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Characterization of Flood Risks and Proposed Development Measures in the Khar Yallah Watershed, Senegal

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Abstract: The Khar Yallah watershed, located on the southern outskirts of the city of Saint-Louis (Senegal), is a rapidly expanding area exposed to recurrent flooding. This vulnerability results from the combined effects of a bowl-shaped topography, poorly permeable hydromorphic soils, highly variable rainfall, and uncontrolled urbanization of flood-prone areas. The objective of this study is to characterize flood risks in the Khar Yallah watershed and to propose appropriate development solutions.

The methodology is based on hydrological and frequency analyses of rainfall data from Saint-Louis (1980–2018), morphometric characterization of the watershed using a high-resolution Digital Elevation Model (DEM), and detailed topographic surveys covering 586 ha. The results indicate an average annual rainfall of 255.77 mm, marked by extreme events that may exceed 300 mm in 24 hours. The watershed, covering an area of 14.03 km², is characterized by very low relief, with more than 55% of its surface located in low-lying areas, which promotes water stagnation.

The proposed solutions combine protective dikes, drainage networks, pumping stations, and urban planning measures. A strong recommendation is made to classify flood-prone areas as non aedificandi zones in order to enhance resilience to climate change.

Keywords: Watershed, Flooding, Characterization, Runoff, Depression Basin

1. Introduction

Rapid urbanization of low-lying areas in coastal cities of West Africa is increasingly occurring in a context of inadequate spatial planning, thereby intensifying population exposure to climate hazards. In Saint-Louis, Senegal, the Khar Yallah depression, located south of the new International Airport, clearly illustrates this dynamic. Accelerated occupation of this naturally flood-prone area—formerly used for agriculture—combined with the absence of drainage infrastructure and appropriate planning strategies, has significantly increased the watershed's vulnerability to flooding.

This vulnerability is further exacerbated by climate change, particularly through the intensification of extreme rainfall events and rising water levels of the Senegal River. Khar Yallah, partly developed to resettle populations displaced by coastal erosion and river flooding, is characterized by low-lying topography, poorly permeable hydromorphic soils, and high exposure to hydro-meteorological hazards. The resulting recurrent floods cause major damage to infrastructure, severely disrupt livelihoods, and threaten the safety of predominantly vulnerable populations.

In response to these environmental, social, and urban challenges, the implementation of integrated flood risk management strategies is essential. In this context, the present study aims to characterize flood risks in the Khar Yallah watershed and to propose an appropriate development plan combining hydrological analysis and spatial planning to enhance territorial resilience under current and future climatic conditions.

2. Materials and Methods

Presentation of the Study Area

Location: The Khar Yallah depression is located near the Senegal River in a low-lying, flood-prone area. Seasonal floods, particularly during September–October, regularly submerge the depression, as observed during the October 2024 floods. The study area is characterized by a natural basin-shaped topography that promotes water accumulation during heavy rainfall or river overflows.

Climate change effects, including sea level rise and intensified precipitation, further aggravate flooding. Saint-Louis, located near the Atlantic Ocean, is particularly vulnerable, with projections indicating that up to 80% of the city could be flooded by 2080, making sustainable land-use planning urgent.

In addition, coastal erosion caused by sea encroachment on the Langue de Barbarie—located near Khar Yallah—significantly disrupts the hydrological balance and increases flood risks in adjacent areas.

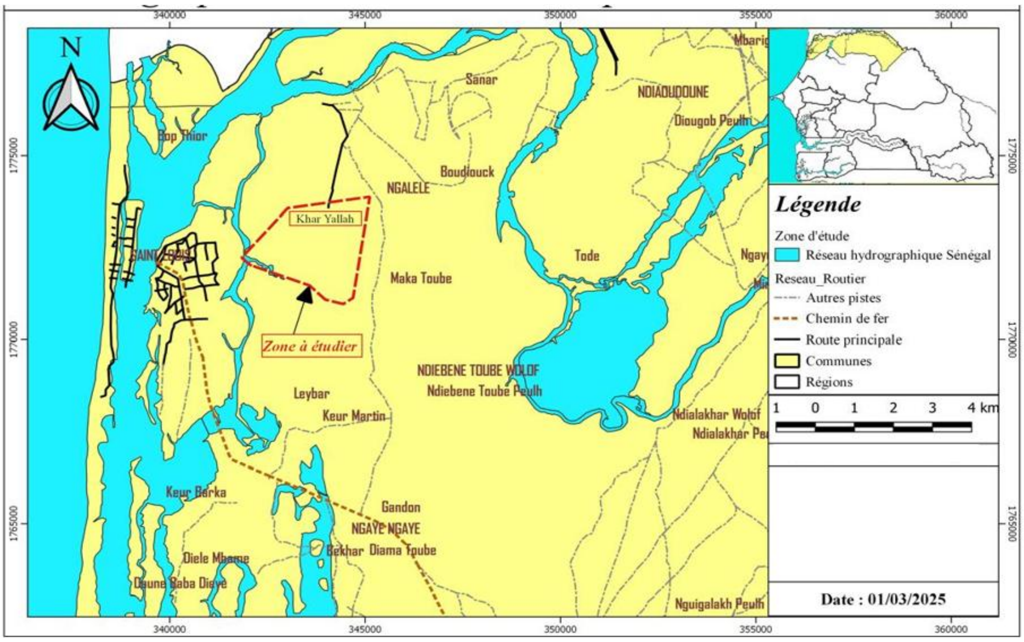

Figure 1: Location of the study area

Hydrology: Hydrological analysis was conducted based on the physical characteristics of the watershed and climatic data, particularly rainfall, while referencing available hydrological measurements from regional rainfall stations.

