JOURNAL OF WATER AND LAND DEVELOPMENT
e-ISSN 2083-4535
Polish Academy of Sciences (PAN) Institute of Technology and Life Sciences – National Research Institute (ITP – PIB)

JOURNAL OF WATER AND LAND DEVELOPMENT
DOI: 10.24425/jwld.2026.158705
2026, No. 69 (IV–VI): 109–119

Multi-temporal analysis of Nouakchott floods (1994–2024) using remote sensing and key hydrological parameters

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RECEIVED 13.10.2025 ACCEPTED 28.01.2026 AVAILABLE ONLINE 16.06.2026

Abstract: The city of Nouakchott has faced a growing incidence of flooding for several decades, exacerbated by climatic, hydrogeological, and anthropogenic factors. This study is based on a multitemporal remote sensing analysis using satellite images from four key years: 1994, 2004, 2014, and 2024. Its objective is to track the spatial and temporal evolution of flooded areas while assessing the hydrological and ecological impacts of these floods on the urban environment.

The flood-prone area of the city, assessed at 10-year intervals (1994, 2004, 2014, and 2024), increased from 0.07 to 0.13%, then to 1.05%, and finally to 3.96%, indicating a marked expansion of flood-affected areas over the decades. This historical trend indicates a worsening problem, with flooded areas now nearly 50 times more extensive than in 1994. This observation is supported by analyses of groundwater behaviour, annual precipitation, and soil infiltration capacity. Rising groundwater levels and soil impermeability affect the spread of flooded areas. The study underscores the urgency of implementing sustainable urban planning policies and improving stormwater management to mitigate the ecological and health risks associated with flooding.

Keywords: ecological impact, flood, groundwater table, Nouakchott, remote sensing

INTRODUCTION

Recurrent flooding in Nouakchott, the capital of Mauritania, presents significant urban and environmental management challenges. Located on a low-lying coastal plain, the city is particularly vulnerable to water accumulation, a phenomenon exacerbated by several interrelated factors: rising groundwater levels, local precipitation, and rapid urbanisation (Senhoury *et al.*, 2016). Climate change is altering the frequency and intensity of rainfall in Sahelo-Saharan Africa, further compounding such problems (Perona *et al.*, 2023). One of the main components influencing local hydrological behaviour is the Nouakchott water table, located in coastal dune sands beneath impermeable clays. Rainfall infiltration, irrigation, anthropogenic inputs from domestic water use, and leaks from sewer networks are its main sources (Caballero *et al.*, 2022; Pezard *et al.*, 2022).

Urban flood risks have increased as a result of this aquifer's progressive rise brought on by sea level rise and inadequate drainage infrastructure (Maliva, 2021). The capital's environmental vulnerability is further increased by the growing threat of saline intrusion to groundwater quality.

The effects of Nouakchott's comparatively low annual precipitation are exacerbated by the limited infiltration capacity of urban soils and the absence of efficient drainage infrastructure. Even low-precipitation events can induce significant water storage, especially in areas with shallow water tables and uncontrolled urbanisation (Ould Sidi Cheikh, Ozer and Ozer, 2007). Regional climate anomalies, such as fluctuations in the West African monsoon system, have frequently been attributed to recent extreme events (Descroix *et al.*, 2016). Remote sensing methods have contributed to analyses of Nouakchott's urban growth and related flood risks. Due to population expansion, the city expanded by 36 km^2 between 1989 and 1999, as evidenced by multitemporal satellite imagery (SPOT HRV, Landsat) (Wu, Courel and Rhun Le, 2003). The degradation of natural coastal dunes has increased vulnerability to floods as a result of this rapid urbanisation, which frequently occurs in low-lying and susceptible locations (Ould Sidi Cheikh, Ozer and Ozer, 2007). Radar images from ENVISAT ASAR show considerable shoreline retreat, mostly south of the port built in 1986 (Hachemi *et al*., 2015). An examination of SPOT data showed that 1.34 km^2 of beaches disappeared between 1989 and 2001, and that the shoreline continued to retreat (Wu, Courel and Rhun Le, 2003).

These studies suggest that combining socioeconomic and climatic data with satellite data enhances understanding of interactions between human activity and the environment. This approach also helps promote sustainable urban growth in dry coastal areas. Recent research also supports the role of soil moisture in causing and worsening floods. Soil moisture levels strongly affect hydrological catchment response, especially in Mediterranean and African regions, where heavy rainfall can trigger flooding (Massari *et al*., 2020; Tramblay *et al*., 2021).

Therefore, annual peak floods often relate more closely to soil moisture peaks than to rainfall maxima. This makes the inclusion of soil moisture crucial in flood prediction models (Tramblay *et al*., 2021). For example, floods in Argentina in 2001 were exacerbated by already high soil moisture levels, which reduced infiltration capacity (Scarpati, Forte Lay and Capriolo, 2008). Similarly, studies in the Beskydy Mountains have shown that soil moisture and suction pressure significantly influence rainwater retention, with high water content limiting infiltration during rainfall events (Koutný, Skoupil and Veselý, 2018).

In light of this, our study employs remote sensing technologies in conjunction with hydrological and climatic data to examine the spatiotemporal evolution of floods in Nouakchott over a thirty-year period. The research contributes to a better understanding of the relationships among precipitation variability, soil infiltration capacity, shallow groundwater rise, and rapid urban expansion. It aims to support more resilient and sustainable urban management by identifying the most vulnerable areas and long-term trends. This study follows an integrated environmental assessment approach, which is essential for anticipating climate-change-driven risks in Sahelo-Saharan coastal cities.

