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Assessment of Flood Risks and Their Spatial Modelling in the City of
Laghouat Using Geographic Information Systems and Remote Sensing.

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Dedication

To my noble parents,

To those who toiled for my sake and stayed up late to ensure my comfort,

To those whose prayers were the secret to my success,

To my father, who taught me that knowledge is light, and to my mother, who taught me
that prayer is a weapon,

To those whose names I bear with pride and honour...

To my beating heart and the crown of my head...

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الملخص:

تهدف هذه الدراسة إلى تقييم مخاطر الفيضانات في مدينة الأغواط باستخدام نظم المعلومات الجغرافية (GIS) والاستشعار عن بُعد. وقد تم إجراء محاكاة هيدرولوجية لوادي مزي لتحديد تأثير تغيرات مستوى المياه على المناطق المحيطة. كما تم دمج عوامل مثل الانحدار، وكثافة الشبكة الهيدروغرافية، والارتفاع، والغطاء الأرضي، باستخدام التحليل الهرمي (AHP) لإنشاء خريطة لمخاطر الفيضانات. وقد تم التحقق من دقة هذا النموذج من قِبل الجهات المختصة والسكان. تُقدّم هذه الدراسة خريطة لمخاطر الفيضانات في الأغواط، تم إنشاؤها باستخدام نظم المعلومات الجغرافية، مما يوفر لصناع القرار أساساً علمياً للتخطيط الحضري الذي يأخذ هذه المخاطر في الحسبان.

الكلمات المفتاحية: تقييم مخاطر الفيضانات، نظم المعلومات الجغرافية، الاستشعار عن بُعد، عملية التسلسل الهرمي التحليلي، التحليل متعدد المعايير، الأغواط.

Abstract:

This study aims to assess flood risks in the city of Laghouat using Geographic Information Systems (GIS) and remote sensing. A Water-level-based flood inundation scenarios for the M'zi Valley was carried out to determine the impact of changes in water levels on the surrounding areas. Factors such as slope, hydrographic network density, elevation and land cover were also integrated using the Analytic Hierarchy Process (AHP) to create a flood hazard map. The accuracy of this model was verified by the relevant authorities and the local population. This study presents a flood hazard map for Laghouat, created using geographic information systems, which provides decision-makers with a scientific basis for urban planning that takes these risks into account.

Keywords: flood risk assessment, geographic information systems, remote sensing, analytical hierarchy process, multi-criteria analysis. Laghouat.

Résumé :

Cette étude vise à évaluer les risques d'inondation dans la ville de Laghouat à l'aide des systèmes d'information géographique (SIG) et de la télédétection. Une simulation hydrologique de l'oued M'zi a été réalisée afin de déterminer l'impact des variations du niveau d'eau sur les zones environnantes. Des facteurs tels que la pente, la densité du réseau hydrographique, l'altitude et la couverture du sol ont également été pris en compte à l'aide de l'analyse hiérarchique (AHP) afin d'établir une carte des risques d'inondation. La précision de ce modèle a été vérifiée par les autorités compétentes et la population. Cette étude présente une carte des risques d'inondation à Laghouat, élaborée à l'aide de systèmes d'information géographique, qui fournit aux décideurs une base scientifique pour un aménagement urbain tenant compte de ces risques.

Mots-clés : évaluation des risques d'inondation, systèmes d'information géographique, télédétection, processus d'analyse hiérarchique, analyse multicritère, Laghoua

General Introduction:

Floods are among the most frequent and destructive natural disasters worldwide, causing severe human and economic losses. Flash floods in arid and semi-arid regions pose a serious threat due to their immense destructive power and the element of surprise.

Algeria has experienced numerous devastating flash floods, the most significant of which were the Bab El Oued flood in Algiers in 2001, the Oued Mezab flood in Ghardaïa in 2008, and the Oued M'zi flood in Laghouat in 2016; these floods caused severe material damage and loss of life.

The city of Laghouat, situated in the Saharan Atlas, is particularly vulnerable to this phenomenon, as the Oued M'zi – one of the largest wadis in Algeria – flows through it. The region has experienced several floods, notably the wadi flood in 2016 and the flooding in the city centre, which occurs periodically during the rainy season; however, no comprehensive site-specific risk assessment has been carried out for the city.

This study aims to bridge this gap by assessing this hazard in the city of Laghouat. Firstly, the foothill catchment of The M'zi Valley was studied by determining its area and shape in order to understand its nature; the study was then divided into two sections: one section focuses on hydrological modelling of the The M'zi Valley, identifying scenarios for rising water levels and determining the relationship between flooding in the wadi and flooding in the city centre; the second section involves a study of the city centre using multi-criteria decision analysis (MCDA) based on information systems Geographical analysis, specifically using the 'Analytic Hierarchy Process' (AHP). The aim was to produce a final flood hazard map for the city and to assess the extent to which buildings and roads would be affected. This was achieved by conducting two surveys, distributed to residents and experts (technical bodies), to validate the results obtained from the study.

The findings of this study provide a scientific basis for flood hazard management in Laghouat, presenting a map of the area's most at hazard, an assessment of the infrastructure and buildings at hazard, as well as recommendations and guidance for decision-makers. It is hoped that this research will contribute to mitigating these risks in the city.

Research Problem:

The city of Laghouat suffers from frequent flash floods, particularly in the city centre, causing significant damage and road closures. Despite these problems, no assessment of these risks has been carried out, nor have any effective solutions been found. As a first step towards understanding this phenomenon and gaining insight into it, an important and fundamental question must be raised, namely: **What are the main factors causing the recurrent flooding in the city centre?**

Research Objectives:

This study primarily aims to assess flood hazard using Geographic Information Systems (GIS) and remote sensing. This main objective is divided into the following sub-objectives:

First, analysing the topographic and hydrological characteristics of the Laghouat drainage basin, including slope, elevation, drainage network, drainage density, and basin shape.

Hydrological modeling of the M'zi Valley and visualizing the impact of the valley's water level on adjacent areas.

Developing a multi-criteria spatial model of flood hazard in the city of Laghouat by integrating criteria (slope, elevation, distance to the M'zi Valley, drainage density, and land use) using the Analytic Hierarchy Process (AHP) and Weighted Overlay Analysis in ArcGIS.

Preparing a flood hazard map for the city of Laghouat and classifying it into five categories (very low, low, medium, high, and very high).

Assessing the impact of flood hazard on buildings and roads by integrating flood hazard maps with layers such as built-up areas.

Research Methodology:

This study adopts a quantitative and spatial analytical approach, focusing primarily on the processing and analysis of geospatial data within a Geographic Information System (GIS) environment, supported by qualitative data collected through field studies. This multi-methodological approach is justified by the need to integrate physical data (topographical, hydrological and climatic) with human data (land use, exposure and perception) in order to produce a comprehensive assessment of flood risks. The data collection phase drew on several sources: A 30-metre resolution Digital Elevation Model (DEM) was obtained from the USGS, along with Landsat 8 satellite imagery for land-use classification, precipitation data for the period 1994–2024 extracted from the NASA POWER database, and building and road data from OpenStreetMap. The methodological framework was organised into four

main stages. Firstly, the hydrological characteristics of the Wadi Mazi catchment were analysed through morphometric calculations, and a water level simulation was carried out using Global Mapper software. To simulate four scenarios of rising water levels (2 m, 4 m, 6 m, 8 m) and assess their impact on neighbouring urban areas. Secondly, flood risk criteria were selected, namely elevation, slope, drainage density and land use; each criterion was then re-rated on a standardised five-point scale ranging from very low to very high. Thirdly, the weights of the criteria were determined using the Analytic Hierarchy Process (AHP), based on a pairwise comparison matrix validated by the consistency ratio; a weighted overlay analysis was then carried out in ArcGIS 10.8 To produce the final flood hazard map for the city of Laghouat. Fourthly, exposure was assessed by integrating the risk map with layers showing buildings and roads to identify infrastructure at risk. Finally, to validate the spatial model, two field studies were conducted — the first involving 30 residents and the second involving 10 experts from the relevant technical bodies (the Municipal Building Office, the Water Resources Directorate and the National Sanitation Office) — to verify the model's accuracy and identify the actual causes of flooding in the city centre, particularly the role of drainage channels and pumping stations. The software used in this study includes ArcGIS 10.8 for spatial analysis and map production; Global Mapper for simulating water-level scenarios; Google Earth Pro for measuring valley cross-sections; and Microsoft Excel for statistical analysis and graphical representation of the questionnaire data.

To provide a clear overview of the methodology adopted in this study, the following organisational chart summarises the general research design, from the collection of primary data through to the final assessment and validation of flood risks. It illustrates the logical progression of the study, highlighting the key stages of the methodology, the types of data used, the spatial analysis techniques applied, and the expected results.

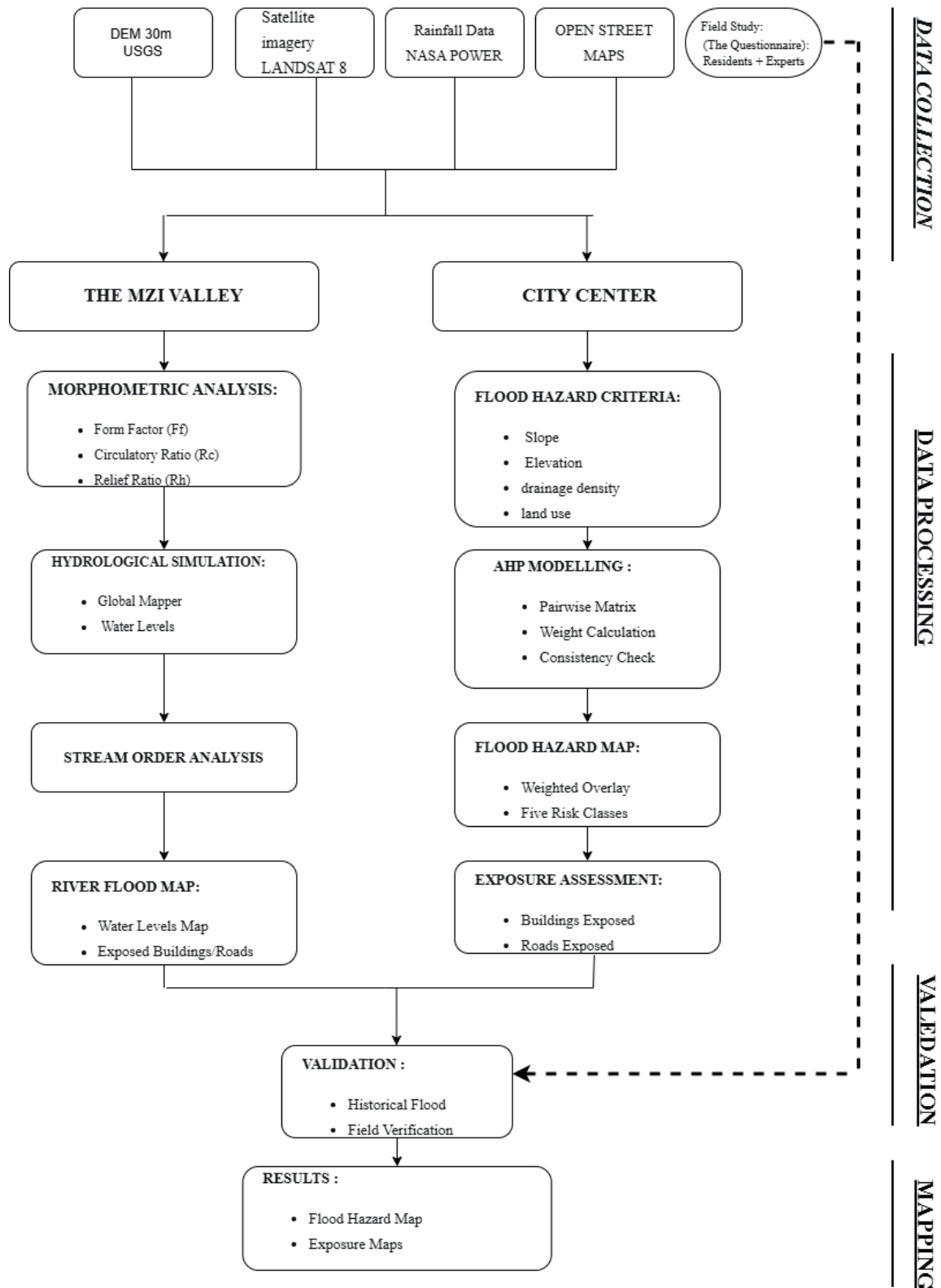


Figure 1:organizational chart for the research methodology

Chapter I: General Framework of the Study

1.Introduction:

This chapter aims to provide a scientific definition and classification of floods, with a focus on urban and flash floods as these are relevant to the subject of our studies also reviews the fundamental concepts and capabilities offered by Geographic Information Systems (GIS) and remote sensing in terms of data acquisition, spatial analysis and risk mapping, as well as the principles of spatial modelling of natural hazards.

The chapter then examines the fundamental principles of Geographic Information Systems (GIS) and remote sensing, highlighting their capabilities in data collection, spatial analysis and hazard mapping. It also discusses the role of spatial modelling in natural hazard assessment, with a focus on multi-criteria decision analysis (MCDA).

This chapter provides an overview of flood hazard assessment using geographic information systems and cites examples from international, local and national studies

2.Floods, concepts, types and impacts:

Floods are among the most well-known natural disasters in the world, and there are several definitions of this phenomenon, as outlined in a research paper for **INTEGRATED RESEARCH ON DISASTER RISK**

" A flood is generally defined as the overflow of water from a stream channel onto normally dry land in the floodplain (riverine flooding), higher-than-normal levels along coasts and lakes, or the ponding of water at or near the point where the rain fell " (IRDR, 2014)

" Hydrologists define flood as a sudden increase in water discharge that caused a sudden peak in the water level. Once flood is over, the water level will drop back to near-constant base flow or no flow " (ALI, 2018)

All definitions agree that a flood is a sudden rise in water levels above normal, which is what causes this disaster to result in material and human losses.

For the purposes of this study, a flood is defined as an event in which water levels rise above normal thresholds, resulting in the inundation of land that is not normally flooded, and potentially causing damage to life, property and infrastructure. This definition encompasses both river floods (resulting from the overflow of watercourses) and floods caused by heavy rainfall (resulting from the accumulation of surface water).

2.1. Types and causes of flooding:

Floods vary depending on their source, the speed at which they occur and their geographical location, and are classified as:

2.1.1. Urban flooding:

Urban flooding is a genuine cause for concern, as it causes damage to homes, infrastructure, household goods and buildings in general, and results in significant economic losses through its impact on the industrial and commercial sectors; this, in turn, creates a humanitarian crisis due to job losses amongst the workforce. It also affects transport systems; therefore, it is important to understand the causes and impacts of different types of flooding on urban areas.

Urban floods typically stem from a complex combination of causes. The urban environment is subject to the same natural forces as the natural environment and the presence of urban settlements exacerbates the problem.

Urban areas can be flooded by rivers, coastal floods, pluvial and groundwater floods and artificial system failures, all of which are discussed in detail below. In cities and towns, areas of open soil that can be used for water storage are very limited.

2.1.2. River or fluvial floods:

River flooding occurs when surface water runoff exceeds the capacity of natural channels to accommodate it. The excess water overflows the riverbanks and flows into adjacent low-lying areas.

The flow of water in a river and the height it reaches depend on natural factors such as the amount and timing of rainfall, as well as human factors such as the presence of dams or earthworks. River flooding can be slow, for example, due to continuous heavy rainfall, or rapid, for example, as a result of rapid snowmelt. Flooding can be caused by heavy rainfall from monsoons, cyclones, or tropical depressions. These problems can also be related to drainage blockages caused by landslides, ice, or debris, which can cause flooding in areas upstream from the blockage.

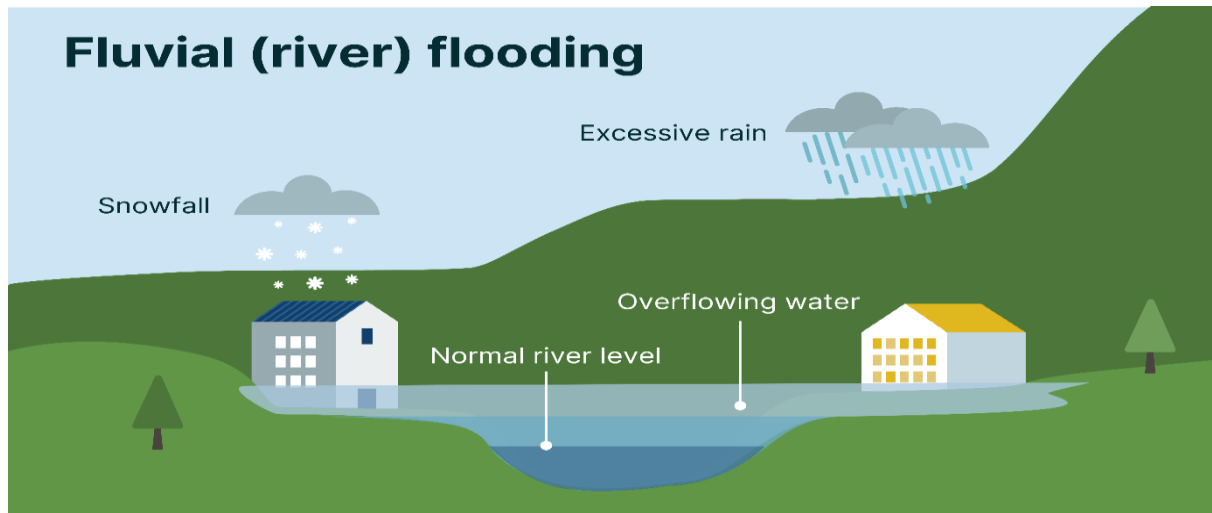


Figure 2: Fluvial flooding

2.1.3. Pluvial or overland floods:

Pluvial floods also known as overland floods are caused by rainfall or snowmelt that is not absorbed into the land and flows over land and through urban areas before it reaches drainage systems or watercourses. This kind of flooding often occurs in urban areas as the lack of permeability of the land surface means that rainfall cannot be absorbed rapidly enough, flooding results. Pluvial floods are often caused by localized summer storms or by weather conditions related to unusually large low-pressure areas. Characteristically, the rain overwhelms the drainage systems, where they exist, and flows over land towards lower-lying areas. These types of floods can affect a large area for a prolonged period of time.

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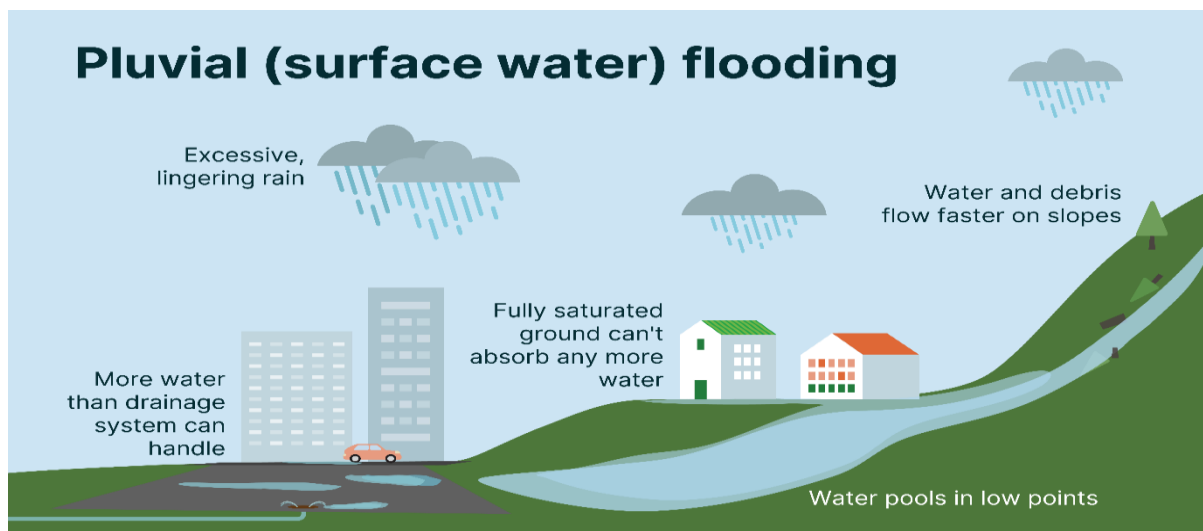


Figure 3: Pluvial flooding

2.1.4. Coastal floods:

Coastal floods arise from incursion by the ocean or by sea water. They differ from cyclic high tides in that they result from an unexpected relative increase in sea level caused by storms or a tsunami caused by seismic activities.



Figure 4: Coastal flooding

2.1.5. Groundwater floods:

Groundwater levels rise during the winter or rainy season and then fall during the summer or dry season. Groundwater flooding occurs when the water table in an aquifer beneath a given area rises to ground level. This usually happens after prolonged periods of heavy, continuous rainfall. In dry areas, groundwater flooding is more likely to occur, and it can cause flooding. Groundwater flooding is more likely in low-lying areas above permeable rock. When these areas are developed, the impact of groundwater flooding can be very costly.

Groundwater flooding can also occur when the aquifer that was previously used for water supply is no longer used. If the amount of water pumped decreases, the groundwater level will rise accordingly.

Because groundwater typically responds more slowly than rivers, groundwater flooding can take weeks or months to subside. Preventing groundwater flooding is more difficult than preventing surface flooding, although in some areas, water pumps can be installed to lower the groundwater level. Therefore, flooding may also occur if pumping systems fail, and this

may be the reason behind the phenomenon of near-permanent flooding. Since groundwater usually responds slowly compared to rivers, groundwater flooding might take weeks or months to dissipate. It is also more difficult to prevent than surface flooding, though in some areas water pumps can be installed to lower the water table. Flooding can also therefore occur in the event of the failure of pumping systems and may underlie the phenomenon of semi-permanent flooding.

