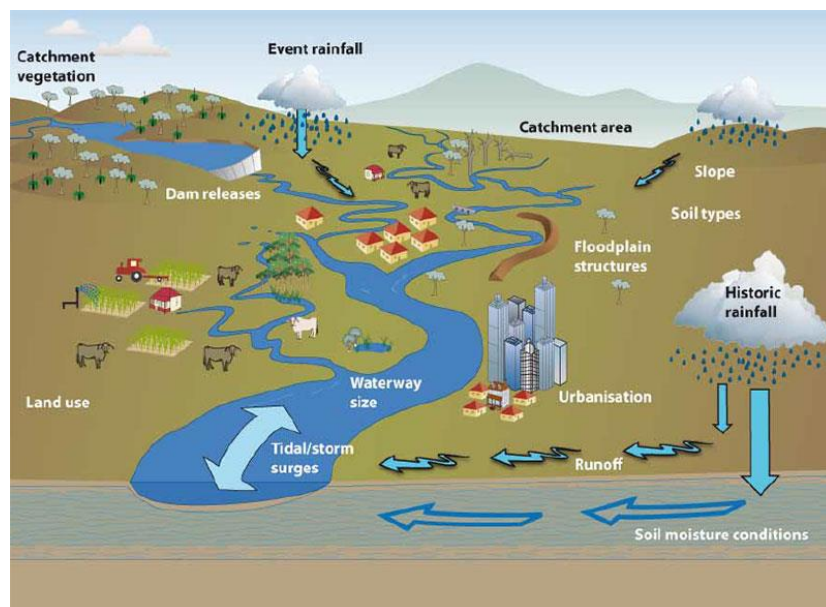
### I.7.3 Geological causes:

➤ **Topography:** The natural topography of an area has a vital role in flooding, Areas with steep slopes can cause water to flow rapidly. and in case of heavy precipitation will cause floods along the channel. While low and flat areas such as plains have difficulty draining water quickly. so when there are heavy downpours, the water can collect and accumulate resulting in flash floods in these areas.

Generally, the narrow drainage channels and the presence of natural or human obstacles that impede the flow increase the susceptibility to flooding.

➤ **Groundwater conditions and soil saturation:** High groundwater levels or the presence of impermeable layers of soil can obstruct water infiltration and contribute to excess surface runoff. In areas with limited groundwater recharge or poor permeability, excess rainfall can quickly saturate the soil and lead to flooding. Similarly, in areas with high soil saturation or waterlogged conditions, even moderate rainfall can lead to runoff and surface flooding since the ground is already unable to absorb additional water. These conditions can further worsen flood risks and increase the vulnerability of an area to flooding events.

While the listed causes of floods are more typical causes, it is imperative to comprehend that floods may occur due to a variety of causes, it may be specific or localized flood factors. Each flood occurrence is unique and might result from a unique interplay of various factors. As a result, flood causes can vary based on characteristics such as geographic location, climate, weather patterns, and human activity in the area.



**Figure I.4** Illustration of flood factors <sup>[10]</sup>

## **I.8 Flood consequences:**

### **I.8.1 Economic consequences:**

Since 1980 floods have caused over \$1 trillion in damage, accounting for about 40 % of natural catastrophe losses. [11]

As it may have drastic consequences, affecting a variety of industries. Damage to infrastructure, such as roads, bridges, and structures requires enormous repair and reconstruction costs. Furthermore, floods frequently cause damage and loss of real estate and assets, leaving individuals and communities with financial and emotional liabilities. The business sector faces additional challenges, with flood-related closures and impeding operations, resulting in financial losses along with potential layoffs. Floods may additionally have detrimental effects on food production and agriculture, damaging crops, animals, and agricultural infrastructure. This, consequently, might result in food insecurity, increased food costs, and long-term effects for the affected regions. Floods can disrupt the supply chain, creating difficulties in the supply of products and services, with adverse effects across different sectors. Overall, floods have far-reaching consequences for infrastructure, the economy, agriculture, and insurance, highlighting the significance of integrated flood prevention, management, and mitigation techniques.

### **I.8.2 Environmental consequences:**

Devastating effects on ecological systems and the environment as a whole. One of the gravest repercussions is the destruction of ecosystems and biological diversity caused by floods. Floodwaters can cause habitat loss and species relocating, resulting in long-term ecological disturbance. Additionally, floods contribute to soil erosion and degradation by carrying away topsoil and depleting necessary nutrients. This can have an unfavorable effect on agricultural production and land quality overall. Furthermore, floods can pollute water bodies by collecting pollutants and toxic chemicals, causing harm to aquatic life and reducing water quality.

A further impact is the disturbances of natural habitats since flood occurrences could change the structure and composition of ecosystems, affecting the delicate balance of flora and fauna. Floods can also trigger the leakage of pollutants and toxic materials stored in industrial areas or waste sites, endangering both human and environmental health. When dealing with flood management and devising ways to alleviate their ecological implications, it is essential to consider these environmental impacts.

### **I.8.3 Public health consequences:**

As floodwaters might become contaminated with bacteria, viruses, and parasites, the presence of stagnant waters and poor sanitation in flood-affected regions may significantly raise the risk of waterborne illnesses such as cholera, dysentery, etc. Furthermore, the spread of vector-borne illnesses such as malaria and dengue fever can widespread as floods create ideal breeding grounds for disease-carrying mosquitos and other vectors. The health risks further escalate as floodwaters contaminate water supplies and disrupt proper food handling and storage, leading to potential outbreaks of gastrointestinal illnesses. Moreover, the mental health impacts of floods should not be overlooked, as individuals and communities may experience emotional distress, anxiety, and post-traumatic stress disorders in the aftermath of such disasters. Floods can also exacerbate existing mental health conditions. Access to healthcare services may become limited or compromised during and after floods due to damaged infrastructure, displacement, and overwhelmed healthcare facilities. Addressing these health-related challenges requires a comprehensive approach, focusing on clean water provision, vector control measures, public health awareness, mental health support, and ensuring adequate healthcare services in flood-prone areas.

### **I.8.4 Social consequences:**

Floods have major social consequences, causing population displacement and the loss of properties, assets, and stability. These difficulties not only have material consequences but also emotional and psychological effects. Social disruption and fragmented communities are common as people are scattered, hindering social connections and support networks. Education and social services are disrupted, damaging the continuity of essential services. The consequences emphasize the importance of comprehensive support systems and community resilience. In the face of flood events, addressing social impacts is crucial for the well-being and recovery of affected populations.

### **I.8.5 Infrastructure consequences:**

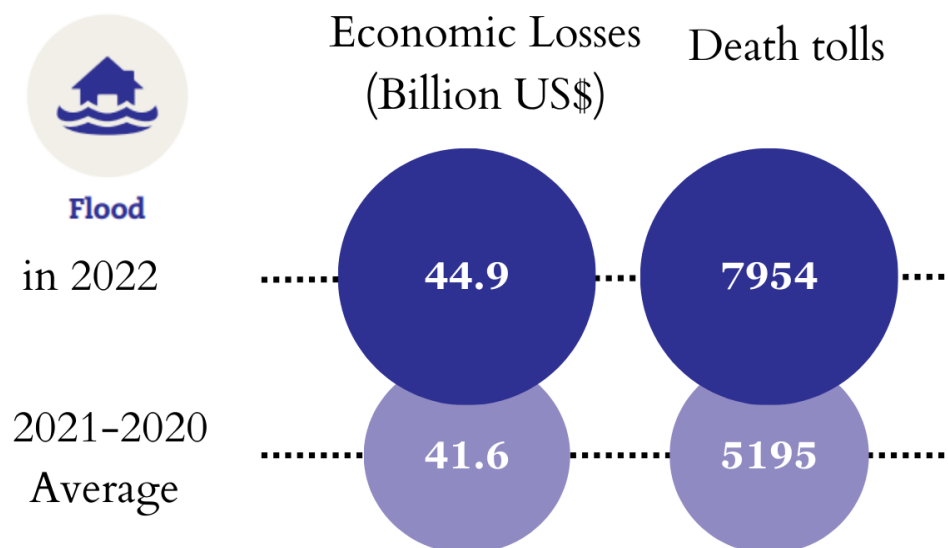
Infrastructure is crucial for the functioning and connectivity of societies. When a flood occurs, it may cause severe damage to infrastructure and services. The transportation infrastructure, which includes roads and bridges, can be subject to serious damage, causing interruptions in travel. Communication networks, including telephone lines and internet connections, are susceptible to damage during floods, leading to communication malfunctions. Moreover, Similarly, the infrastructure for energy and water services is adversely affected, restricting access to potable water and electricity.

Public facilities and services, such as schools and hospitals, face damage, hindering their functionality. Moreover, floods disrupt utilities like water treatment plants and sewage systems, exacerbating the challenges faced by communities. Addressing these impacts requires resilient infrastructure and security measures to ensure the continuity of essential services during and after flood events.

#### **I.8.6 Secondary hazards and risks:**

Following a flood, secondary hazards and risks can emerge, such as the displacement of soil and debris causing landslides, the heightened risk of electrical accidents and fires due to damage to electrical systems, etc.

The effects of floods can be intricate and interconnected, requiring the acknowledgment of various factors. The outcomes of a flood event depend on elements such as the flood's intensity and duration, the emergency plans and flood management undertaken, the vulnerability of the affected population, and the resilience of the infrastructure and ecosystems within the region.



**Figure I.5.** Economic losses and death tolls of floods in the past three years in the world <sup>[13]</sup>

### **I.9 Flood forecasting methods :**

Changing climate, sea level rise, subsidence, and land use changes have profound implications for the combined impact on flooding by changing precipitation, infiltration, abstraction, and drainage characteristics. With the predicted sea level rise of two to four feet over the next century, increases in runoff from urbanizing watersheds, land subsidence, and changes in precipitation intensity and duration, these hazard floods are expected to exceed levels observed in the past significantly. <sup>[14]</sup>

According to the Emergency Event Database EM-DAT, The total of 176 flood events in the year before is slightly higher than the average from 2020 to 2021 (168) with estimated economic losses of 44.9 billion (US \$)in 2022. <sup>[13]</sup>

Additionally, the total death toll of 5916 in the last year surpassed each of the 2020-2021 death tolls 5066, and 5389 sequentially. <sup>[15]</sup>

Observing, understanding, predicting, mitigating, and recovering from the impacts of a single hazard remains a challenge. So hazard events pose tremendous challenges for scientists, engineers, and first responders to anticipate, mitigate, and recover from the combined impacts of changing hazard drivers. Addressing these hazard challenges of monumental scale requires a comprehensive, long-term strategy. These efforts must include advanced understanding, assessment, and prediction of natural and human-induced variations in our environment. we must be able to identify and assess the magnitude of current threats, evaluate various preventative and corrective actions, and predict future floods. <sup>[14]</sup>

Flood prediction and modeling generally include approximate descriptions of the transformation processes rainfall- runoff. A variety of hydrologic flood prediction models are used for forecasting. They can be categorized into physical models and mathematical models (data-driven). Commonly, physical hydrodynamic models are used to simulate urban pluvial flooding. They can be divided into one-dimensional (1 D) hydrodynamic models such as the SWMM model, two-dimensional (2 D) hydrodynamic models such as the TELEMAC-2D model, and 1 D-2D hydrodynamic models such as MIKE URBAN. These models solve the shallow water equation numerically. However, they can only be applied to small areas using a fine spatial resolution and cannot be scaled to produce flood hazard maps for large areas. <sup>[16]</sup>

While data-driven model forecasting methods assimilate measured climate and hydrometeorological parameters to provide better insights, including Auto-Regressive (AR), Auto-Regressive, and Moving Average (ARMA), Auto-Regressive Integrated Moving Average (ARIMA), Linear Regression (LR), and Multiple Linear Regression (MLR) <sup>[17]</sup>

## **I.9.1 GIS-based Multicriteria Analysis methods in flood forecasting :**

### **I.9.1.1 Geographic information systems(GIS):**

Geographic information systems have emerged as an essential tool for urban and resource planning and management. Their capacity to store, retrieve, analyze, model, and map large areas with huge volumes of spatial data has led to an extraordinary proliferation of applications. Geographic information systems are now used for land use planning, utility management, landscape assessment and planning, transportation and infrastructure planning, market analysis, facilities management, and many other applications. <sup>[18]</sup>

### **I.9.1.2 Multicriteria analysis (MCA):**

MCA methods are decision-making methods that help provides a structured framework for evaluating alternatives based on multiple criteria, allowing decision-makers to consider various factors and perspectives in the decision-making process, incorporating Multicriteria Analysis (MCA) with flood forecasting introduces a data-driven element to the decision-making process. MCA involves the use of data to evaluate and compare alternatives based on multiple criteria In the context of flood forecasting.

#### **• Analytic Hierarchy Process :**

The AHP has been developed by Saaty in 1980, The AHP is a general theory of measurement. It is used to derive ratio scales from both discrete and continuous paired comparisons. These comparisons may be taken from actual measurements or from a fundamental scale which reflects the relative strength of preferences and feelings <sup>[19]</sup>

It is considered a mathematical technique of multi-criteria decision-making. Researchers have relied mainly in their strategy to assess the impact of flood hazards on integrating AHP approach with other approaches such as GIS and artificial intelligence (AI) to estimate flood risk in specified areas. <sup>[20]</sup>

#### **• FUZZY Analytic Hierarchy Process:**

Fuzzy AHP is a hybrid method combining the Fuzzy logic concept, the mathematical tool of the fuzzy set theory with the analytic hierarchy analysis. The task of multi-criteria evaluation in the conditions of non-statistical uncertainty, often using linguistic expressions, is very effectively formulated using the theory invented by Zadeh. <sup>[21]</sup>

Fuzzy AHP was first mentioned and introduced by Hwang and Yoon In their paper, Hwang and Yoon recognized the limitations of traditional Analytic Hierarchy Process when dealing with uncertain and subjective information.

They introduced the concept of fuzzy numbers and linguistic terms to express preferences in pairwise comparisons within the AHP framework.

By incorporating fuzzy set theory, they extended AHP to handle imprecision and uncertainty more effectively, leading to the development of Fuzzy AHP. Hwang and Yoon's work laid the foundation for further research and evolution of FAHP, and their paper is widely regarded as the seminal work that introduced the concept of Fuzzy Analytic Hierarchy Process into the field of decision-making. [22]

The combination of Analytic Hierarchy Process or Fuzzy Analytic Hierarchy Process and Geographic information systems leverages the strengths of both methodologies, providing a more comprehensive and spatially-informed decision-making framework. However, it is important to note that the integration of AHP or FAHP and GIS requires careful consideration of data quality, appropriate spatial analyses, and effective communication of results.

### **I.10 Conclusion :**

In conclusion, floods are natural phenomena that threaten lives, infrastructure, and the environment. They can occur as a consequence of various factors such as heavy rainfall, human activities, climate change, and geographical characteristics. Floods have wide-ranging consequences economically, environmentally, socially, health, and infrastructure. More effective flood protection and forecasting methods ought to be used to efficiently limit flood losses. the approach of the GIS-based multicriteria analysis in flood forecasting is widely used in recent times, Geographic Information Systems combined with the multicriteria analysis methods integrate various data sources and criteria to provide accurate, reliable, and timely forecasting, supporting better flood risk management.

**Chapter II .**  
**Description of the watershed of**  
**Wadi El Sahel**

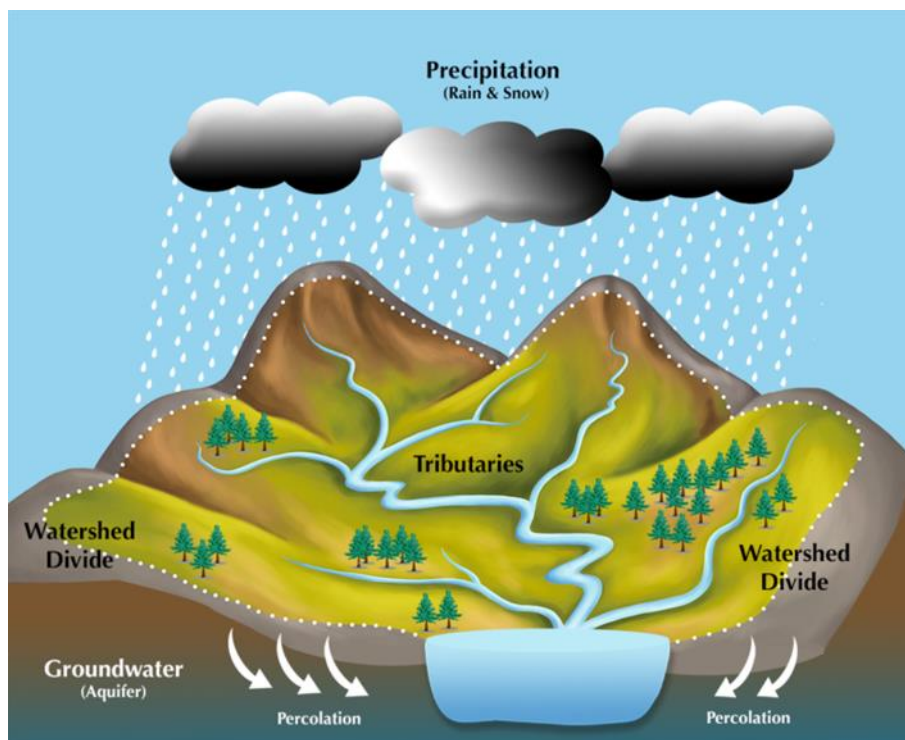
## II.1 Introduction:

A thorough study of the watercourse catchment area is essential before any digital modeling or any phenomenon study. The purpose of this chapter is to provide general knowledge of the main characteristics of the Soummam watershed in general and the sub-watershed of Wadi El Sahel more precisely. So this part will be first and foremost illustrative and subjective. Firstly, we will describe the sub-watershed area overall, by locating it geographically and studying its topology and geology. and lastly, analyzing the main watercourse and its tributaries.

## II.2 The watershed Concept:

The catchment area collects the runoff water which recharges the water table. This region is determined by its geographical and topographical area, climatic conditions, geology, flora, and soil; it can be a subterranean, lake, river, or complicated network.

More specifically a watershed may be regarded as a "system", which is a hydrologically closed element in which no flow penetrates from the outside and all excess precipitation evaporates or flows through a main watercourse to the outlet.

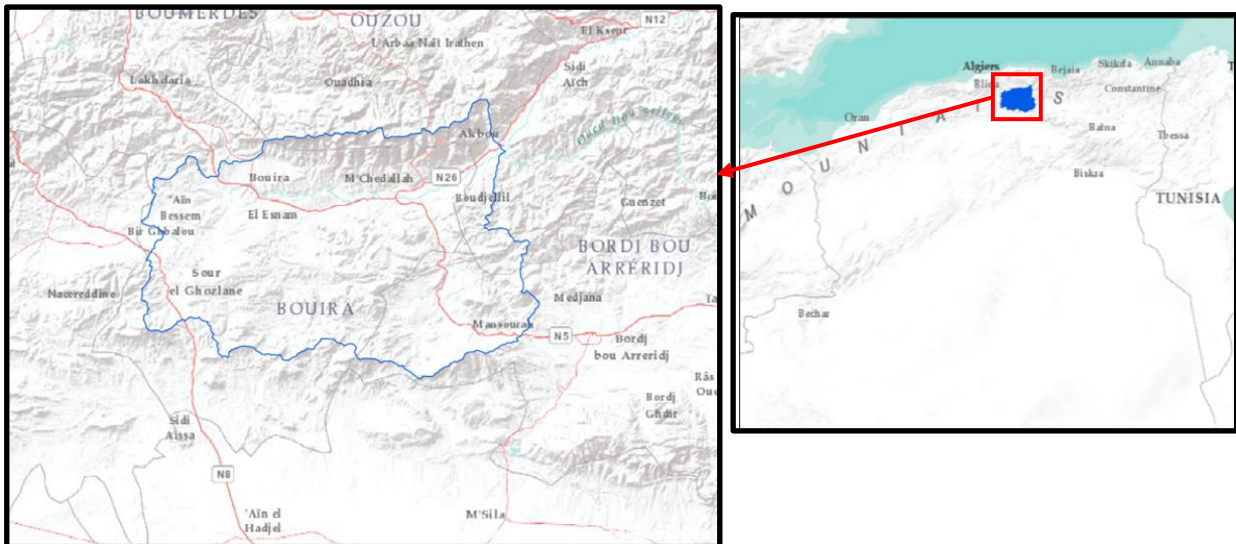


**Figure II. 1.** Illustration of a watershed [23]

### II.3 The geographic location of the watershed of Wadi El Sahel (Soummam):

The watershed of the Sahel wadi is in the northeastern part of Algeria, between 3°60' and 4°70' east longitude and 36°00' and 36°50' north latitude." The watershed of the Sahel Wadi runs northwest to southeast. It consists majorly of communes in the Wilaya of Bouira and some other communes located in the Wilaya of Bejaia. It is bordered by:

- To the north: the Great Kabylie Mountains (Djurdjura massif).
- To the east, along the Little Kabylie Mountains."
- To the south are the Bibans and Mansourah mountains, and to the southeast are the Hodna mountain foothills.
- To the west, it is constrained by the Isser and Sébaou rivers. It has an extremely uneven form.