MATERIALS AND METHODS

STUDY AREA

The study area covers the urban agglomeration of Nouakchott, the capital of Mauritania, located between latitudes 17°57'N and 18°10'N and longitudes 15°57'W and 16°06'W (Fig. 1). The coastal region has a dry Sahelian climate, low annual rainfall, rapid urban growth, and high flood susceptibility (Ould Sidi Cheikh, 2007). Nouakchott, founded in 1957, lies between the Sahara Desert and the Atlantic Ocean on a narrow coastal plain known as Aftout Es Sahli. The city is less than 5 km from the ocean and is separated from it by a thin sandy barrier. The area includes a large depression that frequently floods, with ground elevations between 1 and 4 m, intersected by wide dune ridges.

DATA USED

The analysis relies on multitemporal Landsat images (5 TM, 7 ETM+, 8, and 9 OLI) acquired between 1994 and 2024 via USGS Earth Explorer (30 m resolution) (Tab. 1). With thresholds tailored to each sensor in accordance with guidelines for urban and semi-arid environments, flooded areas were identified using the modified normalised difference water index (*MNDWI*) (Xu, 2006). These thresholds were 0.0–0.1 for Landsat 5 (Xu, 2006; Du *et al*., 2016), 0.0–0.2 for Landsat 7 (Chang *et al*., 2022), and 0.2–0.3 for Landsat 8–9 (Du *et al*., 2016; Chang *et al*., 2022). To maintain a robust threshold, a sensitivity study compared the results with Google Earth and Sentinel-2 (10 m) data. These steps established a reliable method for analysing spatiotemporal flood patterns.

The digital elevation model (DEM) was derived from the ALOS PALSAR dataset (12.5 m resolution). The data were combined, reprojected into WGS84/UTM 28N, and vertically adjusted following Wu's (2007) guidelines. This provided a precise topographic base for evaluating flood risk.

DATA PROCESSING

The processing of Landsat images was conducted using ArcGIS Pro, following a series of methodological steps aimed at ensuring the quality and reliability of the analyses:
- radiometric correction: this was used to normalise reflectance values between different dates and sensors, thereby correcting instrumental differences (Kalidhas and Sivakumar, 2022);
- atmospheric correction: this minimises the attenuation of electromagnetic (EM) radiation caused by scattering and absorption by molecules and aerosols in the Earth's atmosphere, thereby improving water-body detection (Xu, 2006).

After these corrections, the images were analysed using the *MNDWI* (modified normalised difference water index), while accounting for sensor-specific characteristics.

This index, based on the combination of the green and short-wave infrared (SWIR) bands, allows for effective mapping of flooded surfaces, particularly in urban or vegetated environments (Xu, 2006).

The *MNDWI* formula proposed by Xu (2006) is expressed as follows:

$$MNDWI = \frac{\mathrm{Green} - \mathrm{SWIR}}{\mathrm{Green} + \mathrm{SWIR}} \tag{1}$$

where: Green = the green band (band 2 for Landsat 5/7 and band 3 for Landsat 8/9), SWIR = the short-wave infrared band (band 5 for Landsat 5/7 and band 6 for Landsat 8/9).

This formulation significantly improves water-surface detection by reducing confusion with built-up or vegetated areas.

The layers generated by the *MNDWI* were integrated into a Geographic Information System (GIS) to visualise and quantify land-cover changes before and after flood events.

VALIDATION OF THE *MNDWI* CLASSIFICATION

To satisfy the need for an independent validation of the flood maps, a formal accuracy assessment was performed. A total of 300 control points was generated in ArcGIS Pro using the Create Accuracy Assessment Points and Update Accuracy Assessment Points tools.