Rainfall Analysis: Rainfall data from the Saint-Louis station were analyzed. Annual rainfall records from 1980 to 2018 exhibit high temporal variability with very few missing data. This time series is representative of regional rainfall conditions.

Daily rainfall data were used to develop daily hyetographs in order to estimate water inputs to the watershed.

Equipment: The following equipment was used in this study:

Figure 2: GPS station, Handheld GPS and Hydraulic auger

Topographic Data Collection: Topographic surveys aimed to validate and complement satellite data used to characterize the watershed by providing precise terrain modeling. Their main objectives were to produce detailed mapping of geometric features (relief, infrastructure, hydraulic networks), essential for:

- Designing appropriate flood mitigation structures (dikes, drains, retention basins);
- Optimizing construction planning;
- Ensuring consistency between field data and hydrological analyses.

To ensure reliable results, the surveys followed a rigorous approach, structured in three phases:

Establishment of Control Points: A base traverse was established around the survey area. Control points were materialized using durable concrete markers arranged in a grid. Three control benchmarks were installed, each engraved with a unique identification number. Measurements were carried out using two differential GPS units and referenced to the Senegal geodetic system using the RRS2-R067 benchmark at Diama. planimetric accuracy reached 2 cm.

Surface Surveys of Natural Terrain: Topographic surveys covered a total area of 586 ha, including an intentional extension beyond the study perimeter to improve DEM accuracy. A systematic 25 m × 50 m grid was applied, corresponding to an average density of 8 points per hectare. This rigorous approach enabled the generation of a high-resolution DEM essential for flow analysis, identification of critical depressions, and optimization of flood mitigation infrastructure.

Linear Surveys: Linear surveys focused on infrastructures such as tracks, roads, power lines, and existing drains. Measurements captured slope changes, direction changes, and transverse sections every 25 m, ensuring accurate modeling of linear features.

Pedoclimatic Data Collection: Climatic data from the Saint-Louis meteorological station were used. Soil samples were collected in the field using a hydraulic auger and analyzed in the laboratory.

3. Results & Discussion

Annual Rainfall Variability

Annual rainfall in the Sahelian region is highly variable, and Saint-Louis is no exception. The average annual rainfall is 255.77 mm. Values range from a minimum of 58.6 mm in 1992 to a maximum of 593.6 mm in 2010, indicating a difference of more than 535 mm between the driest and wettest years.

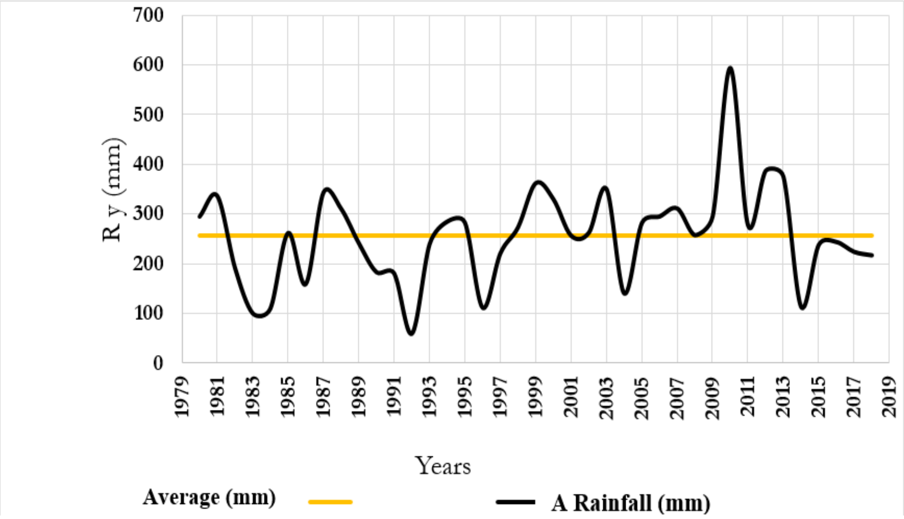

Figure 3: Variations in annual rainfall (mm) in Saint-Louis from 1980 to 2018

Frequency Analysis of Rainfall:

The statistical analysis of annual rainfall made it possible to estimate frequency-based rainfall values, including the median, five-year return period rainfall (wet and dry), ten-year return period rainfall (wet and dry), and rainfall associated with 50-year and 100-year return periods (wet and dry) for the Saint-Louis station. The values were fitted using the normal distribution. The results are summarized in Table 1.