**Figure II. 2.** Location of the watershed of the Sahel Wadi (soummam)

**Table II. 1.** The areas of the sub-watersheds of the Sahel Wadi (Soummam)

(A.N.R.H., 1979, 1980)

Under watershed	Code	Area (km <sup>2</sup> )
Wadi Eddous	1501	903.00
Wadi Zaiane	1502	1012.00
Upstream Wadi El Sahel	1503	430.00
Wadi Azerou	1504	1084.00
Downstream Wadi El Sahel	1505	326.00

#### II.4 The climatic conditions of the region's geodynamic context:

The climate in the Sahel Wadi (Soummam) watershed differs from one area to the other. It depends on the three climate types: temperate coastal climate in the lower parts of Oued Soummam, Atlas Tellien climate in the middle, and the upper part of the Soummam.

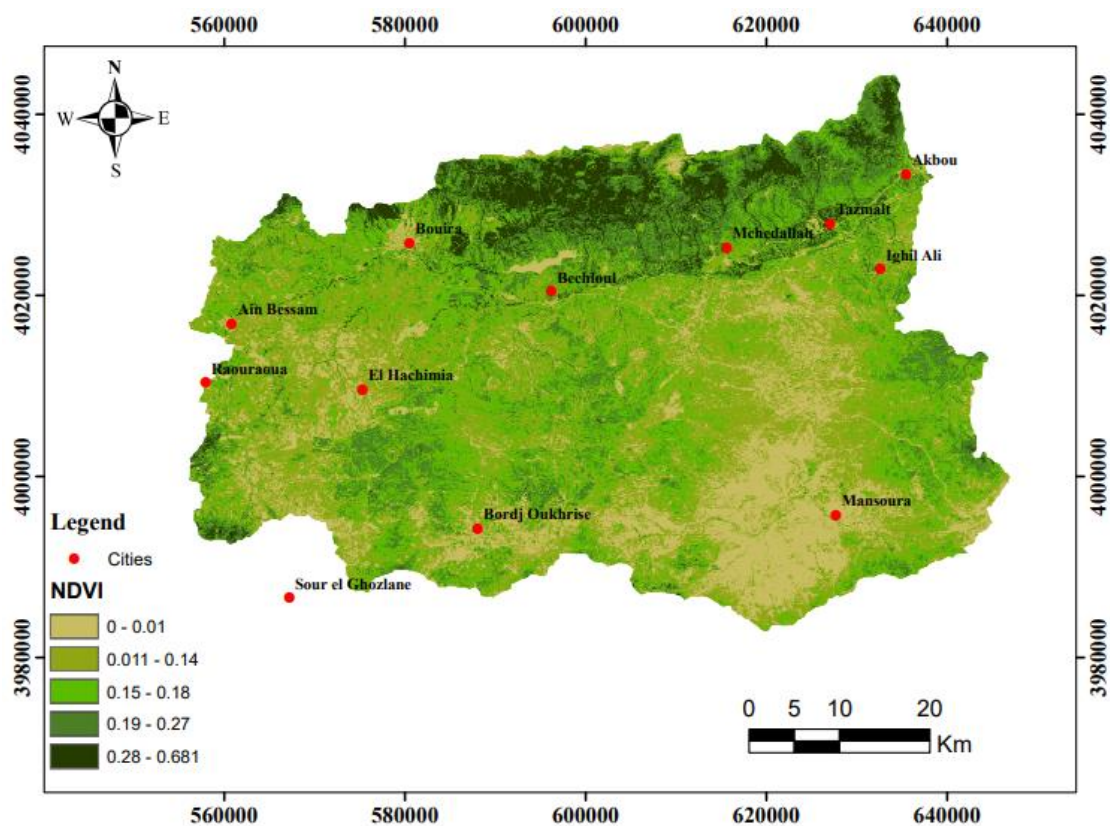
##### II.4.1 Coastal climate: <sup>[24]</sup>

The average temperature ranges from 18°C near the sea to 15°C among the most pronounced elevations. The monthly averages have an annual amplitude ranging from 14°C to 16°C. The relative humidity is relatively high, with a very low amplitude diurnal cycle. Annual averages at 18 hours are 70% and 60% to 65% at 13 hours. The average annual rainfall rises gradually from west to east, but more dramatically with altitude. It ranges from 400 mm to 500 mm at 800 m altitude in the Sahel Valley. The precipitation regime has a maximum in December and a low in July. One of the most distinguishing elements of this climate is the alternation of sea and land winds. The sirocco wind blows 20 to 30 days out of the year. White frosts are extremely unusual, occurring about 0 to 2 days per year on average.

### II.4.2 Plant cover :

The vegetation in the Sahel Wadi (Soummam) watershed is of the Mediterranean type and it is quite diverse. The upper Sahel's alluvial plains are dominated by oak trees. Olive orchards and vineyards dot the lower and the middle of the sub-watershed.

The plant cover is less dense in the middle of the Sahel. The vegetation of the plain is thick but fundamentally transient, generated by enormous and vast fields of diverse vegetable crops. The trees in the area are certainly fundamental for a thriving lumber sector, However, this vegetation has been exposed to wildfire in recent years but hopefully, it will be reforested owing to the efforts of both the government and the people.



**Figure II. 3.** Normalized Difference Vegetation Index of the Sahel Wadi (soummam)

### II.4.3 Geology : [23]

At the watershed of the Sahel Wadi (Soummam), we can see different geological formations:

- ❖ The Quaternary: alluvium along the Wadis and at the level of the high plains.
- ❖ The Continental Pliocene: siliceous and river gravels crown the Sahelian slope. In some other places, the terrain is conglomeratic, if not stony.
- ❖ The Miocene: Essentially, this is the Lower Miocene.
- ❖ The Oligocene: mostly clay-sandstone. It abounds from Tazmalt westward, as well as on either side of the Sahel valley. It may be found in the Gouraya and Beni-Mansour ranges.
- ❖ The Eocene: entirely marly, occasionally calcareous-marly. It is mostly found on the upper plains.
- ❖ The Cretaceous period is typically represented with flysch. It stretches from the Biban chain to the highlands of Little Kabylie. The Upper Cretaceous (Senonian) facies is marly. It is schistose, with benches hundreds of meters deep and occasional sandstone intercalations in the middle Cretaceous (Albian), and only appears in the vicinity of Béni-Mansour and the Bibans chain. In the Lower Cretaceous, it is sandstone, possibly carbonated sandstone.
- ❖ The Jurassic: it is most visible at the level of the limestone chain and along its continuation to the east. It is mostly calcareous-dolomitic.
- ❖ The Triassic has gypsy-saline facies and is represented in the southern Tell by conglomerates and reddish sandstones, while in the northern Tell by conglomerates and reddish sandstones.

### II.5 The soils :

The Sahel Wadi (Soummam) basin's soils are mostly calcareous (rich in limestone), Water changes the absorbent compound, and these soils are permeable because they have a light consistency.

Unsaturated soils to the north of the basin may not include limestone, and their clays may be more numerous at the surface than at deep; their source rock is typically impermeable or creates impermeable decomposition products, The soils along the valleys are clay deposits known as alluvial soils, which have an undifferentiated profile or minimal organic matter deposition on the surface. Besides, there are calcareous soils.

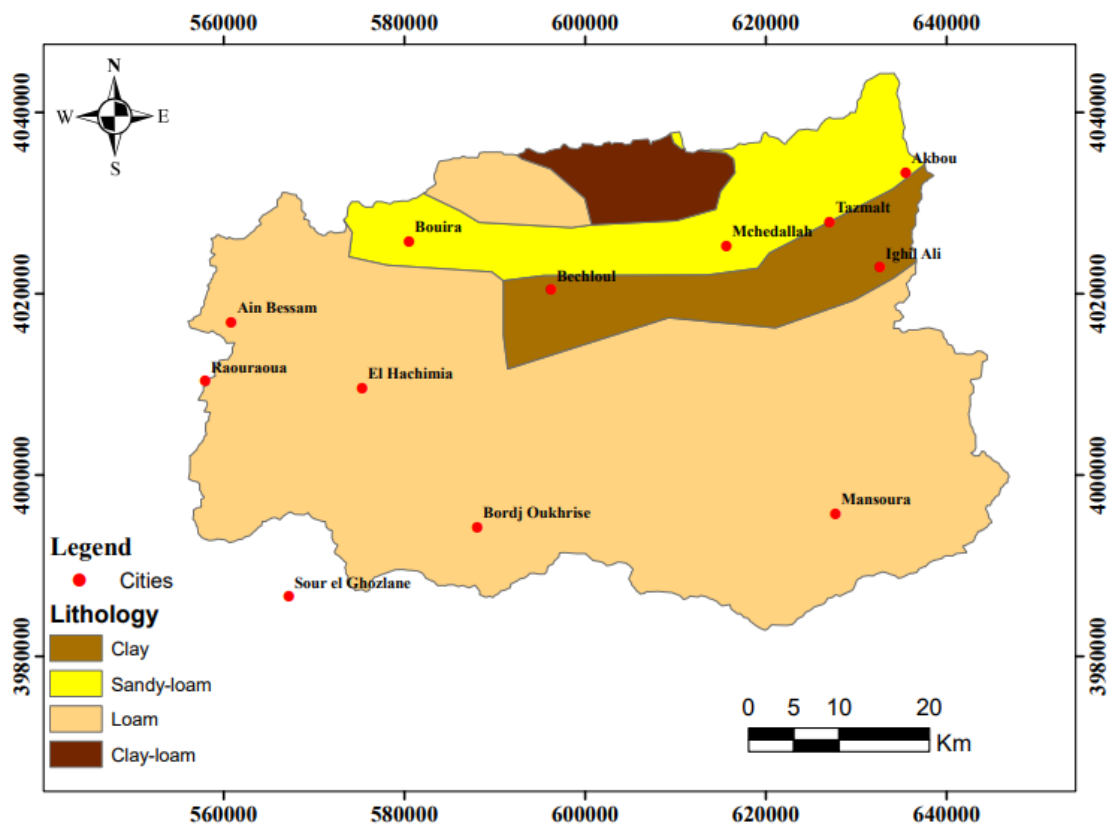


Figure II. 4. The lithology of the Sahel Wadi

## II.6 Physical properties : <sup>[24]</sup>

The physical environment in which the hydrological cycle occurs differs from one basin to another due to a range of physical, morphological, and geometrical characteristics that frequently interfere with the streamflow. The examination of these factors provides a better understanding of the reasons for variance in the hydraulic regimes of the basin. The Sahel Wadi basin is divided into five sub-basins, the boundaries of which are proportional to the hydrological units regulated by hydrometric stations. Thus, physical features are studied for each component tracked by gauging stations.

### II.6.1 Morphometric parameters :

A watershed's morphological features (shape, elevation, slope, relief, etc.) are pivotal to its hydrological cycle. Which in practical terms are amenable to quantifiable analysis, and therefore, ought to be provided beforehand of any study. The form of the watersheds, as measured by the Gravelius compactness index, that consequently affects the streamflow. The following parameters are the determining factors for the catchment dimension:

- **Area** = 3751.15 Km<sup>2</sup>
- **Perimeter** = 332.80 Km

#### II.6.1.1 The Gravelius compactness index (Kg):

The Gravelius compactness index is determined by comparing the calculated perimeter of the basin of the study case to the perimeter of a circle of an equal area.

$$Kg = \frac{P}{2\sqrt{\pi A}} = 0.28 \times \frac{P}{\sqrt{A}}$$

**With:**

- » **Kg:** is the Gravelius compactness index;
- » **A:** catchment area (km<sup>2</sup>);
- » **P:** catchment perimeter (km);
- » **L:** is the length of the equivalent rectangle;
- » **W:** is the width of the equivalent rectangle.

<b>Kg = 1</b>	The watershed is circular.
<b>Kg = 1,12</b>	The watershed is a square.
<b>Kg ≈ 1</b>	The watershed is rounded and compact.
<b>Kg differs from 1</b>	The watershed is elongated.

↳ **Kg=1.53**

### II.6.1.2 Equivalent rectangle :

The concept of an equivalent rectangle allows any form of a catchment area to be reduced to a rectangular shape with the same area, perimeter, and compactness index.

It is presented to be able to compare basins in terms of the effect of their geometric properties on the streamflow.

» The length of the equivalent rectangle:

$$L = \frac{Kg\sqrt{A}}{1.12} \left[ 1 + \sqrt{1 - \left(\frac{1.12}{Kg}\right)^2} \right] = 140.67 \text{ km}$$

» The width of the equivalent rectangle:

$$W = \frac{Kg\sqrt{A}}{1.12} \left[ 1 - \sqrt{1 - \left(\frac{1.12}{Kg}\right)^2} \right] = 26.66 \text{ km}$$

### II.6.2 Terrain parameters :

The reliefs of a watershed play an indisputable role in its hydrological behavior; it significantly determines the land's capacity to runoff, infiltrate, and vaporize the water.

The Sahel basin is a very uneven surface, with the Djurdjura, ranges to the north, the Bibans and Djebels Mansourah mountains to the south, and the Small Kabylie mountains to the east. The topography of the basin changes dramatically from Bouira to Akbou. The watershed's highest peak (Lalla Khedidja 2308 m) is located in this region, near M'Chedallah. The altitude gradually decreases as you go from Akbou towards the north.

#### II.6.2.1 Elevation properties :

In view of the fact that altitude influences the behavior of hydrological factors, it is justifiable to determine the distribution of the catchment area (in km<sup>2</sup> and the percentage of total area) by altitude range. The hypsometric curve may be applicable to derive four different types of distinguishable altitudes:

##### ❖ The mean height

The mean height of the sub-basins controlled by hydrometric stations is estimated by the A.N.R.H services from their respective hypsometric curves.

$$\gg H_{\text{mean}} = \frac{\sum H_i \times A_i}{A} = 778 \text{ m}$$

**With :** • **Hmean:** Mean height from the approved base chart;

• **A:** planimetric area of the envelope curve representing the volume of the basin.

### ❖ The Median height

The median height corresponds to the elevation read at the abscissa point 50% of the entire surface of the basin on the hypsometric curve. This magnitude is close to the mean height in cases where the hypsometric curve of the basin in question has a regular slope.

$$\gg H_{\text{median}} = 760 \text{ m}$$

### ❖ The Maximum and minimum height

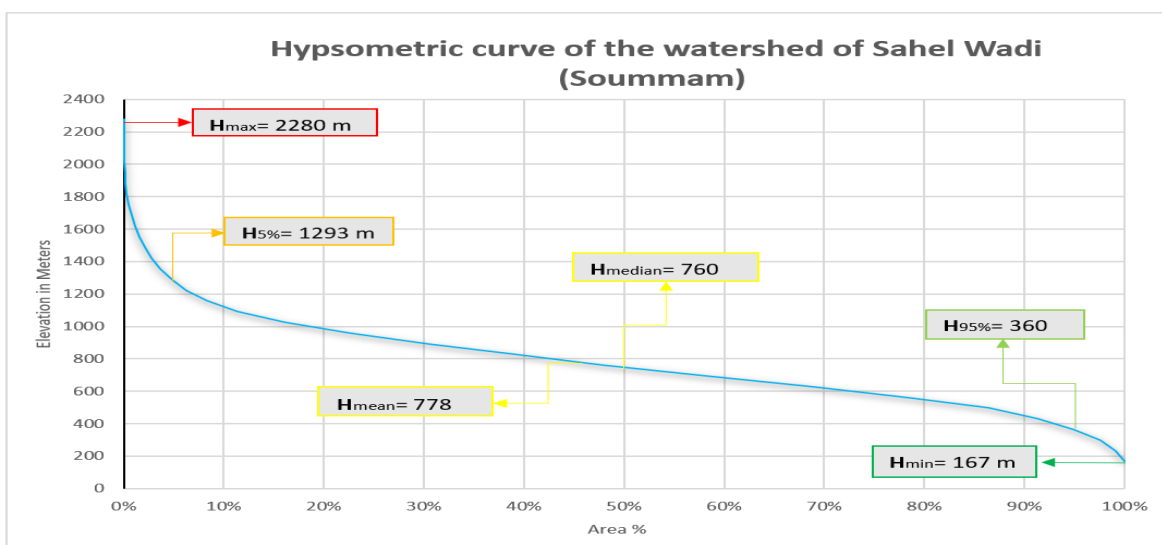
They are directly obtained from topographic maps. The maximum height is the highest point in the basin, while the minimum height is the lowest point, which is usually at the outflow. These two variables are crucial for developing correlations with climatological variables such as temperatures, precipitation, and so on. They determine the watershed's altimetric amplitude and contribute to the slope calculation.

$$\gg H_{\text{max}} = 2280 \text{ m} ; \gg H_{\text{min}} = 167 \text{ m}$$

## II.6.2.2 The hypsometric curve :

The relief is defined by the hypsometric curve, which shows the distribution of sub-basin elevations based on the related surfaces. It is measured by graphing the cumulative surfaces of the partial surfaces between two successive level curves ( $l_i$ ,  $l_{i+1}$ ) and the associated heights on the coordinate axis on the abscissa axis.

A hypsometric curve is an adequate tool for comparing different watersheds or sub-watersheds. It may also be used to estimate the average rainfall in a catchment region and provide information about the hydrological behavior of a catchment and its drainage system. The hypsometric curve is created by accumulating the elevation histogram. Therefore, it is attainable to determine the average elevation, the most frequent altitude, and the global slope index of the basin.



**Figure II. 5.** The hypsometric curve of the watershed of the Sahel Wadi (Soummam)

### II.6.3 Slope and relief indices:

#### II.6.3.1 Global index of Roche:

The relief plays a key role because it majorly impacts the runoff capacity of the land. Its interpretation can be made using the global slope index  $I_g$  given by the relationship:

$$I_g = \frac{D}{L} = \frac{(1293-360)}{140667} = 0.0066 = 0.66\%$$

**With:** »  $I_g$ : global index of Roche.

» **D**: Height difference (m), On the previously drawn hypsometric curve, we take the points where the upper or lower surface equals 5% of the total surface. **H5** and **H95** are the elevations between which 90% of the basin's surface falls. As a result, the difference in height **D** equals (**H5** - **H95**).

» **L**: length of the equivalent rectangle.

**Table II. 2.** Classification of relief according to  $I_g$  by ORSTOM

Very low relief	$I_g < 0.002$
Low relief	$0.002 < I_g < 0.005$
Fairly low relief	$0.005 < I_g < 0.01$
Moderate relief	$0.01 < I_g < 0.02$
Fairly high relief	$0,02 < I_g < 0.05$
High relief	$0.05 < I_g < 0.5$
Very high relief	$0.5 < I_g$

### II.6.3.2 Slope index:

It is to a certain extent an artificial index that takes into account the influence of the slope factor on the hydrological regime of the basin.

This index is calculated from the equivalent rectangle. It is equal to the sum of the square roots of the average slopes of each of the elements weighted by the surface under study, is equal:

$$I_s = \frac{1}{L} \sum_{i=1}^n \left[ X_i \sqrt{\frac{d}{X_i}} \right]$$

- With:**
- » **I<sub>s</sub>**: Roche slope index (%);
  - » **L**: Equivalent rectangle length (m);
  - » **X<sub>i</sub>**: distance between two curves on the rectangle (m);
  - » **d**: distance between two successive contour lines (m);
  - »  $\frac{d}{X_i}$ : the ratio slope of an element (%).

### II.6.4 Specific height differential :

the absence of a direct correlation between the global slope index of a basin with the surface of the same basin made comparing basins of different sizes inaccurate and unachievable.