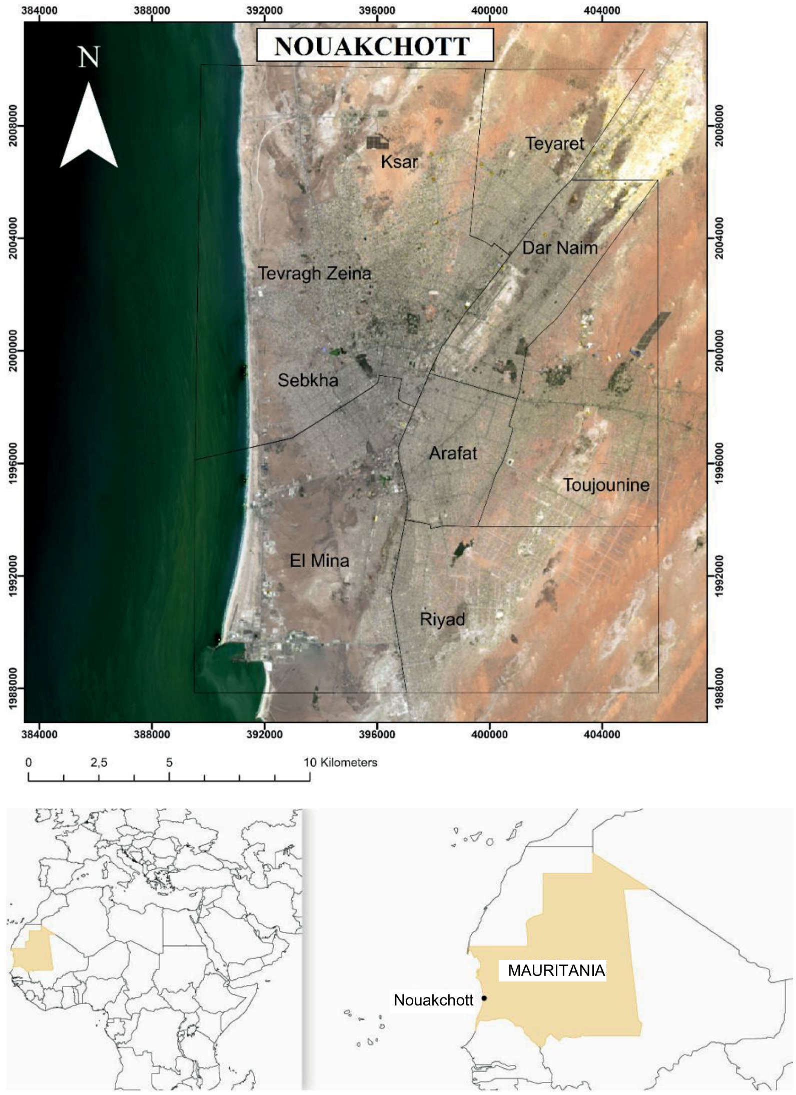

Fig. 1. Location of Nouakchott; source: own elaboration

Table 1. Modified normalised difference water index (*MNDWI*) parameters and flood thresholds applied to different generations of Landsat satellites

Satellite	Green band	SWIR band	*MNDWI* formula	Flood threshold	Reference
Landsat 5 TM	band 2 (B2)	band 5 (B5)	(B2 – B5) / (B2 + B5)	*MNDWI* > 0.0–0.1	Xu (2006), Du *et al.* (2016)
Landsat 7 ETM+	band 2 (B2)	band 5 (B5)	(B2 – B5) / (B2 + B5)	*MNDWI* > 0.0–0.2	Chang *et al.* (2022)
Landsat 8 OLI	band 3 (B3)	band 6 (B6)	(B3 – B6) / (B3 + B6)	*MNDWI* > 0.2–0.3	Du *et al.* (2016)
Landsat 9 OLI-2	band 3 (B3)	band 6 (B6)	(B3 – B6) / (B3 + B6)	*MNDWI* > 0.2–0.3	Chang *et al.* (2022), Roy, Singh and Mazumdar (2025) milieux secs

Explanation: SWIR = short-wave infrared.
Source: own elaboration based on literature.

They were interpreted visually using high-resolution Google Earth imagery from 2024 and Sentinel-2 MSI data at 10 m resolution from 2014 and 2024. The selected areas – Sebkha, El Mina, Arafat, Riyad, Tevragh Zeina, Ksar, Dar Naïm, Toujounine, and Teyaret – were representative of flooded areas, temporary wetlands, and non-flooded areas (urbanised zones, dunes, and dry soils).

The confusion matrix was computed using Compute Confusion Matrix in ArcGIS Pro, yielding the following (Sivanpillai *et al.*, 2023):

– overall accuracy (*OA*)

$$OA\ (\%) = p_0 = \frac{TP + TN}{\mathrm{N}} 100 \tag{2}$$

– user's accuracy (*UA*)

$$UA(\%) = \frac{\mathrm{TP}}{C_{NW}} 100 \tag{3}$$

– producer's accuracy (PA)

$$PA(\%) = \frac{\mathrm{TP}}{R_W} 100 \quad (4)$$

– the Kappa coefficient

$$Kappa = \frac{p_0 - p_c}{100 - p_c} \quad (5)$$

where: p_0 = observed proportion of agreement, TP = (true positives) = number of pixels correctly classified as "water", TN = (true negatives) = number of pixels correctly classified as "non-water", N = total number of pixels in the confusion matrix, C_{NW} (classified water) = total number of pixels classified as "water" in the map, R_W = (reference water) = total number of "water" pixels in the ground truth dataset, p_c = expected proportion of agreement by chance.

This step allows for the rigorous quantification of *MNDWI* performance in the detection of flooded areas within the semi-arid urban environment.

CLIMATIC AND HYDRODYNAMIC CONDITIONS

In Nouakchott, coastal flooding results from the interaction of several factors, including rainfall, soil infiltration capacity, and groundwater levels. The city's vulnerability is amplified by its low elevation, with some areas lying below sea level (Senhoury *et al.*, 2016; Ould Sidi Cheikh, Ozer and Ozer, 2007).

Rainfall

Rainfall records were obtained from the Nouakchott meteorological station for the period 1931–2024. The series is marked by substantial interannual variability and a general declining tendency, with remarkably high totals during the 1940s–1950s and a prolonged drought from 1968 to 1986, followed by an alternation of wet and dry years typical of Sahelian climates. To provide a formal evaluation of the long-term signal, which is essential for detecting trends, non-parametric approaches were used. The Mann–Kendall test was applied to assess trend significance, and the magnitude of the trend was estimated using the Theil–Sen estimator, based on the annual rainfall series available for statistical processing. Such an increase in irregularity might be related to regional patterns of climate change and could potentially affect flood risk in Nouakchott (Senhoury, 2014; Sidi, 2024).

Soil infiltration capacity

Soil infiltration capacity – largely determined by moisture content and permeability – plays a key role in limiting runoff, the main driver of urban flooding. Therefore, full knowledge of soil infiltration behaviour is vital for developing successful flood-risk management plans. Infiltration rates vary greatly among soil types: sandy soils, for example, usually have high infiltration rates and therefore maintain a high rate of water uptake, while heavier clay-type soils have much lower rates (Kuok *et al.*, 2023). Soil porosity and permeability, associated with soil structure, are major factors controlling these capacities. Overall, sandy and loamy soils offer better water retention and infiltration than clay soils (Alhassoun, 2009; Kuok *et al.*, 2023; Nimmo and Shillito, 2023).

Groundwater dynamics

Groundwater dynamics play a decisive role in the onset and persistence of floods, particularly in areas where interactions between surface water and groundwater are significant. Understanding these interactions is essential for improving the accuracy of hydrological models and flood-risk management, as groundwater can sustain flows and prolong flood duration (Berghuijs *et al.*, 2024).