Table 1: Statistical distribution of annual rainfall (mm):

Station	Dry spells					Median	Mean	Wet spell				
	0.01	0.02	0.05	0.1	0.2	0.5		0.8	0.9	0.95	0.98	0.99
St L	26.9	53.7	93.9	129.7	172.9	255.77	255.7	338.5	381.8	417.5	457.7	484.6

This table describes the statistical distribution of annual precipitation at the Saint Louis rain gauge station, expressed in millimeters (mm), through various percentiles, the median, and the mean. The data reveal significant climatic variability and a pronounced asymmetry in rainfall distribution.

Dry spells (percentiles 0.01 to 0.2) indicate critical thresholds for drought years. For example, only 1% of years (percentile 0.01) record less than 26.95 mm of rainfall, an extremely low level. Conversely, wet spells (percentiles 0.8 to 0.99) show high totals: 20% of years (percentile 0.8) exceed 338.56 mm, and 1% of years (percentile 0.99) reach or surpass 484.60 mm, an exceptional figure.

The median (255.77 mm) indicates that half of the years have precipitation below this value. In contrast, the mean (484.60 mm) is much higher, reflecting an extreme right-skewness in the distribution. This difference is explained by the impact of a few very wet years (notably those at the 0.99 percentile), which pull the mean upwards. Indeed, the mean coincides with the 0.99 percentile, meaning that 99% of years have rainfall below 484.60 mm, but the remaining 1% are so intense that they strongly influence the mean.

Interannual variability is striking: precipitation ranges from 26.95 mm (extreme drought) to 484.60 mm (extreme wetness). The wet percentiles (0.8 to 0.99) increase rapidly, highlighting that extreme rainfall events occur mainly in the top 20% of wettest years. For instance, between the 0.8 percentile (338.56 mm) and the 0.99 percentile (484.60 mm), the gap is 146 mm, illustrating the intensity of exceptional events

In terms of practical implications, these data highlight two major risks:

Recurring droughts: The low percentiles (0.01 to 0.2) indicate that very dry periods occur regularly, necessitating careful water resource management.

Floods and heavy rainfall events: The high percentiles (0.95 to 0.99) point to the risk of extreme events, with totals exceeding 417 mm (95th percentile), which can lead to floods or agricultural damage.

The data analysis, using the graphical fitting of annual rainfall to the Gaussian distribution, showed that the climate of the study area is characterized by pronounced instability, with mean precipitation largely influenced by rare but intense events. This statistical asymmetry, along with the wide gaps between percentiles, should inform adaptation strategies, particularly in urban planning and natural hazard prevention (see figure below).

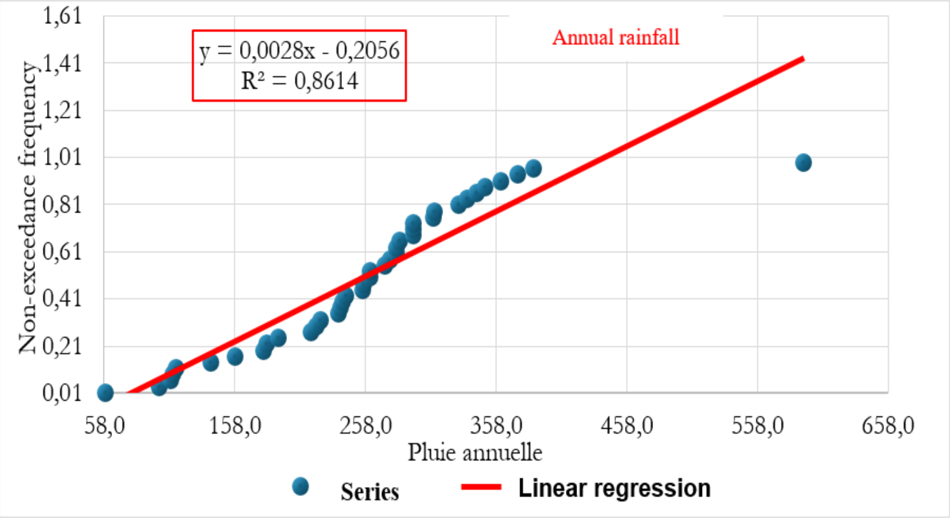

Figure 4: Graphical fitting of annual rainfall to the Gaussian distribution

Daily Rainfall:

Daily rainfall is the smallest time step for measuring precipitation, except for sub-hourly rainfall. Heavy daily rainfall plays an important role in the formation of floods in the studied watersheds. A clear correlation exists between flood peaks and intense rain showers that cause flooding. The daily rainfall series was used to determine quantiles. The Gumbel distribution was employed to calculate recurrent rainfall. The table below presents the distribution of daily rainfall in the study area.

Table 2: Frequency of daily rainfall (mm)

Station	**Frequency**					
	0,5 2 ans	0,2 5 ans	0,1 10 ans	0,05 20 ans	0,02 50 ans	0,01 100 ans
Saint louis	123.60	175.92	210.56	243.78	286.79	319.02

The data presented in this table reveal a marked increase in extreme daily rainfall intensities in the study area according to their rarity. The analysis shows that a biennial event reaches 123.60 mm/day, while a centennial event peaks at 319.02 mm/day, representing an increase of nearly 160%. This growth is not linear: it is particularly pronounced for longer return periods, with increments rising from an average of +35.5 mm for the decadal event to +76.5 mm for the higher return periods.