Unlike applying the specific height differential **D<sub>s</sub>**

$$D_s = I_g \sqrt{A} = 406.22 \text{ m}$$

**Table II. 3.** The second classification of the O.R.S.T.O.M

Very low relief	<b>D<sub>s</sub> &lt; 10</b>
Low relief	10 < <b>D<sub>s</sub></b> < 25
Fairly low relief	25 < <b>D<sub>s</sub></b> < 50
Moderate relief	50 < <b>D<sub>s</sub></b> < 100
Fairly high relief	100 < <b>D<sub>s</sub></b> < 250
High relief	250 < <b>D<sub>s</sub></b> < 500
Very high relief	500 < <b>D<sub>s</sub></b>

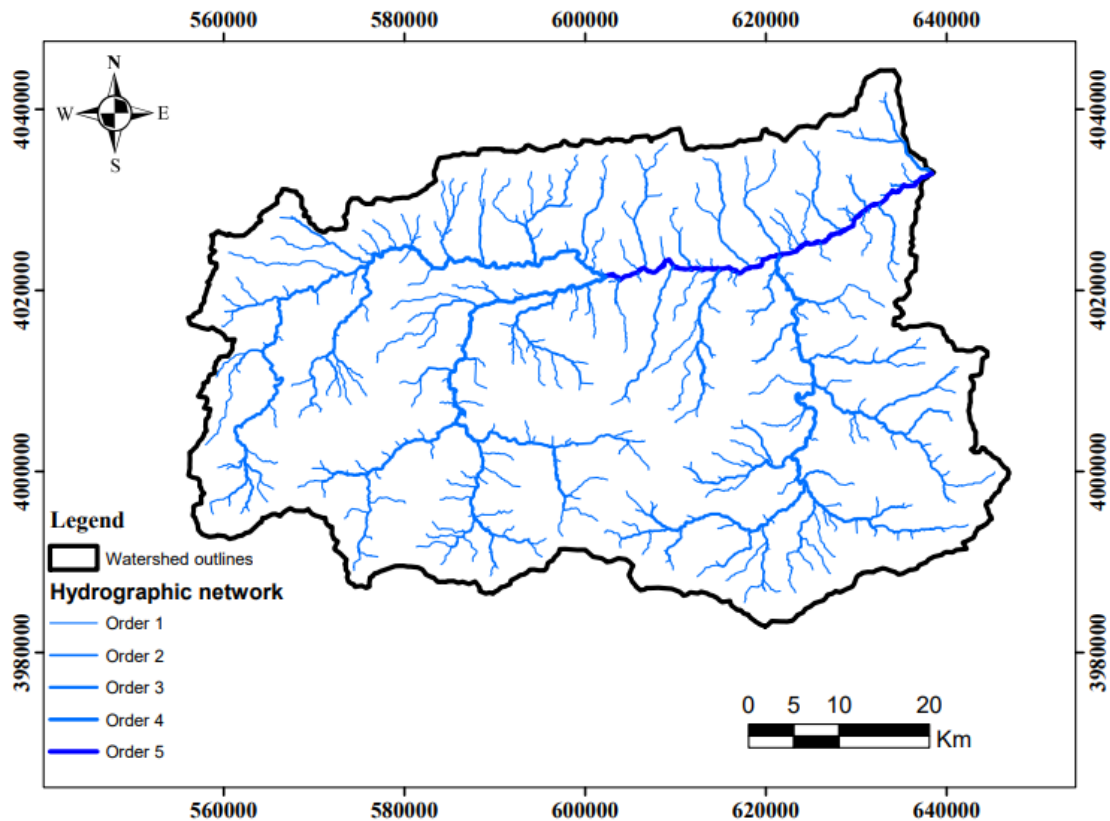
## II.7 The hydrographic characteristics of the watershed

### II.7.1 The hydrographic network is defined as follows:

- It consists of natural streamflows through which unconfined water runoff over the ground surface or infiltrated to become groundwater either in the form of a spring or by return along the bed of the watercourse. [25]
- natural or artificial watercourses, temporary or permanent. [26]

#### II.7.1.1 The hydrographic network:

The watershed of the Sahel Wadi is composed of a well-developed hydrographic network. The primary hydrographic network is formed by a single river and its tributaries: the Sahel, tributaries from the northwest and from the south, etc.



**Figure II. 6.** A map of the hydrographic network of the Sahel Wadi watershed (Soummam).

### II.7.2 The degree of development of the hydrographic network:

The development degree of the hydrographic network is measured by the following parameters:

#### ❖ Drainage density:

The drainage density is defined as the ratio between the length of the flow channels and the area of the basin.

$$Dd = \frac{\sum Li}{A} = \frac{1459.70}{3751.15} = 0.39 \text{ Km}^{-1}$$

**With:** » **Dd:** Drainage density ( $\text{km}^{-1}$ );

»  $\sum Li$ : sum of the lengths of the rivers (km);

» **A:** Area of the watershed ( $\text{km}^2$ ).

The drainage density is determined by the geology (structure and lithology) of the watershed's topographic features, and to some extent, by climatological and anthropic circumstances. Essentially, drainage density levels range from 3 to 4 in surfaces where the flow is restrictedly developed and concentrated, to more than 1000 in areas where the flow is distributary with minimal infiltration. According to Schumm, the "stream stability constant" which is the inverse value of the drainage density,  $C=1/Dd$ . A single hydrographic vector (section of the network) determines the basin area required to sustain stable hydrological conditions.

#### ❖ Hydrographic density:

Hydrographic density represents the number of flow channels per unit area.

$$A_d = \frac{\sum Ni}{A} = \frac{773}{3751.15} = 0.21 \text{ Km}^{-2}$$

**With:** » **A<sub>d</sub>:** hydrographic density also called Area density ( $\text{km}^{-2}$ );

» **N<sub>i</sub>:** number of watercourses;

» **A:** basin area ( $\text{km}^2$ ).

The drainage density **Dd** and hydrographic density **Ad** have a logical correlation, as shown by the following formula:

$$A_d = a \times D_d^2$$

Where **a** is an adjustment coefficient.

**Table II. 4.** Calculation of drainage density of the hydrographic network

Order	Number of valleys	$\sum Li$	Drainage density Km <sup>-1</sup>	Hydrographic density Km <sup>-2</sup>
1	394	738.64	0.2	0.1
2	167	372.52	0.01	0.04
3	105	187.55	0.05	0.03
4	65	113.74	0.03	0.02
5	42	47.25	0.01	0.01
total	773	1459.7	0.39	0.21

**II.7.3 The torrentiality coefficient (C<sub>t</sub>):**

The torrentiality coefficient is obtained using the formula :

$$C_t = \frac{N_1}{A} \times Dd = \frac{394}{3751.15} \times 0.39 = 0.041 \text{ Km}^{-3}$$

**With :**

- » **C<sub>t</sub>**: torrentiality coefficient.
- » **N<sub>1</sub>**: number of thalwegs of order 1.
- » **A**: basin area (km<sup>2</sup>).
- » **Dd**: drainage density (km/km<sup>2</sup>).

**II.7.4 Concentration time:**

The concentration time is the time it takes for the furthest raindrop to arrive at the outlet.

Giandotti's formula can be used to estimate it:

$$T_c = \frac{4\sqrt{A} + 1.5L}{0.8\sqrt{H_{mean} - H_{min}}} = \frac{4\sqrt{3751.15} + 1.5 \times 47.25}{0.8\sqrt{(778 - 167)}} = 16 \text{ hours}$$

**With :**

- » **L**: length of the main thalweg;
- » **A**: catchment area (km<sup>2</sup>).

**Table II. 5.** Geometric and hydro morphometric characteristics of the basin

Parameters	Symbol	Unit	Value
Area	A	km <sup>2</sup>	3751.15
Perimeter	P	km	322.80
Compactness coefficient	Kg	/	1.54
Length of the equivalent rectangle	L	km	140.67
Equivalent rectangle width	W	km	26.66
Roche slope index	I <sub>s</sub>	%	1.5
Global slope index	I <sub>g</sub>	%	0.66
Specific height difference	D <sub>s</sub>	m	406.22
Landform type	/	/	strong relief
Mean height	H <sub>mean</sub>	m	778
Maximum height	H <sub>max</sub>	m	2280
Minimum height	H <sub>min</sub>	m	167
Height <sub>5%</sub>	H <sub>5%</sub>	m	1293
Height <sub>95%</sub>	H <sub>95%</sub>	m	360
length of the mainstream	L <sub>s</sub>	km	47.25
Drainage density	Dd	Km/km <sup>2</sup>	0.39
Mean slope of Wadi El Sahel	I <sub>m</sub>	m/km	1.45
Torrentiality coefficient	C <sub>t</sub>	/	0.041
Concentration time	T <sub>c</sub>	Hours	16
Flood propagation speed	V <sub>f</sub>	m/s	0.82
Horton classification	order	/	5

## **II.8 Conclusion:**

The extraction and the assessment of the geomorphological and hydrometric characteristics of the studied watershed, as part of the digital terrain model and after evaluating these parameters, To summarize, Wadi El Sahel drains a basin with an area of 3751.15 km<sup>2</sup>, and a perimeter of 322.80 km, its elongated shape with a fairly strong relief, by the specific height difference of 933 m, a slope average 0.66%, and an altitude of 2280 m.

Additionally, the climate in this basin is nonuniformly containing three (3) types as well as the different types (4) of soil which vary from north to south and from east to west, Furthermore, the location of the maximum height is 2280 m at the summit of Lala Khadidja. Lastly, the analysis of morphological parameters affirmed that the diversity of the geological formation of the area impacts and shapes the vegetation in one way or another.

## **Chapter III .**

# **Flood Susceptibility Mapping in the sub watershed of Wadi El Sahel**

### **III.1 Introduction:**

Multi-criteria analysis methods (MCA) and Geographic Information Systems (GIS) are practical tools used in decision-making processes and especially in flood management. While the MCAs permit the integration of various criteria and factors to evaluate and prioritize different flood management strategies, the GIS provides a spatial framework for analyzing and visualization data. When combined, these processes can upgrade flood risk assessment, floodplain managing plans, and emergency response planning.

### **III.2 Method and software used:**

#### **III.2.1 Analytical hierarchy process:**

The Analytical Hierarchy Process (AHP) technique was developed to identify and map high flood-risk locations in Wadi Sahel. AHP is a multi-criteria decision-making method that maps flood risk by integrate several features/conditioning factors such as drainage density, slope, soil type, rainfall, elevation, distance to the river, modified normalized difference water index, topographic wetness index, and normalized vegetation index. A hazard map was created based on a variety of parameters.

#### **III.2.2 Presentation of the ArcGIS software:**

ArcGIS is software for operating a Geographic Information System (GIS).

This software allows the acquisition, storage, updating, manipulation, and processing of geographic data. In addition, it allows for precise mapping and spatial analysis according to the desired scale.

The guiding principle of a GIS is as follows:

We have on one side the geometric data and on the other the attribute data, this data is stored in digital format and organized by layers (also called (shapefiles) in ArcGIS).

Arcgis is a system combining client software (ArcView, ArcEditor, ArcInfo, and ArcExplorer) and server software (ArcSDE and ArcIMS).

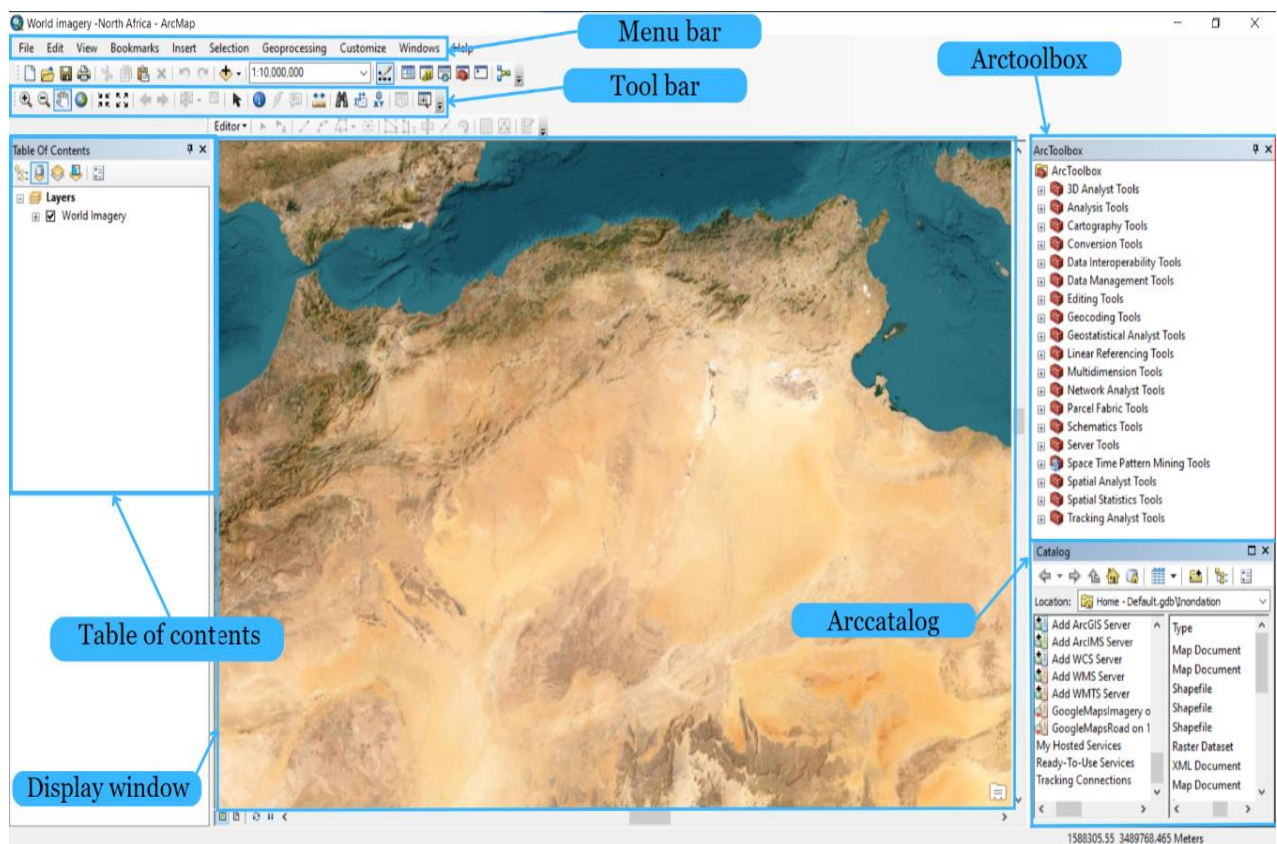
ArcView is a Geographic Information System for viewing, querying, analyzing to explore, select, display, edit, analyze, symbolize, and classify data or to automatically create, update or manage metadata. ArcView 10.8 includes ArcCatalog, ArcMap, and a lightweight version of ArcToolBox.

ArcCatalog provides the user with functions for:

- ❖ Data manipulation (create, define, move, rename, etc.).
- ❖ Data consultation (display, query, etc.).
- ❖ Data documentation (metadata).

ArcMap is the central application of ArcView. It allows you to perform the following tasks:

- ❖ Visualize spatial and attribute data (Labelling, symbology, feature filtering, etc.).



**Figure III. 1.** An overview of ArcMap with integrated windows for ArcToolbox and ArcCatalog

### III.3 Data sources and methodology

#### III.3.1 Data sources :

**Table III. 1** below illustrates the type of data collected, resolution, sources, and date of acquisition, as well as the relevance of utilized data in this study:

**Table III. 1.** Data sources

<i>DATA</i>	<i>Resolution /scale</i>	<i>Source</i>	<i>Date acquired</i>	<i>Relevance</i>
<b>Rainfall Data</b>	35 years (1970–2004)	National Agency for Hydraulic Resources (Fr. Agence Nationale des Ressources Hydrauliques –ANRH)	2022	Generation of rainfall layer
<b>SRTM (DEM)</b>	30 m	<a href="https://earthexplorer.usgs.gov/">https://earthexplorer.usgs.gov/</a>	2022	Generation of slope, elevation, DD, TWI, DR
<b>Landsat 08 OLI</b>	30 m	<a href="https://earthexplorer.usgs.gov/">https://earthexplorer.usgs.gov/</a>	2022	land cover classification, generation NDVI, MNDWI
<b>ISRIC world soil Grids</b>	250 m	<a href="https://soilgrids.org/">https://soilgrids.org/</a>	2022	Generation of Lithology layer

### III.3.2 Methodology:

Flood susceptibility mapping assesses the vulnerability of a sub-watershed to flooding using methodologies like AHP and Fuzzy AHP. It involves gathering data on topography, land use, soil, rainfall, and historical floods. The data is standardized, and factors influencing flood susceptibility are identified, weighted using AHP, and adjusted with fuzzy logic in Fuzzy AHP. Evaluation models analyze the factors, combining the weighted overlay technique to create a flood susceptibility map. Validation is done by comparing the map with inventory flood map. GIS software is used to interpret and visualize the map for better presentation.

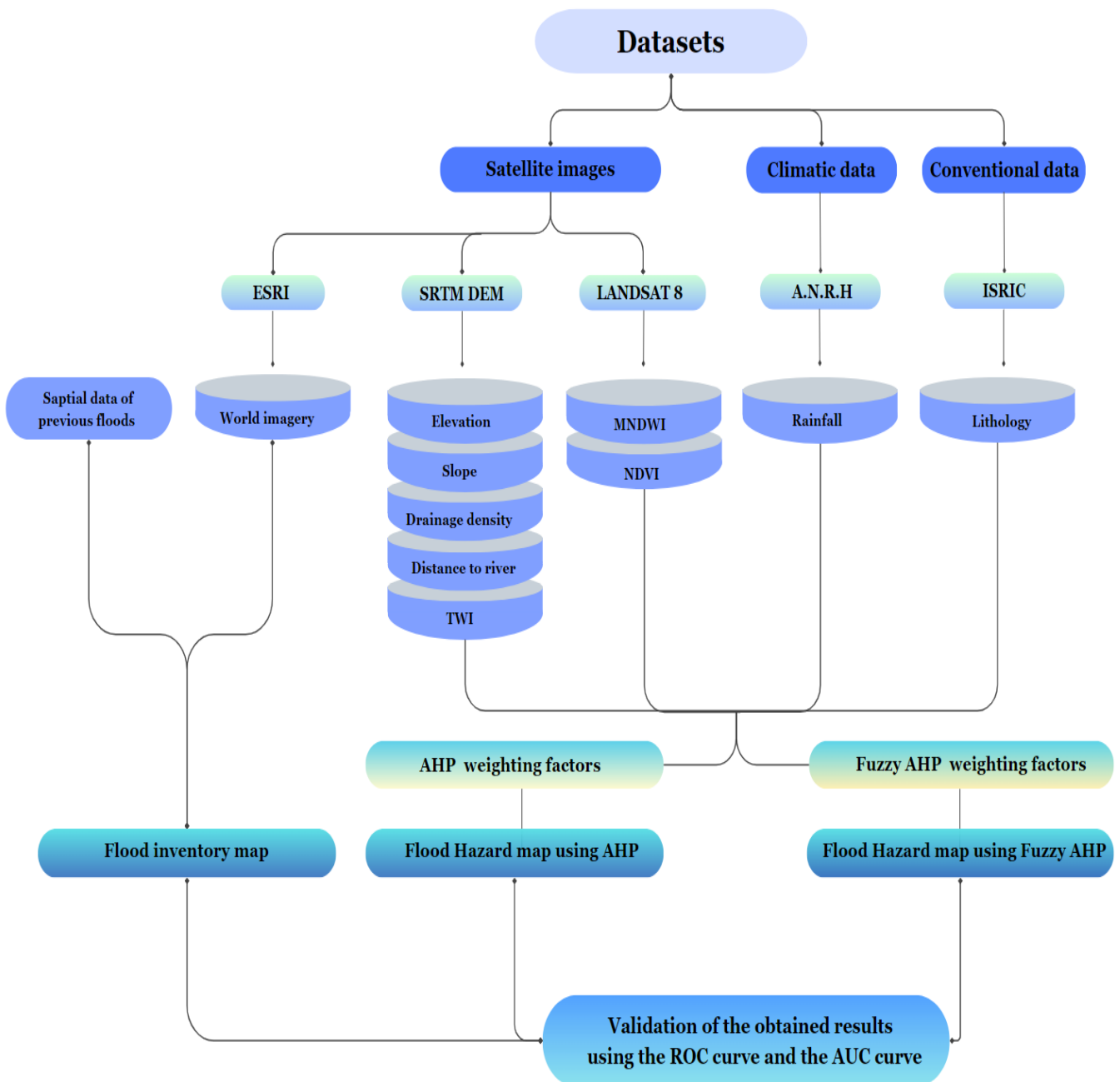


Figure III. 2. Flowchart of the proposed approach

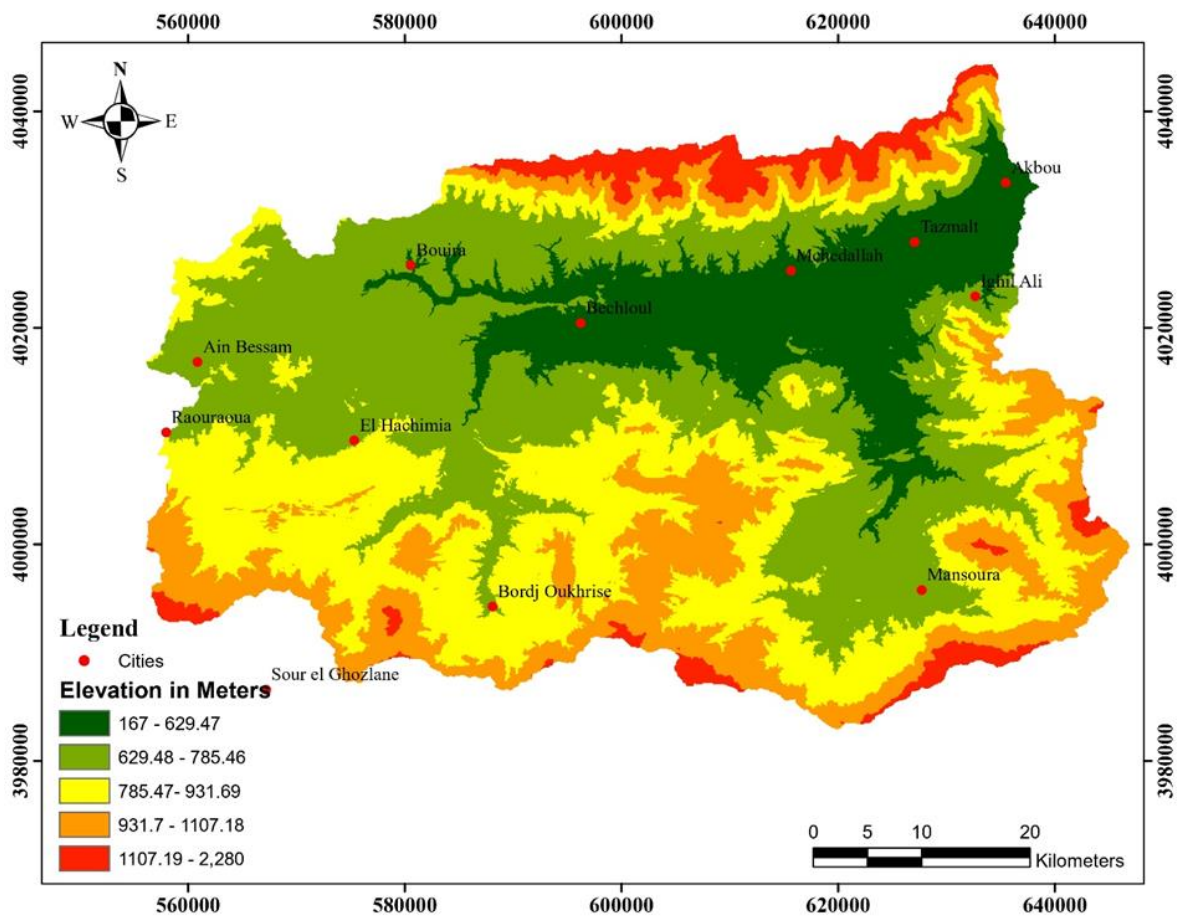
### III.4 Application of the methodology in Wadi Sahel

#### III.4.1 Data preprocessing

##### III.4.1.1 Determination of the Elevation in the sub-watershed of Wadi Sahel:

Using Arc GIS software, the elevation data of SRTM are plotted (**Figure III. 3**). The maximum and minimum elevation of the study area is 2280 meters and 167 meters sequentially. In this case study, the elevation varies from low to high due to hydrological characteristics.