This impact can be exacerbated in urban areas: even without channel overflow, flooding can occur because of rapid increases in the water table following heavy rainfall. This contribution of groundwater to runoff is frequently neglected in traditional models based on surface runoff (Mancini *et al.*, 2020). Including this subsurface source can therefore be essential for accurate flood forecasting and robust infrastructure design.

The groundwater dynamics data for Nouakchott used in this study come from the National Water Resources Center (CNRE) and cover the years 2014 and 2024.

RESULTS

ANALYSIS OF FLOOD EVOLUTION IN NOUAKCHOTT (1994–2024)

This analysis examines the evolution of flooded areas in the city of Nouakchott, Mauritania, through a series of maps spanning three decades (Fig. 2).

The 1994 map, the earliest in the series, shows a very limited presence of flooded zones. Only a few small blue patches appear, mainly in the El Mina district and a few scattered locations. This situation suggests either low rainfall during that year or a higher soil infiltration and drainage capacity at that time.

Ten years later, the 2004 map presents a pattern very similar to that of 1994, with very few flooded areas. Some small, localised patches are visible, particularly in the Sebkha district. This may indicate relatively dry climatic conditions or adequate infrastructure capable of managing runoff volumes during that period.

A noticeable change appears in the 2014 map. A greater number of locations are flooded than in prior decades, although flooding is not as widespread as on the most recent map. Tevragh Zeina, Sebkha, Arafat, and El Mina are all affected by the growing number and dispersion of blue patches. Stronger rainfall events or the gradual deterioration of drainage infrastructure caused by rapid urbanisation could explain this increase. The African Development Bank reported in 2014 that about half of the people living in Nouakchott were affected by serious floods in August and September 2013 (BAD, 2014). Current mapping shows that flooding has worsened. Sebkha and Arafat, along with the western coast, are experiencing widespread flooding. The north–south direction of the flooding suggests that the ground is saturated and that drainage systems cannot handle the volume of water. This situation aligns with current concerns regarding the impacts of climate change and rapid, often uncontrolled, urbanisation in Nouakchott, which increasingly expose the city to extreme events (World Bank, 2023).

The evaluation yielded an average overall accuracy across all years of 90.5%; user's accuracy for the water class is 92.25%, while producer's accuracy is 88%, with a Kappa coefficient of 0.8.

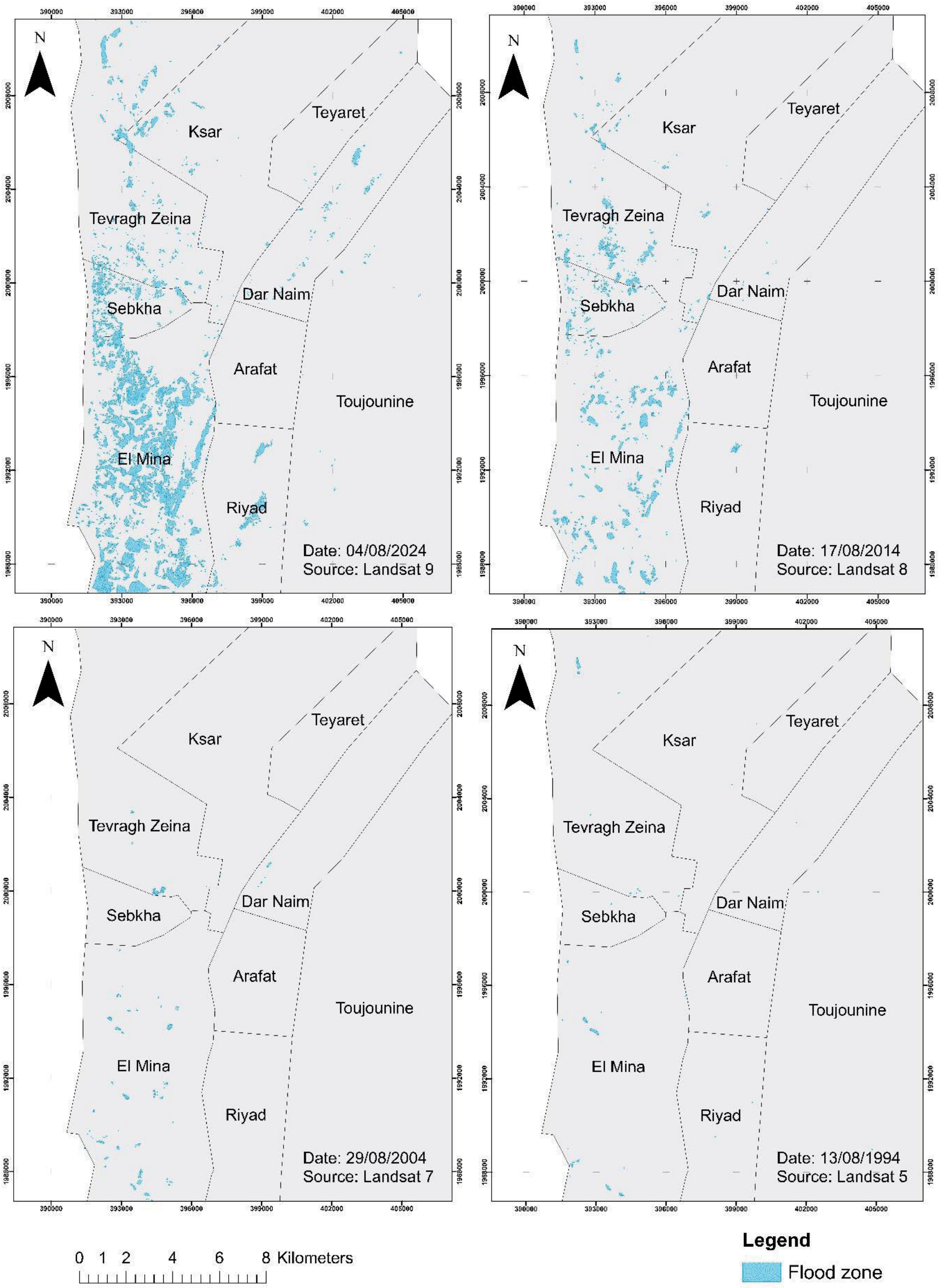

Fig. 2. Flood evolution maps in Nouakchott (1994–2024); source: own study

These indicators demonstrate a high degree of accuracy, above 88% for all years, and Kappa coefficients greater than 0.80, indicating very good agreement between the *MNDWI*-derived maps and ground truth.