2.1.6. Failure of artificial systems:

Man-made systems containing water are susceptible to failure, and the resulting water leakage can lead to flooding. Examples include burst main water or drainage pipes, as well as failures in pumping systems, dams, or breaches in flood barriers. This type of flooding is not limited to locations typically considered flood-prone, although low-lying areas and those behind engineered barriers are more vulnerable. Flooding often begins rapidly, as system failure causes water to leak at high pressure and speed. For example, a dam collapse can be catastrophic due to the sheer volume and speed of the water. Similarly, the collapse of earth dams, bridges, or other water barriers can cause devastating floods, which can persist for extended periods if there are insufficient outlets for the water.

2.1.7. Flash floods:

The U.S. National Oceanic and Atmospheric Administration (NOAA) defines flash flooding as flooding that peaks within six hours of the onset of heavy rainfall. Flash floods can be caused by localized thunderstorms, the sudden release of water from a dam, a landslide, a glacier, or upstream ice accumulation. Factors contributing to flash flooding, in addition to the intensity and duration of rainfall, include the condition of the land surface, the topography, and the slope of the drainage basin.

Urban areas are particularly vulnerable to flash flooding because a large proportion of their surfaces consist of impermeable streets, roofs, and parking areas, where very rapid surface runoff occurs. Flash floods pose a significant threat because they occur suddenly and are difficult, if not impossible, to predict. While they typically affect a limited area compared to other types of flooding, they can still cause extensive damage due to the high speed of the water flow and the large amounts of debris they carry, including rocks, trees, and vehicles. (Halifax, 2024)

The city of Laghouat, through which the M'zi Valley flows, is highly susceptible to flash floods, which typically begin with a brief period of heavy rainfall. Urban expansion, which threatens natural drainage systems, exacerbates this existing hazard.

2.1.8. Semi-permanent flooding:

In some cases, urban settlements are built on land which is flooded regularly and for long periods of time. Often these areas may lie below sea level or where the water table is close to the surface. This is usually the case where settlements are informal, unplanned and built on less expensive land due to rapid urban expansion and the poverty of the inhabitants.

(Abbas K, Robin , & Jessica , 2012)

2.2. The impacts of floods:

2.2.1. People:

Floods worldwide pose a range of risks to human life, health, and well-being. While economic losses are increasing, direct deaths from floods may decrease over time with the implementation of preventative measures, particularly in developed countries.

According to the Emergency Event Database (EM-DAT), more than 100 million people have been affected by floods annually over the past three decades. This is reason enough for governments to take action to reduce these statistics.

2.2.2. Buildings and contents:

Buildings and their contents can be affected directly and indirectly by flooding in a variety of ways. In cities, direct impacts include physical damage to buildings and their contents, while indirect impacts include the disruption of industrial or commercial operations. The impact of flooding on homes and households can be catastrophic, as fast-flowing floodwaters can sweep away entire buildings and communities. Depending on their structural design and the characteristics of the flood, many buildings may survive the flood but will still suffer extensive damage and require significant repairs and restoration.

Damage to public buildings, such as hospitals, clinics, educational institutions, and important cultural sites, can have other indirect impacts, including disruptions to education, which may lead to a decline in children's academic performance in the long term. Similarly, there is likely to be a reduction in the ability to provide healthcare and support in both the short and long term.

2.2.3. Cascading impacts:

Flood events can be a catalyst for other disasters both natural and human-made, or can be part of a chain of cascading events mentioned above. A dramatic recent example of this phenomenon is the damage to the Fukushima nuclear power generator in Japan after the 2011 tsunami: a massive-scale disaster arose at the end of a chain initiated by an earthquake. A common secondary effect of flooding is large mudflows and landslides, as was observed in Korea in 2011. Catastrophic failure of interconnected infrastructure can also cause a man-made disaster if, for example, dam controls fail due to loss of power or flood damage. Chemical or sewage related pollution of water supply can result from damage to factories or treatment plants. In considering the impact of floods, and the benefits of prevention, the potential for cascading impacts should not be overlooked.

(Abhas K, Robin , & Jessica , 2012)

3.Geographic Information Systems (GIS):

Geographic Information Systems (GIS) are data systems that enable the creation, management, analysis, and mapping of data. By linking data to maps and integrating metadata with location data, these systems provide a foundation for mapping and analysis in science and business.

GIS helps in understanding geographic trends, connections, and context, improving communication, efficiency, management, and decision-making.

Thousands of companies use GIS to create maps, share information, conduct analyses, and solve problems, transforming the way the world works. GIS makes it possible to visualize geographically relevant issues. These systems apply spatial science through tools that promote understanding and collaboration, helping to extract useful information from all types of data.

3.1. Applications of Geographic Information Systems in Flood Risk Assessment:

- **Topographic analysis:** Deriving elevation, slope and drainage networks from Digital Elevation Models (DEMs).
- **Land use:** Using satellite imagery and analysing it using GIS software.

- **Hydrological analysis:** identification of catchment areas, calculation of flow accumulation and discharge density.
- **Multi-criteria analysis:** integration of multiple factors (elevation, slope and land use) to produce hazard maps.
- **Exposure assessment:** Identifying buildings and infrastructure at hazard.
- **Model validation:** Comparing the model's results with field data.

4.Remote sensing (RS):

Remote sensing – also known as Earth observation – refers to the process of obtaining information about objects or areas on the Earth's surface without the need for direct physical contact. According to the official definition adopted in 1973, Remote sensing is defined as the body of knowledge and techniques used to determine the physical and biological characteristics of objects through measurements taken from a distance, without physical contact with those objects. Most remote sensing instruments record information about an object by measuring the transmission of electromagnetic energy from its reflective or emitting surfaces. One of the fundamental principles of remote sensing is that all objects on the Earth's surface – whether water, vegetation, soil or buildings – possess unique 'spectral signatures' that determine how they reflect, absorb or emit electromagnetic radiation. By measuring these spectral characteristics, it becomes possible to identify, classify and monitor features on the Earth's surface.

Remote sensing technologies enable images of the Earth's surface to be captured across a variety of wavelength bands within the electromagnetic spectrum. The electromagnetic spectrum results from the decomposition of electromagnetic radiation into its constituent frequencies, which range from short wavelengths (such as gamma rays and X-rays) to long wavelengths (such as microwaves and radio waves). The wavelength range represented by an image within the electromagnetic spectrum is a fundamental characteristic of remote sensing images. The main spectral bands used in remote sensing include: the visible band, the near-infrared band, the short-wave infrared band, the thermal infrared band, and the microwave band. Some images show solar radiation reflected within the visible and near-infrared ranges of the electromagnetic spectrum, whilst others show measurements of energy emitted from the Earth's surface itself, specifically within the thermal infrared range. In contrast, the energy measured in the microwave band indicates the Earth's surface response to energy transmitted from the spacecraft itself; this type of sensing is known as 'active

remote sensing', where the energy source is provided by the sensing platform itself. Examples include Synthetic Aperture Radar (SAR) and LiDAR. Systems in which remote sensing measurements rely on an external energy source, such as the sun, are known as passive (or non-active) remote sensing systems; examples of which include the optical sensors on board the Landsat, SPOT and Sentinel-2 satellites.

The remote sensing process comprises seven fundamental stages: (a) the energy source; (b) radiation and the atmosphere; (c) interaction with the target; (d) detection of energy by the sensor; (e) transmission, reception and processing; (f) interpretation and analysis; and (g) application. The fundamental principle of remote sensing is similar to the mechanism of human vision, as it arises from the interaction between three essential elements: the energy source, the target, and the carrier (the platform carrying the sensor).

The performance of a remote sensing system is determined by four types of resolution: spatial resolution (the size of the smallest object that can be detected, such as 30 metres for Landsat, 10 metres for Sentinel-2, and 1 metre for IKONOS); spectral resolution (the number and width of spectral bands); radiometric resolution (the number of quantisation levels); and temporal resolution (the frequency of visits or observations, such as 16 days for Landsat, 5 days for Sentinel-2 and 6 days for Sentinel-1). These accuracy parameters determine how suitable a sensor is for monitoring a particular phenomenon; For example, monitoring flash floods requires a high degree of temporal accuracy.

Remote sensing data requires pre-processing before analysis can begin; this pre-processing includes: radiometric corrections (converting digital numbers into reflectance values and removing the effects of solar angle and sensor ageing), geometric corrections (correcting for distortions caused by the Earth's curvature, surface topography and platform motion), and atmospheric corrections (removing the effects of scattering and absorption). Following the initial processing, the image analysis stage involves the use of classification methods (supervised and unsupervised) and the calculation of spectral indices, such as the 'Normalised Difference Water Index' (NDWI), To extract water bodies, and the 'Normalised Difference Vegetation Index' (NDVI) for monitoring vegetation cover. The accuracy of the extracted information must also be verified using error matrices (confusion matrices), Kappa coefficients, and ground truth points.

Remote sensing faces several limitations and challenges, including cloud cover, which affects optical sensors; the high cost of high-resolution imagery; the availability of data; and

limited spatial resolution when monitoring certain phenomena. Despite these limitations, remote sensing techniques provide valuable data for assessing flood risks at multiple levels, including: land-use and land-cover classification; digital elevation models (DEMs); mapping flood extent using synthetic aperture radar (SAR) imagery Such as Sentinel-1 satellite imagery, mapping floodplains, monitoring changes in land use, and estimating rainfall rates. (M.V.K, P.S, K , & S.K, 2003).

5.Principles Of Remote Sensing:

5.1. An interdisciplinary science:

Remote sensing is an interdisciplinary science that brings together a variety of fields such as optics, spectroscopy, imaging, computer science, electronics, communications and satellite launch technologies. These technologies work together to form an integrated system known as a ‘remote sensing system’. This system operates through several stages, each of which is a fundamental pillar of the process’s success; starting with the emission of electromagnetic energy from a source, this encompasses its deployment and interaction with the target, right through to the final stages of recording, transmitting, processing and interpreting the data obtained. The complex nature of this system explains why remote sensing relies on such a wide range of scientific and technical disciplines.

5.2. The three main elements:

The fundamental principle of remote sensing mimics the mechanism of human vision; it arises from the interaction of three essential elements:

- **Energy source:** This is the origin of electromagnetic radiation. This source may be the Sun (in the case of passive remote sensing) or an artificial source, such as a radar antenna (in the case of active remote sensing). Without an energy source, it is impossible to obtain any information about the target.
- **Target:** The object, surface or phenomenon being observed. The target may be the Earth’s surface (land, water, vegetation or buildings), the atmosphere or the ocean. The physical and chemical properties of the target determine how it interacts with the electromagnetic radiation falling upon it. The platform: This is the platform on which the sensor is mounted. This platform may be a ground-based device (ground-based remote sensing), an aircraft (airborne remote sensing), an unmanned aerial vehicle (UAV/drone), or a satellite (space-based remote sensing). The choice of

platform determines the altitude, the area of coverage and the spatial resolution of the data acquired.

The interaction between these three elements generates the signal that is recorded by the sensor for subsequent analysis.

5.3. The seven stages of the remote sensing process:

The remote sensing process consists of seven fundamental stages, all of which are essential to the success of the process as a whole:

- **Energy source:** the origin of electromagnetic radiation. The Sun is the primary source for passive (inert) systems, whilst active systems rely on their own internal energy source.
- **Radiation and the atmosphere:** Energy transfer through the atmosphere. During this stage, the radiation undergoes absorption and scattering by atmospheric particles (such as aerosols, water vapour and ozone), which modifies the signal reaching the sensor.
- **Interaction with the target:** Interaction of electromagnetic radiation with the Earth's surface. Depending on the properties of the target, the radiation may be reflected, absorbed, transmitted through the object, or re-emitted.
- **Energy detection by the sensor:** The sensor detects the reflected or emitted energy. The sensor converts the incoming radiation into an electrical signal, which is subsequently converted into digital form.
- **Transmission, reception and processing:** Transmission of data to ground stations, followed by an initial processing stage (radiometric and geometric corrections).
- **Interpretation and Analysis:** Extracting useful information through visual or digital analysis. This includes image classification, calculation of spectral indices, and monitoring of changes.
- **Application:** Using the information obtained in practical applications such as flood risk mapping, land-use planning, agricultural monitoring and environmental management.

5.4. The Four Types of Resolution:

The performance of a remote sensing system is determined by four types of resolution:

- **Spatial Resolution:** The smallest object that can be detected; this is equivalent to the area on the ground represented by a single pixel. Examples: 30 metres for the Landsat satellite, 10 metres for the Sentinel-2 satellite, and 1 metre for the IKONOS satellite.
- **Spectral resolution:** The number and width of spectral bands. A sensor with high spectral resolution is characterised by the presence of multiple narrow bands, enabling precise differentiation between surface materials. Examples: Landsat 8 (11 bands) and Sentinel-2 (13 bands).
- **Radiometric resolution:** The number of quantisation levels used to represent the measured radiation intensity. Examples: 8-bit = 256 levels; 12-bit = 4,096 levels. Higher radiometric resolution allows for the detection of subtle differences in reflectance.
- **Temporal resolution:** The time interval over which the satellite passes over the same area; an example is 16 days for landsat, 5 days for Sentinel-2, 6 days for Sentinel-1.

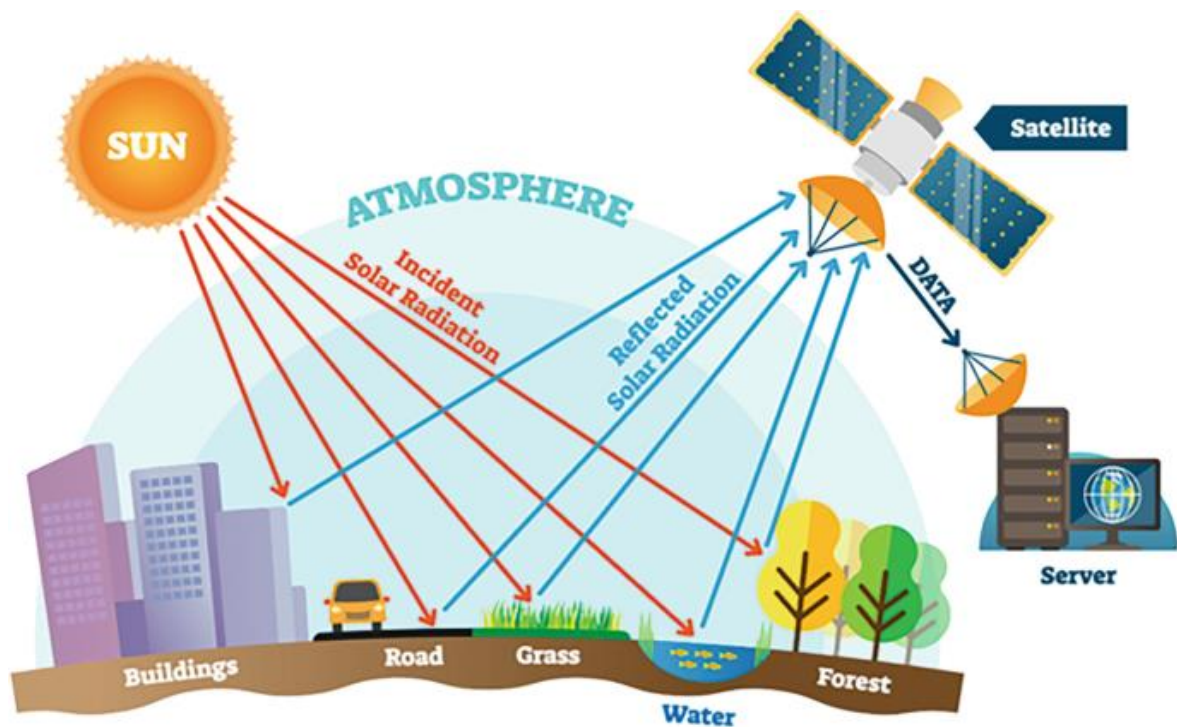


Figure 5: Remote sensing process

The following figure illustrates the structural approach to the fundamental principles of passive detection, as explained in the previous sections. The interactions between the three fundamental components of the system the energy source (the Sun), the channel (the Earth's surface) and the carrier (the satellite) have been demonstrated.

The process involves a series of successive steps. Essentially, solar radiation passes through the atmosphere and reaches the Earth's surface. Consequently, this interaction with various surfaces (houses, roads, grass, water and forests) can produce a unique spectral signature. Part of this radiation is reflected back to the satellite, whilst the other part is absorbed or transmitted. The reflected radiation is captured by detectors mounted on the edge of the satellite, Whilst the other part is either absorbed or transmitted. The reflected rays are captured by detectors mounted on the edge of the satellite, which convert the light signal into digital data. This data is ultimately transmitted to a receiving station on Earth (the server), where it is processed, analysed and interpreted to produce actionable, objective information, such as solar radiation maps or flood risk maps.

This illustration shows the concept of a satellite-based observation system that enables the identification of the physical and biological characteristics of Earth's surfaces and aids in the analysis of reflected electromagnetic radiation. It is based on the fundamental concepts developed in this section: the energy source, interaction with the atmosphere and the cable, the receiver's recording, and the transmission of data to the ground stations.

5.5. Remote sensing in flood studies:

Remote sensing refers to the collection of information about the Earth's surface without direct contact, using satellites or aircraft. Satellite imagery provides valuable data for assessing flood risks, including:

- **Land-use/land-cover classification:** Identification of built-up areas, vegetation cover and bare land.
- **Digital elevation models:** Extraction of topographical features.
- **Floodplain mapping:** Identification of areas prone to flooding.
- **Monitoring changes:** Monitoring changes in land use that affect flood hazard.

6.Spatial Modelling of Natural Hazards:

- **Spatial modeling:** a key part of geographical information science, blends geographic data to help us understand spatial phenomena. It shows processes, patterns, and how things relate in space, often using geographic coordinates and considering spatial dependence (autocorrelation) and heterogeneity. A main idea, Tobler's First Law of Geography, says “that everything is related, but closer things are more related “. If we don't consider this spatial autocorrelation, we might get wrong results from statistical models that assume observations are independent.

Spatial modelling, particularly real-time satellite imagery, plays a pivotal role in monitoring, identifying, and assessing the severity of natural hazards, such as floods and earthquakes. Balancing image quality with the frequency of capture is sometimes crucial for hazard assessment. Combining images captured at different times and under varying lighting conditions helps create a more comprehensive picture of how these conditions change. For example, combining images of different resolutions can improve the accuracy of natural hazard identification and assessment.

Geographic Information Systems (GIS) are fundamental to processing, analysing, and visualizing data related to natural hazards. GIS tools enable operations such as scaling and overlay analysis, which are essential for hazard mapping and assessment. Integrating GIS with statistical software, such as the ArcGIS Binding package for R and ArcGIS, allows for advanced geospatial analysis for environmental modelling, including its application in natural hazards.

Overall, spatial modelling utilizes GIS, satellite imagery, statistics, and advanced computing to create an effective way to address the numerous challenges posed by natural hazards. This helps improve forecasting, monitoring, and the development of hazard reduction plans.

7.Literature Review:

7.1. Global Studies:

7.1.1. Floods in Valencia, Spain (2024):

In October 2024, the Valencia region in eastern Spain was hit by devastating flash floods caused by unprecedented heavy rainfall. The floods claimed the lives of more than 220

people, destroyed thousands of homes and vehicles, and brought transport and essential services in the region to a standstill. This disaster is considered one of the most severe floods in Spain's modern history.

This disaster has shown that developed countries are not immune to flash floods, and that climate change is increasing the severity and frequency of extreme weather events even in temperate regions. It has also revealed the vulnerability of urban infrastructure to heavy rainfall, despite being more advanced than that in developing countries. (RT, 2024)



Figure 6: Floods in Valencia, Spain

7.1.2. Floods in Derna, Libya:

The storm named Daniel hit eastern Libya hard on September 10th. It brought floods that devastated Derna, causing widespread damage and many deaths. This event registers as one of the worst natural disasters in the country's history.

That day, the storm impacted cities such as Benghazi, Al-Bayda, Al-Marj, Sousa, and Derna. Derna was hit the hardest because dams holding back water in Valley Derna broke.

Due to the destruction, the residents of Derna faced a major crisis. Many had trouble finding shelter as they fled, and the damage to infrastructure, as well as the closure of many healthcare facilities, created real suffering.



Figure 7: Derna floods

7.1.3. Morocco floods

Heavy rains over the past weeks, along with water released from full dams like the Valley El Makhazine Dam (at over 140 percent capacity), have made the Loukkos River rise sharply. This has caused the river to overflow, flooding areas in and around Ksar El Kebir.

The Sebou River has also risen, impacting places like Sidi Kacem and Sidi Slimane. Flooding has hit villages, roads are blocked, and sandbags have been used to reinforce riverbanks to stop more flooding. (aljazeera, morocco floods, 2024)

Moroccan officials have started a large evacuation, moving over 143,000 people, mostly as a precaution to save lives. (aljazeera, morocco floods, 2024)

The evacuation is said to be the largest ever in the area, especially in Larache province. Boats and helicopters are being used, and shelters have been set up in nearby cities like Tangier and Tetouan.

7.2. National and Local Studies:

7.2.1. Bab El oued floods:

The Bab El oued floods in November 2001 are considered flash floods, which means a large amount of water came very quickly. This disaster wasn't just because of the weather; it happened because of unusual natural conditions combined with weak city buildings.

1. How the Water and Weather Worked

From November 9 to 10, 2001, cold air from the north met warm, wet air from the tropics. This caused more than 260 mm of rain in fewer than 24 hours, which is the same as three months' worth.

How Hard It Rained: The rain was heavier than weather stations had seen in many years.

How Fast the Water Ran Off: The ground got wet fast, so the rain turned into runoff instead of going into the ground.

2. Land Features

The Bab El oued area sits where water flows from the Bouzareah and Sidi Bennour highlands, which have slopes as steep as 20-30%.