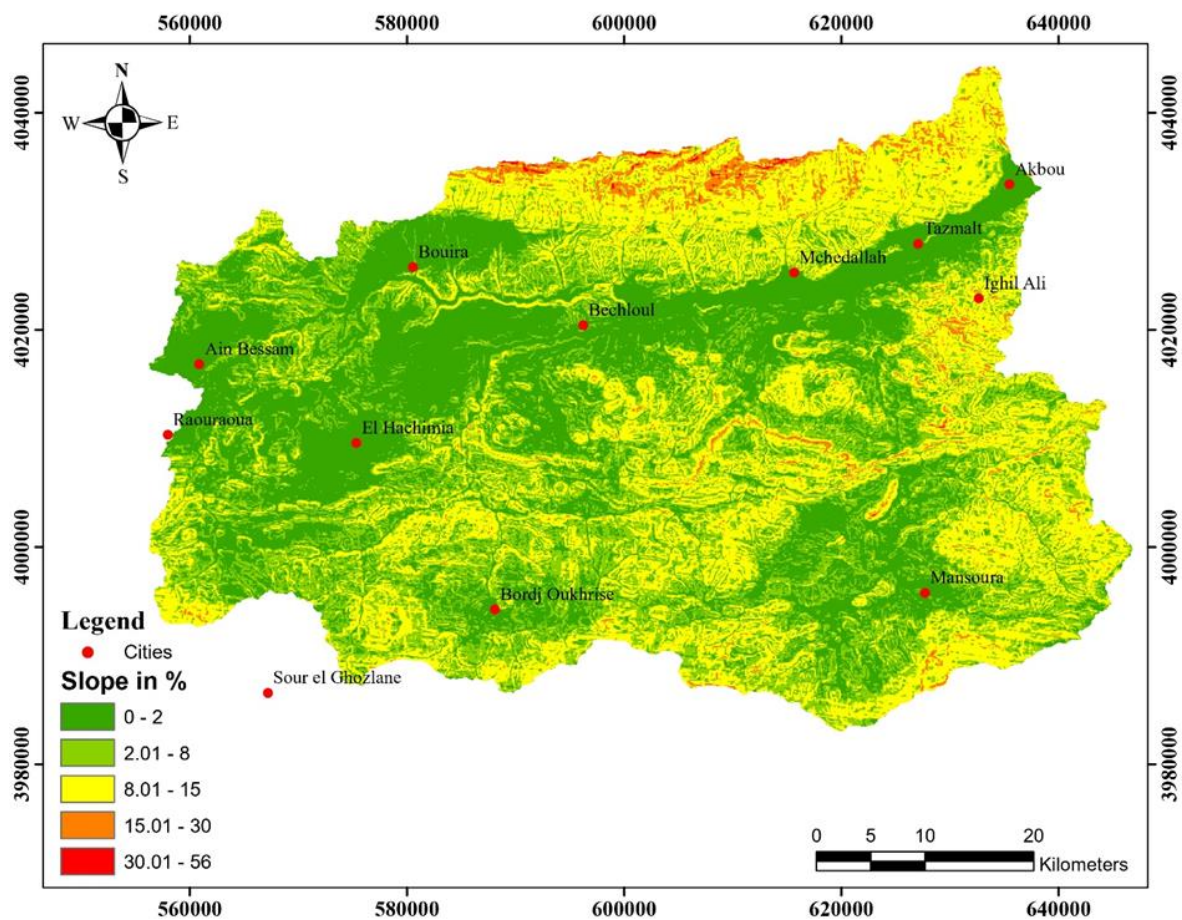
High elevation lands range from 1107.19 to 2280 meters additionally the lower elevation lands fall within 167–629.47 meters. These lands are covered by 10.58% and 31.16% area of the study area in succession.



**Figure III. 3 .** Elevation map of the watershed of the Sahel wadi (Soummam)

### III.4.1.2 Mapping the Slope in the sub-watershed of Wadi Sahel:

The slope is a dominant factor in determining the runoff infiltration rate. A steep slope indicates steeper terrain and as a result, the water will run off over the surface until it reaches a flat, or a mild slope which signifies a flat surface where the water becomes a body of water and/or emerges with another body of water (lake, sea, ocean, etc.). The slope map is prepared from DEM in ArcGIS 10.8 software. In this study, the slope data has been classified into 5 classes (**Figure III. 4**) very low (0–2)%, low (2.01–8)%, medium (8.01–15)%, high (15.01–30)%, very high (30.01– 56)%. The categories occupy 10.45%, 45.58%, 27.82%, 15.13% and 1.01% of land in the study area respectively.



**Figure III. 4.** Slope map of the watershed of the Sahel wadi (Soummam)

### III.4.1.3 Mapping the Drainage density in the sub-watershed of Wadi Sahel:

Precipitation is any type of water that falls onto the surface of a drainage basin, which is a form of the water cycle that extremely affects the drainage density. As a result, the drainage density factor significantly impacts predictions of flash floods occurring. Furthermore, inefficient or corrupt management of the sewage system can increase the probability of floods, including watershed overflow and occasional flooding incidents in particular zones. However, due to the significant impact that drainage density may have. Determining it using ArcGIS software's line density tool was quite efficient. The output drainage density map (Figure III. 5) for this research region ranged between 0 and 1.05 km/km<sup>2</sup> at a resolution of 30 m.

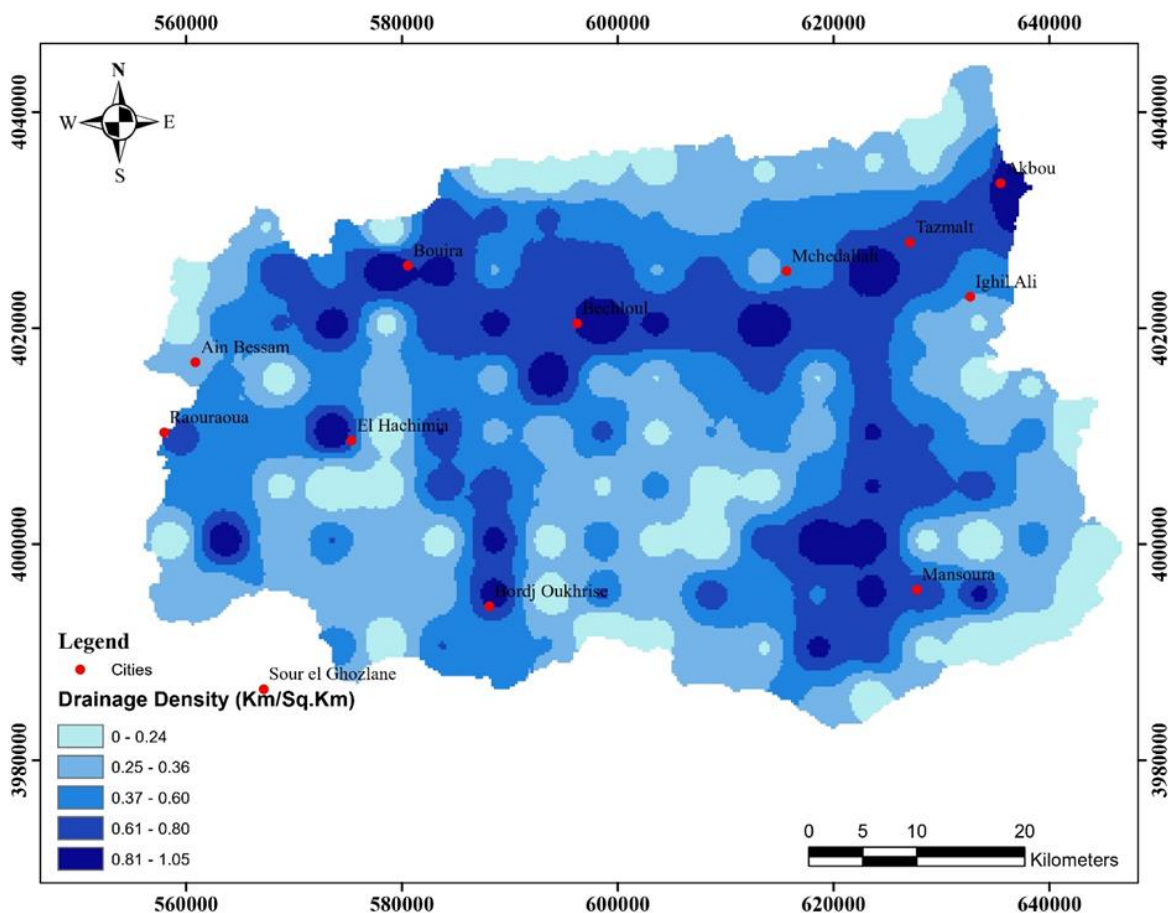
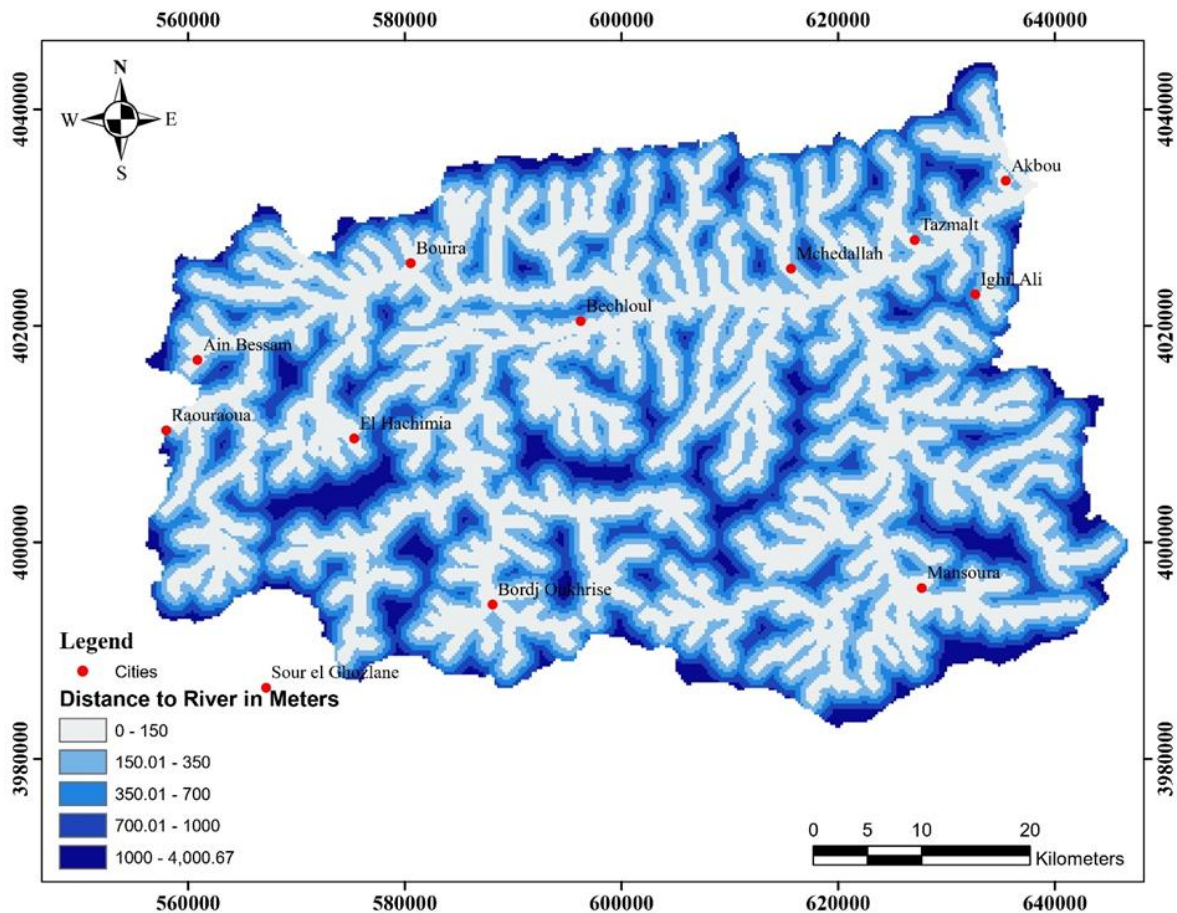


Figure III. 5. Drainage density map of the watershed of the Sahel wadi (Soummam)

#### III.4.1.4 Mapping the Distance to River in the sub-watershed of Wadi Sahel:

The distance to the river has a considerable impact on the water overflow. Flood extent and intensity are much more impactful in areas adjacent to rivers and streams. Stream networks were identified using ArcMap. At last, a raster with a spatial resolution of 30 meters per pixel was acquired to represent the distance to the watercourses.



**Figure III. 6.** Distance to river map of the watershed of the Sahel wadi (Soummam)

### III.4.1.5 Mapping the Topographic Wetness Index in the sub-watershed of Wadi Sahel:

The Topographic Wetness Index assesses how slope influences the hydrological cycle. this index exhibits the water accumulation tendency in certain areas, while the local slope demonstrates the gravitational force effect on water flow. Topographic Wetness Index is widely used to anticipate soil moisture and its water retention capacity. The slope and DEM measurements were used in the process (see **Figure III. 7**) using the formula:

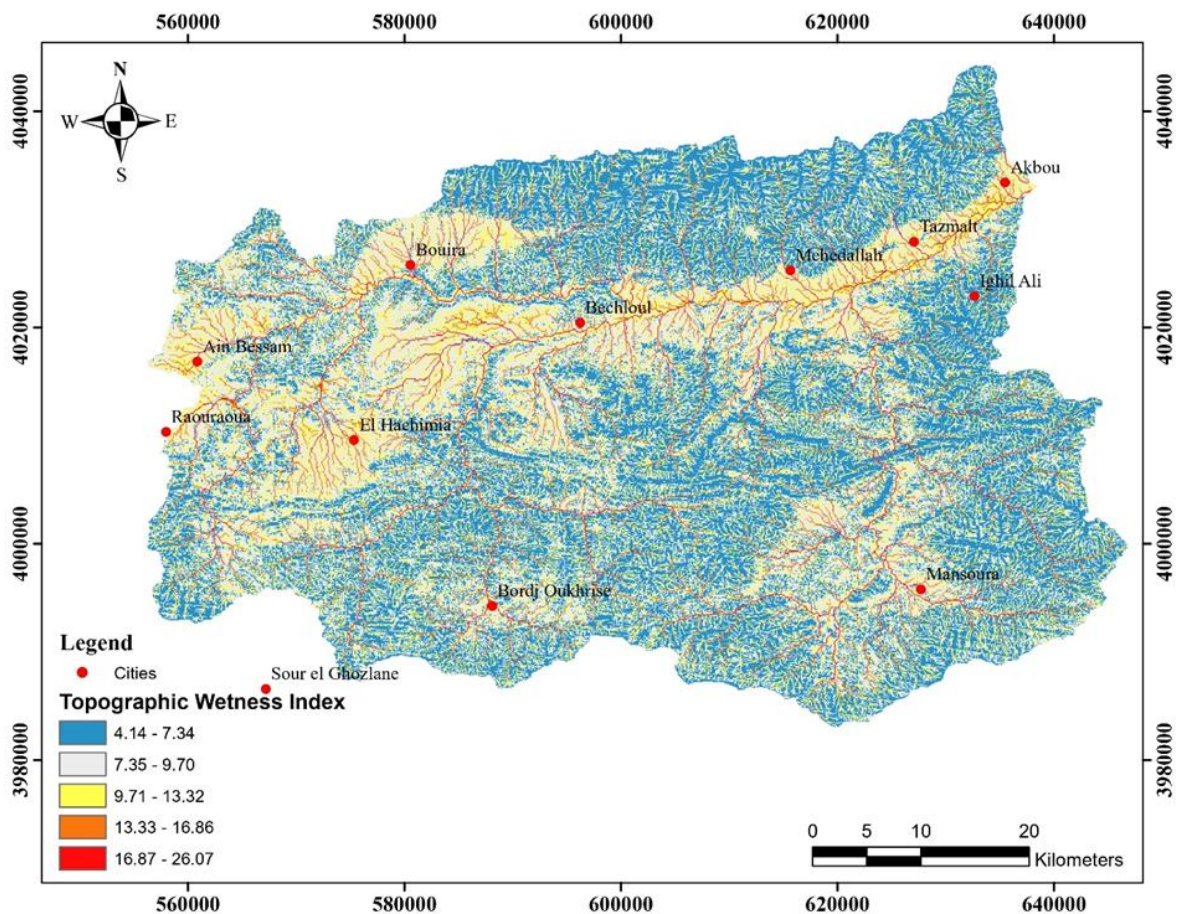
$$TWI = \ln(A/\tan\beta) \text{ [27]}$$

With:

**A:** the specific catchment area.

**Tan $\beta$ :** the local slope angle in degrees.

The specified catchment area is an integration of surface and subsurface drainage from an upslope region per unit contour width.



**Figure III. 7.** Topographic Wetness Index map of the watershed of the Sahel wadi (Soummam)

### III.4.1.6 Mapping the Modified Normalized Difference Water Index in the sub-watershed of Wadi Sahel:

The concept of Modified Normalized Difference Water Index (MNDWI) was first developed by Xu [28]. MNDWI is generally applied for determining the availability of water features and land cover by eliminating atmospheric noise and terrain disturbances [29]

In this study, the modified normalized difference water index map has been generated from Landsat 8 image in ArcGIS 10.8 software using the following formula.