DIGITAL ELEVATION MODEL (DEM) OF NOUAKCHOTT

Processing of the digital elevation model

The topographic survey of Nouakchott, carried out within several studies (GRESARC, 2006; Ould Sidi Cheikh, Ozer and Ozer, 2007; Senhoury *et al*., 2016), enabled the mapping of flood-prone areas in the city. These studies revealed that approximately one-third of urbanised areas are located at extremely low elevations and are therefore highly exposed to flooding.

Simulations were conducted (Fig. 3) to better understand the potential extent of flooding in Nouakchott in 2024, particularly in several sectors characterised by very low terrain, including El Mina, Sebkha, Tevragh Zeina, Riyad, and Dar Naïm.

The map displays elevation values ranging from −1 m to over 40 m:

- the areas in dark and light blue, which represent the lowest elevations at or below sea level, are mainly in the western parts of the city, specifically El Mina and Sebkha; these areas are at risk from rising groundwater, flooding, and saltwater intrusion;
- the yellow zones, located at slightly higher elevations, are still in danger of flooding, especially during periods of heavy rainfall;

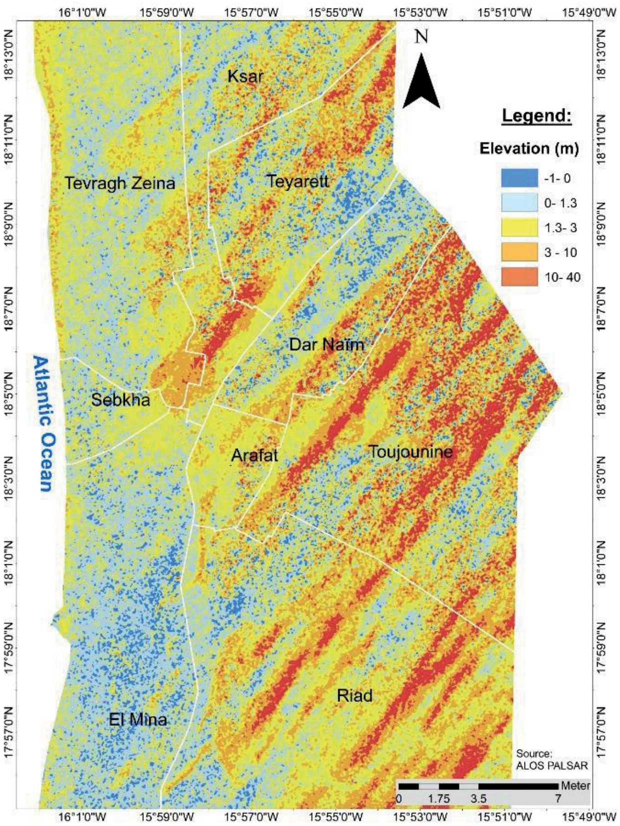

Fig. 3. Elevation map of the city of Nouakchott; source: own study

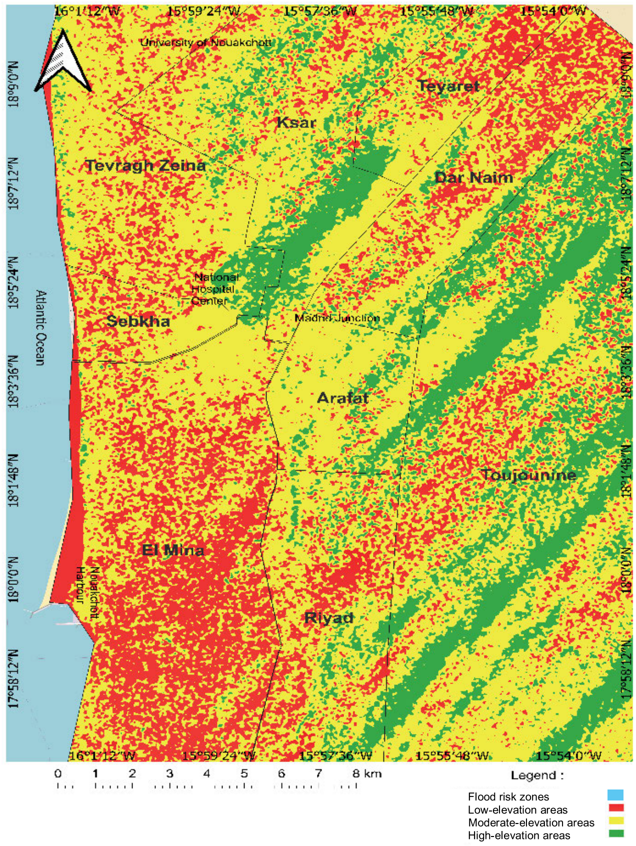

Fig. 4. Flood risk classification for the city of Nouakchott; source: own study

– the orange and red areas, primarily in the eastern (Toujounine, Riyad) and central (Dar Naïm, Teyarett) sections of the city, consist of sandy ridges or dunes that offer some protection against floodwaters.