Water Flow: The steep hills made the rainwater flow fast like mud, with enough power to carry away rocks and cars.

City Problems: The area is a natural place for water to drain from the mountains, but buildings were put on top of these waterways, so they were in danger of being hit by the fast-moving water.

3. Drainage and Building Problems

Later studies showed that the city's water system couldn't handle the heavy flows.

Blocked Drains: Trash and debris blocked the underground channels, causing flooding above the ground. (aljazeera, bab el ouad floods, 2001)

Covered Valleys: Some of the area was built over natural valleys that were put in small cement pipes. These pipes broke when too much water pushed on them. (aljazeera, bab el ouad floods, 2001)

7.2.2. Floods in the M'zab Valley:

The M'zab Valley basin shows a distinct relationship between a tough desert environment and human actions over a long time. Found in a dry area, the basin's water system relies on sporadic, intense rainfall. Floods happen regularly, but they pose threats because of the region's land features and recent human-made changes. This paper studies this issue using scientific methods, looking at the natural causes, what results from it, and ways to handle it.

7.2.3. Flood of Aflou:

The 2013 floods in the city of Aflou serve as a prime example of the hydrological risks in the region, where heavy rainfall caused widespread flooding. Technical studies, particularly analyses conducted by the (ASAL) using the Alsat-2A satellite, have documented the impact on areas adjacent to National Road 23 and the northern regions , with many hectares of agricultural land and residential areas damaged. This highlights the need to adopt a strategy for urban planning and the protection of infrastructure from the risks of flooding.



Figure 8: Flood affective areas



Figure 9: The impact of floods on agricultural lands

The 2013 Aflou flood, occurring within the same geographical province as Laghouat, serves as a particularly pertinent analogue for comparative analysis. Despite this, a comprehensive, GIS-based flood hazard assessment has yet to be undertaken specifically for Laghouat city itself. The objective of this thesis is consequently to address this identified research deficit.

8. Conclusion:

This chapter delineates the theoretical and methodological framework for flood risk assessment within the Laghouat region. The preceding analysis indicates that urban flash floods constitute the primary immediate hazard in semi-arid urban environments. Geographic Information Systems (GIS) and remote sensing serve as critical instruments for the integration of spatial datasets, concurrently.

The review underscored several salient observations:

Flooding events typically arise from the intricate interplay among precipitation patterns, topographic characteristics, land utilization, and the efficacy of drainage infrastructure.

The expansion of urban development into floodplain areas demonstrably heightens vulnerability to such events.

Compared to regions in northern Algeria, the Laghouat region has received comparatively limited research attention.

Analysis of Geographic Information Systems (GIS) has shown that these technologies are indispensable for modern flood risk assessment. GIS systems enable the integration, overlay and analysis of multiple spatial parameters, whilst remote sensing provides up-to-date data on land cover and the effects of historical floods; together, they produce hazard maps as well as location-specific maps that enable decision-makers to take appropriate action for flood risks.

***Chapter II: Study Area: Laghouat –
Geographical, Climatic, and Urban
Characteristic***

1.Introduction:

This chapter defines the study area in Laghouat, providing a comprehensive description of its geographical, physiographic, climatic, hydrological, and urban characteristics. A thorough understanding of the natural and human topography of Laghouat is essential for subsequent flood risk assessments. The chapter focuses particularly on the M'zi Valley, the main waterway crossing the urban area, given its role as a primary source of flood hazard. Morphometric analysis of the M'zi Valley basin provides crucial insights into the basin's flood response characteristics. Furthermore, rainfall data analysis and spatial interpolation methods identify the precipitation patterns that contribute to flooding. The chapter concludes with an examination of urban expansion patterns, highlighting the gradual encroachment of the city onto the natural floodplain.

2.Geographical and Administrative Location:

The state of Laghouat is situated on National Road No. 1, 400 kilometres south of the capital, Algiers. It is designated as Province No. 03 in the country's administrative division. It is bordered to the north by the state of Tiaret, to the west by the state of Bechar, to the south by the state of Ghardaïa, and to the east by the state of Djelfa. Its capital is the city of Laghouat.

The municipality of Laghouat is situated in the east of the state and is bordered to the north by the municipality of Sidi Makhlouf, to the west by the municipality of El Kheng, to the east by the municipality of El Assafiya, and to the south by the municipality of mekhareg . It covers an area of 400 square kilometres, equivalent to 1.6% of the province's total area, and is considered one of its smallest municipalities.

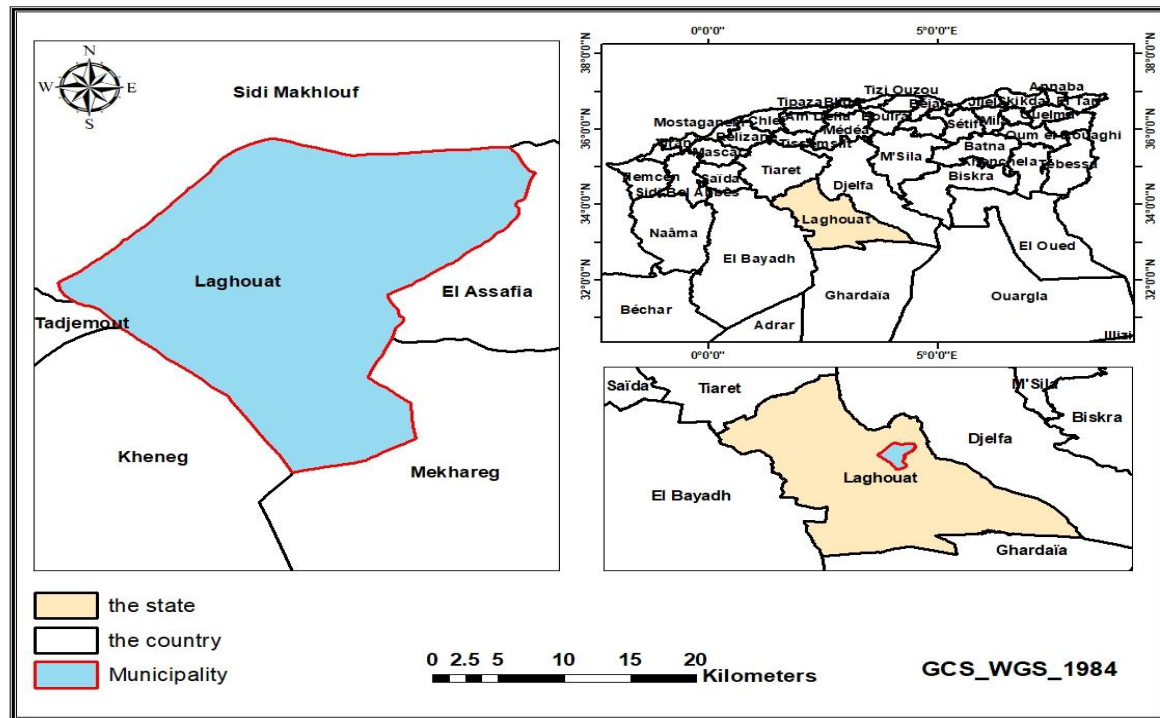


Figure 10:Geographical Location

3. Physiographical and Geomorphological Setting:

The municipality of Laghouat is characterised by several mountain ranges forming part of the Saharan Atlas. These ranges are mainly located to the north of the municipality and have the following features:

Mount Milak: Located to the north-east of Laghouat, it rises to a height of 1,081 metres.

Mount Ahmar (Kaf El Tarf): Located to the south-west of the municipality, its reddish colour is due to its geological composition; it reaches an altitude of 783 metres.

Mount Dakhla: Located to the east of the municipality, it extends northwards to the municipality of Messaad and has an average altitude of 856 metres.

These mountain ranges are of interest to tourists because of their rock carvings and historical drawings, which bear witness to the region's history, although they remain largely unspoilt.

3.1. Soil

By studying the soil element, we can identify its various formations and characteristics to determine its suitability for construction or agriculture.

Most of the land consists of sand, clay, and limestone, with mountainous areas being the most common. As for sand, it is found throughout most of the region, particularly concentrated in its south.

By studying the surface formations of the municipality, we conclude that most of the land is permeable, with the exception of some impermeable areas.

The desert, specifically the Hassi R'mel district in the southern part of Laghouat province, encompasses what is known as the Saharan Plateau and includes the districts of Ain Madhi and the southern part of Ksar El Hirane.

The permeability of this soil is a crucial factor in assessing flood hazard. Most of the land is permeable due to its sandy composition, which facilitates water infiltration and reduces surface runoff. However, in the urban areas of the city centre, impermeable surfaces (roads, buildings, and parking lots) have replaced the natural soil, significantly increased surface runoff and contributing to the increased hazard of flooding.

The slopes vary. Regarding the slopes in the municipality, most of the surface is flat, meaning the slopes are between 0% and 3 %, while the mountainous areas have a slope ranging between 12 % and 25%.

4. Hydrological and Climatic Characteristics:

4.1. Hydrology:

Rainfall in this region is irregular, averaging 160 mm annually, and experiences severe droughts in some years.

The province relies heavily on groundwater for its drinking water needs, thanks in particular to one of the largest underground reservoirs, located near the provincial capital.

Surface water comes mainly from valleys (valleys), the most important of which are: M'zi Valley, which passes through the city of Laghouat; Valley Messaad; Valley Taouil; and Valley Menaghich. These waterways are irregular and have limited flow.

4.1.1. Valley M'zi watershed:

M'zi Valley originates from Jebel Amour and flows towards laghouat. Just beyond the floodplain immediately below Qasr al-Hiran, it takes the name Valley Jidi, which it retains until it flows into Shatt al-Malghigh.

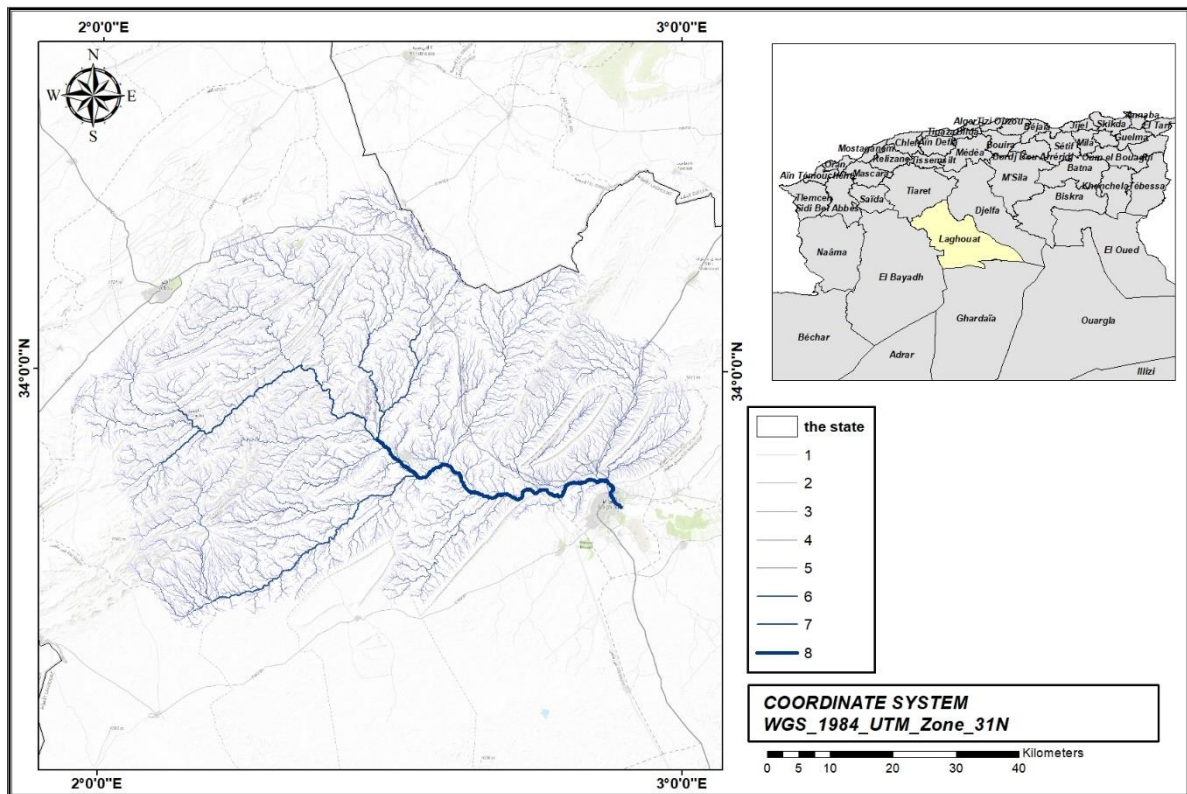


Figure 11: Watershed valley M zi

4.1.2. Morphometric analysis:

Data for valley m zi basin:

Area (A) = 4400.5 km²

Length (L) = 89 km

Perimeter (P) = 369.06 km

Maximum elevation (MAX) = 1593 m

Minimum elevation (MIN) = 740 m

4.1.3. Form Factor (Ff) By HORTON:

This describes the degree of elongation or circularity of the catchment. If the value is less than 0.2, the catchment is elongated, which means a lower hazard of flooding; if the value is greater than 0.8, the catchment is circular, which means a higher risk of flooding. (Padala & Aneesh, 2024)

$$Ff = \frac{A}{L^2}$$

$$L^2 = 89^2$$

$$= 5929$$

$$Ff = \frac{4400.5}{7921}$$

$$Ff = 0.55$$

The obtained result is .0.55 indicating that the basin is semi-circular and compact in shape; this suggests a very high probability of water reaching the outlet (the city of Laghouat).

4.1.4. Circulatory Ratio (Rc) By MILLER:

It measures how close the basin is to a perfect circle; the closer it is to 1, the rounder it is; if it is further away, the basin is elongated. (Adeeba, Fawziyah, & Ahamd, 2021)

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

$$= 4 \times 3.14159 \times 4400.5 = 55290$$

$$P^2 = 369.06^2 = 136200$$

$$Rc = \frac{55290}{136200}$$

$$Rc = 0.406$$

This finding suggests that the basin is closer to a circular shape, which is why the hazard of flooding is high.

4.1.5. Relief Rito (Rr)By STANLEY A. SCHUMM:

It is a geomorphological indicator that measures the gradient of a basin and is used to predict flash floods. (Albert Schumm, 1956)

$$\mathbf{Rh} = \frac{H}{L}$$

$$\mathbf{H} = 1593 - 740 = 853$$

$$\mathbf{L} = 89 \text{ km} = 89000 \text{ m}$$

$$\mathbf{Rh} = \frac{853}{89000} = 0.01$$

Although there is a significant drop in elevation, the length of the channel means the gradient is gentle; the result is an average flow rate, which contributes to the severity of the flooding when it reaches the city.

4.2. Climate:

The climate is semi-arid, characterised by hot summers and cold winters, with significant rainfall in December and January. In mountainous areas (altitude > 800 m), annual rainfall ranges from 300 to 400 mm.

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANN
1994	14.75	14.57	17.55	4.11	4.9	3.45	2.31	7.73	53.63	70.9	15.73	1.83	211.46
1995	9.74	8.53	20.95	8.92	2.52	14.98	0.03	4.49	20.72	16.44	6.67	17.76	131.75
1996	46.39	31.64	48.23	14.19	24.7	18.98	13.05	6.88	14.93	1.24	0.94	14.79	235.96
1997	19.18	1.77	2.94	43.1	9.87	2.73	1.06	29.73	48.04	12.77	27.4	15.21	213.80
1998	4.08	9.09	2.28	17.32	15.7	1.84	0.09	10.78	9.95	3.49	1.97	4.25	80.84
1999	57.81	12.01	18.09	4.64	1.39	9.03	4.5	9.3	14.88	17.34	25.24	40.85	215.08
2000	0.07	0	5.51	5.7	7.51	0.76	0.36	3.52	52.48	14.98	6.87	11.16	108.92
2001	19.19	5.32	0.48	4.52	3.41	0	0.69	10.8	32.1	50.42	12.19	25.98	165.1
2002	5.18	0.97	2.1	18.68	3.94	4.26	3.98	27.18	5.68	16.63	16.72	6.36	111.68
2003	28.36	10.56	13.21	6.46	13.6	1.13	2	7.52	11.42	40.76	19.57	20.9	175.45
2004	8.72	3.24	16.06	50.66	31.7	8.23	2.39	42.6	10.2	18.77	16.73	21.71	230.97
2005	3.42	10.83	8.35	2.59	0.33	17.39	14.07	23.07	44.89	30.69	16.14	13.03	184.8
2006	50.85	21.75	1.69	22.64	26.6	3.91	12.7	6.02	12.95	3.15	15.67	34.03	211.98
2007	2.96	12.16	17.12	23.19	17	0.53	7.76	10.31	26.26	15.54	5.43	4.29	142.54
2008	2.75	5.65	5.63	0.64	20.8	19.63	7.68	5.21	48.37	57.44	6.81	12.64	193.21
2009	36.61	14.47	18.58	28.01	6.04	7.37	5.06	2.59	50.17	1.4	7.14	10.58	188.02
2010	11.95	21.85	6.64	16.87	28.2	13.1	7.52	13.67	7.37	29.42	7.06	3.71	167.37
2011	7.61	7.45	28.95	46.95	18	22.92	6.67	5.95	14.13	29	20.5	7.56	215.67
2012	3.32	2.38	22.99	26.23	3.12	5.97	1.06	11.65	18	32.51	22.16	6.57	155.96
2013	8.96	5.81	12.1	18.65	11.8	2.18	7.85	5.04	10	11.01	12.46	33.86	139.76
2014	9.42	10.84	13.02	0.39	15.7	15.79	1.4	8.75	13.42	3.46	26.58	8.78	127.57
2015	6.73	21.61	4.6	0.34	2.27	5.89	0.01	21.74	37.53	26.34	8.54	0.01	135.61
2016	2.18	8.89	7.75	15.3	7.91	0.89	1.03	9.55	34.16	3.54	18.18	13.73	123.11
2017	44.49	1.61	0.85	11.12	6.59	9.43	1.97	0.68	6.8	13.63	3.32	4.82	105.31
2018	11.03	8.44	14.4	42.18	38.2	3.83	0.18	47.16	29.45	31.9	12.81	3.44	243.05
2019	12.88	0.94	15.29	21.1	2.06	0.12	17.87	17.34	26.33	12.57	8.96	3.14	138.6
2020	8.38	0	10.6	32.68	3.58	7.06	2.66	1.04	14.25	0.5	22.8	4.78	108.33
2021	2.54	4.83	8.77	1.65	42	12.56	0.45	8.91	6.04	3.7	13.01	2.08	106.54
2022	1.29	12.64	32.76	32.07	6.03	0.31	4.17	0.7	22.59	54.53	1.54	6.19	174.82
2023	2.19	8.32	0.93	4.5	32.7	16.19	0.48	1.95	17.06	2.35	2.73	7.68	97.09
2024	2.13	5.07	6.98	5.71	2.41	3.93	0.12	8.64	31.67	33.23	5.29	6.68	111.86

Table 1: Rainfall data for Laghouat province over a 30-year period

In the central part of the province, the climate is desert-like and dry, with rainfall of between 50 and 150 mm. In the south, winters are mild and summers very hot, accompanied by sandstorms, with annual rainfall of less than 50 mm.

4.2.1. Analysis of Rainfall Data for Laghouat City (1994-2024):

Meteorological data for the Laghouat province were sourced from the NASA POWER repository, encompassing a continuous thirty-one-year span extending from 1994 to 2024. A temporal baseline of this length offers sufficient statistical robustness to evaluate long-term atmospheric variability and establish emergent precipitation trends within the local geography.

Evaluation of the aggregate dataset yields a mean annual precipitation value of approximately 160 mm. This baseline observation aligns with the established characterization of the local climate as semi-arid, a classification typically reserved for ecosystems receiving between 100 and 300 mm of moisture annually. Beyond this general categorization, closer inspection of the historical sequence highlights considerable inter-annual volatility. The upper limit of observed precipitation occurred in 2018 with an accumulation of 243.05 mm, whereas the regional minimum was recorded in 1998 at just 80.84 mm. The resulting absolute difference of over 162 mm essentially doubles the region's expected yearly mean. Such pronounced temporal disparity underscores a defining atmospheric reality of the area, demonstrating the highly irregular year-to-year water availability that fundamentally shapes semi-arid environments.

An analysis of annual rainfall data indicates that seven years recorded precipitation exceeding 200 mm: 2018, 2004, 2011, 1999, 2006, 1994, and 1996. These seven years constitute approximately 22.5 percent of the study period, suggesting an average recurrence interval of four to five years for high rainfall events. Conversely, years characterized by rainfall totals below 100 mm include 1998, 2000, 2017, 2020, and 2023. These drier periods represent about 16 percent of the study duration and are sufficient to induce drought conditions with potentially adverse effects on water resources and agricultural production.

Of particular note, 2018 was not only the wettest year within the period but also an exceptional event, with precipitation exceeding the annual average by over 50 percent. Such extreme years present a significant hazard to urban areas, as existing infrastructure and urban planning may not be adequately equipped to manage substantial water volumes within a compressed timeframe. In semi-arid regions, flash floods often ensue from intense rainfall following extended dry spells, primarily because antecedent soil desiccation diminishes infiltration capacity, leading to a substantial increase in surface runoff.

The analysis of the rainfall data revealed three primary characteristics. Firstly, an average annual rainfall of 160 mm was observed, which is consistent with a semi-arid climatic classification. Secondly, substantial inter-annual variability was evident, with precipitation totals ranging from 81 to 243 mm. Thirdly, the occurrence of exceptionally wet years, exemplified by 2018, presents a considerable hydrological hazard to the urban environment. These observed patterns will serve as foundational considerations for the spatial interpolation process discussed in the subsequent section, wherein discrete point measurements from meteorological stations will be transformed into a continuous rainfall distribution map across the entire study region.