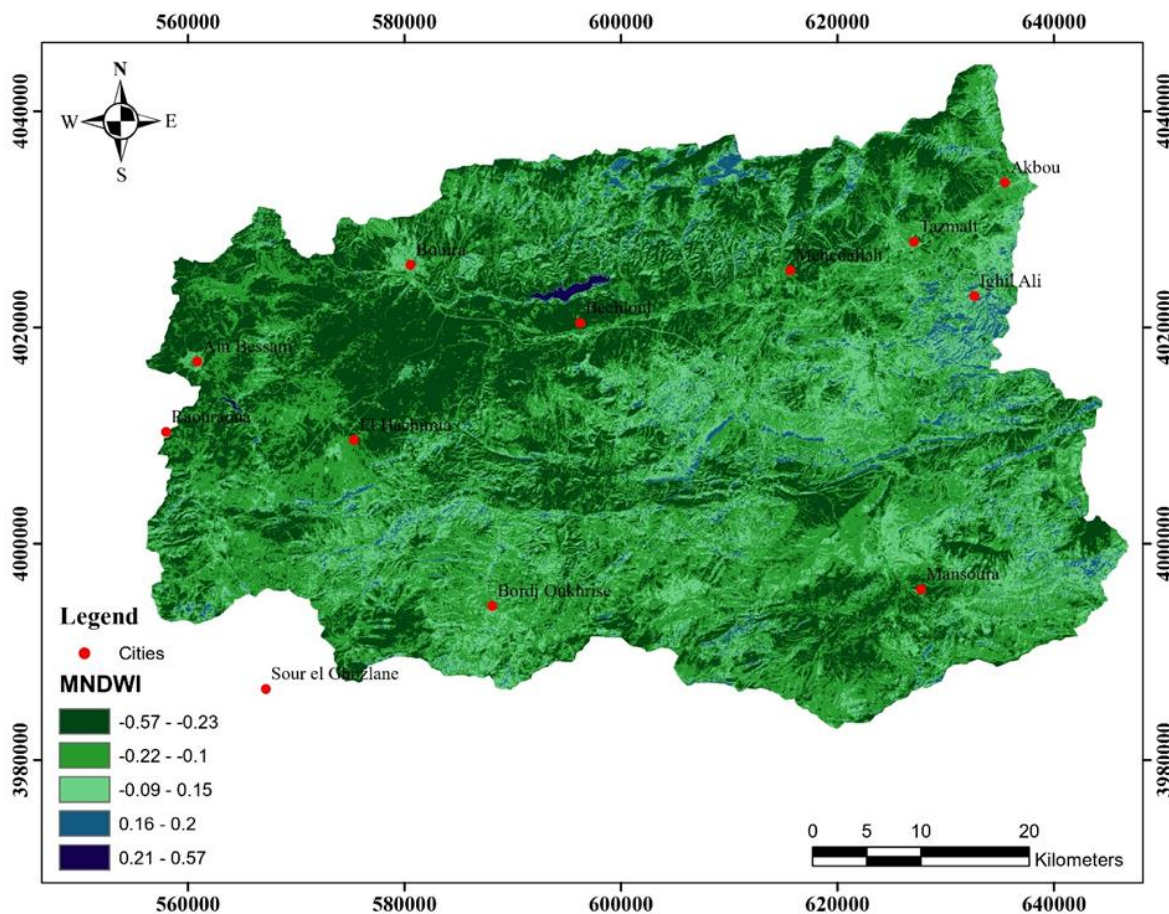
$$\text{MNDWI} = (\text{Green} - \text{SWIR}) / (\text{Green} + \text{SWIR})$$

With:

- Green: bands in satellite remote sensing monitor water and vegetation information.<sup>[30]</sup>
- SWIR: Short Wavelength InfraRed provides strong contrast for high-resolution imaging.<sup>[31]</sup>

This map is classified into five categories:

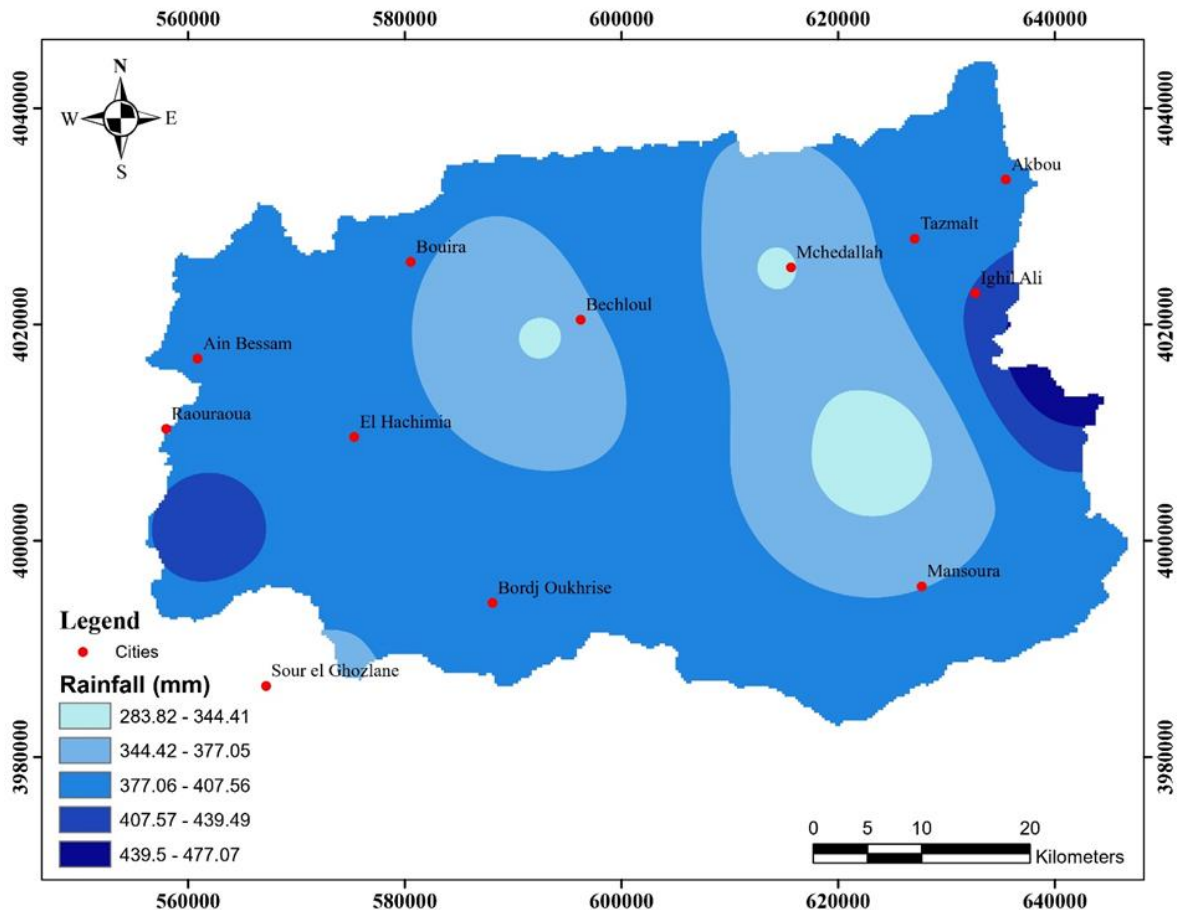
- 1- Very low (-0.57 to -0.23);
- 2- Low (-0.22 to -0.1);
- 3- Medium (-0.09 to 0.15);
- 4- High (0.16 to 0.2);
- 5- Very high (0.21 to 0.57).



**Figure III. 8.** Modified Normalized Difference Water Index map of the watershed of the Sahel wadi (Soummam)

### III.4.1.7 Mapping the Rainfall in the sub-watershed of Wadi Sahel:

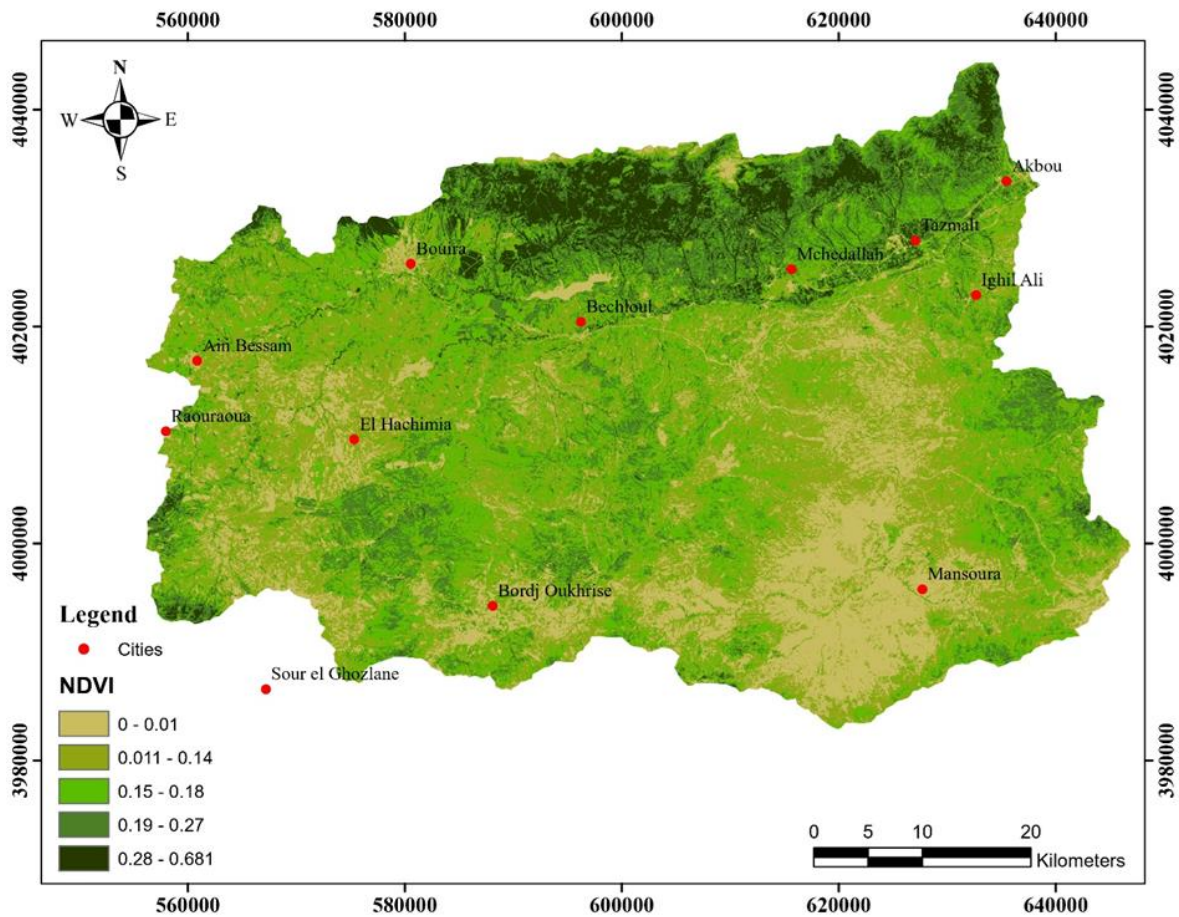
In the process of analyzing the spatial variability of precipitation, and using the interpolation method the precipitation values were obtained from the precipitation stations for the whole surface of the catchment area. It is notable that precipitation decreases from south to north and west to east throughout the region. It varies quantitatively between 283 mm and 477 mm over the entire area.



**Figure III. 9.** Rainfall map of the watershed of the Sahel wadi (Soummam)

### III.4.1.8 Mapping the Normalized Difference Vegetation Index in the sub-watershed of Wadi Sahel:

The vegetation cover in the Sahel Wadi region is distinctive, In the north it majorly consists of forests and plants that form a dense vegetation cover, whilst the vegetation cover is medium in the southwest, yet .in the southeast of the region the vegetal cover is quite poor.



**Figure III. 10.** Normalized Difference Vegetation Index map of the watershed of the Sahel wadi (Soummam)

### III.4.1.9 Mapping Lithology in the sub-watershed of Wadi Sahel:

Infiltration is the soil's ability to allow water to flow from aboveground into the subsurface. it depends majorly on the nature of the soil. the smaller the pore size, the lower the infiltration rate, and vice versa. therefore, clay and compact soils have the lowest infiltration rate due to the small pore sizes while it increases in sandy soils and so on.

The soil nature of our study area is divided into:

sandy-loam (506.74 Km<sup>2</sup>) and loam (2742.14 Km<sup>2</sup>) which occupies relatively a vast surface of the study area, followed by clay (355.12 Km<sup>2</sup>) and clay-loam (147.13 Km<sup>2</sup>) that occupies a fairly small area compared to other soil types.

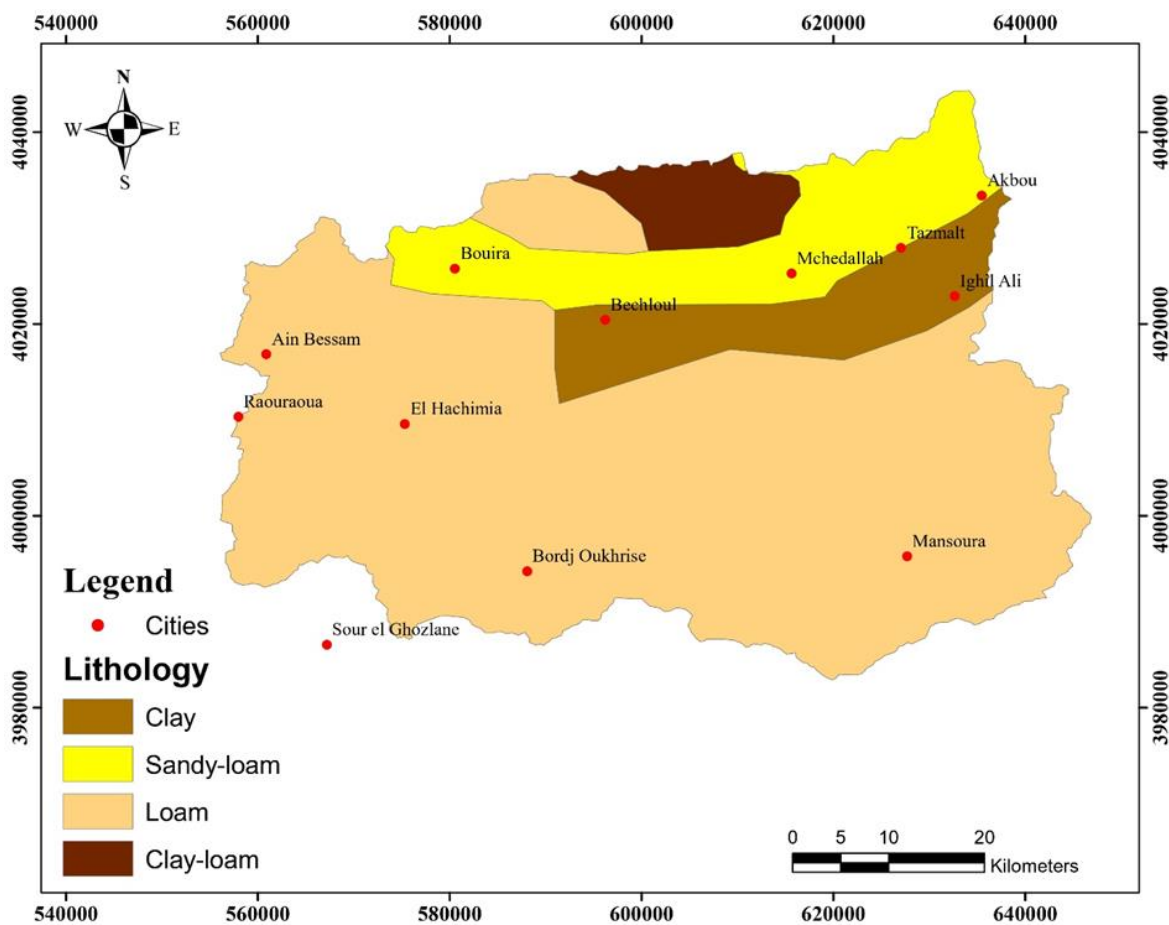


Figure III. 11. Lithology map of the watershed of the Sahel wadi (Soummam)

### III.5 Hierarchical Analysis methodology:

The flowchart demonstrates the methodological steps applied in this study (**Figure III. 2**) nine thematic layers of the map have been used. GIS has been applied to integrate all nine thematic layers, while AHP is applied to determine the weightage of each thematic layer. Finally, We compared the flood risk map with previous events and Google Maps. All nine thematic layers have been integrated to delineate floods in Wadi Sahel through the overlay "spatial analyst tool" available in Arc GIS 10.8 software (Waiker and Nilawar, 2014). Before the overlaying process, all the vector form of maps were converted into raster format and the weightage of each thematic layer were determined. Individual spatial layers were also reclassified for the value ranging from 1 to 5, where 1 refers to very low impact and 5 indicates very high impact. The rank has been categorized based on existing data, and field survey experience. The weightage of each thematic layer was estimated by using the Analytical Hierarchy Process and Fuzzy the Analytical Hierarchy Process. In AHP or Fuzzy AHP, different steps were used to obtain weightage for each class as well as the consistency index. The following steps were applied:

Developing a decision matrix,  $D_{M \times N}$  for two methods.

$$\begin{array}{c}
 \text{Attribute} \quad 1 \quad 2 \quad 3 \quad - \quad - \quad N \\
 \\
 D_{M \times N} = \begin{array}{c}
 1 \left| \begin{array}{cccccc}
 d_{11} & d_{12} & d_{13} & - & - & d_{1N} \\
 2 \left| \begin{array}{cccccc}
 d_{21} & d_{22} & d_{23} & - & - & d_{2N} \\
 3 \left| \begin{array}{cccccc}
 d_{31} & d_{32} & d_{33} & - & - & d_{3N} \\
 - & - & - & - & - & - \\
 - & - & - & - & - & - \\
 M \left| \begin{array}{cccccc}
 d_{M1} & d_{M2} & d_{M3} & - & - & d_{MN}
 \end{array} \right.
 \end{array} \right.
 \end{array}
 \end{array}
 \end{array}
 \end{array}$$

**Figure III. 12.** Decision matrix,  $DM \times N$  [27]

The principle of development is the following matrix:

- Calculating the eigenvectors ( $V_p$ ) for each criterion of each item using the following equation:

$$V_p = \sqrt[n]{W_1 \times W_2 \times \dots \times W_n}$$

With:

**n:** represents the number of parameters.

**Wn:** represents the ranking of the main parameters.

- Determining the weighting coefficients ( $C_p$ ) using the following formula:

$$C_p = \frac{v_p}{v_{p1} + v_{p2} + \dots + v_{pn}}$$

It is important to note that the sum of  $C_p$  for all parameters in a matrix must be equal to 1.

- Normalizing the matrix by dividing each element in it by the sum of its respective column.
- Deriving the priority vector (C) by calculating each row average in the matrix.
- Multiplying each column of the matrix by its corresponding priority vector (C) to obtain the global priority (D).
- Dividing each priority (D) by the corresponding priority vector (C) to infer the rational priority (E).
- Calculating the maximum eigenvalue ( $\lambda_{max}$ ) using the equation:

$$\lambda = E/N$$

- The consistency ratio has been calculated to justify the coherence of the interpretation.

$$CR = CI/RI$$

- Where CI is the consistency index, RI is Saaty's ratio index (Table 6). CI is quantified using the following:

$$CI = (\lambda_{max} - N) / (N - 1)$$

In the following table,  $\lambda_{max}$  is an eigenvalue. CR value is accepted if it is less than 0.1 ( $CR < 0.1$ ). Otherwise, values must be reconsidered, revised, and reevaluated.

### III.5.1 Weighting using Analytical Hierarchy Process:

**Step 01:** Development of pair-wise comparison matrix (**Table III. 3 & Table III. 4**)

The AHP evaluation scale is a vital component of the Analytic Hierarchy Process, enabling structured decision-making. It assigns relative values to criteria and alternatives but is subjective and can introduce biases. To address this, involving diverse stakeholders, promoting open discussions, and establishing clear criteria are important. With proper implementation, the AHP evaluation scale can be a valuable tool for making informed decisions in different situations.

Where the interpretation is made using the AHP Evaluation scale Saaty (1980) (**Table III. 2**)

**Table III. 2.** AHP evaluation scale (Saaty, 1980).

Degree of importance	Interpretation
1	Equal importance.
3	Moderate importance.
5	Strong importance.
7	Very strong or demonstrated importance.
9	Extreme importance.
2,4,6,8	Intermediate value between the two adjacent judgments.
the equivalent of the values above	If activity i has relative importance of $a_{ij}$ when compared to activity j, then j has importance $1/a_{ij}$ when compared to i.

#### III.5.1.1 Pairwise matrix for flood susceptibility using Analytic Hierarchy Process:

The application of a pairwise matrix for flood susceptibility using the Analytic Hierarchy Process (AHP) is a practical approach to assess and prioritize areas based on their vulnerability to floods. This matrix allows decision-makers to systematically compare and evaluate different factors and their relative importance in determining flood susceptibility. By considering pairwise comparisons, such as land cover, slope, rainfall intensity, and proximity to water bodies, the matrix enables the identification of key factors and their respective weights. This information is crucial in creating a comprehensive flood susceptibility map that can aid in effective flood management, land use planning, and emergency response strategies. The pairwise matrix for flood susceptibility using AHP provides a structured and quantitative approach, enhancing decision-making processes in mitigating the impacts of floods and ensuring the safety of vulnerable areas and communities.