Classification of flood risk zones

A classification of flood risk for Nouakchott derived from the digital elevation model (Fig. 3) is presented in Figure 4. Three risk zones are identified: high (red), moderate (yellow), and low (light green).

The classification considers elevation changes and topographic gradients, which affect surface-water flow and urban flood susceptibility. According to this classification:

- most high-risk areas (marked in red) are in low coastal areas such as Sebkha, El Mina, and Riyad; these areas contain geographical depressions that pool water, increasing the likelihood of rainfall runoff, rising groundwater, and occasional seawater intrusion;
- moderate-risk areas (marked in yellow) cover much of the urban centre (Ksar, Tevragh Zeina, Arafat), where elevations are intermediate; because there is no adequate drainage system, many neighbourhoods can still flood during heavy rainfall;
- areas with higher ground (Teyaret, Dar Naïm, parts of Toujounine, and Arafat) have better natural drainage and a lower likelihood of direct flooding; they are therefore classified as low-risk zones (marked in green).

VARIATION IN PRECIPITATION

Nouakchott and its surrounding areas receive the highest rainfall in August and September. These rains are closely linked to the movement of the Intertropical Convergence Zone (ITCZ) and the penetration of the West African monsoon. Climatic data indicate that average monthly totals peak in September at 43.5 mm, followed by August at 39.4 mm (Fig. 5). The average rainfall values were calculated for the period 1931–2024.

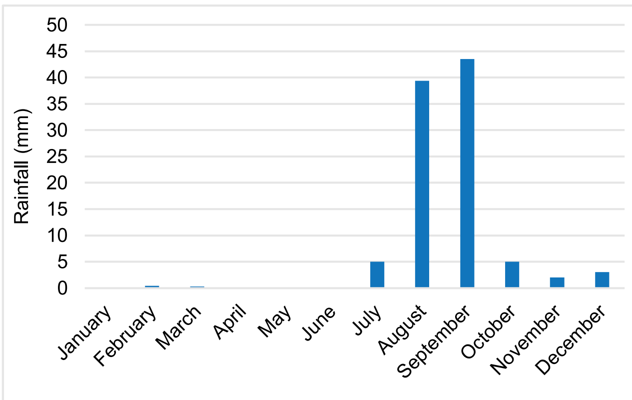

Fig. 5. Average monthly rainfall in the study area; source: own study

The analysis of annual rainfall totals between 1931 and 2024 shows a general decreasing trend. However, exceptional events occurred, including 267 mm in 1956, 263 mm in 1944, and 241.3 mm in 1943. A marked decline occurred between 1968 and 1986, followed by an irregular alternation of wet and dry years (Fig. 6). The trend tests on annual rainfall data (1931–2024) revealed a statistically significant monotonic trend. The Mann–Kendall test indicates a declining trend, with a statistic of −0.179 and a p-value of 0.0106. The Theil–Sen estimate represents an average decrease of −0.55 mm·yr^{-1}, with a 95% confidence interval of [−1.00; −0.13] mm·yr^{-1}.

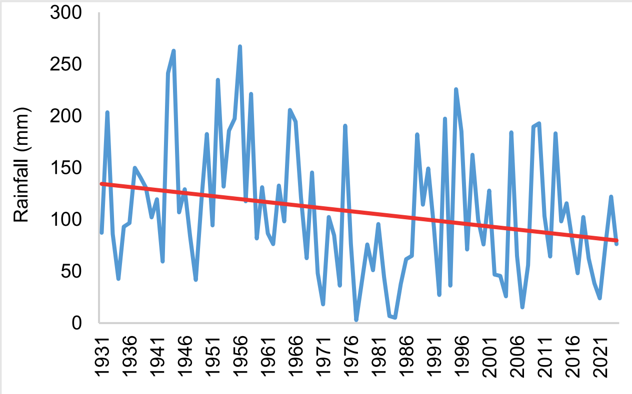

Fig. 6. Evolution of annual rainfall totals in Nouakchott; source: own study

ANALYSIS OF SOIL PHYSICAL PROPERTIES

Soil infiltration capacity, influenced by texture, structure, and compaction, plays a key role in urban flood management.

The average measurements of soil moisture content and permeability in three borrow pits located in Nouakchott, classified according to their flood risk level – low (L), medium (M), and high (H) – are presented in Table 2. These characteristics are essential for understanding the hydrological behaviour of soils during extreme rainfall in a vulnerable urban context such as Nouakchott.

PIEZOMETRIC DATA

Water depth was measured in piezometers in 2014 (March, August, November) and 2024 (March, August, November). Overall, the 2014 and 2024 profiles remain comparable (Fig. 7), indicating relative groundwater stability over the decade, with seasonal fluctuations associated with rainfall.

Analysis of Nouakchott's piezometric data from 2014 to 2024 reveals a steady decline in water-table depth in several areas. This implies that groundwater levels are rising, moving closer to the surface, and potentially causing emergence. Although the northern districts (Dar Naïm and Toujounine) remain relatively stable, the southern and central districts (El Mina, Ksar, and Teyaret) appear to face the greatest risk. This situation highlights the need for improved monitoring and sound groundwater management practices, given the city's vulnerability to flooding, soil salinisation, infrastructure damage, and health issues.