4.2.2. Comparative Analysis of IDW and Kriging for Rainfall Interpolation:

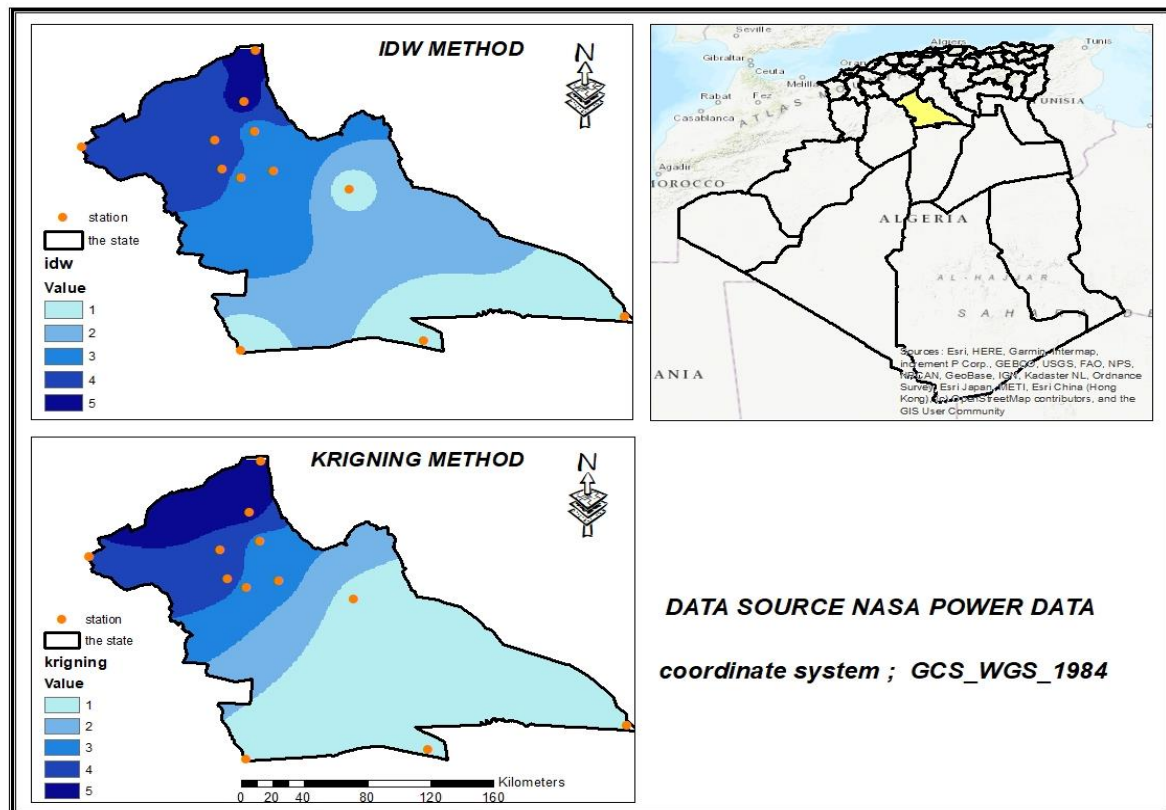


Figure 12:IDW and Kriging for Rainfall Interpolation map

Following an analysis of the rainfall characteristics and the inherent variability observed in the Laghouat region, the present investigation proceeds to the subsequent phase. This involves transforming the discrete point data acquired from the NASA POWER database into a spatially continuous representation, thereby illustrating rainfall distribution across the

entire study area. This methodological step, commonly referred to as spatial interpolation, is critical. Its necessity stems from the understanding that flood events are not confined to specific measurement points but can manifest across any location within a given watershed. Specifically, two distinct spatial interpolation techniques were employed: Inverse Distance Weighting (IDW) and Ordinary Kriging. Subsequently, a comparative analysis of the generated results was conducted to ascertain the most accurate and appropriate methodology for this specific application.

The IDW method is based on a simple principle: nearby points have more influence on estimating an unknown value than distant points. It uses a mathematical equation that assigns weights inversely proportional to distance raised to a specific power. In this study, a power of 2 was used, as it is the most common in similar studies. IDW was applied to the annual rainfall data, and the resulting map showed several characteristics. The researcher observed the appearance of a concentric ring pattern, known as the "bullseye" effect, around each measurement point, where successive rings of high values appear around the station and then decrease with distance. This pattern is artificial and does not reflect natural geographical reality, where the transition between different rainfall zones should be gradual rather than ring-like. The IDW map also showed sharp transitions at the boundaries between different stations' zones of influence, especially in southern areas where stations are more dispersed. Nevertheless, IDW managed to show the general trend of rainfall distribution.

In contrast, Ordinary Kriging represents a statistically more sophisticated approach. This method extends beyond mere distance-based considerations by initially assessing the spatial correlation among measurement points through the application of a variogram function. Such an analysis provides insight into the inherent spatial structure of the dataset, particularly how a variable like rainfall might fluctuate with increasing distance between observation points. Consequently, Kriging proceeds to determine optimal weights for each measurement point, thereby yielding an estimate characterized as the Best Linear Unbiased Estimator (BLUE). For the purposes of this investigation, Ordinary Kriging was implemented utilizing a spherical variogram model, which demonstrated the most appropriate fit to the observed data. (Gabriele & Danilo, 2013).

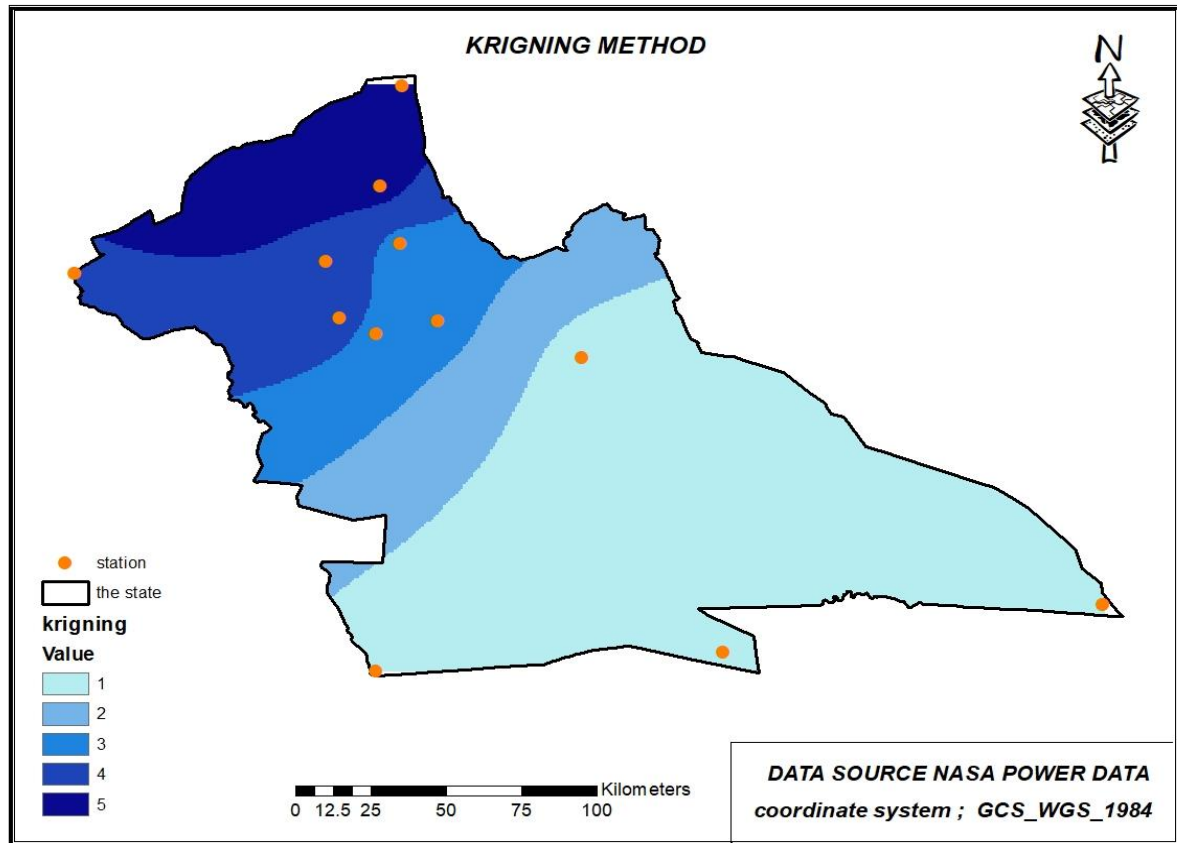


Figure 13:Kriging for Rainfall Interpolation map

The Kriging interpolation yielded a more spatially coherent and less abrupt pattern compared to the Inverse Distance Weighting (IDW) method. The artificial "bullseye" effect, characteristic of IDW, was alleviated, giving way to a continuous and gradual transition between distinct rainfall zones. High-rainfall regions in the northern sector were precisely demarcated, exhibiting boundaries consistent with the mountainous topography of the Saharan Atlas. Correspondingly, low-rainfall areas in the southern sector were consistently delineated, aligning with the prevailing arid desert climate. A salient feature of Kriging is its capability to produce a variance map, or Kriging variance, which quantifies the estimation uncertainty at each spatial coordinate. This map indicated that the highest levels of uncertainty were concentrated in the southeastern portions of the province, an observation attributable to the sparse and dispersed distribution of existing measurement stations. Such information is instrumental for decision-makers, as it highlights optimal locations for deploying additional measurement infrastructure to minimize future estimation variance. (M.A, Oliver, & Webster, 2007).

In conclusion, Ordinary Kriging was selected to produce the final rainfall distribution map for the Laghouat region. This map will serve as a key input for the flood hazard assessment model in the following sections of this chapter. The study also recommends adding additional rainfall measurement stations in the southern and eastern parts of the province.

5. Urban Growth:

5.1. Stages of City Growth:

The city of Laghouat has witnessed significant transformations and developments since independence, particularly in its growth and expansion, which has come at the expense of agricultural lands, especially palm oases. It has benefited from important projects and programs that have accelerated urban development.

Its growth is linked to its location, which serves as a link between different parts of the country.

5.1.1. The French Colonial Period:

With the arrival of French settlers, several European-style houses were built in a grid pattern, in addition to the construction of a hospital and military barracks, all situated adjacent to the city centre. This area was named ‘Al-Gharbiya’ (the West), as expansion in this direction. Expansion then continued through the construction of roads towards the oases, with the creation of two main axes in the middle of the northern and southern oases. This was accompanied by the construction of housing along these axes, from which several access points branched off within the oases.

5.1.2. Intermediate phase (1962–1974):

This phase was characterised by continued unplanned growth within the oases, with the construction of individual dwellings, as well as the establishment of neighbourhoods on the southern side of the city, such as the Sadqiyah, al-Muqaddar and Shatit neighbourhoods, among others, as a result of the influx of rural residents from neighbouring areas into the city, owing to its industrial zone, which attracted labour, consequently, expansion took place towards the northern and southern oases.

5.1.3. Intermediate phase (1984–2008):

During this phase, the city's urban fabric underwent significant expansion, with the area failing to accommodate this growth, which occurred particularly following the latest administrative reorganisation; this led to the expansion of part of the urban fabric at the expense of the oasis separating the city from M'zi Valley and the agricultural lands.

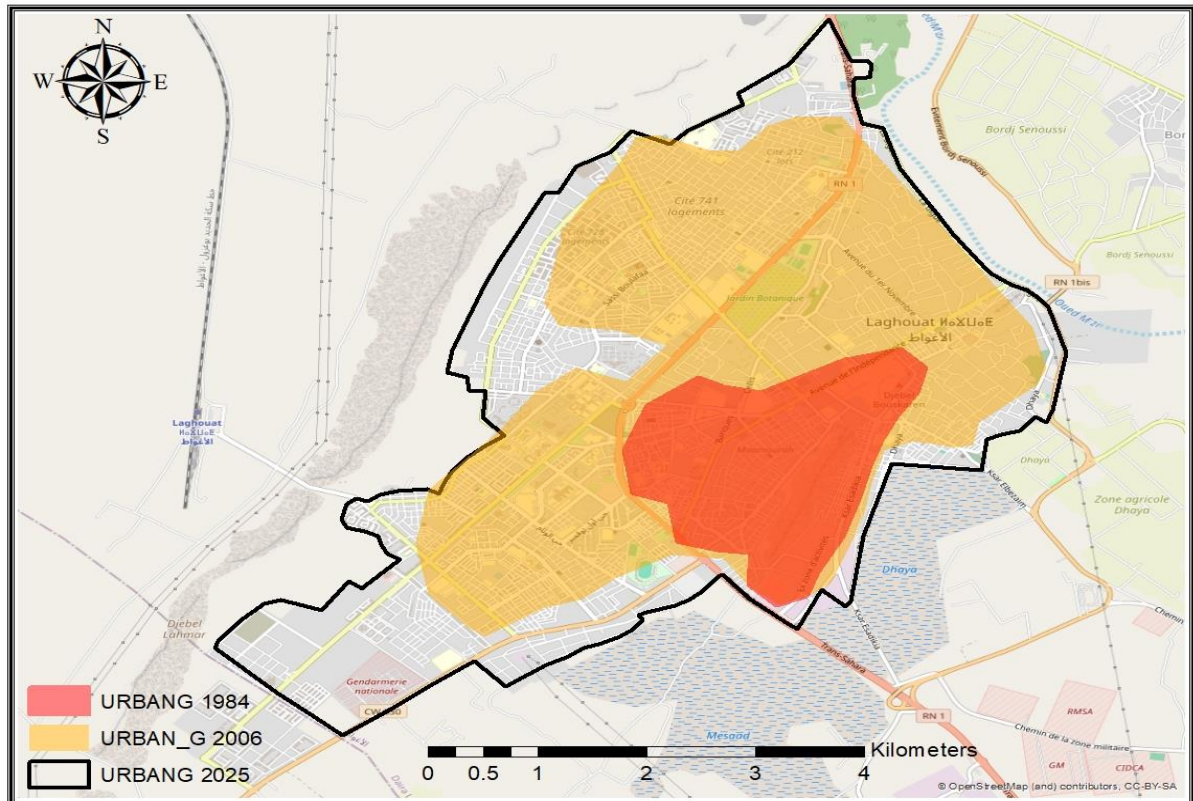


Figure 14:Urban growth of the city of Laghouat map

6.Conclusion:

This chapter provides a comprehensive overview of Laghouat, the designated study area. The discussion encompasses its geographical location, physiographic characteristics,

climatic conditions, hydrological network, and the discernible patterns of urban development.

Key observations derived from this analysis are as follows:

Laghouat climate is predominantly semi-arid, characterized by irregular annual precipitation averaging 160 mm.

Valley M'zi functions as the principal watercourse traversing the urban area and represents the most significant flood hazard.

Uncontrolled urban expansion has encroached upon agricultural land and natural floodplains, consequently escalating the region's vulnerability to flood events.

Topographically, the city centre exhibits relatively flat terrain, with slopes typically ranging from 0-3%, whereas the surrounding mountainous areas feature considerably steeper gradients, approaching 12%.

Chapter III: APPLIED ANALYSIS AND RESULTS

1.Introduction:

This chapter examines the practical application of hydrological modeling techniques for the M'zi Valley using the GLOBAL MAPPER software. It also explores spatial analysis for flood risk assessment in the city of Laghouat. The chapter moves from description to analysis, transforming spatial data into actionable hazard information.

This chapter aims to simulate water level rise scenarios in the M'zi Valley and at-risk areas, and to produce integrated spatial flood hazard maps using a multi-criteria decision analysis methodology based on Geographic Information Systems (GIS). This methodology includes the following factors: slope, elevation, distance to the M'zi Valley, drainage density, and land use.

Each criterion was reclassified on a standardized scale, weighted using Analytic Hierarchy Process (AHP), and the results were compiled through weighted overlay analysis using ArcGIS software.

2. Flood simulation for M'zi Valley (GLOBAL MAPPER):

2.1. Methodology:

Digital elevation model was downloaded from Open Topography, along with a shapefile for M'zi Valley, and these were exported to Global Mapper. A simulation was then carried out to assess the water level in M'zi Valley at various elevations (2 metres, 4 metres, 6 metres, 8 metres).

The depth of the valley was determined using a cross-section of the valley created with Google Earth Pro; the valley is 3 metres deep at its widest point and 5 metres deep at its narrowest. This variation in depth reflects the difference in the valley's storage capacity.

Based on these data, simulation scenarios were designed according to four levels representing gradual stages of water overflowing the natural channel:

- **2-metre water level:** This represents the start of water overflowing the banks in the wide sections, where the depth is 3 metres; this is a minor flooding scenario.

- **4-metre water level:** This represents a complete overflow of the wide section, exceeding the maximum depth of 3 metres, and the start of the water reaching the edge of the narrow section, which is 5 metres deep; this is a moderate flood scenario.
- **6-metre water level:** This represents a complete overflow of the narrow section beyond the maximum depth of 5 metres, with water spreading widely along the banks; this is a severe flood scenario.
- **Water level of 8 metres:** This represents an exceptional (catastrophic) flood scenario, equivalent to twice the maximum depth of the narrow section, and covers the worst-case hydrological scenarios.

2.2. Characteristics of M'zi Valley:

The cross-section of the valley, which determines the volume of water it can hold before flooding. In the case of M'zi Valley, the cross-sectional area at the widest point is approximately (width 535 m $\times$ depth 3 m) = 1,605 m², whilst at the narrowest point it is (105 m $\times$ 5 m) = 525 m².

When the water level exceeds the valley rim and the volume of water exceeds the storage capacity, flooding occurs. The simulation showed that a water level of 4 metres exceeds the valley rim at the wide section, whilst the narrow section requires a water level of 5 to 6 metres to exceed the rim.

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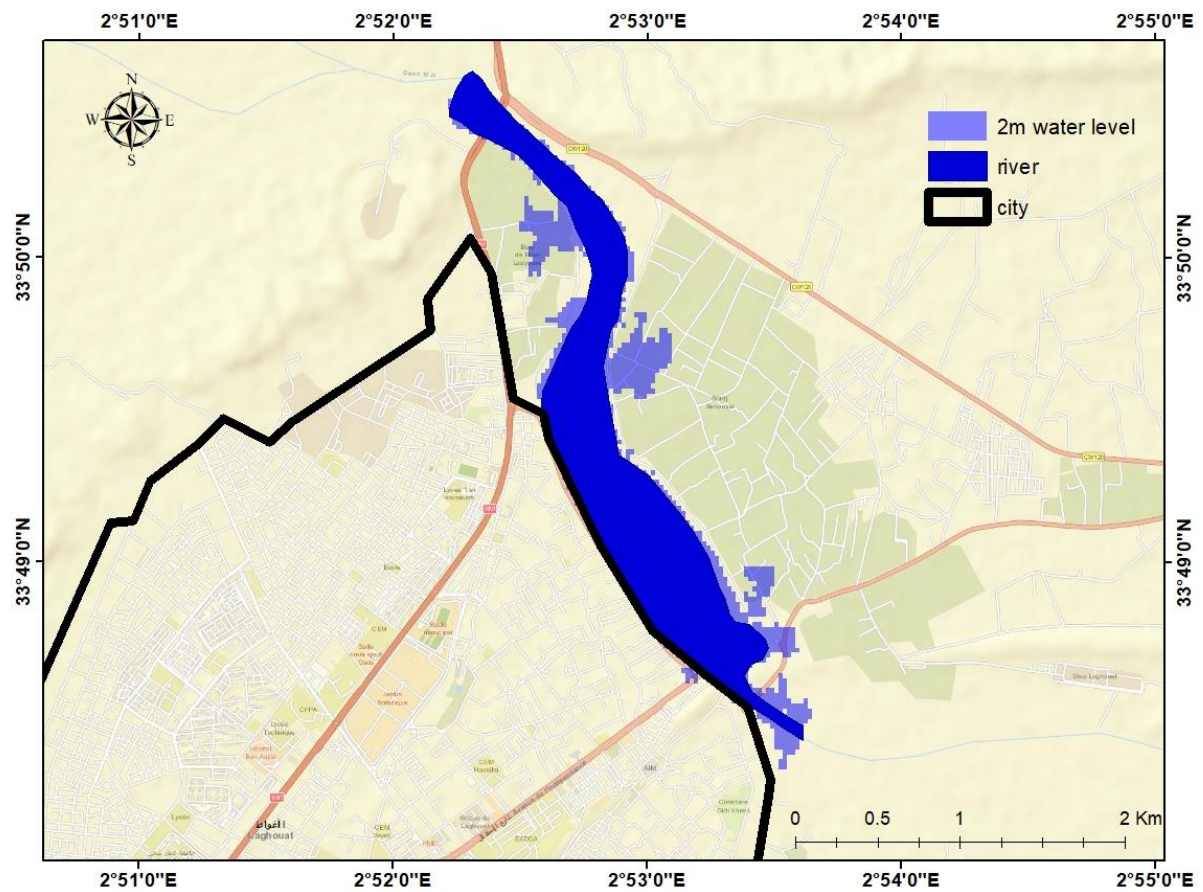


Figure 15:the water level 2m map

Analysis: The flooding is confined to the main river channel, where it does not extend beyond the riverbanks, agricultural areas and neighbouring residential buildings; this water level does not pose any danger.