**Table III. 3.** Pairwise comparison matrix for flood susceptibility using AHP

PARAMETERS	E	S	DD	DR	TWI	MNDWI	RAINFALL	NDVI	L	VP	CP
<b>E</b>	<b>1</b>	2	3	4	5	6	7	8	9	4.15	0.31
<b>S</b>	0.50	<b>1</b>	2	3	4	5	6	7	8	3.01	0.22
<b>DD</b>	0.33	0.50	<b>1</b>	2	3	4	5	6	7	2.11	0.16
<b>DR</b>	0.25	0.33	0.5	<b>1</b>	2	3	4	5	6	1.46	0.11
<b>TWI</b>	0.20	0.25	0.33	0.50	<b>1</b>	2	3	4	5	1.00	0.07
<b>MNDWI</b>	0.17	0.20	0.25	0.33	0.50	<b>1</b>	2	3	4	0.69	0.05
<b>RAINFALL</b>	0.14	0.17	0.20	0.25	0.33	0.50	<b>1</b>	2	3	0.47	0.04
<b>NDVI</b>	0.13	0.14	0.17	0.20	0.25	0.33	0.50	<b>1</b>	2	0.33	0.02
<b>L</b>	0.11	0.13	0.14	0.17	0.20	0.25	0.33	0.5	<b>1</b>	0.24	0.02
<b>SUM</b>	<b>2.83</b>	<b>4.72</b>	<b>7.59</b>	<b>11.45</b>	<b>16.28</b>	<b>22.08</b>	<b>28.83</b>	<b>36.50</b>	<b>45.00</b>	<b>13.46</b>	<b>1.00</b>

**Table III. 4.** Normalized pairwise comparison matrix for flood susceptibility using AHP

PARAMETERS	E	S	DD	DR	TWI	MNDWI	RAINFALL	NDVI	L	WEIGHTED SUM VALUE	CP	W/CP	SUM(W/CP)/9
<b>E</b>	0.31	0.45	0.47	0.43	0.37	0.31	0.25	0.20	0.161	2.94	<b>0.31</b>	9.55	<b>9.25</b>
<b>S</b>	0.15	0.22	0.31	0.33	0.30	0.25	0.21	0.17	0.143	2.10	<b>0.22</b>	9.38	
<b>DD</b>	0.1	0.11	0.16	0.22	0.22	0.20	0.18	0.15	0.125	1.25	<b>0.16</b>	7.95	
<b>DR</b>	0.08	0.07	0.08	0.11	0.15	0.15	0.14	0.12	0.107	1.01	<b>0.11</b>	9.33	
<b>TWI</b>	0.06	0.06	0.05	0.05	0.07	0.10	0.11	0.10	0.09	0.69	<b>0.07</b>	9.34	
<b>MNDWI</b>	0.05	0.04	0.04	0.04	0.04	0.05	0.07	0.07	0.072	0.48	<b>0.05</b>	9.34	
<b>RAINFALL</b>	0.04	0.04	0.03	0.03	0.02	0.03	0.04	0.05	0.054	0.33	<b>0.04</b>	9.34	
<b>NDVI</b>	0.04	0.03	0.03	0.02	0.02	0.02	0.02	0.02	0.036	0.23	<b>0.02</b>	9.39	
<b>L</b>	0.03	0.03	0.02	0.02	0.015	0.01	0.01	0.01	0.018	0.17	<b>0.02</b>	9.61	
<b>SUM</b>											<b>1.00</b>	<b>83.22</b>	

**Table III. 5.** Random Index (RI) value (Saaty, 1990).

N	1	2	3	4	5	6	7	8	9	10	11	12
<b>RI</b>	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48

### III.5.1.2 Consistency Ratio (C.R):

➤ Calculation of Consistency Ratio (C.R):

**Table III. 6.** Normalized vector for flood susceptibility using AHP

PARAMETERS	E	S	DD	DR	TWI	MNDWI	RAINFALL	NDVI	L	SUM	C	D=A×C	E=D/C	Λmax	CI	CR
E	0.35	0.42	0.40	0.35	0.31	0.27	0.24	0.22	0.20	2.76	0.31	3.25	10.59	9.46	<b>0.06</b>	0.04
S	0.18	0.21	0.26	0.26	0.25	0.23	0.21	0.19	0.18	1.96	0.22	2.27	10.38			
DD	0.12	0.11	0.13	0.17	0.18	0.18	0.17	0.16	0.16	1.39	0.15	1.24	8.05			
DR	0.09	0.07	0.07	0.09	0.12	0.14	0.14	0.14	0.13	0.98	0.11	1.23	11.25			
TWI	0.07	0.05	0.04	0.04	0.06	0.09	0.10	0.11	0.11	0.69	0.08	0.75	9.87			
MNDWI	0.06	0.04	0.03	0.03	0.03	0.05	0.07	0.08	0.09	0.48	0.05	0.49	9.13			
RAINFALL	0.05	0.04	0.03	0.02	0.02	0.02	0.03	0.05	0.07	0.33	0.04	0.32	8.60			
NDVI	0.04	0.03	0.02	0.02	0.02	0.02	0.02	0.03	0.04	0.23	0.03	0.19	7.29			
L	0.04	0.03	0.02	0.01	0.01	0.01	0.01	0.01	0.02	0.17	0.02	0.19	10.00			
SUM	<b>1.00</b>	<b>1.00</b>	<b>1.00</b>	<b>1.00</b>	<b>1.00</b>	<b>1.00</b>	<b>1.00</b>	<b>1.00</b>	<b>1.00</b>		<b>1.00</b>		85.17			

### ➤ Consistency Ratio Analysis in Hierarchical Decision Making:

The result of the analysis indicates that the consistency level in the hierarchical analysis is 4%, which is below the threshold of 10%. This suggests that the judgments made in the pairwise comparisons of the hierarchy are considered reasonable. Having a consistency level below 10% is normally adequate, as it indicates a higher level of validity and reliability in the decision-making process. It implies that the judgments are relatively stable and do not contain significant inconsistencies or contradictions. Furthermore, this result ensures the reliability of the analysis and the validity of the decision-making outcomes based on the hierarchical structure.

#### III.5.1.3 AHP rating of sub-criteria for flood susceptibility zonation:

The AHP rating of sub-criteria for flood susceptibility zonation is a crucial process that utilizes the Analytic Hierarchy Process. It involves assigning relative weights and importance to factors such as rainfall patterns, topography, land use, drainage systems, and flood history. This ranking system helps identify the most influential factors and allocate appropriate weights to each, facilitating the creation of accurate flood susceptibility zonation maps. Using a systematic approach, decision-makers can prioritize actions and allocate resources effectively for mitigating the impact of floods in susceptible areas.

**Table III. 7.** AHP rating of sub-criteria for flood susceptibility zonation

Elevation									
Class	VL	L	M	H	VH	Rating	$\lambda$ max	CI	CR
283.82 - 344.4	1	2	3	4	5	0.42	5.09	0.023	0.02
344.4 - 377.05	0.50	1	2	3	4	0.26			
377.05 - 407.6	0.33	0.50	1	2	3	0.16			
407.6 - 439.5	0.25	0.33	0.5	1	2	0.10			
439.5 - 477.07	0.20	0.25	0.33	0.5	1	0.06			
SUM	2.28	4.08	6.83	10.5	15	1.00			
SLOPE									
Class	VL	L	M	H	VH	Rating	$\lambda$ max	CI	CR
0 - 2	1	2	3	5	7	0.44	5.04	0.01	0.01
2 - 8	0.50	1	2	3	5	0.26			
8 - 15	0.33	0.50	1	2	3	0.15			
15 - 30	0.20	0.33	0.5	1	2	0.09			
30 - 56	0.14	0.20	0.33	0.5	1	0.05			
SUM	2.18	4.03	6.83	11.5	18	1.00			
Drainage Density									
Class	VL	L	M	H	VH	Rating	$\lambda$ max	CI	CR
0.003 - 0.25	1	0.5	0.33	0.2	0.13	0.05	5.03	0.01	0.01
0.25 - 0.36	2	1	0.5	0.33	0.2	0.09			
0.36 - 0.6	3	2	1	0.5	0.33	0.15			
0.6 - 0.8	5	3	2	1	0.5	0.26			
0.8 - 1.06	8	5	3	2	1	0.45			
SUM	19.00	11.50	6.83	4.03	2.16	1.00			

Distance to river									
Class	VL	L	M	H	VH	Rating	$\lambda$ max	CI	CR
0 - 150	1	3	5	7	9	0.50	5.37	0.09	0.08
150 - 350	0.33	1	3	5	7	0.26			
350 - 700	0.20	0.33	1	3	5	0.13			
700 - 1000	0.14	0.20	0.33	1	3	0.07			
1000 - 4,000.67	0.11	0.14	0.20	0.33	1	0.04			
SUM	1.79	4.68	9.53	16.33	25.00	1.00			
Topographic Wetness Index									
Class	VL	L	M	H	VH	Rating	$\lambda$ max	CI	CR
4.14 - 7.35	1	0.5	0.33	0.2	0.14	0.05	5.04	0.01	0.01
7.35 - 9.7	2	1	0.5	0.33	0.2	0.09			
9.7 -13.33	3	2	1	0.5	0.33	0.15			
13.33 - 16.86	5	3	2	1	0.5	0.26			
16.86 - 26.07	7	5	3	2	1	0.44			
SUM	18.00	11.50	6.83	4.03	2.18	1.00			
Modified Normalized Difference Water Index									
Class	VL	L	M	H	VH	Rating	$\lambda$ max	CI	CR
-0.58 - -0.23	1	0.5	0.33	0.25	0.14	0.06	5.05	0.01	0.01
-0.23 - -0.1	2	1	0.5	0.33	0.25	0.10			
-0.1 - 0.15	3	2	1	0.5	0.33	0.16			
0.15 - 0.2	4	3	2	1	0.5	0.26			
0.2 - 0.57	7	4	3	2	1	0.43			
SUM	17.00	10.50	6.83	4.08	2.23	1.00			
Rainfall									
Class	VL	L	M	H	VH	Rating	$\lambda$ max	CI	CR
283.82 - 344.4	1	0.5	0.33	0.2	0.14	0.05	5.04	0.01	0.01
344.4 - 377.05	2	1	0.5	0.33	0.2	0.09			
377.05 - 407.6	3	2	1	0.5	0.33	0.15			
407.6 - 439.5	5	3	2	1	0.5	0.26			
439.5 - 477.07	7	5	3	2	1	0.44			
SUM	18	11.50	6.83	4.03	2.18	1.00			
Normalized Difference Vegetation Index									
Class	VL	L	M	H	VH	Rating	$\lambda$ max	CI	CR
0 - 0.01	1	2	3	4	5	0.42	5.09	0.02	0.02
0.01 - 0.14	0.50	1	2	3	4	0.26			
0.14 - 0.18	0.33	0.50	1	2	3	0.16			
0.18 - 0.27	0.25	0.33	0.50	1	2	0.10			
0.27 - 0.681	0.20	0.25	0.33	0.5	1	0.06			
SUM	2.28	4.08	6.83	10.50	15.00	1.00			
Lithology									
Class	VL	L	M	H	VH	Rating	$\lambda$ max	CI	CR
Clay	1	0.5	0.33	0.25	///	0.10	4.04	0.01	0.01
SANDY-LOAM	2	1	0.5	0.33	///	0.16			
LOAM	3	2.00	1	0.5	///_	0.278			
CLAY-LOAM	4	3.00	2.00	1	///	0.47			
SUM	10.00	6.50	3.83	2.08	///	1.00			

**Table III. 8.** Normalized vector for flood susceptibility

Elevation							
Class	VL	L	M	H	VH	SUM	Priority vector
167 - 629.5	0.44	0.49	0.44	0.38	0.33	2.08	41.62
629.5 - 785.5	0.22	0.24	0.29	0.29	0.27	1.31	26.18
785.5 - 931.7	0.15	0.12	0.15	0.19	0.20	0.81	16.11
931.7 - 1107.18	0.11	0.08	0.07	0.10	0.13	0.49	9.86
1107.18 - 2,280	0.09	0.06	0.05	0.05	0.07	0.31	6.24
SUM	1.00	1.00	1.00	1.00	1.00		100.00
Slope							
Class	VL	L	M	H	VH	SUM	Priority vector
0 - 2	0.46	0.50	0.44	0.43	0.39	2.22	44.36
2 - 8	0.23	0.25	0.29	0.26	0.28	1.31	26.18
8 - 15	0.15	0.12	0.15	0.17	0.17	0.76	15.28
15 - 30	0.09	0.08	0.07	0.09	0.11	0.45	8.92
30 - 56	0.07	0.05	0.05	0.04	0.06	0.26	5.26
SUM	1.00	1.00	1.00	1.00	1.00		100.00
Drainage density							
Class	VL	L	M	H	VH	SUM	Priority vector
0.003 - 0.25	0.05	0.04	0.05	0.05	0.06	0.25	5.05
0.25 - 0.36	0.11	0.09	0.07	0.08	0.09	0.44	8.81
0.36 - 0.6	0.16	0.17	0.15	0.12	0.15	0.76	15.13
0.6 - 0.8	0.26	0.26	0.29	0.25	0.23	1.30	25.93
0.8 - 1.06	0.42	0.43	0.44	0.50	0.46	2.25	45.08
SUM	1.00	1.00	1.00	1.00	1.00		100.00
Distance to river							
Class	VL	L	M	H	VH	SUM	Priority vector
0 - 150	0.56	0.64	0.52	0.43	0.36	2.51	50.28
150 - 350	0.19	0.21	0.31	0.31	0.28	1.30	26.02
350 - 700	0.11	0.07	0.10	0.18	0.20	0.67	13.44
700 - 1000	0.08	0.04	0.03	0.06	0.12	0.34	6.78
1000 - 4,000.67	0.06	0.03	0.02	0.02	0.04	0.17	3.48
SUM	1.00	1.00	1.00	1.00	1.00		100.00
Topographic Wetness Index							
Class	VL	L	M	H	VH	SUM	Priority vector
4.14 - 7.35	0.06	0.04	0.05	0.05	0.07	0.26	5.26
7.35 - 9.7	0.11	0.09	0.07	0.08	0.09	0.45	8.92
9.7 -13.33	0.17	0.17	0.15	0.12	0.15	0.76	15.28
13.33 - 16.86	0.28	0.26	0.29	0.25	0.23	1.31	26.18
16.86 - 26.07	0.39	0.43	0.44	0.50	0.46	2.22	44.36
SUM	1.00	1.00	1.00	1.00	1.00		100.00

Modified Normalized Difference Water Index							
Class	VL	L	M	H	VH	SUM	Priority vector
-0.58 - -0.23	0.06	0.05	0.05	0.06	0.06	0.28	5.61
-0.23 - -0.1	0.12	0.10	0.07	0.08	0.11	0.48	9.60
-0.1 - 0.15	0.18	0.19	0.15	0.12	0.15	0.79	15.71
0.15 - 0.2	0.24	0.29	0.29	0.24	0.22	1.28	25.66
0.2 - 0.57	0.41	0.38	0.44	0.49	0.45	2.17	43.41
SUM	1.00	1.00	1.00	1.00	1.00		100.00
Rainfall							
Class	VL	L	M	H	VH	SUM	Priority vector
283.82 - 344.4	0.06	0.04	0.05	0.05	0.07	0.26	5.26
344.4 - 377.05	0.11	0.09	0.07	0.08	0.09	0.45	8.92
377.05 - 407.6	0.17	0.17	0.15	0.12	0.15	0.76	15.28
407.6 - 439.5	0.28	0.26	0.29	0.25	0.23	1.31	26.18
439.5 - 477.07	0.39	0.43	0.44	0.50	0.46	2.22	44.36
SUM	1.00	1.00	1.00	1.00	1.00		100.00
Normalized Difference Vegetation Index							
Class	VL	L	M	H	VH	SUM	Priority vector
0 - 0.01	0.44	0.49	0.44	0.38	0.33	2.08	41.62
0.01 - 0.14	0.22	0.24	0.29	0.29	0.27	1.31	26.18
0.14 - 0.18	0.15	0.12	0.15	0.19	0.20	0.81	16.11
0.18 - 0.27	0.11	0.08	0.07	0.10	0.13	0.49	9.86
0.27 - 0.681	0.09	0.06	0.05	0.05	0.07	0.31	6.24
SUM	1.00	1.00	1.00	1.00	1.00		100.00
Lithology							
Class	VL	L	M	H	VH	SUM	Priority vector
Clay	0.10	0.08	0.09	0.12	///	0.38	9.60
SANDY_LAOM	0.20	0.15	0.13	0.16	///	0.64	16.11
LOAM	0.30	0.31	0.26	0.24	///	1.11	27.71
CLAY_LOAM	0.40	0.46	0.52	0.48	///	1.86	46.58
SUM	1.00	1.00	1.00	1.00			100.00

### III.5.1.4 Weighting the Factors of the Analytic Hierarchy Process:

The AHP weightage to the factors:

**Table III. 9.** Assigned weightage AHP to the factors

Factor	E	S	DD	DR	TWI	MNDWI	Rainfall	NDVI	L
Weight (W)	0.31	0.22	0.16	0.11	0.07	0.05	0.04	0.02	0.02

The weightage distribution for factors influencing flood susceptibility using the Analytic Hierarchy Process (AHP) is as follows:

Elevation (31%), Slope (22%), Drainage Density (16%), Distance to River (11%), Topographic Wetness Index (7%), Modified Normalized Difference Water Index (5%), Rainfall (4%), Normalized Difference Vegetation Index (2%) and Lithology (2%).

The analysis indicates that elevation and slope are the most critical factors in determining flood susceptibility, followed by drainage density and distance to the river. Topographic wetness index modified normalized difference water index, rainfall, normalized difference vegetation index, and lithology have a relatively lower influence on flood susceptibility.

#### III.5.1.5 Flood Hazard map using AHP:

The purpose of the hazard map is to identify and visualize areas that are susceptible to flooding. By analyzing various parameters and their spatial extent, the map highlights regions that are potentially exposed to climatic hazards leading to flooding incidents. The determination of hazard levels involves assigning different weights according to the Saaty scale.

To illustrate this process, we consider the calculation of the eigenvector ( $V_p$ ) and the weighting coefficient ( $C_p$ ). The specific weights assigned to each element for evaluating hazards can be found in **Table III. 9**.

$$V_p = \sqrt[9]{1 \times 2 \times 3 \times 4 \times 5 \times 6 \times 7 \times 8 \times 9} = 4.14$$

$$C_p = \frac{4.14}{13.46} = 0.31$$

The relative hazard map, which is determined using the Analytic Hierarchy Process (AHP), is obtained by applying the given formula:

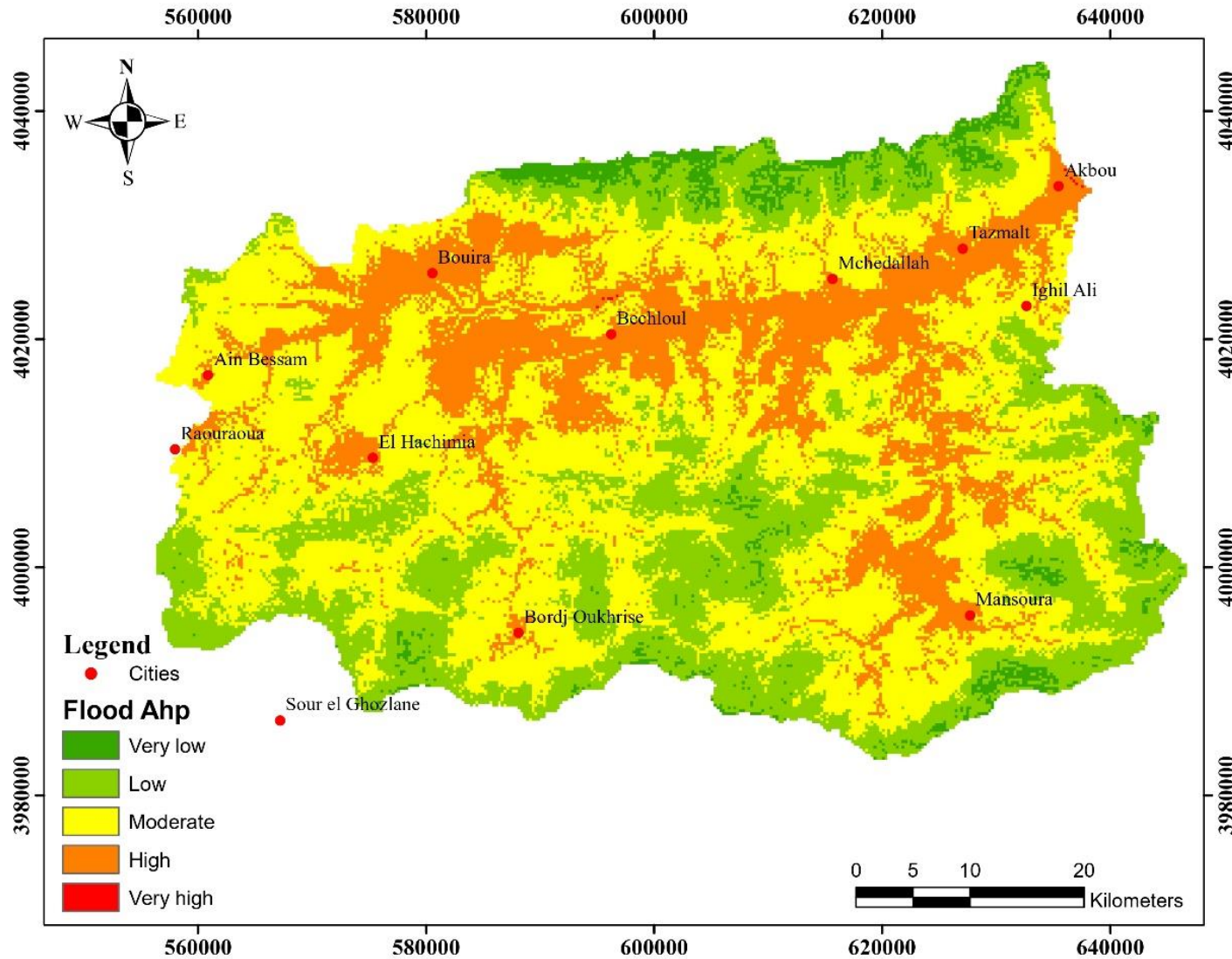
$$\text{Hazard index} = 0.31 \times E + 0.22 \times S + 0.16 \times DD + 0.11 \times DR + 0.07 \times TWI + 0.05 \times MNDWI + 0.04 \times Rainfall + 0.02 \times NDVI + 0.02 \times L$$

Where:

- » **E**: Elevation.
- » **TWI**: Topographic Wetness Index.
- » **S**: Slope.
- » **MNDWI**: Modified Normalized Difference Water Index.
- » **DD**: Drainage Density.
- » **NDVI**: Normalized Difference Vegetation Index.
- » **DR**: Distance to River.
- » **L**: Lithology.