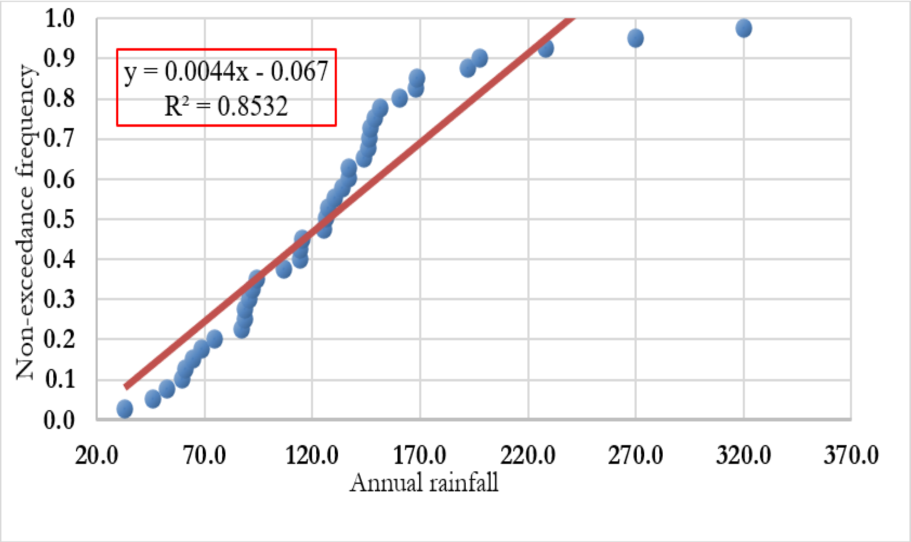

Figure 5: Graphical fitting of maximum daily rainfall to the Gumbel distribution

These values serve as essential references for the design of hydraulic structures. The decadal event at 210.56 mm/day generally serves as a critical threshold for standard infrastructure design, while the 50-year event at 286.79 mm/day already represents an exceptional level requiring specific protective measures.

In the context of climate change, where the intensity of extreme precipitation tends to increase, such frequency analyses become even more important. They provide a solid quantitative basis for rational risk management but must be integrated into a dynamic and adaptive approach to accommodate expected changes in rainfall patterns. The observed non-linear progression particularly emphasizes the need to strengthen the resilience of systems against the rarest yet most destructive events.

Watershed Characterization:

The characterization aims to determine the morphometric and physiographic parameters of the watershed in order to better assess surface water contributions, which are the sources of flooding in the study area. To achieve this, the watershed was delineated using satellite images in the form of a digital elevation model (DEM) with a resolution of 2 m × 2 m. Figure 6 presents a synthesized view of the watershed in the digital elevation model.

Relief Characteristics:

Maximum elevations reach 8 m on plateaus, while minimum elevations reach −2.4 m in lowlands. Approximately 55.04% of the watershed lies in low-lying areas, many below sea level, favoring water stagnation and flooding.

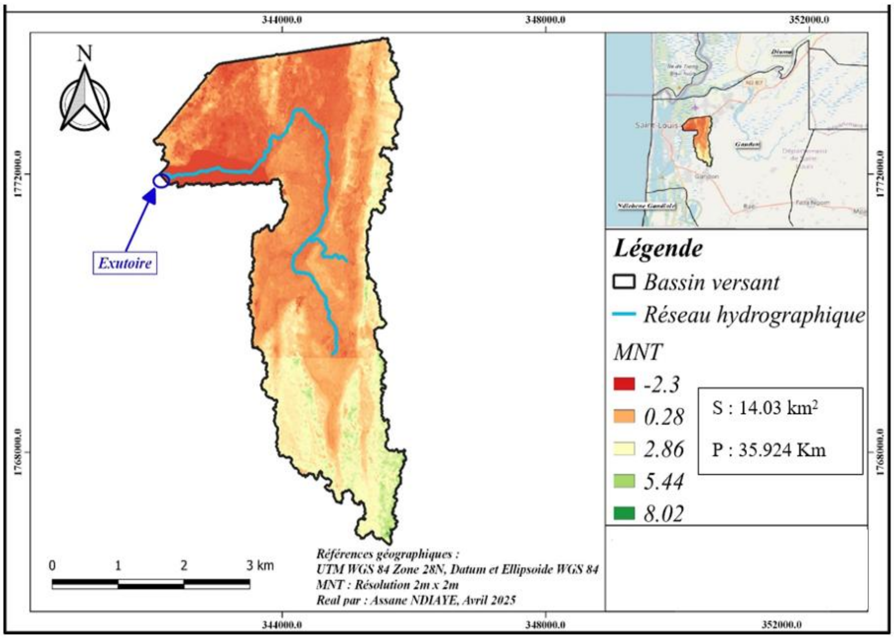

Figure 6: Khar Yalla watershed in DEM

he Khar Yalla watershed covers a total area of 14.03 km² and belongs to the class of small watersheds. Based on the arrangement of watercourses, the watershed is subdivided into three sub-watersheds. The map of the Khar Yalla sub-watersheds is shown in the following figure:

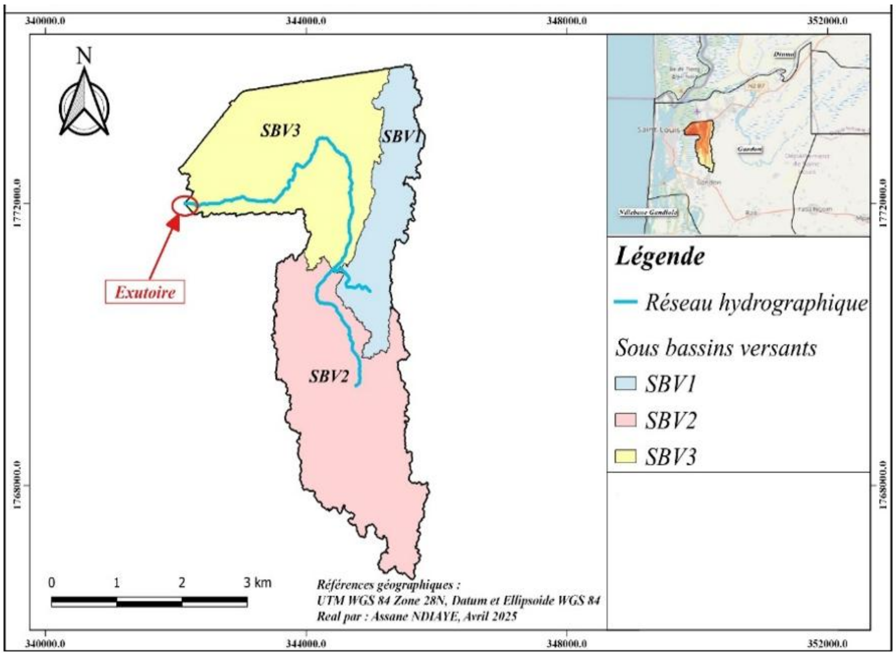

Figure 7: Map of the Khar Yalla sub-watersheds

The compactness index, with a value greater than 2.686, indicates that this watershed has a very elongated shape, which results in a longer time of concentration and a reduced peak discharge at the outlet due to a very long hydraulic path.

Watershed relief characteristics

The relief of the watershed is represented through the hypsometric curve shown below. It provides a synthesized view of the watershed's elevations. This curve illustrates the distribution of the watershed area according to elevation (Figures 3 and 4).

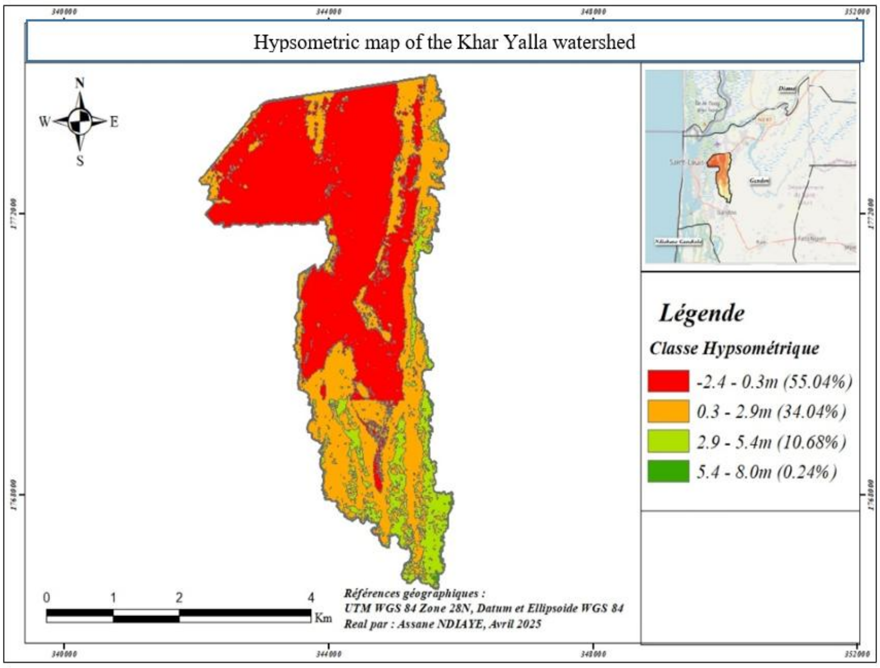

Figure 8: Hypsometric map of the Khar Yalla watershed

The analysis of the watershed's hypsometric map shows that the maximum elevations, measured on the plateau, reach 8 m, while the minimum elevations, measured in the lowlands, are at -2.4 m. These results indicate that 55.04% of the total watershed area is located in the lowlands, with elevations ranging from -2.4 to 0.3 m. The areas corresponding to the slopes account for 44.79% of the total area, with elevations ranging from 0.3 to 5.4 m. In contrast, the plateau, which constitutes only 0.03% of the total area, has elevations between 5.4 and 8 m.