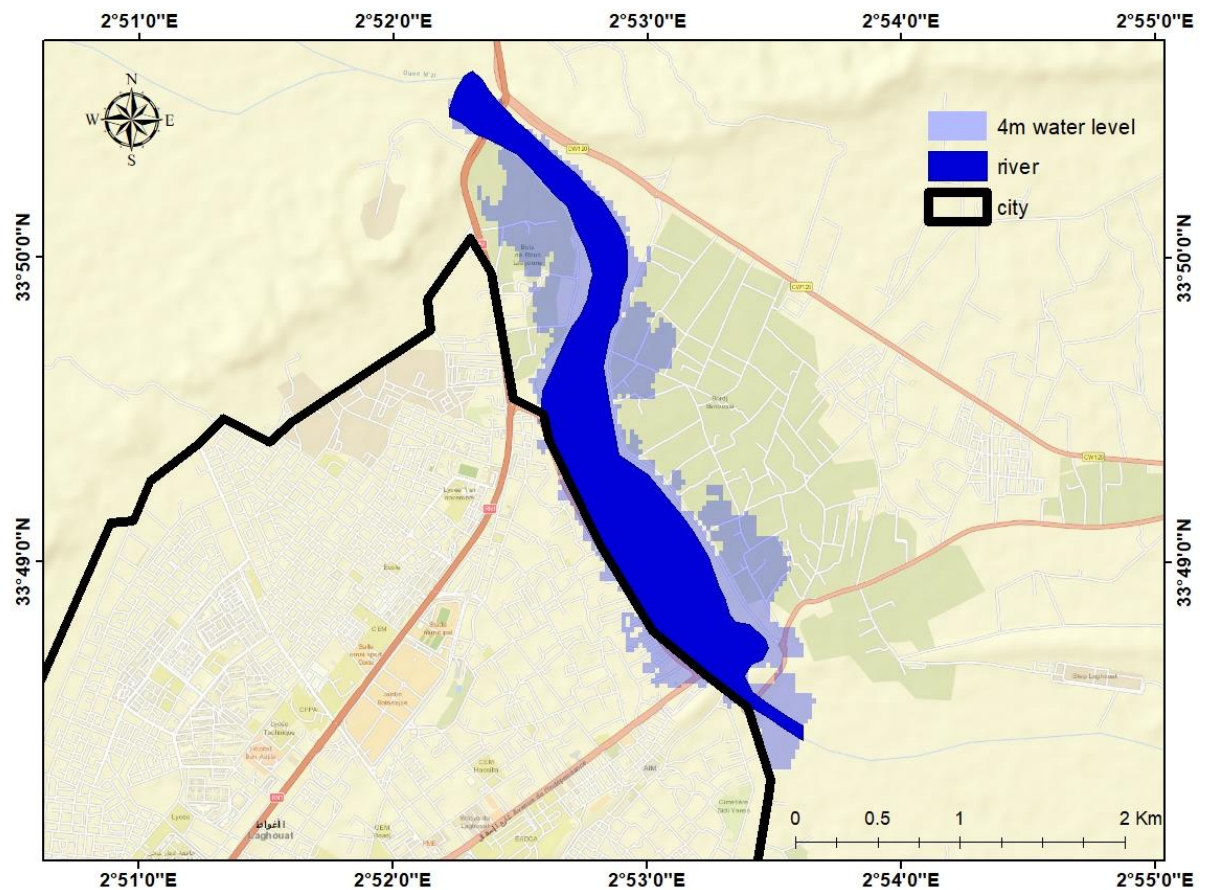


Figure 16:the water level 4m Map

Analysis: The water begins to overflow its banks in the wider sections and starts to affect neighbouring agricultural areas; this is considered a moderate flood, as its impact is slight.

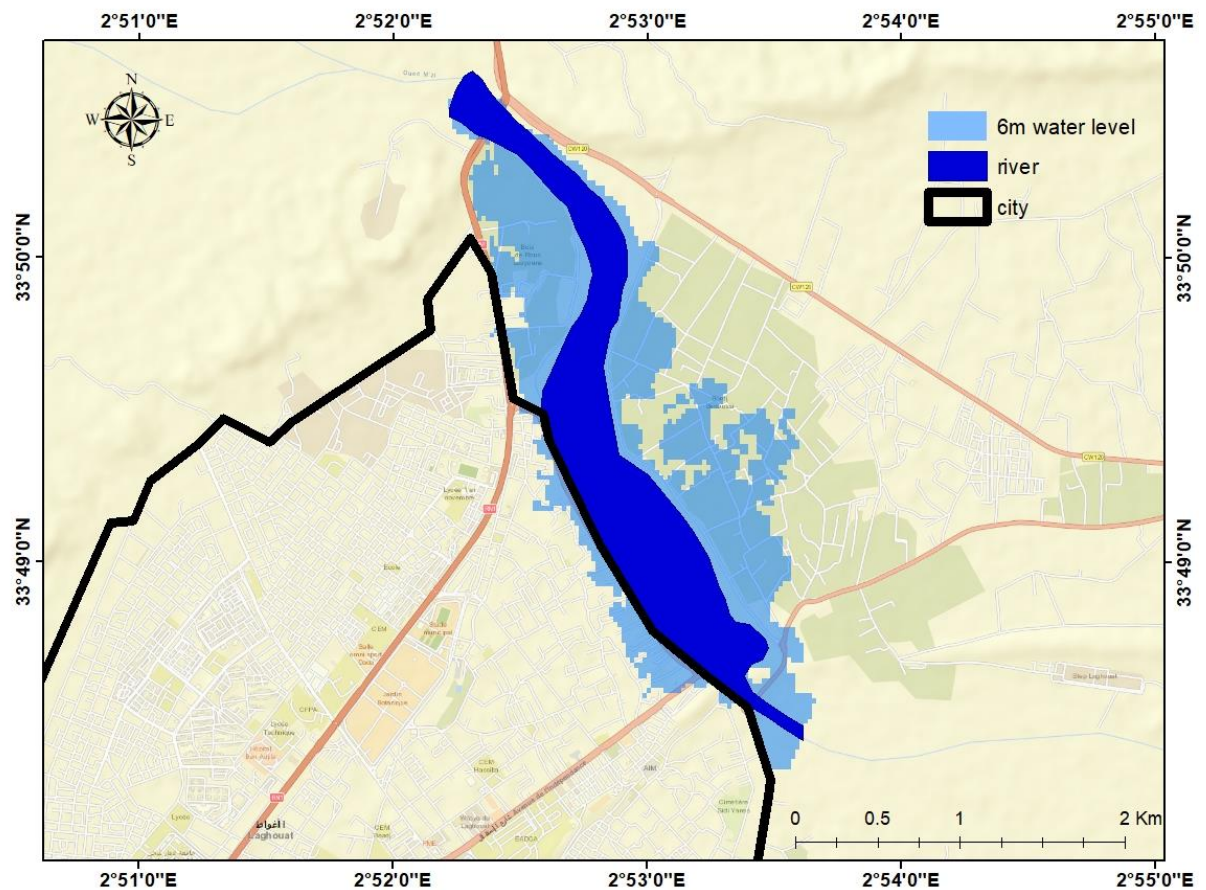


Figure 17:the water level 6 m Map

Analysis: The flood is spreading to cover large areas on both sides of the valley and poses a threat to low-lying residential areas and the roads running alongside the valley.

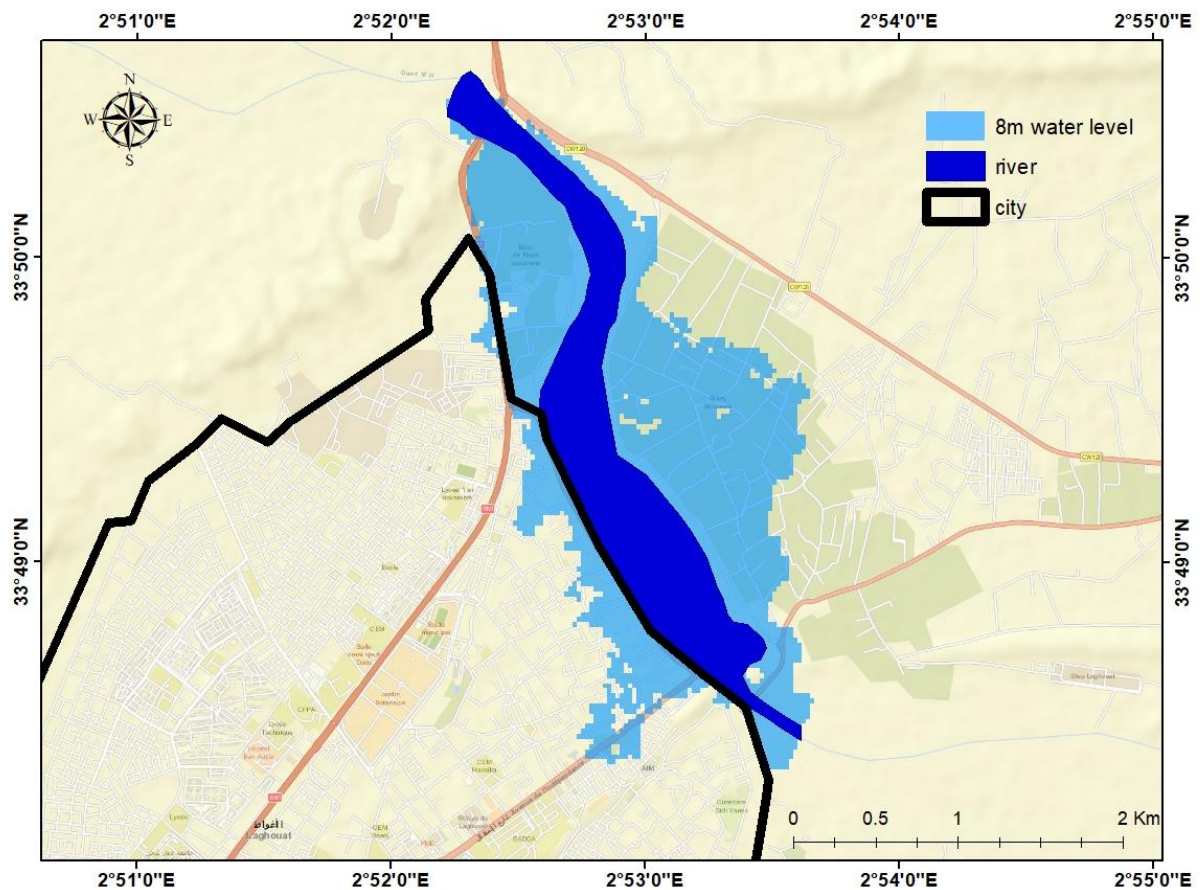


Figure 18: the water level 8 m Map

Analysis: This rise represents a catastrophic scenario in which the flood reaches its maximum extent, submerging low-lying areas and significantly affecting the city's infrastructure.

2.3. Combine the levels of water that were previously extracted:

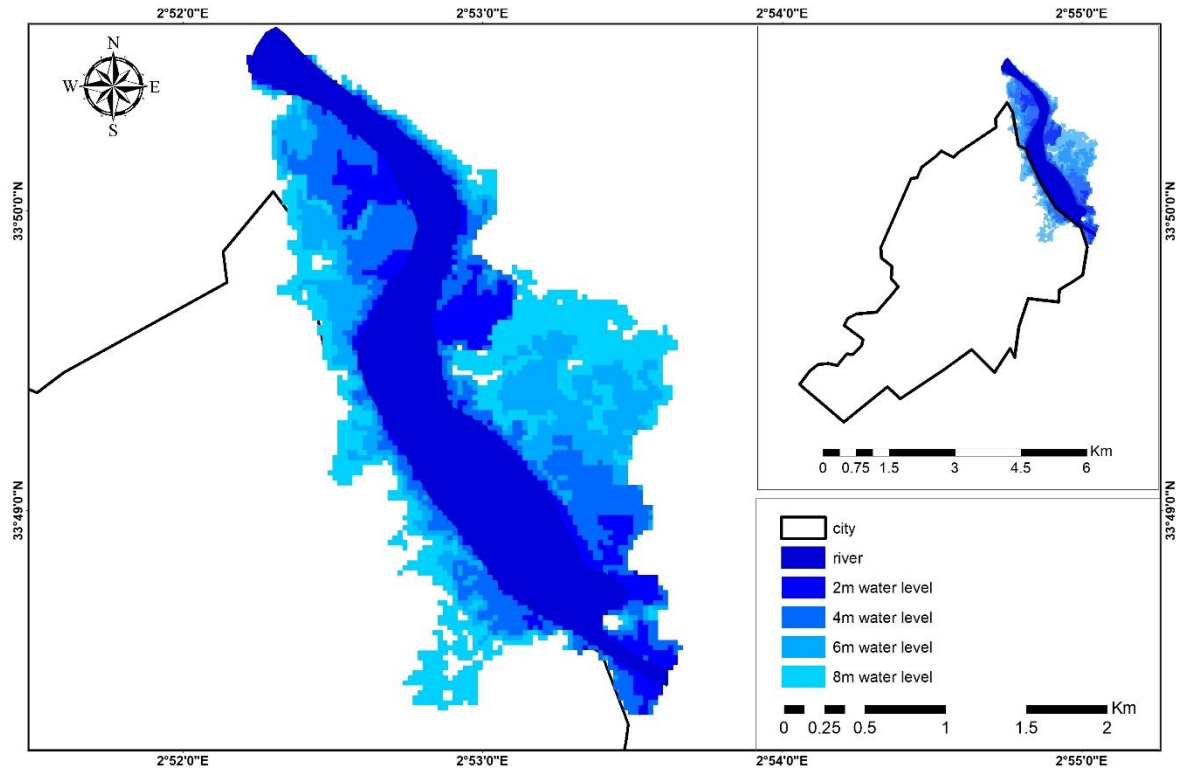


Figure 19:Map of water levels

The water levels have been combined into a single map to provide a comprehensive view of the valley flood, and a colour gradient has been used to indicate the water levels.

2.4. Areas at risk of flooding due to rising water levels in M'zi Valley:

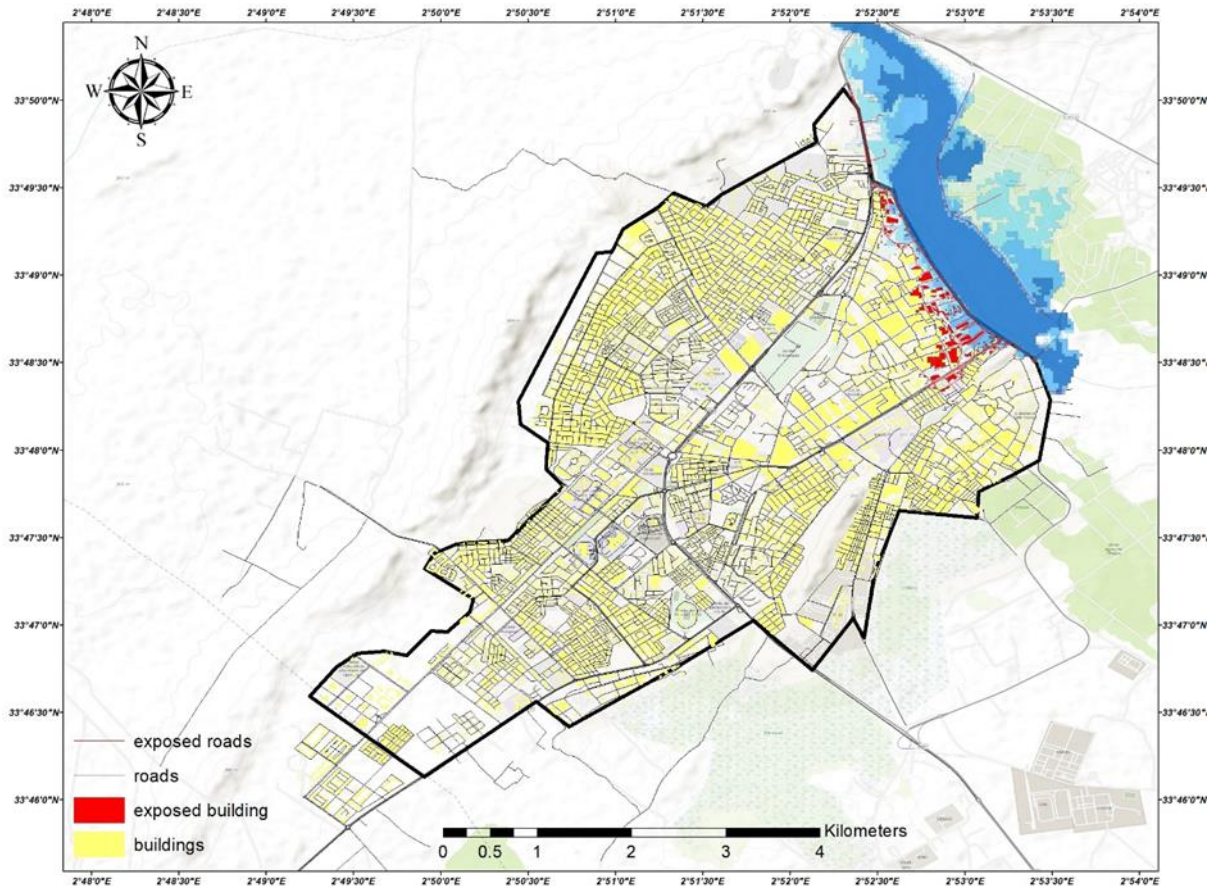


Figure 20:Map of exposed buildings and roads

Water level	risk roads	neighbourhoods
2 metres	0	0
4 metres	Rahba – la digue – carrefour PTT road (RN1)	Gouatines – djoudi aek - rahba
6 metres	Ouazene – l ecole– pasteur –Elhadjadj	Gouatines – zgage el hadjadj - ouazene
8 metres	Rogti ahmed – el istiklal – djoudi belkacem – laabadna – 1er november – bedara – sahraoui Mohamed – RN1	Souadek – laabadna – bedara – mgataah – bab dzair – rahbat el zaitoun – el Gharbia – ouazene – bordj snouci

Table 2:roads and neighborhoods are at risk with every rise in water levels

2.5. Historical water levels:

The city of Laghouat has a long history of flooding, the most notorious of which was the 2016 flood, which caused significant damage and led to the collapse of the Sidi Hakoum Bridge. The highest water levels were recorded in M'zi Valley, where the water rose to a height of 1 metre in the neighbourhoods adjacent to the M'zi Valley due to the water overflowing its main channel; this means that the water level rose to more than 5 metres.



Figure 21: The Sidi Hakoum Bridge moments before it collapsed during the 2016 floods

prevalent in analogous research endeavours and are particularly well-suited for application in semi-arid regions characterized by a pronounced susceptibility to flash flood phenomena.

- **Selected Flood Hazard Criteria and Justification:**

criterion	justification	Data source
slope	Controls runoff velocity and water accumulation; flat areas increase flood risk	Derived from DEM
Elevation	Lower areas are more prone to flooding; higher areas act as refuges	DEM
Drainage Density	Higher density indicates greater runoff concentration	Calculated from stream network
Land Use / Land Cover	Impervious surfaces (urban) increase runoff; vegetation reduces it	Landsat-8

Table 3: Flood Hazard Criteria and Justification

4.2. Spatial modelling of flood risk in the centre of Laghouat:

This phase of the study aims to identify areas at risk of flooding in the centre of Laghouat by integrating four key criteria: elevation, slope, drainage density and land use. It focuses on areas where conditions are ideal for water accumulation, namely: low elevation, gentle slopes, an inadequate natural drainage network, and a predominance of built surfaces that prevent water infiltration.

4.3. Criteria used in the analysis:

4.3.1. Slope Map:

The slope map was derived from the same DEM using the Slope tool in ArcGIS. The map illustrates the distribution of slope values in the city centre. It shows that most of the area has a very low slope, ranging between 0% and 3%, which reflects the flat nature of the city. This characteristic causes water to remain stagnant for long periods, with no natural gradient for it to drain away, thereby increasing the likelihood of black spots forming. There are some areas with a steep gradient (more than 8 %) in the northern and eastern peripheries, but these lie outside the densely populated urban area.

4.3.2. Reclassification of Slope:

The slope map derived from the Digital Elevation Model (DEM) underwent reclassification. This process was informed by the understanding that steeper topographical gradients facilitate more rapid surface runoff, consequently reducing the associated flood hazard. Conversely, areas exhibiting flatter slopes tend to promote water retention, thereby increasing the susceptibility to flooding.