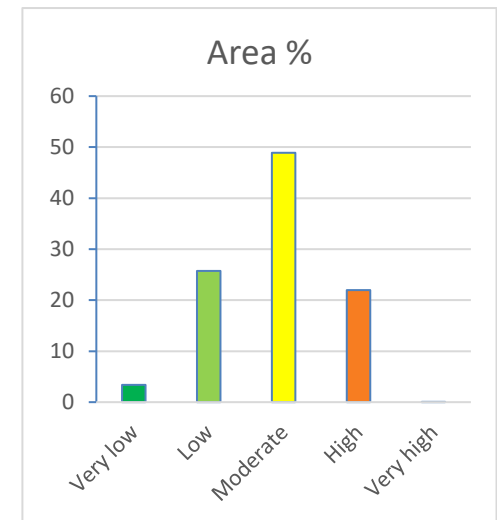
Lastly, the weighted sum technique in ArcGIS 10.8 software was utilized for superimposing (overlay) all the factors to generate a flood risk map.

**Table III. 10.** Effect flood in the watershed



**Figure III. 14.** Flood hazard map made using Hierarchical Analysis Process

Effect	Area (km <sup>2</sup> )	Area %
Very low	127.16	3.39
Low	965.17	25.73
Moderate	1883.94	48.89
High	824.12	21.97
Very high	0.75	0.02
<b>Total</b>	<b>3751.15</b>	<b>100</b>



**Figure III. 13.** Flood effect diagram in the watershed

The flood risk assessment conducted in this study applied hierarchical analysis and produced a map (**Figure III. 14**) and adjacent to **Table III. 10**. The map categorized the flood risk into five distinct levels, ranging from very low to very high. Within the Sahel Soumam watershed, areas with very-low, low-to-medium, and medium risk of flooding accounted for 3.39%, 25.73%, and 48.89% respectively, covering a total estimated area of 2926.27 km<sup>2</sup>. These regions are characterized by steep slopes, vegetated areas, agricultural land, and medium to high elevations. High and very high-risk areas constituted 21.97% and 0.02% respectively, approximately to 824.88 km<sup>2</sup> of the study area.

Significantly, the municipalities of Akbou, Tazmelt, M'chedalah, Bouira, Mansoura, Haizer, and Bachloul were identified as being at substantial risk of flooding, with some areas classified as very high risk. A thorough analysis of the flood risk map, In addition to the maps used in the analysis, it was recognizable that elevation, slope, and drainage intensity had a major impact. which is validated by the weighted values of the coefficients calculated in **Table III. 9**. It is crucial to identify areas prone to flood risks, as demonstrated in this study, for effective mitigation and planning purposes.

### **III.5.2 Weighting using Fuzzy Analytic Hierarchy Process:**

The Fuzzy Analytical Hierarchical Process (FAHP) is a decision-making method that combines fuzzy logic and analytical hierarchy process (AHP). It handles complex decisions by breaking them down into a hierarchical structure and using linguistic assessments. Fuzzy AHP incorporates subjective judgments and fuzzy sets to evaluate criteria and calculate overall rankings. It helps decision-makers navigate uncertainty and ambiguity, providing a robust and flexible approach to decision analysis and prioritization.

#### **III.5.2.1.Pair-wise comparison matrix using Fuzzy Analytic Hierarchy**

##### **Process:**

TFN (Triangular Fuzzy Number) scale is a numerical representation used in fuzzy logic and fuzzy set theory to represent uncertainty or vagueness. It is a way to express fuzzy membership or degree of truth within a defined range. A TFN scale consists of three parameters: the lower limit, the central value, and the upper limit. It is called a "triangular" fuzzy number because it forms a triangle on a graph, with the central value representing the peak of the triangle. The TFN scale allows for the representation of imprecise or uncertain information in a quantitative manner, enabling fuzzy logic systems to handle and reason with fuzzy or vague inputs.

The mathematical equations used in the following tables (**Table III. 13 & Table III. 14**) for the Fuzzy Hierarchical Analysis Matrix.

• **The mathematical expression of the Triangular Fuzzy Number:** [32]

A triangular fuzzy number (TFN) is usually denoted as  $\tilde{x} = (l; m; u)$  where the parameters  $l$ ,  $m$ , and  $u$  represent respectively the smallest value, the most likely value, and the greatest value of a fuzzy set. The membership function  $\mu(x)$  of each TFN can be defined using the following expression:

$$\mu(x) = \begin{cases} \frac{(x-l)}{(m-l)} & \text{if } x \in [l, m] \\ \frac{(u-x)}{(u-m)} & \text{if } x \in [m, u] \\ 0 & \text{if otherwise} \end{cases}$$

After the determination of the triangular fuzzy numbers, the FAHP is used to map the flood susceptibility through the following steps:

**Step 1** the construction of the fuzzy evaluation matrix based on the pairwise comparison of the different factors using TFN as listed in **Table III. 11**. The fuzzy evaluation matrix is expressed as follows:

$$\tilde{A} = \begin{bmatrix} 1 & \tilde{a}_{12} & \dots & \tilde{a}_{1n} \\ \tilde{a}_{21} & 1 & \dots & \tilde{a}_{2n} \\ \dots & \dots & 1 & \dots \\ \tilde{a}_{n1} & \tilde{a}_{n2} & \dots & 1 \end{bmatrix}$$

Where  $(\tilde{a}_{ij})$  is the fuzzy triangular number.

**Table III. 11.** conversion sales for AHP and FAHP

**Step 2** The value of the fuzzy synthetic extent with respect to the  $i$ th object is expressed as:

$$R_i = \sum_{j=1}^m M_{gi}^j \otimes [\sum_{j=1}^n \sum_{j=1}^m M_{gi}^j]^{-1}$$

$$\sum_{j=1}^m M_{gi}^j = (\sum_{j=1}^m l_i \sum_{j=1}^m m_i \sum_{j=1}^m u_i)$$

$$[\sum_{j=1}^n \sum_{j=1}^m M_{gi}^j]^{-1} = (\frac{1}{\sum_{i=1}^n u_i}, \frac{1}{\sum_{i=1}^n m_i}, \frac{1}{\sum_{i=1}^n l_i})$$

**Step 3** the degree of the possibility of two triangular fuzzy numbers  $M_1 = (l_1; m_1; u_1)$  and  $M_2$  equals  $(l_2; m_2; u_2)$ , where  $M_2 \geq M_1$ , is defined as:

$$V(M_2 \geq M_1) = \sup_{y \geq x} [\min(\mu_{M_1}(x), \mu_{M_2}(y))]$$

and can be expressed as:

$$V(M_2 \geq M_1) = \text{hgt}(M_1 \cap M_2) = \mu_{M_2}(d) = \begin{cases} 1 & \text{if } m_i \geq m_1 \\ 0 & \text{if } l_1 \geq u_2 \\ \frac{l_1 - u_1}{(m_2 - u_2) - (m_1 - l_1)} & \text{Otherwise} \end{cases}$$

**Step 4** the degree of possibility for a convex fuzzy number great than K convex fuzzy numbers  $M_i$  ( $i = 1, 2, \dots, k$ ) can be expressed as:

$$V(M \geq M_1, M_2, \dots, M_k) = V[(M \geq M_1) \text{ and } (M \geq M_2) \text{ and } \dots \text{ and } (M \geq M_k)] = \min V(M \geq M_i), i = 1, 2, 3, \dots, k$$

Let  $d(A_i) = \min V(S_i \geq S_k)$ , for  $k = 1, 2, \dots, n; k \neq i$

then the weight vector is given by:

$$W = (d'(A_1), d'(A_2), \dots, d'(A_n))^T$$

where  $A_i = (i = 1, 2, 3, \dots, n)$  are n elements.

**Step 5** the normalized weight vector is given by:

$$W = (d(A_1), d(A_2), \dots, d'(A_n))^T$$

Where W is non-fuzzy number.

**Table III. 12.** TFN scale

TFN SCALE	L	M	U
1	1	1	1
2	0.5	1	1.5
3	1	1.5	2
4	1.5	2	2.5
5	2	2.5	3
6	2.5	3	3.5
7	3	3.5	4
8	3.5	4	4.5
9	4	4.5	4.5
1/2	2/3	1	2
1/3	1/2	2/3	1
1/4	2/5	1/2	2/3
1/5	1/3	2/5	1/2
1/6	2/7	1/3	2/5
1/7	1/4	2/7	1/3
1/8	2/9	1/4	2/7
1/9	2/9	2/9	1/4

**Table III. 13.** Pairwise matrix for flood susceptibility using Fuzzy AHP

Parameters	E			S			DD			DR			TWI			MNDWI			Rainfall			NDVI			L		
	L	M	U	L	M	U	L	M	U	L	M	U	L	M	U	L	M	U	L	M	U	L	M	U	L	M	U
<b>E</b>	<b>1</b>	<b>1</b>	<b>1</b>	0.5	1	1.5	1	1.5	2	1.5	2	2.5	2	2.5	3	2.5	3	3.5	3	3.5	4	3.5	4	4.5	4	4.5	4.5
<b>S</b>	0.67	1	0.5	<b>1</b>	<b>1</b>	<b>1</b>	0.5	1	1.5	1	1.5	2	1.5	2	2.5	2	2.5	3	2.5	3	3.5	3	3.5	4	3.5	4	4.5
<b>DD</b>	0.5	0.67	1	0.67	1	0.5	<b>1</b>	<b>1</b>	<b>1</b>	0.5	1	1.5	1	1.5	2	1.5	2	2.5	2	2.5	3	2.5	3	3.5	3	3.5	4
<b>DR</b>	0.4	0.5	0.67	0.5	0.67	1	0.67	1	0.5	<b>1</b>	<b>1</b>	<b>1</b>	0.5	1	1.5	1	1.5	2	1.5	2	2.5	2	2.5	3	2.5	3	3.5
<b>TWI</b>	0.33	0.4	0.5	0.4	0.5	0.67	0.5	0.67	1	0.67	1	0.5	<b>1</b>	<b>1</b>	<b>1</b>	0.5	1	1.5	1	1.5	2	1.5	2	2.5	2	2.5	3
<b>MNDWI</b>	0.29	0.33	0.4	0.33	0.4	0.5	0.4	0.5	0.67	0.5	0.67	1	0.67	1	0.5	<b>1</b>	<b>1</b>	<b>1</b>	0.5	1	1.5	1	1.5	2	1.5	2	2.5
<b>Rainfall</b>	0.25	0.29	0.33	0.29	0.33	0.4	0.33	0.4	0.5	0.4	0.5	0.67	0.5	0.67	1	0.67	1	0.5	<b>1</b>	<b>1</b>	<b>1</b>	0.5	1	1.5	1	1.5	2
<b>NDVI</b>	0.22	0.25	0.29	0.25	0.29	0.33	0.29	0.33	0.4	0.33	0.4	0.5	0.4	0.5	0.67	0.5	0.67	1	0.67	1	0.5	<b>1</b>	<b>1</b>	<b>1</b>	0.5	1	1.5
<b>L</b>	0.22	0.22	0.25	0.22	0.25	0.29	0.25	0.29	0.33	0.29	0.33	0.4	0.33	0.4	0.5	0.4	0.5	0.67	0.5	0.67	1	0.67	1	0.5	<b>1</b>	<b>1</b>	<b>1</b>

**Table III. 14.** Pairwise matrix for flood susceptibility using Fuzzy AHP (continue to **Table III. 13**)

Fuzzy geometric mean			Fuzzy weights			Initial weights (Wi)	Normalized Weights (W)
L <sub>gm</sub>	M <sub>gm</sub>	U <sub>gm</sub>	L <sub>w</sub>	M <sub>w</sub>	U <sub>w</sub>		
1.75	2.24	2.65	0.15	0.22	0.34	0.23	0.22
1.44	1.89	2.07	0.12	0.18	0.26	0.19	0.18
1.16	1.55	1.75	0.10	0.15	0.22	0.16	0.15
0.93	1.25	1.44	0.08	0.12	0.18	0.13	0.12
0.74	1.00	1.16	0.06	0.09	0.15	0.10	0.10
0.60	0.80	0.93	0.05	0.08	0.12	0.08	0.08
0.49	0.64	0.74	0.04	0.06	0.09	0.06	0.06
0.41	0.53	0.60	0.04	0.05	0.08	0.05	0.05
0.38	0.45	0.49	0.03	0.04	0.06	0.05	0.04
7.89	10.36	11.82				<b>1.05</b>	<b>1.00</b>
0.08	0.10	0.13				<b>Sum</b>	

**Table III. 15.** Assigned weightage Fuzzy Analytic Hierarchy Process to all factors

Factor	E	S	DD	DR	TWI	MNDWI	Rainfall	NDVI	L
Weight (W)	0.22	0.18	0.15	0.12	0.10	0.08	0.06	0.05	0.04

The weightage for factors influencing flood susceptibility using the Fuzzy Analytic Hierarchy Process (AHP) is as follows:

Elevation (22%), Slope (18%), Drainage Density (15%), Distance to River (12%), Topographic Wetness Index (10%), Modified Normalized Difference Water Index (8%), Rainfall (6%), Normalized Difference Vegetation Index (5%) and Lithology (4%).

The analysis indicates that elevation and slope are the most critical factors in determining flood susceptibility. Drainage density, distance to the river, and topographic wetness index also play significant roles. The modified normalized difference water index, rainfall, normalized difference vegetation index, and lithology have relatively lesser influence in this analysis. The fuzzy AHP approach considers uncertainties and linguistic preferences in assigning the weights to the factors.

### III.5.2.2 Flood Hazard map using Fuzzy Analytic Hierarchy Process:

To calculate the overall influence of each criterion on flood hazard, the "Raster Calculator" tool in ArcGIS was used to multiply the rasters criterion by their respective weightage values obtained from pairwise comparisons. The next step is superimposing the weighted rasters to create a composite raster that represents the combined influence of all criteria on flood hazards. The "Raster Calculator" tool can also be used for this step.

An overlay analysis was performed to assess the flood risk in the study area. During this stage, relative weightage values were determined for each factor using Fuzzy AHP. Finally, the weighted sum technique in ArcGIS 10.8 software was applied to superimpose all the factors and generate a flood risk map.

The relative hazard map, which is determined using the Fuzzy Analytic Hierarchy Process (AHP), is obtained by applying the given formula:

$$\text{Hazard index} = 0.22 \times E + 0.18 \times S + 0.15 \times DD + 0.12 \times DR + 0.10 \times TWI + 0.08 \times MNDWI + 0.06 \times \text{Rainfall} + 0.05 \times NDVI + 0.04 \times L$$

**With:** » **E:** Elevation.

» **TWI:** Topographic Wetness Index.

» **S:** Slope.

» **MNDWI:** Modified Normalized Difference Water Index.

» **DD:** Drainage Density.

» **NDVI:** Normalized Difference Vegetation Index.

» **DR:** Distance to River.

» **L:** Lithology.

Table III. 16. Effect flood in the watershed

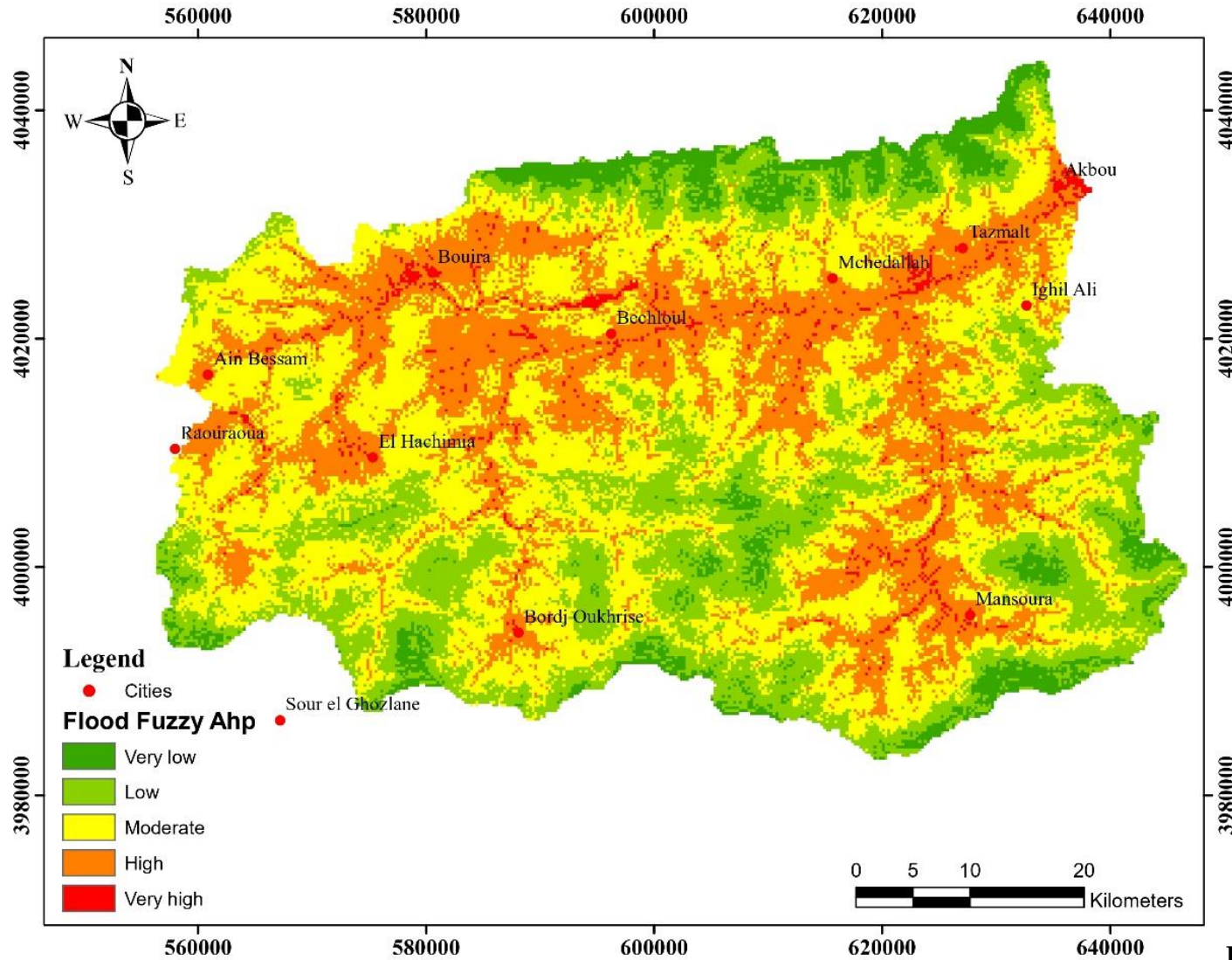


Figure III. 16. Flood hazard map using Fuzzy Analytic Hierarchy Process

Effect	Area (km <sup>2</sup> )	Area %
Very low	241.95	6.45
Low	846.26	22.56
Moderate	1538.34	41.1
High	1053.69	28.09
Very high	67.52	1.8
<b>Total</b>	<b>3751.15</b>	<b>100</b>

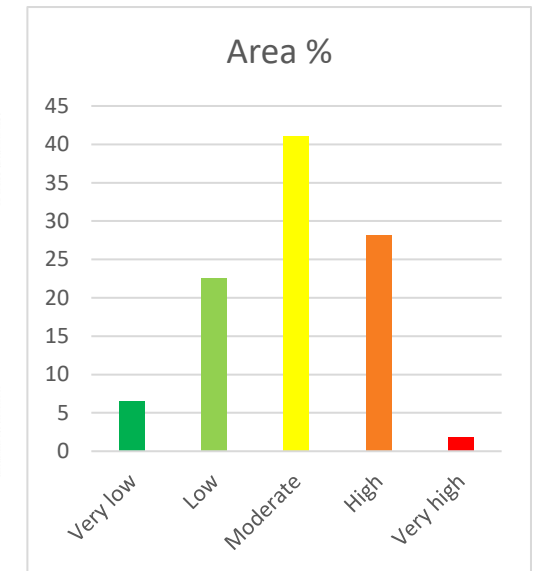


Figure III. 15. Flood effect diagram in the watershed

The Fuzzy hierarchical analysis utilized in this study resulted in a flood risk map (**Figure III. 16**) and the adjacent table (**Table III. 16**) that classified the risk into five levels, ranging from very low to very high. Within the Sahel Soumam watershed, areas with very low, low, and medium risk of flooding covered 6.45%, 22.56%, and 41.1% respectively, approximately a total area of 2629.93 km<sup>2</sup>. These regions were characterized by high slopes, vegetated areas, agricultural land, and medium to high elevations. High and very high-risk areas constituted 28.09% and 1.8% respectively, covering 1121.22 km<sup>2</sup> of the study area.

Moreover, the municipalities of Akbou, Tazmelt, M'chedalah, Bouira, Mansoura, Haizer, Bechloul, Ain Besam, Raouraoua, Bourj Okhris, Al Hachimia, and Ighil Ali were identified as being at high and very high risk of flooding. An analysis of the flood risk map, In addition to the maps used in the analysis, revealed that elevation, slope, and drainage density had a significant impact. The other parameters had varying degrees of influence, ranging from medium to low. This highlights the advantage of utilizing fuzzy hierarchical analysis, that establishes the significance of all the parameters. then validated by the weighted values calculated in (**Table III. 15**). Identifying flood hazards, as demonstrated in this study is essential for urban management.