MAPPING OF FLOOD RISK ZONES IN NOUAKCHOTT

The spatial distribution of flood vulnerability in Nouakchott in 2024 is shown in Figure 8. The map was produced by integrating various physical and hydrological parameters identified as major

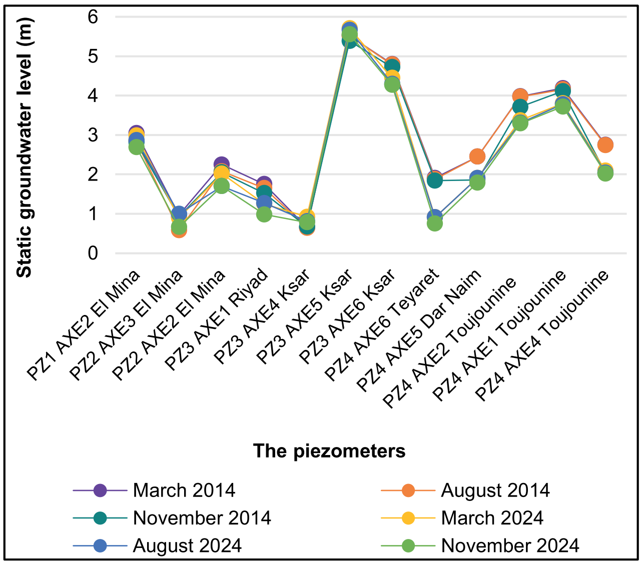

Fig. 7. Variation of static piezometric levels for the years 2014 and 2024 across different periods (March, August, and November); source: own study

drivers of flood processes from 1994 to 2024. The integration of these layers offers a synthetic view of areas that are highly vulnerable to flood disasters. The classification is mainly based on the DEM, which indicates that low-lying areas are highly prone to flood risk. These data are reinforced by other parameters that affect flood patterns, such as groundwater depth, soil type, permeability, moisture, and rainfall. The area currently affected by flooding, identified using the *MNDWI* index, is shown in blue. The remaining area is divided into three classes: high risk, moderate risk, and low risk. The western and southern sectors of the city, including Sebkha, El Mina, and Riyad, experience the greatest incidence of flooding and are at the highest risk.

DISCUSSION

Although relatively young, the city of Nouakchott (Fig. 1) has experienced rapid demographic growth, increasing from 1,800 inhabitants in 1957 to around 800,000 in 2013 (Senhoury *et al.*, 2016), and then to nearly 1,446,761 inhabitants according to the 2023 census (ANSADE, 2023). Its spatial arrangement is defined by radial development and a predominance of low-rise, scattered housing. Plot subdivisions and the development of new neighbourhoods have allowed the city to grow progressively, while older subdivisions have only been partially developed. The unplanned and unregulated settlement of new migrants on undeveloped land on the outskirts of the city, or even inside the existing urban fabric, has exacerbated this spread. This growth has

Table 2. The average water content and permeability in three borrow areas

Borrow area	Soil	Mean water content ±standard deviation (%)	Mean permeability ±standard deviation ($m \cdot s^{-1}$)
Low risk (L)	sand	0.833 ±0.32	$9.55 \cdot 10^{-4} \pm 4.05 \cdot 10^{-5}$
Medium risk (M)	sandy loam	4.4 ±0.6	$8.81 \cdot 10^{-5} \pm 1.98 \cdot 10^{-6}$
High risk (H)	sandy loam	5.65 ±0.65	$6.73 \cdot 10^{-5} \pm 3.79 \cdot 10^{-6}$

Source: own study.

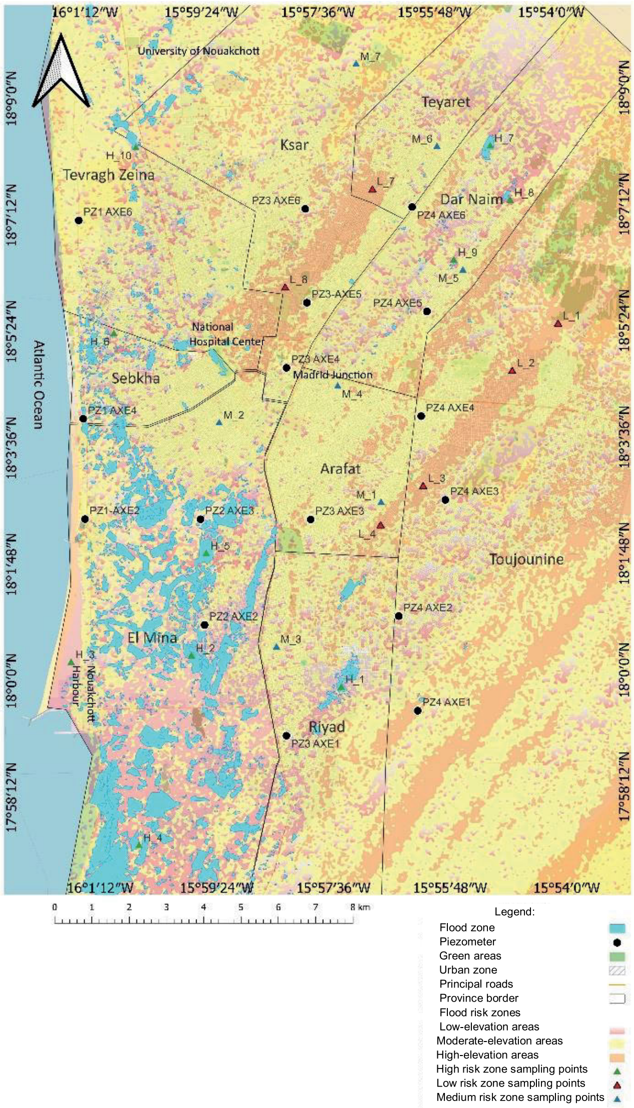

Fig. 8. Map of flood risk areas in Nouakchott; source: own study

led to development in several areas within low-lying, sensitive coastal zones (Senhoury *et al.*, 2016). Flood maps from 1994 to 2024 (Fig. 2) show a clear increase in flood extent and severity. Flooded areas accounted for 0.07%, 0.13%, 1.05%, and 3.96% of the urban surface in 1994, 2004, 2014, and 2024, respectively. This trend shows a substantial rise in flood risk, with a more than 50-fold increase over 30 years. Floods were limited between 1994 and 2004, similar to what occurred in Lagos prior to the encroachment of wetland regions (Adelekan, 2010) and in Cotonou, where unchecked urbanisation of marshlands caused persistent flooding (Dossou and Glehouenou-Dossou, 2007).