Slope Range (%)	Hazard Level	Flood Implication
> 15	Very Low	Rapid drainage no water accumulation
10 - 15	Low	Moderate drainage
5 - 10	Moderate	Some water accumulation possible
3 - 5	High	Slow drainage water tends to accumulation
0 - 3	Very high	Very flat high-water accumulation

Table 4: Reclassification of Slope

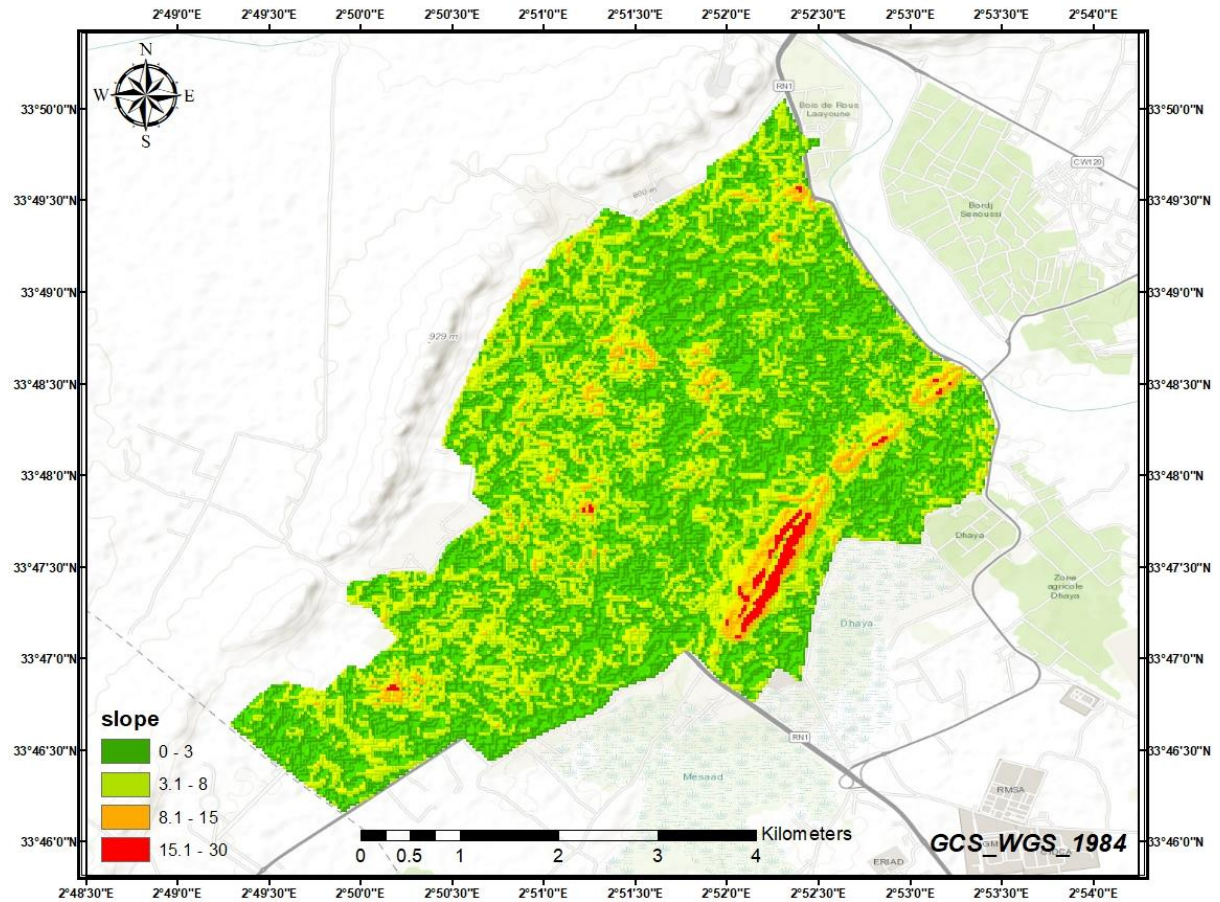


Figure 23: Map of slope

The Digital Elevation Model (DEM) underwent reclassification, a process predicated on the understanding that regions of lower elevation exhibit a heightened susceptibility to inundation. This vulnerability is attributed to the inherent gravitational flow of water, which naturally converges and accumulates within topographical depressions.

A low gradient (0–2 %) is a key factor in the formation of black spots, as it prevents the natural drainage of water. These areas have been assigned high hazard ratings.

4.3.3. Elevation map:

The elevation map was derived from a digital elevation model with a resolution of 30 metres. The figure illustrates the elevation distribution in the centre of Laghouat, where values range from 740 metres in the low-lying areas to over 780 metres in the higher areas (the surrounding hills). The map shows that most of the city centre lies at an altitude of

between 740 and 760 metres, making it a relatively low-lying area prone to water accumulation. This low elevation explains why surface water flows towards these areas, particularly during heavy rainfall or when drainage systems fail.

Elevation range (m)	Hazard level	Flood implication
> 800	Very low	High ground safe from flooding
780 - 800	Low	Moderately safe
760 - 780	Moderate	Intermediate risk
740 - 760	High	low – lying area flood - prone
< 740	Very high	Floodplain highest risk

Table 5:Reclassification of Elevation

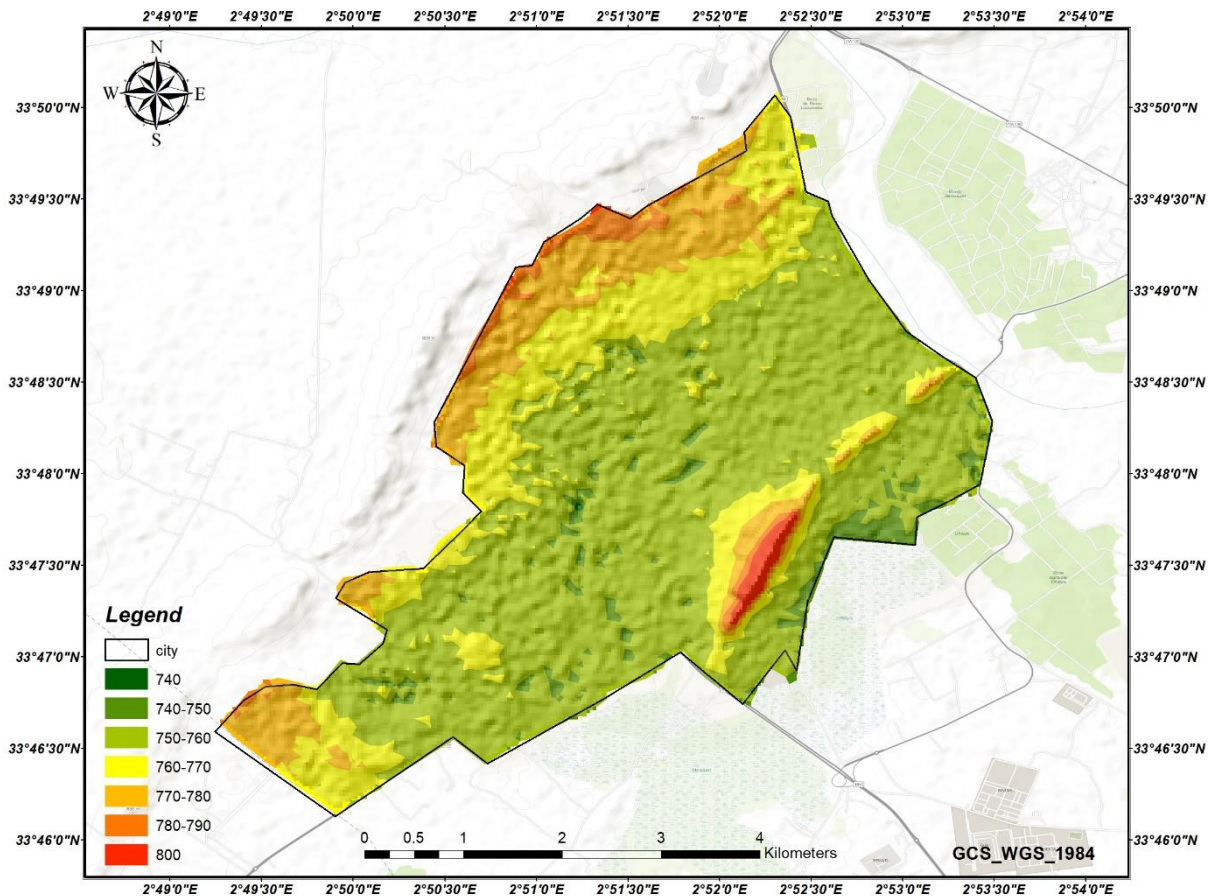


Figure 24: Map of elevation

Low-lying areas are considered to be the most at hazard, as water naturally flows to the lowest points. Consequently, they have been assigned high hazard ratings in the analysis.

4.3.4. Drainage Density:

Drainage density was calculated using the Line Density tool in ArcGIS, based on the network of valleys extracted from the DEM. The map illustrates the distribution of drainage density in the city centre. The results show that drainage density is very low in most parts of the city centre; this lack of a natural drainage network means that surface water cannot find natural pathways to drain away, increasing the hazard of it pooling in low-lying areas.

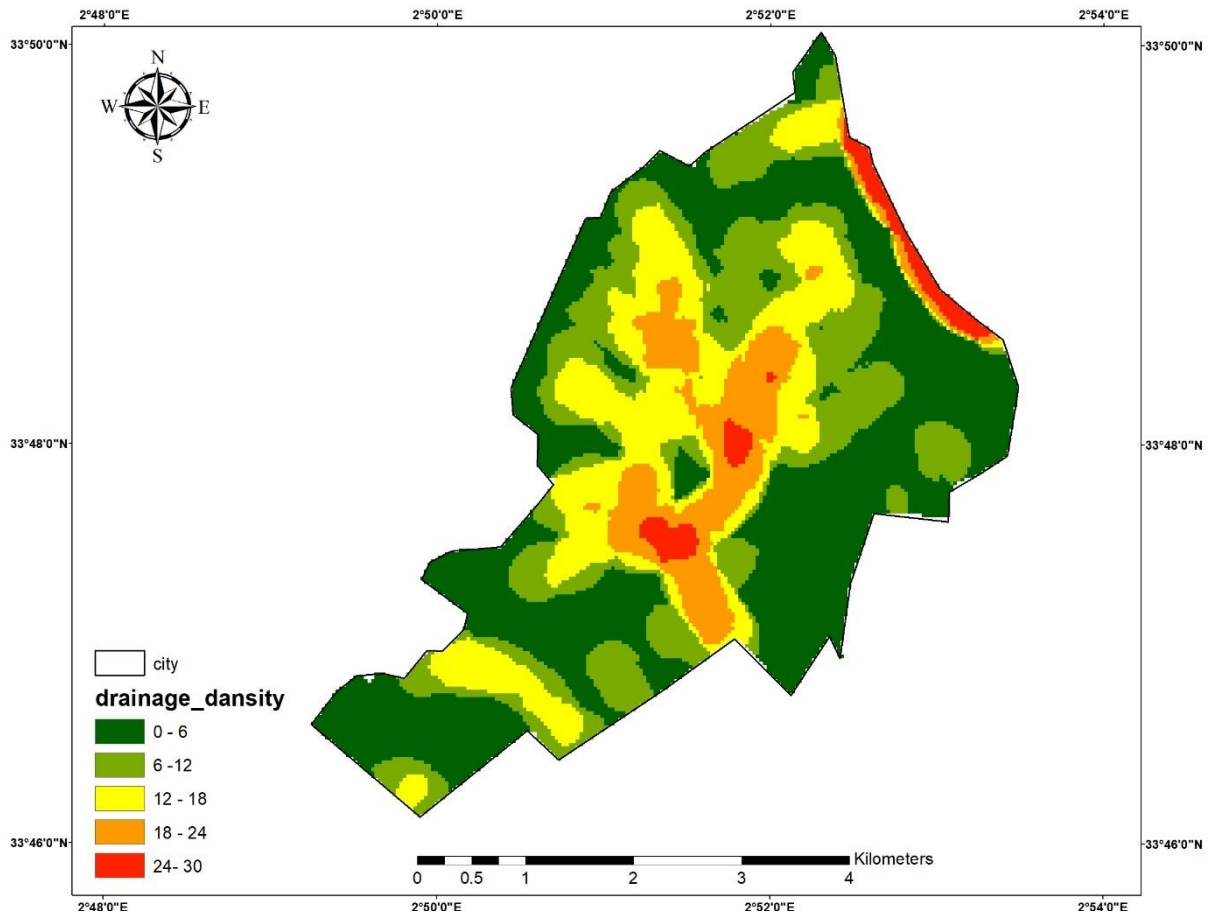


Figure 25: Map of drainage density

The lack of drainage infrastructure in the city centre explains why this area is the most prone to flooding, despite the low rainfall. Areas with zero drainage infrastructure have been assigned the highest hazard ratings.

4.3.5. Land Use Map:

The land use map was produced through the classification of Landsat 8 satellite imagery. The map shows that the centre of Laghouat is characterised by a clear predominance of built-up areas, which cover most of the region. Some bare and vegetated areas are also visible on the outskirts. Built-up areas are concentrated in the city centre, where residential, administrative and commercial buildings are located, whilst barren areas cover unused land, and vegetated areas are limited to a few small parks.

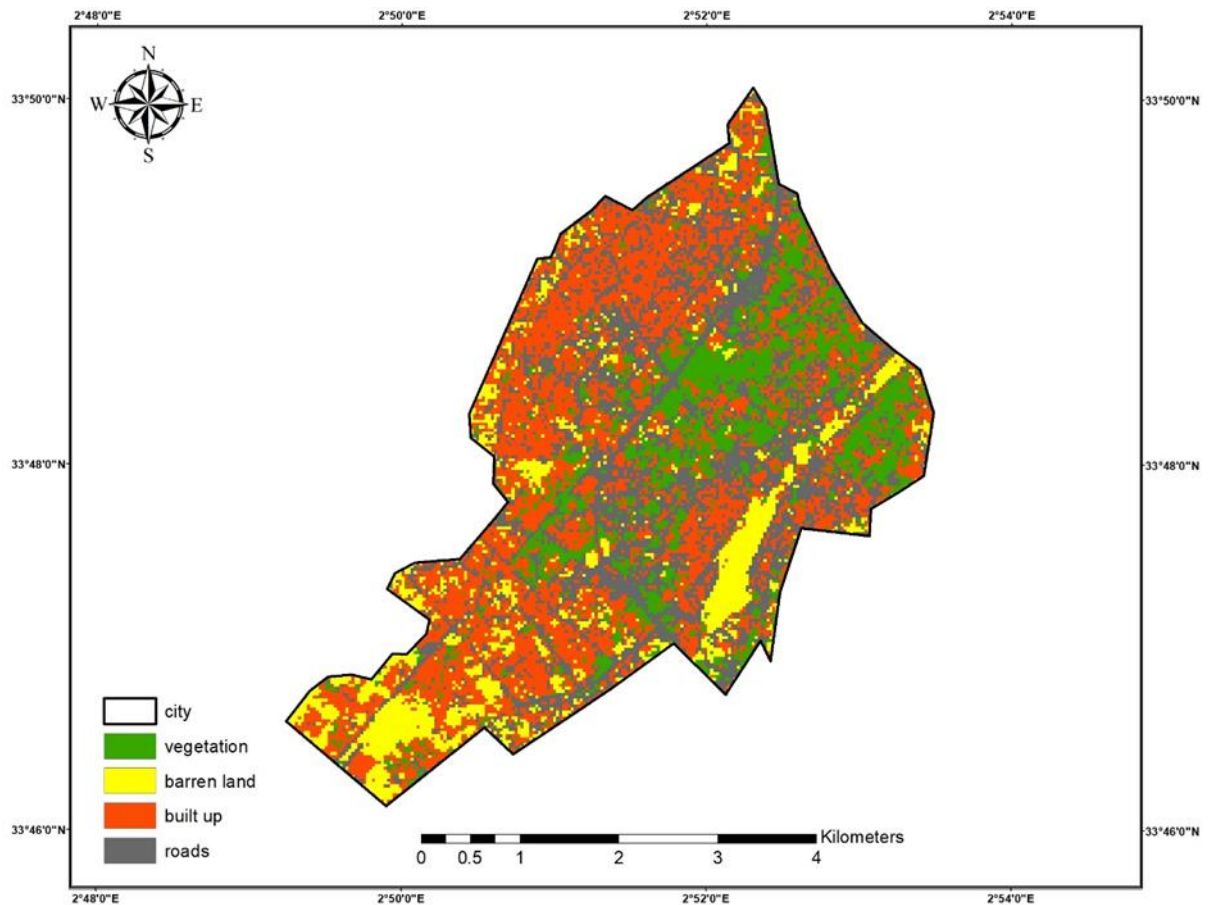


Figure 26: land use map

Built-up areas (concrete and tarmac surfaces) prevent water from seeping into the ground, thereby increasing the volume of surface runoff. They have therefore been assigned the highest hazard rating (5).

5.The Analytic Hierarchy Process (AHP):

The Analytic Hierarchy Process (AHP) is a method of “measurement through pairwise comparisons and relies on the judgments of experts to derive priority scales”. It has been one of the most widely used multiple criteria decision-making tools.”. It is used by decision makers and researchers, because it is a simple and powerful tool (Roberto & Russo, 2015).

Analytic Hierarchy Process (AHP) is a multi-criteria decision-making method, developed by Saaty (1980), which enables decision-makers to determine the relative weights of multiple criteria through pairwise comparisons. This method uses a scale of 1 to 9 to compare criteria, calculates priority weights, and checks for consistency using the consistency ratio ($CR < 0.10$). The Analytic Hierarchy Process (AHP) is particularly valuable in flood risk assessment using Geographic Information Systems (GIS) to determine the significance of various risk factors. (Saaty, 1980)

5.1. Pairwise Comparison Matrix :

- **Saaty Scale :**

Grade	Meaning
1	The two criteria are equally important
2	Between (1) and (3)
3	One criterion is slightly more important than the other
4	Between (3) and (5)
5	One criterion is much more important than the other
6	Between (5) and (7)
7	One criterion is far more important than the other
8	Between (7) and (9)
9	One criterion is absolutely more important than the other

Table 6:Satty Scale

- The matrix:

Factors	Elevation	slope	Drainage Density	Land use
Elevation	1	2	3	4
slope	0.5	1	2	3
Drainage Density	0.33	0.5	1	2
Land use	0.25	0.33	0.5	1

Table 7: The matrix

- Weight Calculation:

Column	Total
Elevation	$1+0.5+0.33+0.25 = 2.08$
slope	$2+1+0.5+0.33 = 3.83$
Drainage density	$3+2+1+0.5 = 6.5$
Land use	$4+3+2+1 = 10$

Table 8: Weight Calculation

- Normalization:

Factors	Elevation	Slope	Drainage density	Land use	Class average (weight)
Elevation	$1/2.08 = 0.48$	$2/3.83=0.52$	$3/6.5=0.46$	$4/10=0.4$	0.465
Slope	$0.5/2.08=0.24$	$1/3.83=0.26$	$2/6.5=0.31$	$3/10=0.3$	0.278
Drainage density	$0.33/2.08=0.16$	$0.5/3.83=0.13$	$1/6.5=0.15$	$2/10=0.2$	0.160
Land use	$0.25/2.08=0.12$	$0.33/3.83=0.09$	$0.5/6.5=0.08$	$1/10=0.1$	0.097

Table 9: Normalization

- Final weights:

Standard	Weight	Percentage
Elevation	0.465	46.5 %
Slope	0.278	27.8 %
Drainage density	0.160	16 %
Land use	0.097	9.7 %
Total	1	100 %

Table 10:Final weights

5.2. Consistency Ratio:

5.2.1. Calculating λ_{max} (the largest eigenvalue):

- Matrix $\times$ Weights:

Standard	Matrix $\times$ Weights	The result
Elevation	$(1 \times 0.465) + (2 \times 0.278) + (3 \times 0.160) + (4 \times 0.097)$	1.889
Slope	$(0.5 \times 0.465) + (1 \times 0.278) + (2 \times 0.160) + (3 \times 0.097)$	1.122
Drainage density	$(0.33 \times 0.465) + (0.5 \times 0.278) + (1 \times 0.160) + (2 \times 0.097)$	0.646
Land use	$(0.25 \times 0.465) + (0.33 \times 0.278) + (0.5 \times 0.160) + (1 \times 0.097)$	0.385

Table 11:Matrix $\times$ Weights

- Result $\div$ Weight:

Standard	Result $\div$ Weight
Elevation	$1.889 / 0.465 = 4.06$
Slope	$1.122 / 0.278 = 4.04$
Drainage density	$0.646 / 0.160 = 4.04$
Land use	$0.385 / 0.097 = 3.97$

Table 12:Result $\div$ Weight

$$\lambda_{\text{max}} = (4.06 + 4.04 + 4.04 + 3.97) / 4 = 16.11 / 4 = 4.03$$

5.3. Consistency Index (CI) :

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

where n = the number of parameters (4)

$$CI = (4.03 - 4) / (4 - 1) = 0.03 / 3 = 0.01$$

5.4. Consistency Ratio (CR):

- where RI (Random Index) is from the Saaty table (Saaty, 1980):

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

$$CR = 0.01 / 0.90 = 0.011$$

5.5. Consistency Check:

$$\lambda_{\max} = 4.03$$

$$CI \text{ (Consistency Index)} = 0.01$$

$$RI \text{ (Random Index)} = 0.90$$

$$CR \text{ (Consistency Ratio)} = 0.011$$

$$CR = 0.011 < 0.10$$

The weights are valid and consistent

5.6. Hazard Map Equation:

$$\text{Flood Hazard} = (\text{Elevation} \times 0.465) + (\text{Slope} \times 0.278) + (\text{Drainage Density} \times 0.160) + (\text{Land Use} \times 0.097)$$

6. Final hazard map:

This is the final hazard map for the centre of Laghouat. Hazard values range from 1 (very low) to 5 (very high). The black dots indicate areas that have been assigned a hazard rating of 4 or 5.