### III.5.3 Comparison between flood hazard map AHP and Fuzzy AHP:

The two results provided analogous outcomes about the flood risk assessment achieved using these two methodologies. Both studies categorized the flood risk into five levels, ranging from very low to very high. They also identified specific areas within the Sahel Soumam watershed that were at higher risk of flooding.

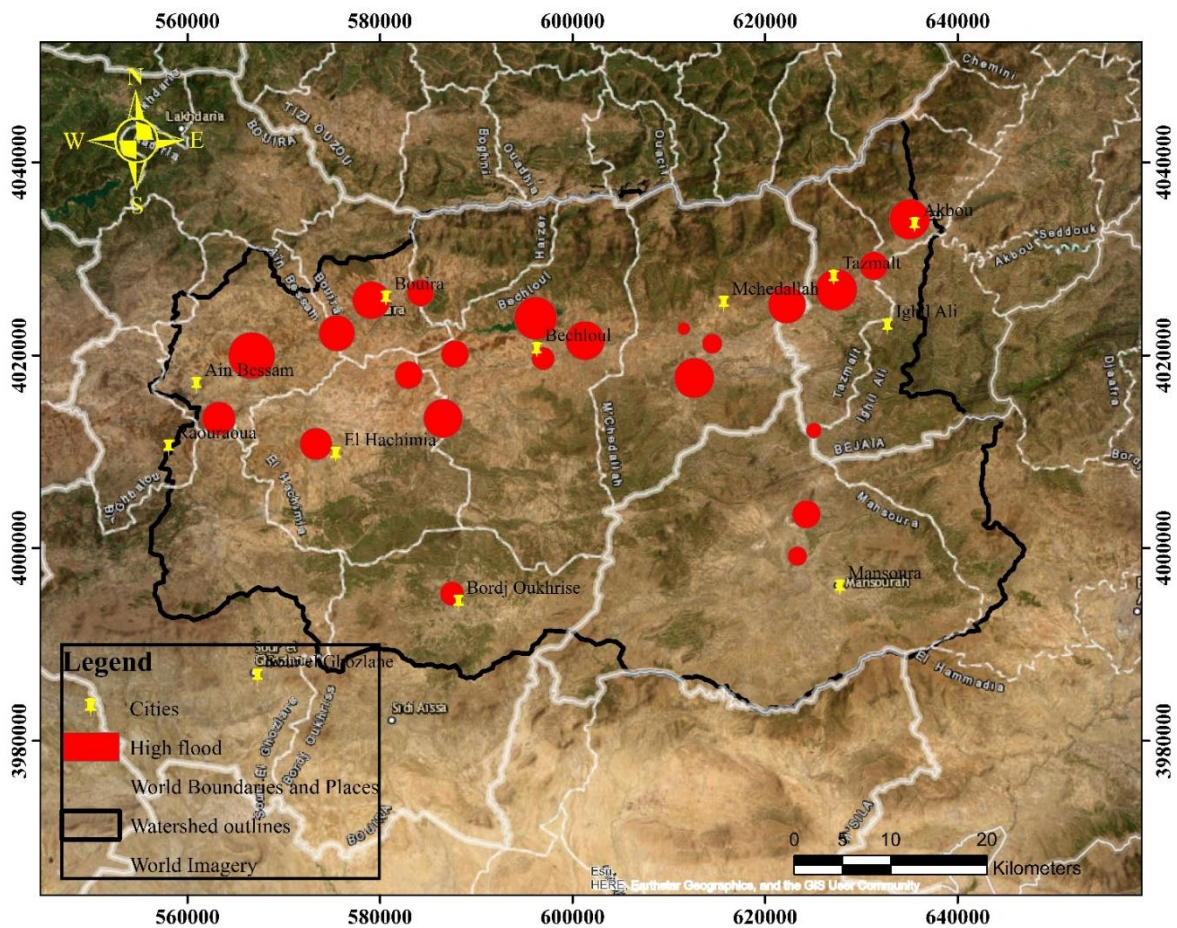
In the first study, hierarchical analysis was applied, and the produced map showed that low, low-to-medium, and medium-risk areas covered 3.39%, 25.73%, and 48.89% respectively, with a total estimated area of 2926.27 km<sup>2</sup>. High and very high-risk areas constituted 21.97% and 0.02% respectively, covering 824.88 km<sup>2</sup>.

**Table III. 17.** Flood hazard in the watershed using AHP & Fuzzy AHP

Flood effect	AHP	Fuzzy AHP
	Area km <sup>2</sup>	
Very low	127.16	241.95
Low	965.17	846.26
Moderate	1883.94	1538.34
High	824.12	1053.69
Very high	0.75	67.52
<b>Total</b>	<b>3751.15</b>	

The municipalities of Akbou, Tazmalt, M'chedallah, Bouira, Mansoura, Haizer, and Bechloul were identified as being at substantial risk, with some areas classified as very high risk. The analysis highlighted the significant impact of elevation, slope, and drainage density on flood risk.

In the second study, fuzzy hierarchical analysis was used, and the resulting map indicated that areas with very low, low, and medium risk of flooding covered 6.45%, 22.56%, and 41.1% respectively, with a total estimated area of 2629.93 km<sup>2</sup>. High and very high-risk areas 28.09% and 1.8% respectively, covering 1121.22 km<sup>2</sup>. The municipalities identified as being at high and very high risk included Akbou, Tazmalt, M'chedallah, Bouira, Mansoura, Haizer, Bechloul, Ain Besam, Raouraoua, Bourj Okhris, Al Hashimia. (Figure III. 17).



**Figure III. 17.** High flood hazard in watershed of Wadi Sahel Soumam

### III.6 The inventory map of floods using data from previous events and satellite image ‘World Imagery’:

Soumam region, exactly Wadi El Sahel, withstood many flood incidents previously, that caused many losses. The collected spatial data for some previous events (**Figure III. 18**) and the spatial satellite imagery data provided by Google Maps in this region were used for generating the inventory map .



**Figure III. 18.** Some pictures of previous floods in the Sahel Wadi <sup>[38][39]</sup>

### III.6.1 The spatial data of the pervious flooding events in the sub-watershed Wadi El Sahel :

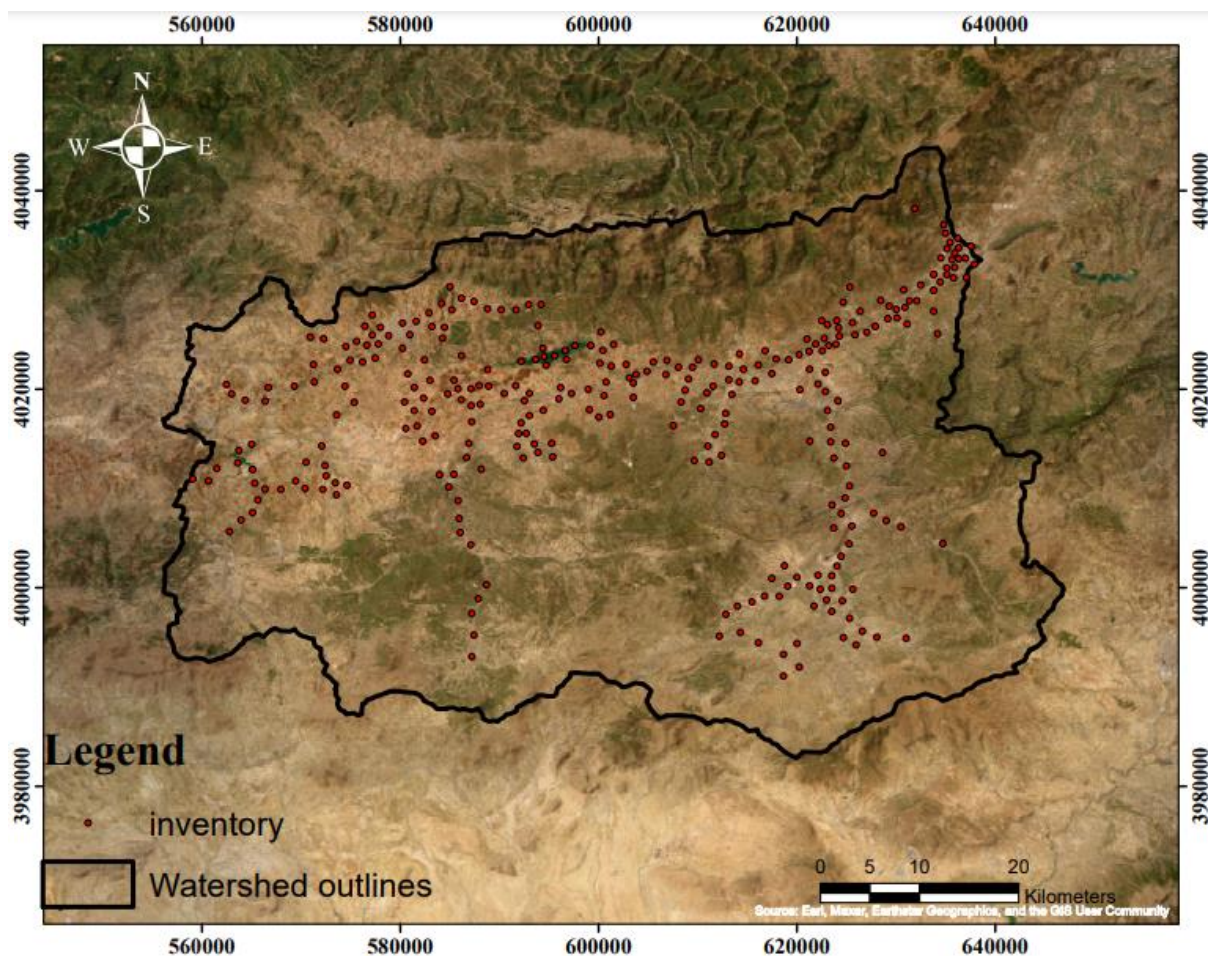
The following table contains the collected data for the date and the place of the pervious flooding in the study area .

**Table III. 18.** spatial data for previous events in Wadi Sahel Soummam <sup>[39]</sup>

<b>Date</b>	<b>Place</b>
<b>13 May 2006</b>	<i>Guendouza « Akbou », BEJAIA</i>
<b>27 February 2015</b>	<i>Ichoukar , Ait R'zine , Akbou, Bejaia</i>
<b>20/21 October 2015</b>	<i>Sour el Ghozlane , BOUIRA M'Chedallah, BOUIRA</i>
<b>March 2016</b>	<i>Ighrem , BEJAIA Akbou , BEJAIA</i>
<b>24/06/2017</b>	<i>Ain El Hadjar, BOUIRA Bouira , BOUIRA Ain Aloui , BOUIRA</i>
<b>March 2018</b>	<i>Akbou, BEJAIA Bouzeroual, Akbou, BEJAIA Ighram, BEJAIA Chellata, BEJAIA</i>
<b>11 October 2018</b>	<i>Bouira , BOUIRA</i>
<b>November 2018</b>	<i>Ath Rached, BOUIRA Tiksiridene « Chorfa » , BOUIRA Ain Aloui , BOUIRA</i>
<b>24 January 2019</b>	<i>Akbou , BEJAIA Amirouche « Akbou », BEJAIA Tazmalet , BEJAIA Allaghane « Tazmalet », BEJAIA Localité d'Ichoukar « Aït R'zine », BEJAIA Boudjellil , BEJAIA Beni Mellikèche ,BEJAIA</i>
<b>06 February 2019</b>	<i>Bouira, BOUIRA</i>
<b>10 June 2019</b>	<i>Aïn Bessem, BOUIRA Aïn El Aloui, BOUIRA El Hachimia, BOUIRA Sour El Ghozlane, BOUIRA</i>
<b>21 July 2019</b>	<i>Ighram ,Ahnif. BOUIRA</i>
<b>29 May 2020</b>	<i>Oued El Berdi, BOUIRA</i>
<b>28/29 November 2020</b>	<i>Taharacht « Akbou », BEJAIA Guendouza « Akbou », BEJAIA Ighil Ali « wilaya de BBA »</i>
<b>29 April 2022</b>	<i>El m'hir BBA</i>
<b>04 October 2022</b>	<i>Tazmalet , BEJAIA</i>
<b>05 October 2022</b>	<i>Mansourah BBA</i>

### III.6.2 The inventory Flood map:

The following figure illustrates the inventory map that indicates the previously inundated areas in the sub-watershed of Wadi El Sahel, using satellite images provided by 'World imagery'-ESRI.



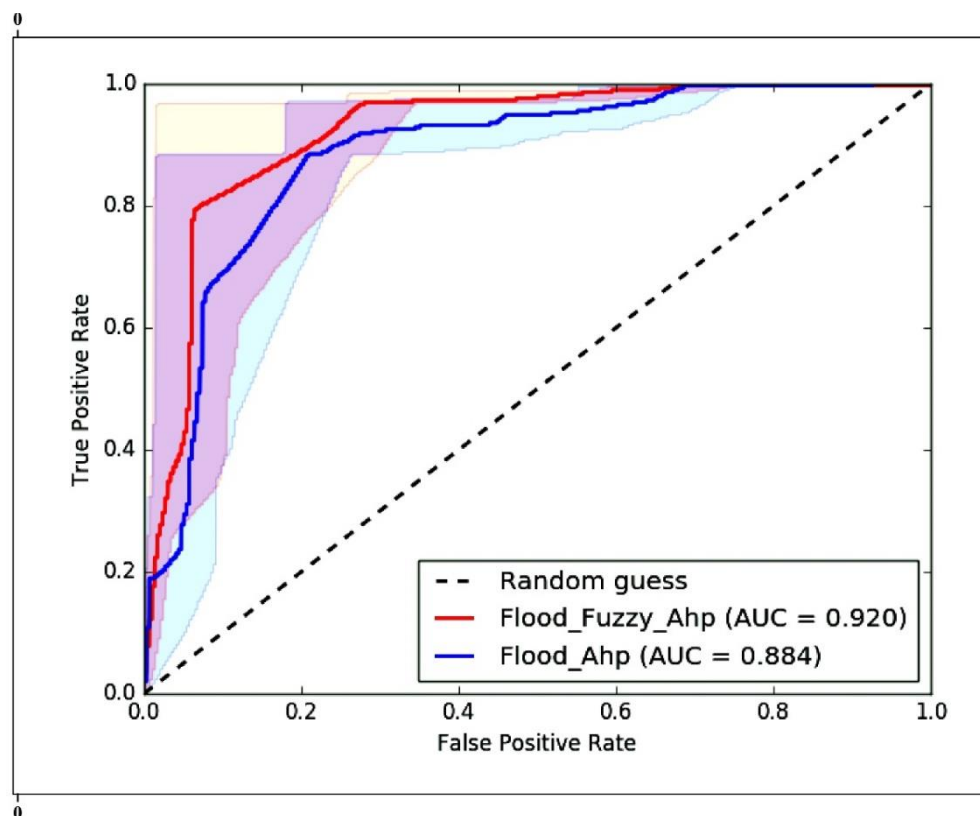
**Figure III. 19.** Map of inventory data of the previous flood events in the Wadi Sahel watershed

In conclusion, the observation of the previous incidents collected in the previous table and the inventory map of floods in the area show the flooding of Wadi Al-Sahel in many of its neighboring areas, which makes those areas periodically at risk of being submerged under the water of the watercourse. In addition, these results are used to validate the results obtained statistically from the AHP method and the Fuzzy AHP.

### III.7 Verification and validation of the results using the ROC (Receiver Operating Characteristic) curve and the AUC (the Area Under the ROC Curve):

The validation method using ROC (Receiver Operating Characteristic) curve and AUC (Area Under the ROC Curve) is a statistical approach to assess the performance of a binary classification model or map. The ROC curve plots the True Positive Rate against the False Positive Rate at different classification thresholds, showing the model's ability to distinguish between positive and negative cases.<sup>[33]</sup>

The AUC value represents the overall performance of the model, with higher values indicating better predictive accuracy. In the context of validating a Flood Hazard map, the ROC curve and AUC analysis help evaluate the map's ability to identify flood and non-flood susceptible areas based on observed flood occurrences.



**Figure III. 20.** The AUC of success rate curve both AHP and Fuzzy AHP

After generating flood susceptibility maps using the AHP and Fuzzy AHP methods, it is integral to validate their reliability. In this study, the validation of flood susceptibility maps was performed using the area under the curve (AUC) metric. AUC measures the accuracy of the flood susceptibility maps by creating success and prediction rate curves. The success rate curve represents the accuracy of the model to existing flood occurrences. It is derived by comparing A dataset of past floods and data for areas expected to be vulnerable to floods with the flood susceptibility map.

The validation process utilized 300 flood instances, including previous floods and vulnerable areas to flooding based on observations from Google Maps. To create the success and prediction rate curves, the ROC module in ArcGIS 10.8 tool was applied for both the AHP and Fuzzy AHP methods. AUC curves were plotted using the true positive rate (training and validation floods) on the x-axis and the false positive rate on the y-axis. The total AUC provides a qualitative assessment of prediction accuracy, with a larger area indicating higher accuracy.

The AUC values range from 0.5 to 1.0 and are used to evaluate the model's accuracy. The qualitative interpretation of AUC values is as follows: excellent (0.9 – 1.0), very good (0.8 - 0.9), good (0.7 - 0.8), average (0.6 - 0.7), and fair (0.5 - 0.6). An AUC value close to 1.0 indicates ideal performance, while a value equal to or less than 0.5 suggests poor performance.

The results showed that the AUC of the success rate curve was 0.884 for the AHP method and 0.92 for the Fuzzy AHP method, corresponding to prediction accuracies of 88.40% and 92.00%, respectively. The AUC values of both methods indicated a very well (AHP) and excellent (Fuzzy AHP) performance in flood susceptibility mapping.

In conclusion, based on the AUC results, it is evident that both the AHP and Fuzzy AHP methods are significantly efficient in flood susceptibility mapping in the study area, with very well and excellent performance, respectively.

### **III.7 Conclusion:**

This study focused on assessing flood hazard in the Soumam region of northern Algeria using two GIS-based multicriteria analysis methods: Analytical Hierarchy Process (AHP) and Fuzzy Analytical Hierarchy Process. The analysis treated nine objective map layers and categorized the flood risk into five levels. Both methods provided similar results and identified high-risk areas within the Sahel sub-watershed (Soumam). The influential factors included elevation, slope, and drainage density. The results of this study emphasized the significance of identifying flood hazards for effective mitigation and planning. The study suggested an enhancement in the management and protection measures for vulnerable municipalities such as Akbou, Bouira, and Mansoura. Overall, the research provided valuable insights into flood management in the region.

# ***GENERAL CONCLUSION***

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## General Conclusion

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In conclusion, floods pose a significant threat to lives, infrastructure, and the environment, and their occurrence is influenced by factors such as heavy rainfall, human activities, climate change, and geographical characteristics. Minimizing flood losses requires the adoption of more effective protection and forecasting methods. The integration of Geographic information systems (GIS) with multicriteria analysis methods has gained popularity in recent years for flood forecasting, allowing for the utilization of diverse data sources and criteria to achieve accurate and reliable predictions.

The study focused on assessing flood risk in the Soumam region of northern Algeria using GIS-based multicriteria analysis methods, namely the Analytical Hierarchy Process (AHP) and Fuzzy Analytical Hierarchy Process. By analyzing nine objective map layers, the researchers categorized flood risk into five levels and identified high-risk areas within the Sahel sub-watershed (Soumam). Key factors contributing to flood hazard identification included elevation, slope, and drainage density. The findings emphasized the importance of identifying flood hazards to facilitate effective mitigation and planning. The study recommended enhancing management and protection measures for susceptible municipalities such as Akbou, Bouira, and Mansoura. Overall, this research provided valuable insights into flood management in the region.

To validate the reliability of the flood susceptibility maps generated by the AHP and Fuzzy AHP methods, the study employed the area under the curve (AUC) metric. Through the comparison of the flood susceptibility maps with a dataset consisting of 300 flood instances and susceptible locations, the AUC values of the success rate curve were determined. The AHP method achieved an AUC of 0.884, corresponding to a prediction accuracy of 88.40%. Meanwhile, the Fuzzy AHP method yielded an AUC of 0.92, indicating a prediction accuracy of 92.00%. These results demonstrated that both methods performed exceptionally well, with the AHP method showing very well performance and the Fuzzy AHP method exhibiting excellent performance in flood susceptibility mapping.

In summary, the AHP and Fuzzy AHP methods significantly contributed to accurately assessing flood hazard in the Soumam region. The integration of GIS with these multicriteria analysis methods proved to be effective in flood hazard assessment, enabling reliable and timely flood forecasting. By utilizing diverse data sources and criteria, these methods support better flood risk management and provide valuable insights for the development of effective flood management strategies in the region and beyond.

To enhance flood management, several steps should be taken. Improving data quality and availability is essential for informed decision-making. Refining criteria selection ensures a holistic assessment of flood management strategies. Incorporating real-time data and monitoring enables timely response and adaptive decision-making. Enhancing modeling capabilities assesses the effectiveness of strategies. Promoting stakeholder collaboration and public awareness fosters inclusive and resilient decision-making. Using GIS-MCA for long-term planning and continuous evaluation helps optimize resource allocation and address emerging challenges.

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