It should be noted that the study area entirely covers the lowlands, representing over 55% of the watershed. Within this area, some elevations are below sea level, reaching as low as -2.4 m in certain zones.

Overall, the watershed has a low relief, which directly affects the slope of the basin and the flow velocity of surface runoff. The above map was also used to generate the hypsometric curve of the watershed to determine the useful elevation range (H5% – H95%) for the calculation of the overall slope index (Ig) and specific density.

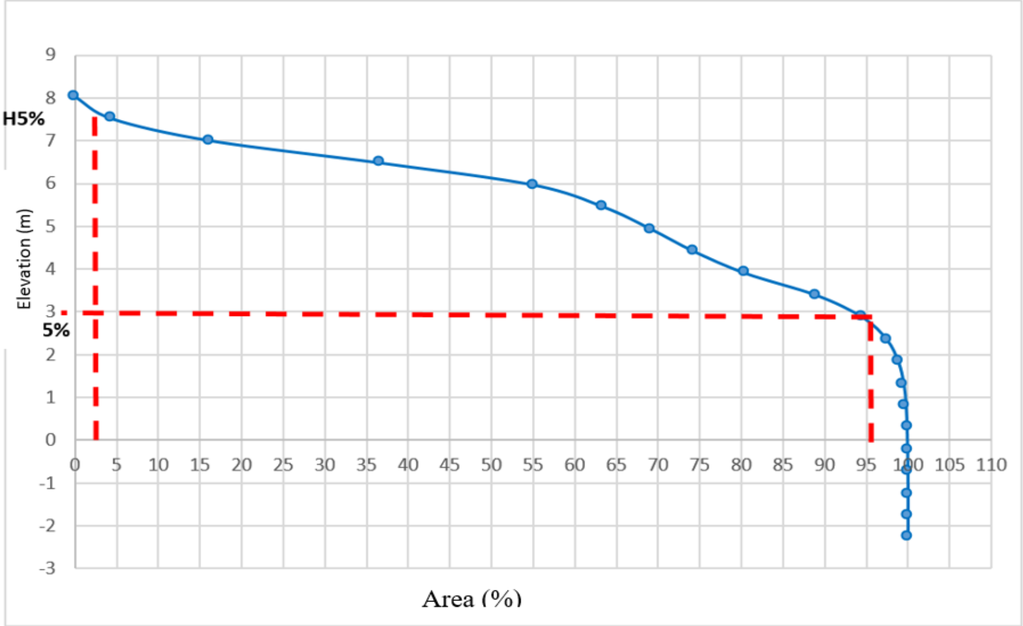

Figure 9: Hypsometric curve of the watershed

The figure above shows that the specific drainage density of the watershed is 36.99 m, which is below 100 m. This suggests that the relief of these basins is relatively low.

These results are consistent with those obtained from the slope classification of the watershed. They show that 54.46% of the watershed area has slopes below 2%, with 31% ranging between 0 and 1%, indicating very gentle slopes. Consequently, more than 50% of the study basin's surface is vulnerable to water stagnation, which can result in extensive flooding of the area.

Drainage network characteristics

The Strahler classification of the Khar Yalla hydrographic network reveals two stream orders. Order 1 represents the tributaries, while Order 2 corresponds to the main stream, as shown in the following figure. Indeed, the drainage network of this watershed is observed to be very sparsely branched. Consequently, its drainage density is very low, with Dd = 0.62 km/km². This low value can be explained by the undifferentiated nature of the drainage network and the low infiltration capacity of the soils present in the study basins.

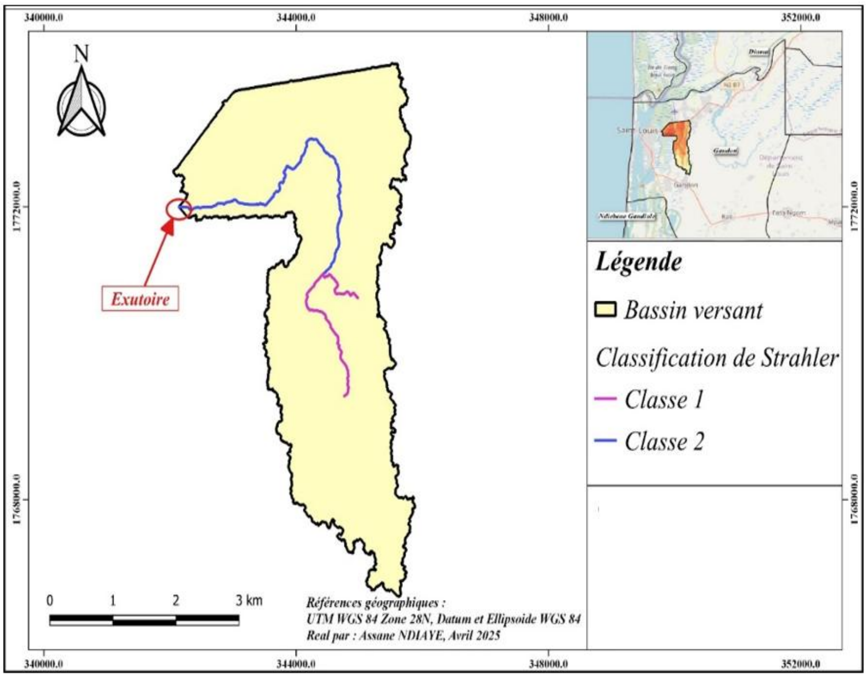

Figure 10: Stream orders of the Khar Yalla watershed according to Strahler

Characterization of the soils in the study area

The soils of the Khar Yalla watershed are mainly composed of two pedological units (the third unspecified unit corresponds to water bodies), namely:

O Red-brown soils: These are deep soils, generally ranging from three to six meters in depth, with a red to reddish-brown color that is almost uniform throughout the profile. They have clay contents between 15 and 25% at the surface and 30 to 40% at depth, and organic matter contents around 0.5%, sometimes higher under dense vegetation. They do not contain iron concretions, and their pH ranges from 4.8 to 5.4. These soils are characterized by low water retention capacity and cover 72.46% of the watershed area.

O Hydromorphic soils: These soils, which exhibit low permeability, are mainly located in the lowlands. They occupy 22.66% of the watershed area. More than 50% of these soils are found within the study area, potentially leading to flooding.

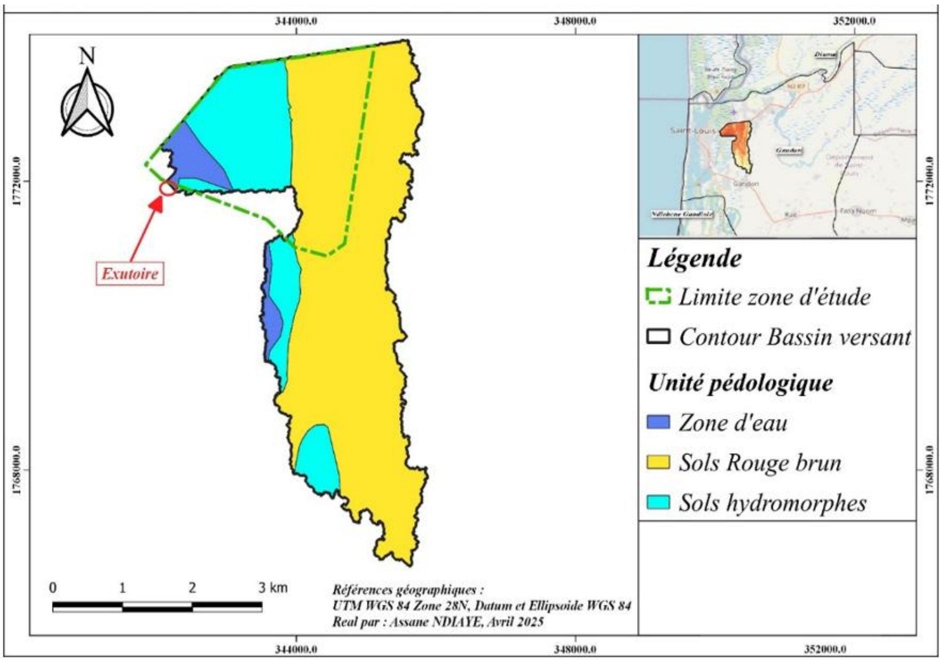

Figure 11: Soil map of the Khar Yalla watershed

The analysis of the figure above shows that 47.18% of the watershed area is used for rainfed crops. These are mainly located on the plateaus and slopes. In the lowlands, specifically within the study area, the soils are largely occupied by mudflats and settlements. This further confirms that the study area is prone to flooding, which in the short term may hinder the expansion of habitable land in this neighborhood.

Interpretation of results

The study area is characterized by a critical geographic setting, with elevations ranging from -1.17 meters to 2.82 meters. These values, measured in regular increments of 0.25 meters (figure below), reveal a predominantly low-lying topography, with nearly half of its area situated below the reference sea level. This configuration exposes the watershed to recurrent flooding risks, which are exacerbated by extreme rainfall events that can reach 319 mm in 24 hours during centennial events. These precipitations, combined with the rise of marine and river waters, regularly transform residential and agricultural areas into retention basins, threatening both infrastructure and local populations. Thus, we have:

Very low areas (-1.17 m to -0.17 m): Located below sea level, these areas are characterized by water-saturated soils and a shallow water table, making the neighborhood extremely vulnerable. High tides and floods from the Senegal River cause permanent or seasonal inundations.

Low areas (-0.17 m to +0.80 m): Although slightly above the reference level, these zones remain critical, experiencing frequent flooding and accelerated riverbank erosion.

Medium areas (+0.80 m to +1.20 m): These slightly elevated zones offer more stable relief and are partially protected from regular flooding. The soils are better drained and less saline, allowing for mixed urban development. However, during extreme events (>300 mm/day), exceptional floods still threaten property and populations. To enhance safety, measures such as retention basins or elevated building foundations are essential. These areas could serve as buffer zones between vulnerable neighborhoods and higher urbanized areas.

High areas (+1.20 m to +2.82 m): Dominating the landscape, these zones represent the most stable parts of the watershed. Their dry and compacted soils are suitable for planned urbanization. Nevertheless, intense runoff during heavy rainfall events causes erosion, affecting the lower areas.