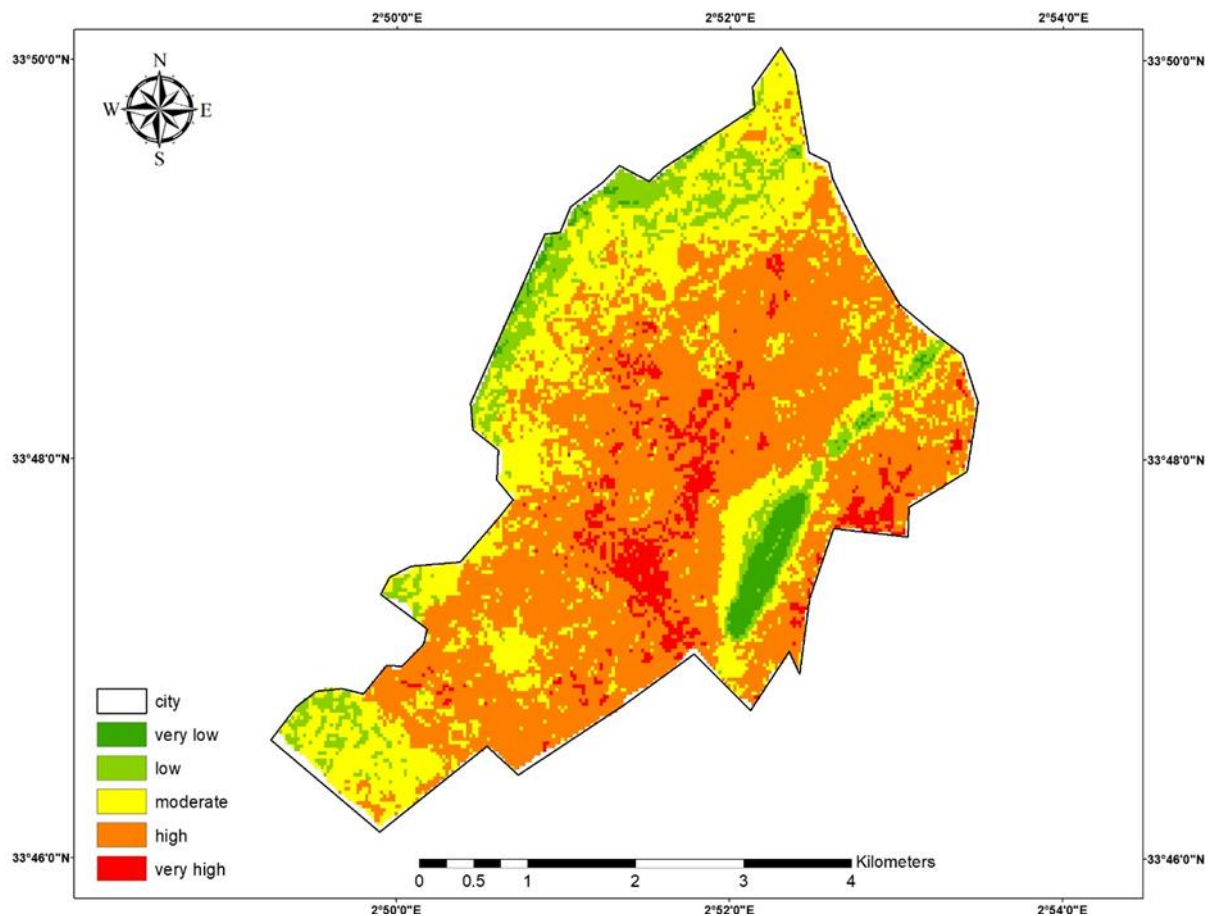


Figure 27: Flood Hazard map of the city of LAGHOUAT

The areas coloured red and orange, which represent high and very high risk levels, are concentrated in the city centre. This confirms the findings of our analysis: the city centre is a natural collection point for surface water, due to the low ground level, the flat terrain, and

the prevalence of impervious surfaces. In contrast, the green areas to the north are considered safe due to their higher elevation and steep terrain.

7.Exposure Assessment: Damaged Buildings and Roads:

7.1 Damaged Buildings:

Buildings located within the black points were identified using the ‘Select by Location’ tool in ArcGIS. The map shows the distribution of damaged buildings in the city centre.

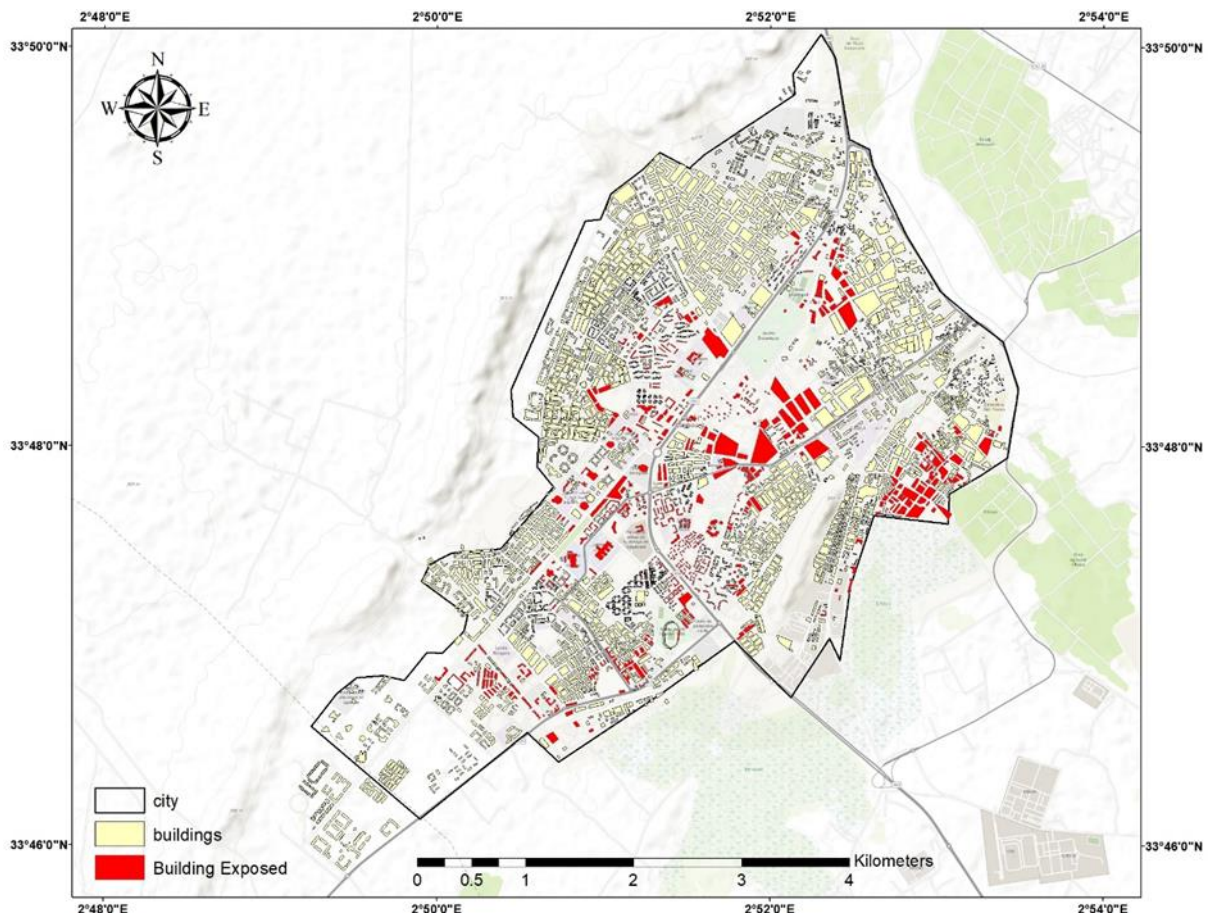


Figure 28: Buildings Exposed Map

7.2. Affected roads:

The roads located within the black spots were identified in the same way. The map shows the distribution of the affected roads in the city centre.

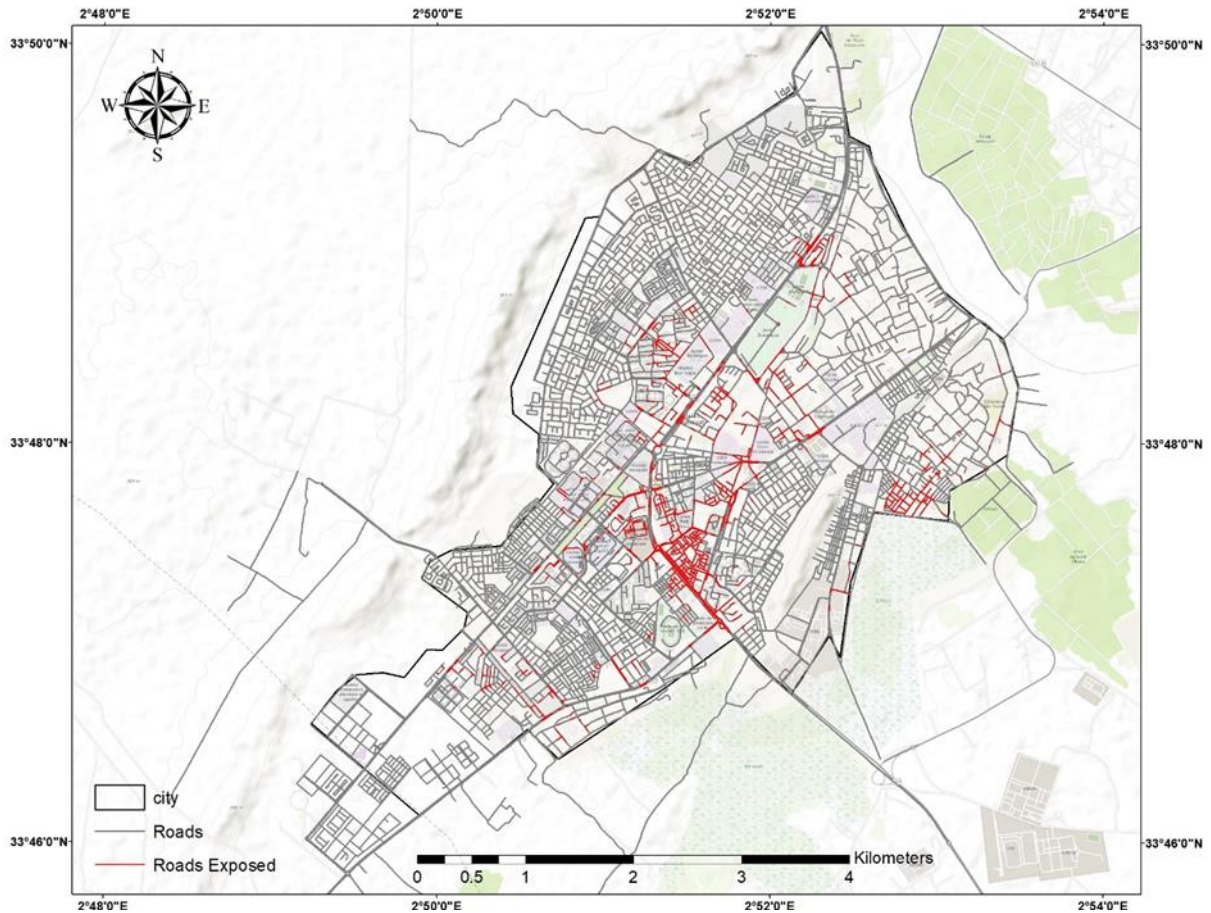


Figure 29:Roads Exposed Map

One of the roads most at risk from flooding is National Road No. 1, which is the city's lifeline and is considered a major thoroughfare; when flooding occurs, this road is closed, bringing traffic in the city to a standstill.

8. Geomorphological Analysis of the Stream Order Map:

The Stream Order Map is one of the fundamental tools in hydro geomorphological analysis, as it reflects the hierarchical structure of the water network and reveals surface runoff patterns and areas of water concentration. This map is based on a Digital Elevation Model (DEM) and the classification of streams according to the Strahler system, where the classification ranges from Order 1 (primary tributaries) to higher orders (main channels).

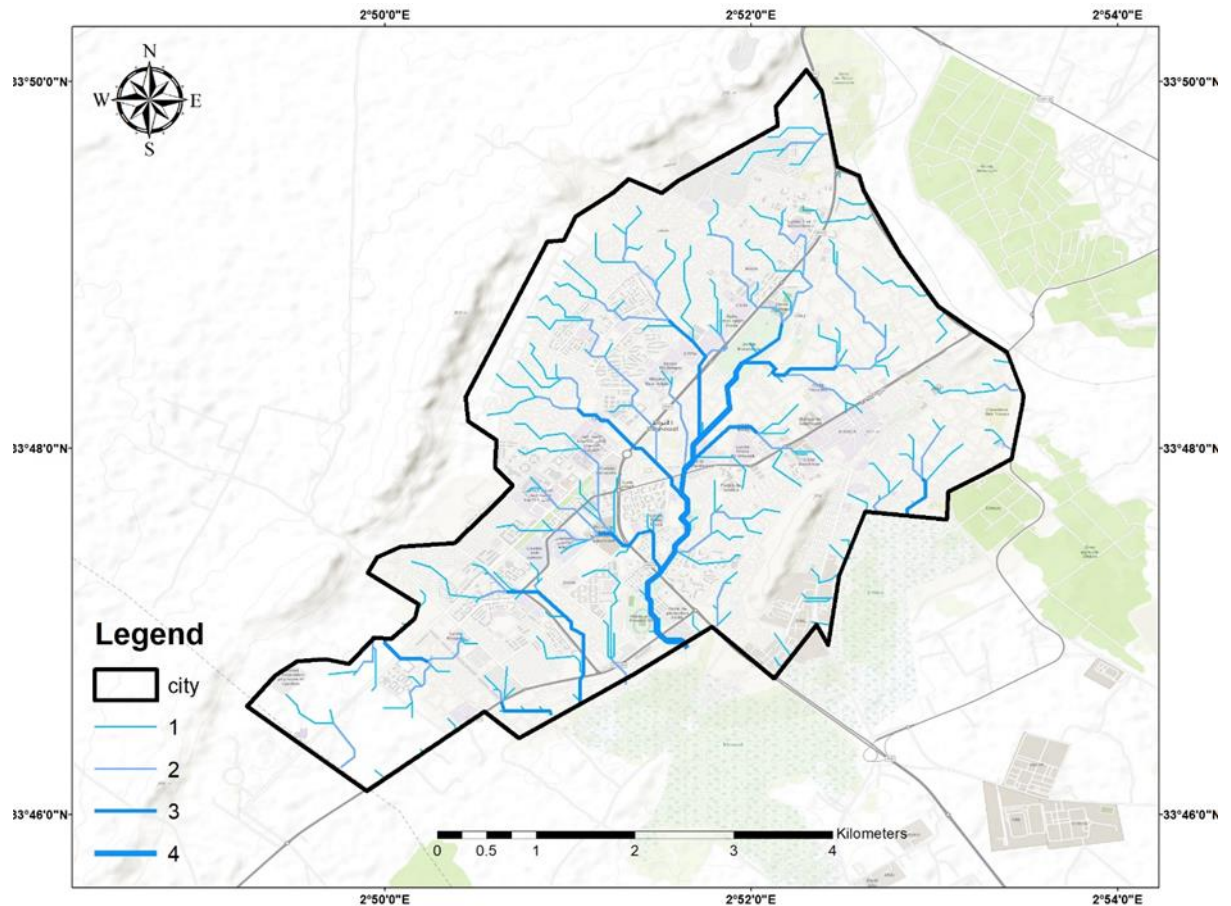


Figure 30: Stream Order Map

8.1. Spatial analysis of flow patterns:

8.1.1. General flow direction:

The map shows that the valley network takes on a semi-circular or fan-shaped form, with tributaries (orders 1, 2 and 3) converging from the north, west and east, all flowing towards order 4 (the main channel), which runs through the centre of Laghouat.

Water is concentrated in the city centre, as evidenced by the fact that all the lower levels (1 and 2) converge towards the main watercourse in the city centre, where the higher levels (3 and 4) are concentrated.

Furthermore, the circular shape of the drainage basin indicates that water collects in the city centre.

8.1.2. Hydrological explanation:

Water flows towards the city centre for several reasons:

Low-lying terrain: The city centre is situated at the lowest point within the catchment.

Shape of the catchment: The semi-circular shape of the catchment results in a short concentration time, with all tributaries reaching the outlet simultaneously.

The arrangement of the valleys: The presence of a fourth-order valley in the city centre confirms that the main channel receives all the water from the higher tributaries.

This spatial distribution of valleys reflects an important hydrological fact: the centre of Laghouat is the point where surface water from all directions converges. This explains why the city centre is prone to flooding even during moderate rainfall, and why the city relies entirely on pumps to drain water from the centre to higher ground.

The fact that the areas with the highest hazard ratings (3 and 4) correspond to the black dots identified in the field study confirms that the valleys are the natural channels that carry water into the city centre. This explains why the hazard of flooding is concentrated in this particular area.

8.1.3. Interpretation of the results:

The results show that the dark patches in the centre of Laghouat city are formed as a result of the interaction of four main factors:

1. Low elevation: Water accumulating in low-lying areas is a natural phenomenon, as water flows to the lowest point in the terrain.
2. Gentle gradient: Flat terrain (0–2 %) traps water and prevents it from draining away, thereby increasing the length of time it remains on the surface.
3. Lack of a natural drainage network: The absence of valleys and watercourses in the city centre means that surface water has no natural channels through which to drain.
4. Predominance of built-up surfaces: Buildings and tarmac prevent water from seeping into the ground, causing it to run off across the surface in search of low-lying areas where it can collect.

These four factors combine in the city centre to create an ideal environment for water to accumulate and, consequently, for flooding to occur, which explains why the hazard is concentrated in this particular area.

9. Field study:

- **The problem of drainage channels and pumps:**

In addition to the spatial analysis of black spots using geographic information systems, a field study was conducted using questionnaires aimed at residents and experts to verify the findings and identify the actual causes of flooding in the centre of Laghouat. This field study yielded significant findings that shed light on the technical and infrastructural dimensions of the problem.

- **Condition of the sewerage system:**

The results of the field study, in particular the expert questionnaires from the Directorate of Water Resources and the National Sanitation Office, showed that the sewerage system in the centre of Laghouat is in a state of clear technical deterioration. The experts noted that these sewers suffer from:

Accumulation of sediment and debris: leads to blockages in the drains and reduces their capacity

Deterioration of infrastructure: much of the network dates back to earlier periods and continues to operate without having been upgraded

Insufficient capacity of existing drains: they are not designed to cope with large volumes of water during heavy rainfall

Damage to certain sections: Cracks and partial collapses in some sections, these problems mean that the drainage channels are unable to fulfil their basic function, particularly during heavy rainfall, when the volume of surface water exceeds the channels' capacity.

- **The problem with wastewater pumps:**

The results of surveys of experts, and in particular the National Sanitation Office, have confirmed that the city of Laghouat relies entirely on pumps to discharge wastewater from the city centre. This total reliance on pumps is due to the city's topography, as the city centre is low-lying and flat (gradient 0–3 per cent), making gravity drainage impossible in most cases.

- **How the Pumps Work:**

The pumps are used to pump wastewater from low-lying areas in the city centre to higher ground, where it can be discharged via the gravity sewer network. This process operates year-round to ensure that water does not accumulate in the city centre.

- **The main problem: pumps breaking down during rainfall:**

Experts have explained that the main problem occurs during heavy rainfall, when the pumps break down or become unable to cope with the large volumes of water. This breakdown leads to:

Pumping stops: The pumps cease to operate due to electrical overloads or mechanical faults.

Water accumulates: Water begins to pool in the city centre as it cannot find a way to drain away.

City centre flooding: The volume of water exceeds the capacity of the drains, causing it to overflow onto roads and pavements and enter buildings.

Traffic paralysis: Water floods the main streets, bringing traffic in the city centre to a standstill.

- **Analysis and Interpretation:**

The problem with the pumps and drainage channels is the key factor in explaining the flooding in the centre of Laghouat. The flat terrain makes natural drainage impossible, the existing network is unable to cope with the volume of water, and the pumps – the only available solution – break down when they are needed most (during rainfall). This combination creates a dangerous situation.

10.Conclusion:

This chapter combined hydrological modelling, multi-criteria analysis based on geographic information systems (GIS), and field verification to assess flood risks in Laghouat. Hydrological modelling of the M'zi Valley using Global Mapper software revealed that water levels exceeding 4 metres cause the river to burst its banks, whilst the historic flood of 2016 (which exceeded 5 metres) led to the collapse of the Sidi Hakoum bridge. Analysis using the Analytic Hierarchy Process (AHP) yielded the following criterion weights:

Elevation (46.5 %), slope (27.8 %), drainage density (16.0 %) and land use (9.7 %), with a correlation coefficient of 0.011. The flood hazard map identified the city centre as the area most at hazard, with black spots (indicating high to very high risk) concentrated in areas where flat, low-lying terrain overlaps with impervious surfaces. An analysis of the watercourse network confirmed that the quasi-circular drainage network directs surface water flow towards the city centre. Field studies have confirmed the accuracy of the hazard zone models and revealed that faults in the sewage pumps and the poor state of the sewerage infrastructure are the main causes of flooding in the city centre. The integrated approach confirms that the hazard of flooding in Laghouat stems from both physical and infrastructure-related factors, necessitating urgent intervention from multiple sectors.

Chapter IV: Analysis and Discussion of Results

1.Introduction:

This chapter presents a comprehensive analysis and discussion of the findings drawn from the applied analyses set out in Chapter 3. Whilst Chapter 3 focused on the technical presentation of the hydrological modelling, the mapping of spatial risks using the Analytic Hierarchy Process (AHP), and field verification, this chapter interprets these results and explains their implications in the context of the research problem and its objectives.

2.Discussion of the results of the hydrological simulation:

2.1. Flood scenarios and their impacts:

The Water-level-based flood inundation scenarios for M'zi Valley, using Global Mapper software, revealed four flood scenarios corresponding to water levels of two metres, four metres, six metres and eight metres. These scenarios represent a gradient in flood severity, ranging from a minor flood to catastrophic inundation.

- **At a level of 2 metres:** the flood remains confined to the main channel and poses no threat to urban areas. This scenario corresponds to light rainfall that the valley can absorb without causing significant flooding.
- **At a level of 4 metres:** the water begins to overflow its banks, covering wider areas of the valley and affecting agricultural land and isolated buildings. This scenario corresponds to moderate rainfall that begins to strain the valley's capacity to absorb water.
- **At a level of 6 metres:** the flood spreads to cover large areas on both sides of the valley, threatening low-lying residential areas and roads. This scenario corresponds to heavy rainfall that exceeds the valley's capacity to absorb it and affects urban areas.
- **At 8 metres:** This represents a catastrophic flood scenario, equivalent to twice the maximum depth of the narrowest part of the valley. This scenario involves the worst possible hydrological conditions, inundating low-lying areas and severely affecting the city's infrastructure.

2.2. Comparison with historical floods:

The simulation results correspond to the historic flood of 2016, which caused severe damage and led to the collapse of the Sidi Hakoum bridge. During this flood, water levels in the M'zi Valley rose to over 5 metres, resulting in the flooding of neighbourhoods adjacent to the valley. This historical verification confirms the realism of the simulation scenarios and highlights the city's vulnerability to flooding.

2.3. The Implications of Flood Risk Management:

The simulation results emphasise the need for proactive flood risk management. The scenario involving 4 water level, which affects agricultural land, highlights the need to activate early warning systems when this level is reached. Meanwhile, the scenarios involving 6 and 8 water level, which affect urban areas, highlight the need for evacuation plans and emergency response protocols to be in place to deal with heavy rainfall events.