Independent validation with Google Earth and Sentinel-2 imagery shows that *MNDWI* segmentation gives a more reliable estimate of flooded areas. The obtained accuracy levels are comparable to the results of Albertini *et al.* (2022) and Sivanpillai *et al.* (2023), who demonstrated the robustness of *MNDWI* for water mapping in urban and arid environments.

Around 2014, Nouakchott's expansion into the sebkhas began to obstruct natural drainage, mirroring the flooding issues in Dakar caused by construction on infiltration basins (Diémé *et al.*, 2024). Data from the African Development Bank report (BAD, 2014) and the extent of flooded areas (1.05%) indicate that the urban system was becoming increasingly vulnerable. By 2024, the increase in flooded areas (3.96%) indicates a system-wide problem, similar to Alexandria, where delta subsidence increases exposure (El-Nahry and Doluschitz, 2010); Jakarta, where land subsidence worsens flooding (Chaussard *et al.*, 2013); and Abidjan, where coastal erosion damages infrastructure (Kouassi *et al.*, 2010). In Nouakchott, this worsening results from the combined effects of uncontrolled urbanisation, increasing soil sealing, and rising groundwater levels.

Flooding results from a combination of natural and anthropogenic factors. Natural factors, accounting for approximately 71.43% of the risk, include low elevation (Figs. 3, 4), low soil permeability (Ould Sidi Cheikh, Ozer and Ozer, 2007), and seasonal rainfall variability (Fig. 6). Examination of annual variability (Fig. 5) shows substantial fluctuations. The highest precipitation values were reached in 1956 (267 mm), 1944 (263 mm), and 1943 (241.3 mm). This was followed by a drought period from 1968 to 1986, after which dry and wet years alternated irregularly. Furthermore, the Mann–Kendall test confirms a declining precipitation pattern. These findings are consistent with Sahelian data and confirm the influence of climate change on extreme events (Senhoury, 2014).

Anthropogenic factors include rapid and unplanned urbanisation (Diagana, 2022), insufficient drainage (Nouaceur, 2013; Niang, 2014), and inadequate waste management. Nouakchott is underlain by several aquifers, including a shallow water table of variable depth (Diagana, 2022). The proximity of this water table is a key determinant of vulnerability, as rising groundwater reduces infiltration and causes surface emergence. Piezometric data (Fig. 7) show a general upward trend in static levels between 2014 and 2024, particularly in El Mina, Sebkha, and Ksar, where groundwater may rise to <1.5 m below the surface, significantly increasing the risk of flooding, salinisation, and structural degradation. In the northern parts of Dar Naïm and Toujounine, water depth is greater (>3 m), which reduces flood risk. Soil types greatly affect the spatial distribution of risk (Tab. 2). Zone L has sandy soils that allow water to pass through quickly and generate little runoff. They contain little water (0.833% ±0.32) but are quite permeable ($9.55 \cdot 10^{-4}$ m·s^{-1}) (Bouwer, 2002). Zone M has sandy-loam soils that retain a moderate amount of water and have medium permeability ($8.81 \cdot 10^{-5}$ m·s^{-1}). Zone H has finer soils that are less permeable and become saturated quickly. This causes standing water, especially when urban compaction further limits infiltration (Brady and Weil, 2016).

There is a clear link between flood risk, as shown in Figure 8, and soil type. The northeast and southeast, marked as low-risk areas (L), have sandy soil. Medium-risk zones (M), such as Arafat and Teyarett, are located in areas undergoing change. Areas labelled as high-risk (H) are mainly situated in Sebkha, El Mina, and southern Riyad. These locations share characteristics such as poor soil drainage, shallow groundwater tables, and limited infrastructure.

From 2014 to 2024, seasonal variations in rainfall strongly influenced groundwater levels; rainfall recharge is the key factor. After the rainy season, groundwater rises, reducing the soil's capacity to absorb water. This situation then leads to increased surface-water accumulation. Analysis of multitemporal Landsat imagery shows that areas with shallow groundwater are most vulnerable to increased flooding. In summary, drainage problems, unplanned urban growth, soil drainage, and water-table depth all strongly affect Nouakchott's water-management capacity. They emphasise the need for integrated urban planning, including the regulation of sebkha urbanisation, the strengthening of drainage systems, routine piezometric monitoring, and the integration of hydrogeological dynamics into spatial-planning policies (Nouaceur, Z., 2013; AfDB, 2014; Niang, 2014; Senhoury *et al.*, 2016).

CONCLUSIONS

It is essential to upgrade drainage and sanitation systems, integrate climate-change adaptation measures into Nouakchott's urban planning, and implement sustainable urban-planning regulations in order to reduce these escalating risks. The case of Nouakchott represents a microcosm of global challenges. Comparisons with other cities, in light of the cited studies, show that the flood crisis is less a matter of geographic inevitability than of an urban development model poorly adapted to environmental and climatic realities.

CONFLICT OF INTERESTS

All authors declare that they have no conflicts of interest relevant to this study.

INSTITUTIONAL REVIEW BOARD STATEMENT

This study did not involve human participants or animals. All analyses were conducted using publicly available satellite imagery, meteorological, and hydrological data. The research adhered to institutional guidelines and was conducted with the approval of the Faculty of Sciences and Technology of Nouakchott.

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