Proposed Solutions:

To protect the watershed from flooding, an integrated approach is essential, combining robust infrastructure, ecological restoration, accessible technologies, and inclusive governance. Although costly, these measures are vital to safeguard populations, preserve ecosystems, and ensure sustainable development in the face of the climate emergency.

The vulnerability of the study area is exacerbated by often informal urbanization, where homes and roads encroach on naturally flood-prone lands. In response to these challenges, the following adaptation measures are proposed:

1. Construct a protective levee accompanied by a surface and underground drainage network and a pumping station to evacuate water;
2. Backfill all low-lying areas of the watershed neighborhood where elevations are below 1.5 m;
3. Relocate populations occupying the watershed outlet.

The construction of a levee, drainage network, and pumping station in Khar Yalla is technically feasible given the human and financial stakes related to flooding. The protective levee, with a length of 2,415 m, will be designed to reach a height of 1.9 m (exceeding twenty-year flood levels) and will be set at an elevation of 1.5 m. It will be built from clay, topped with a 35 cm layer of lateritic soil, and its slopes will be protected with revetments. A surrounding belt of planted mangroves will help mitigate the impact of river overflow.

The drainage network will complement the levee, with primary concrete channels (2 m wide, 1.5 m deep), secondary drains, and a retention basin. This system is intended to channel water toward the pumping station, where it will be pumped and discharged outside the protected area.

The pumping station, equipped with solar-powered pumps to reduce operating costs, will be strategically located in the lowest part of the site.

The construction of a protective levee and a drainage network, even when complemented by a pumping station for water evacuation, does not guarantee complete elimination of the flood risk. This is due to the hydromorphic nature of the soils in the low-lying areas, which become impermeable once saturated, limiting the effectiveness of the drainage systems. To fully protect the site, an underground drainage system is necessary to evacuate lateral seepage.

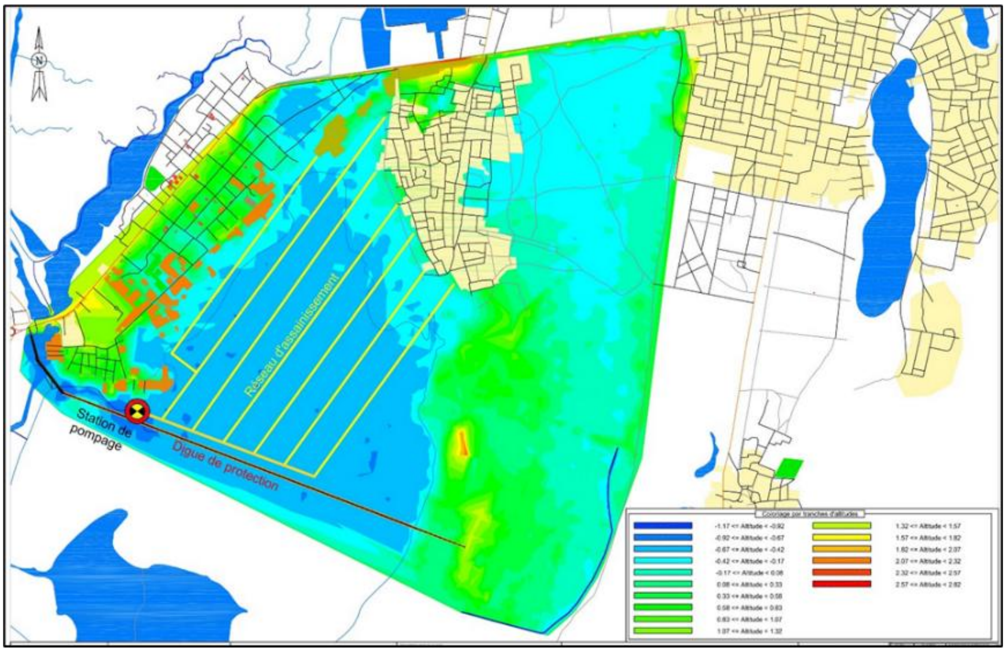

Figure 12: Watershed development plan

4. Conclusion

The characterization of the Khar Yalla watershed reveals a critical situation. Flooding results from multiple factors: extreme rainfall, impermeable soils, basin-shaped topography, and urban pressure on flood-prone areas. Climate projections, including rising river levels and intensifying precipitation, make structural interventions urgent.

Technically feasible solutions are costly (protective levees, drainage networks, backfilling low-lying areas) and have environmental impacts. Therefore, an approach focused on prevention and community resilience is essential.

Given the technical constraints, we recommend strictly prohibiting urbanization in low-lying areas: (1) classify flood-prone zones (-1.17 m to +1.20 m) as "non aedificandi" through a municipal decree, forbidding any new construction or urban expansion, and (2) protect these spaces as ecological buffer zones by restoring mangroves, creating natural water retention basins, and promoting groundwater recharge.

In summary, the survival of Khar Yalla requires a paradigm shift: abandoning the artificialization of flood-prone areas and prioritizing the relocation of the population.

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