3. Discussion of the results of the Analytic Hierarchy Process (AHP) and spatial risk mapping:

3.1. Interpretation of the Analytic Hierarchy Process (AHP) weights:

The Analytic Hierarchy Process (AHP) was applied to determine the relative importance of the four flood risk criteria. The resulting weights were as follows: elevation (46.5 %), slope (27.8 %), drainage density (16.0 %) and land use (9.7 %). The consistency ratio (CR = 0.011) confirmed the validity and consistency of the pairwise comparisons.

Elevation (46.5 %) was given the highest weighting as it directly determines the accumulation of surface water. This corresponds to the topographical reality of the city of Laghouat, where the city centre is situated at the lowest point in the catchment area.

Slope (27.8 %) was given the second-highest weighting as it governs the terrain's ability to drain water. The flat topography of the city centre (gradient of 0 to 3 %) hinders natural water drainage, making it a decisive factor in flood hazard.

Drainage density (16.0 %) reflects the presence or absence of a natural drainage network. The low drainage density in the city centre confirms that surface water lacks natural drainage pathways.

Land use (9.7 %) was given the lowest weighting as it is a supplementary factor influencing the severity of surface runoff. Whilst built-up areas increase surface runoff, they do not directly cause flooding; rather, they amplify the effects of other factors.

4.Validation of spatial modelling:

4.1. Population survey data:

A total of 40 valid questionnaires were collected from residents of the city of Laghouat, numbered from 01 to 40. Each person was asked to provide the name of the neighbourhood in which they live, describe the last flood they witnessed in their neighbourhood, locate the flood on the map, and indicate the maximum water level reached. These points were digitised using ArcGIS.

When compared with the points collected from the questionnaire analysis, we observe that the model accurately identified flood-prone areas.

4.1.1. Results of population survey Questionnaires:

جامعة محمد ابن احمد وهران 2
قسم الجغرافيا وتهئية الاقليم
تخصص هيدروولوجيا مناخ واقليم

23/05/2026

تقييم مخاطر الفيضانات والنمذجة المكثفة في مدينة الاغواط باستخدام نظم المعلومات الجغرافية والاستشعار عن بعد

استبيان

1. ما اسم الحي الذي تسكن فيه ؟
.....

2. منذ كم سنة تسكن في هذا الحي ؟
.....

3. هل سبق ان تعرضت منطقتك للفيضان ؟
نعم ☐ لا ☐

4. بناءا على الخريطة الموجودة امامك ضع علامة (x) على الاماكن التي رأيت فيها الفيضان :


5. متى كان اخر فيضان ؟
.....

6. ماهو المصدر الرئيسي لمياه الفيضان ؟
.....

7. ماهو أقصى ارتفاع وصلت اليه المياه ؟
.....

Among the participants, 22 people confirmed that they had witnessed flooding in their neighbourhoods, whilst 8 confirmed that they had not witnessed any in their neighbourhoods; the majority of people indicated that the last major flood they had witnessed was in 2025. As for their response regarding the maximum height the water reached, their answers ranged from 0.5 metres to 1 metre as the highest level they had witnessed.

Regarding the question: Have your properties ever been subjected to flooding?

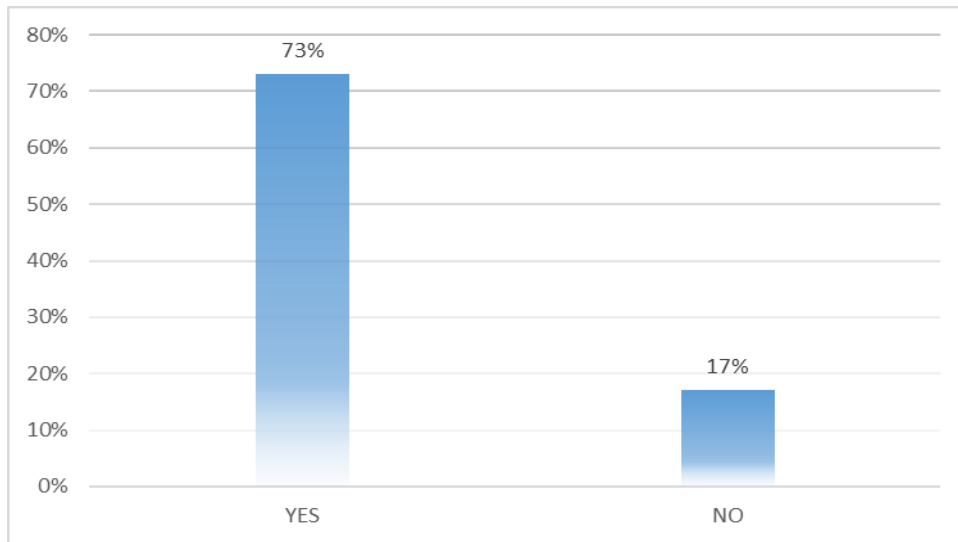


Figure 31: A graph showing the percentage of the population exposed to floods

73% of the surveyed residents experienced flooding of their property, confirming the severity of the problem in the city of Laghouat.

And when asked about the primary source of the floodwaters?

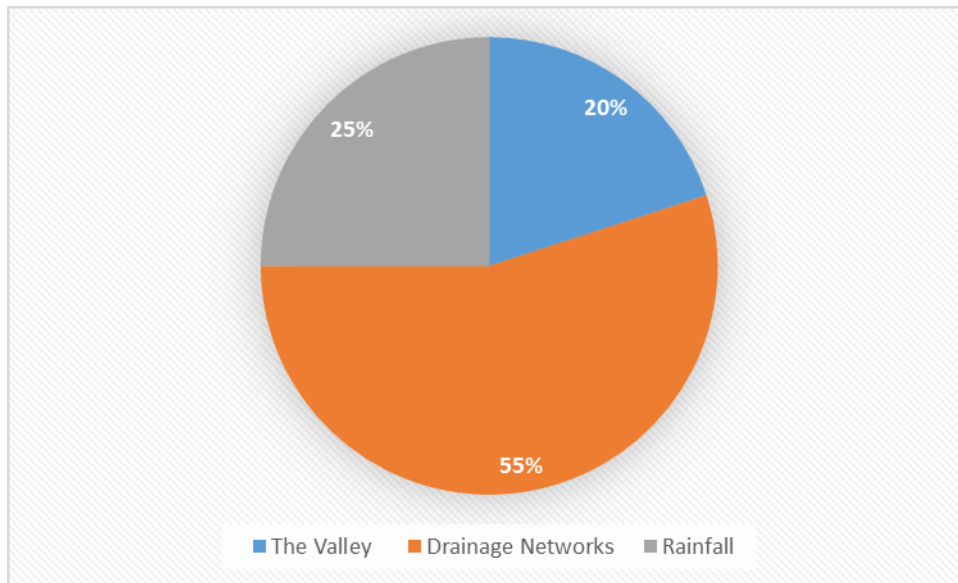


Figure 32: A pie chart illustrating the causes of floods

55% identified the drainage network as the primary source, confirming the hypothesis that the wadi is not the main cause and pointing to other factors related to the sewage channels.

4.2. Results of the Expert survey Questionnaires:

إجابة محمد ابن احمد وهران 2
قسم الجغرافيا وتهيئة الاقليم
تخصص مباح هندولوجيا واثيم

23/05/2026

تقديم ملاحظات القضاة والتمهجة المكثفة في مدينة الاغواط باستخدام نظم المعلومات الجغرافية والاستثمار عن بعد

اسمك

1. ماهي المناطق او الطرق التي تكثر فيها لتدخلكم او شكوى المواطنين بسبب الفيضان؟
.....
.....
.....

2. ما هو مستوى خطورة هذه المناطق؟ مرتفع جدا، مرتفع، متوسط، منخفض، منخفض جدا ☐

3. متى كان اخر حدث فيضان كئيل سجالته الادارة:

4. برأيكم ما هو السبب الرئيسي للفيضان؟
• ارتفاع منسوب مياه وادي مزي ☐
• ضعف قدرة قنوات التصريف على تصريف المياه ☐
• تضاريس المدينة ☐
• سبب آخر ☐ اذكروا:

5. هل تغطي شبكة تصريف مياه الامطار كامل المدينة؟
• نعم تغطية كاملة ☐
• تغطية جزئية فقط ☐
• لا توجد شبكة تصريف مياه الامطار ☐

6. ماهي حالة قنوات الصرف الصحي؟
حالة جدا ☐ : حدة ☐ : متوسطة ☐ : سيئة ☐ : سيئة جدا ☐

7. هل تمتلك الادارة خريطة رسمية خاصة بالمدينة لأخطار الفيضانات؟
نعم ☐ لا ☐

8. ما هو الحل الأنسب الذي يجب ان تتبناه الادارة حسب رأيكم؟
اذكروا:

9. هل ترون بأن تحسين كفاءة شبكات الصرف سيجل المشكلة كليا؟
نعم ☐ لا ☐

10 questionnaires were distributed to experts from three government bodies: the Municipal Office of Construction and Reconstruction, the Directorate of Water Resources, and the National Sanitation Office. The three bodies were asked to identify the area's most prone to flooding, and their responses were largely consistent; they agreed that the areas at hazard are concentrated along National Road No. 01, in some areas adjacent to the valley, and also in the city centre. In their response regarding the causes of the floods, the three bodies agreed that the main cause was the sewage system, followed by the rising water level of the M'zi Valley . The National Sanitation Office confirmed However, the cause is a breakdown in the sewage pumps, as the city relies on pumps to drain water due to its topographical nature; when these pumps fail during rainfall, it causes a major problem, as the water cannot be drained and will accumulate in the city centre, leading to flooding. The Office also confirmed that the cause of the breakdown is the pumps' inability to handle such as it exceeds the capacity of the pumps. However, the cause is a breakdown in the sewage pumps; as the city relies on pumps to drain water due to its topographical nature, a breakdown in these pumps during rainfall causes a major problem, as the water cannot be drained and will accumulate in the city centre, leading to flooding. The Office also confirmed that the cause of the

breakdown is the inability of these pumps to handle such of water, as it exceeds the pumps' capacity. Furthermore, the rainwater drainage network covers only parts of the city and is in a fair to poor condition, which exacerbates the problem. As most authorities recognise, improving the efficiency Drainage networks and their renovation, as well as the upgrading of drainage pumps, could also provide a solution to this problem.

When experts were asked about the primary cause of the flood? the answers were:

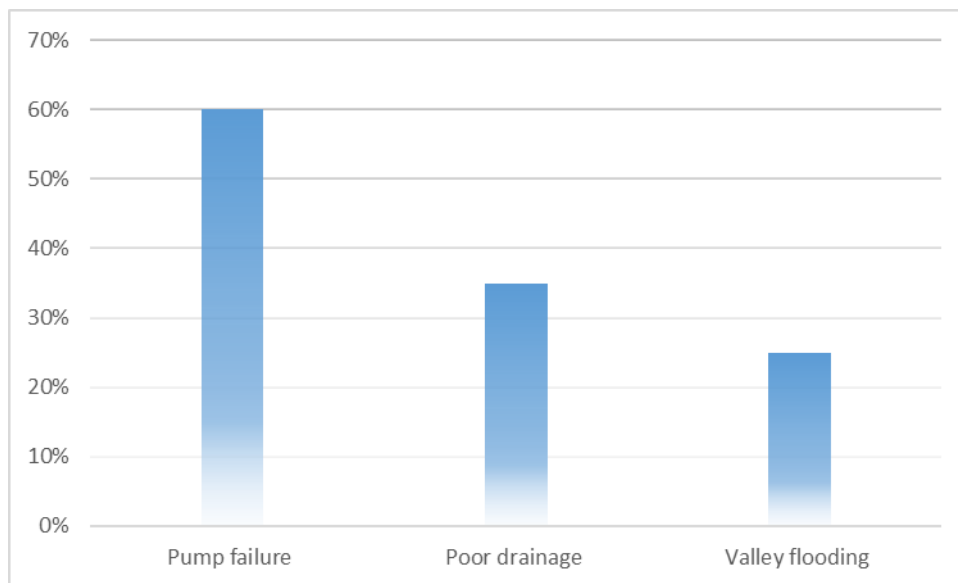


Figure 33:A chart illustrating the causes of floods according to experts.

60% of the experts cited pump failure, confirming the previous hypotheses.

4.3. Conclusion of Results:

The results of the resident and expert surveys conducted in this study provide valuable confirmation of the spatial modelling results presented earlier; the resident survey revealed that the majority of the reported areas are classified as high to very high risk, thereby confirming the model's accuracy in identifying areas at hazard. The results of the expert survey also confirmed the model's accuracy, based on their studies and experience.

These results reinforce confidence in the flood hazard map and support its use as a basis for urban planning and management recommendations.

5. Interpretation of the Flood Risk Map:

The flood risk map has classified the study area into five risk categories: very low, low, medium, high and very high. Areas with high and very high risk (black patches) are concentrated in the city centre, where four factors converge: low elevation, gentle slopes, low drainage capacity and a high proportion of impervious surfaces.

The spatial distribution of areas at risk of flooding confirms that this risk is not random, but is concentrated in areas where topographical conditions and infrastructure create an environment conducive to water accumulation. The northern part of the city is classified as a low-risk area due to its elevation and steep slopes, despite being a source of surface water flow towards the city centre.

6. Discussion of the field study findings:

6.1. The problem of drainage channels and pumps:

The field study, which drew on testimonies from local residents as well as experts, provided crucial insights into the real causes of flooding in the centre of Laghouat.

6.2. State of the sewerage system:

The findings revealed that the sewerage system in Laghouat town centre is suffering from clear technical deterioration:

- **Accumulation of sediment and debris:** leading to blockages and reducing capacity.
- **Deterioration of infrastructure:** a large part of the network dates back to earlier periods and has not been modernised.
- **Insufficient capacity:** not designed to cope with large volumes of water during heavy rainfall.
- **Damage to certain sections:** cracks and partial collapses.

6.3. The problem with sewage pumps:

The city of Laghouat relies entirely on pumps to drain sewage from the city centre due to its flat terrain (gradient 0–3 %), which makes gravity drainage impossible.

The main problem: pumps breaking down during rainfall:

During heavy rainfall, the pumps break down or become unable to cope with the large volumes of water Where:

pumping ceases – as the pumps stop working due to electrical overloads or mechanical failures – water begins to accumulate in the city centre, leading to flooding, with water spilling onto the roads and entering buildings. This results in traffic paralysis, as the main streets are submerged, bringing traffic to a standstill.

6.4. Analysis and Interpretation:

The problem with the pumps and drainage channels is the main factor explaining the flooding in central Laghouat. The flat terrain makes natural drainage impossible, the existing network is unable to cope with the volume of water, and the pumps break down when they are most needed (during rainfall). This combination creates a dangerous situation.

The field study showed that the problem of flooding in central Laghouat is not merely a natural phenomenon, but is fundamentally a structural and technical problem. Due to its low-lying, flat topography, the city relies entirely on pumps to drain sewage; these pumps break down during rainfall as a result of excessive pressure and poor maintenance. Therefore, any radical solution to the flooding problem in Laghouat must begin by addressing the issue of the drainage channels and pumps.

7.Limitations of the study:

Although this study provides a comprehensive assessment of flood risks in Laghouat, several limitations should be acknowledged:

- **Data accuracy limitations:**

The Digital Elevation Model (DEM) used in this study has a resolution of 30 metres. Whilst this resolution is sufficient for regional-level analysis, it may not capture the fine-scale topographical features that influence local flood patterns, such as small drainage channels and road bends.

- **Limitations of hydraulic modelling:**

The hydrological simulation was carried out using Global Mapper software, which provides a simplified representation of flood dynamics. Full two-dimensional hydraulic modelling (such as HEC-RAS 2D) would provide more accurate estimates of water depth and velocity, but requires more comprehensive input data.

- **Limitations of rainfall data:**

Rainfall data were obtained from the NASA POWER database, which provides grid data at a resolution of 0.5 degrees. This may not reflect local variations in rainfall, particularly thunderstorms that cause flash floods.

- **Limitations of the expert assessment in the Analytic Hierarchy Process (AHP):**

The weights for the Analytic Hierarchy Process (AHP) were derived from expert assessments. Although the consistency ratio ($CR = 0.011$) confirmed the validity of the results, increasing the number of participating experts would enhance the reliability of the results

- **Temporal limitations:**

The flood risk map reflects current land use and topographical conditions. Future urban expansion or climate change will require updated assessments.

Despite these limitations, the methodology used is appropriate for a Master's thesis and provides practical information for flood risk management in Laghouat.

8.Recommendations for Urban Planning and Management:

8.1. Short-term recommendations:

Recommendation 1: Immediate suspension of building permits in high-risk areas.

Action: Immediately suspend the issuing of building permits in areas classified as high to very high risk (levels 4–5 on the risk map).

Recommendation 2: Cleaning and rehabilitation of the sewerage network

Action: Carry out a comprehensive clean-up of the main sewerage channels before the rainy season.

Recommendation 3: Maintenance of pumps and backup power systems.

Action: Establish a preventive maintenance programme for sewerage pumps and install backup generators.

8.2. Medium-term recommendations:

Recommendation 4: Adopt the flood risk map into law.

Action: Adopt the flood risk map as an official annex to the land-use plan.

Recommendation 5: Expand the stormwater drainage network.

Action: Expand the stormwater drainage network to cover all areas of the city centre.

8.3. Long-term recommendations:

Recommendation 6: Establish an early flood warning system.

Components: Rainfall gauges upstream, water level sensors in M'zi Valley, and an automated warning system.

Recommendation 7: Incorporating flood risks into the master plan.

Action: Ensure that a flood risk map is included in all future amendments to the master plan for urban planning.

General Conclusion:

This study aimed to assess flood risks in the city of Laghouat using Geographic Information Systems (GIS) and remote sensing, in an effort to fill a significant research gap; the study highlighted the absence of any previous comprehensive spatial assessment of flood risks in this urban centre, situated in a semi-arid environment. The research comprised four analytical stages, each of which yielded important findings which, taken together, form a scientific basis for risk-management-based urban planning in the city of Laghouat.

The theoretical framework of the study emphasised that flash floods in urban areas are considered the most significant natural hazard in semi-arid environments, and that ‘multi-criteria decision analysis’ (MCDA) based on geographic information systems – specifically using the ‘analytic hierarchy process’ (AHP) – represents the most appropriate methodology for assessing flood risks. The study also revealed that, despite numerous studies having been conducted on flooding in cities in northern Algeria – such as ‘Bab El Oued’ and ‘Aflou’ – the Laghouat region has not received sufficient research attention, which justifies the importance of this study.

The description of the study area provided an overview of the landscape of the city of Laghouat. The morphometric analysis of the M’zi Valley catchment revealed that it covers an area of 4,400.5 km² and is 89 km Length, and that it has a compact, semi-circular shape (Form Factor = 0.55), with the valley’s tributaries converging at its mouth near the city of Laghouat; This confluence leads to sudden and rapid floods with very short response times during heavy rainfall. The semi-arid climate is also characterised by significant variation in annual rainfall, with a clear contrast between dry and wet years. The Kriging method was selected due to its superior performance in producing spatially consistent patterns. Topographically, the city centre is characterised by flat terrain, whilst the surrounding mountainous areas are characterised by steeper slopes.

Hydrological modelling was carried out for the Mazi Valley, and scenarios for the rise in the valley’s water level were identified. Four scenarios were tested: 2 metres, 4 metres, 6 metres and a catastrophic scenario of 8 metres. We concluded that, regardless of how high the water level in the valley rises, the water can never reach the city centre but will only affect the areas adjacent to the valley. The impact on buildings and roads was assessed, and hazard and impact maps were produced. The results obtained led us to move on to a study of the city centre, where a set of criteria was integrated into a multi-criteria model to assess flood risks.

These included: slope gradient, elevation above sea level, drainage network density, and land use. These criteria were reclassified according to a standardised five-point risk scale, ranging from ‘very low’ to ‘very high’. A hierarchical analysis was applied to determine the relative weights of each criterion, with elevation assigned a weight of 46.5 per cent, slope 27.8 per cent, drainage density 16.0 per cent, and land use 9.7 per cent, with a consistency ratio (CR) of 0.011 (less than 0.10), confirming the reliability of the weights. The results of the weighted overlay analysis for the reclassified criteria were then combined to produce a final flood risk map; the area was divided into five risk categories. The map shows that high-risk areas are concentrated along the ‘Wadi Mazi’ and in the city centre, where factors such as flat terrain, low elevation and a high proportion of impervious surfaces combine to create ideal conditions for water to pool and accumulate. In contrast, the northern part of the city has been classified as a very low-risk area due to its sloping terrain and higher ground levels, although it is considered a source of floodwater flowing towards the city centre. Spatial overlay analysis revealed that a large number of buildings – the vast majority of which are residential – and a significant portion of the road network are located within areas where the risk ranges from high to very high, necessitating urgent intervention. To corroborate these findings, field studies and surveys were conducted amongst residents and experts; 73 per cent of residents confirmed they had experienced flooding, whilst 60 per cent of experts identified pump failure as the main cause. These results corroborated the findings of our study.

In conclusion, this study has demonstrated that a multi-criteria analysis based on Geographic Information Systems (GIS), supported by field studies and a hydrological model of the valley, provides a cost-effective methodology for assessing flood risks in semi-arid urban environments. The resulting flood risk map and assessment of the level of risk exposure provide a scientific basis for decision-makers in the city of ‘Laghout’ To carry out urban planning based on risk management. Although the city is prone to flash floods, these risks can be mitigated through evidence-based planning; this study has provided the necessary evidence, and it is now up to decision-makers to take the appropriate action. It is hoped that the recommendations set out here will help to reduce flood risks, protect lives and property, and steer the city towards a more sustainable and resilient path of urban development.

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