

Watershed Characterization for the Construction of Khar Yalla Neighborhood Protection Infrastructure in Saint-Louis

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Abstract

This paper focuses on the design of a flood protection scheme in the Khar Yalla district of Saint-Louis, Senegal. This area, located below sea level, is exposed to severe rainfall and groundwater flooding due to its basin-like topography, the low permeability of its clay soils, and the lack of an effective drainage system. The study is based on a comprehensive hydrological analysis of the 44.4 km² watershed, whose annual useful inflow is estimated at approximately 397,567 m³. The 100-year flood flow, estimated at 164.30 m³/s by the ORSTOM method, served as a basis for the design of the structures. The main dike, designed in homogeneous earth with a predominantly clayey content, has a maximum height of 3.44 m, a crest width of 3 m, slopes inclined at 2 H/1 V and a total length of approximately 615 m. A cyclopean concrete gravity spillway was planned in a frontal position to ensure controlled flood evacuation. It is set at a height of 3.3 m, with a useful length of 13.5 m and a maximum height of 3.25 m, incorporating the rolling effect to optimize hydraulic operation. Downstream, a dissipation basin with a step, reinforced by gabions arranged in a staircase, was designed to control the flow speed and limit the risks of erosion. Despite the presence of these structures, some areas of the neighborhood remain difficult to secure. Thus, partial or temporary relocation of the most exposed residents has been considered. The field survey revealed a moderate but lucid acceptability of this option, provided that it is accompanied by a clear framework of compensation, transparency, and dignified rehousing.

Keywords

Basin, Flood, Crest, Rolling, Dissipation

1. Introduction

The city of Saint-Louis, located at the mouth of the Senegal River, is among the areas most vulnerable to the combined effects of climate change, rising sea levels, and increasing urban pressure. Each year, during the rainy season, several neighborhoods are affected by recurring flooding, affecting the safety, health, and living conditions of the population. These floods, caused by runoff water, rising water tables, and sometimes river overflows, cause significant damage: deterioration of housing, loss of property, health insecurity, disruption of economic activities.

The Khar Yalla district, in particular, is extremely vulnerable due to its low-lying topographical position, saturated clay soils, dense and informal urbanization, and inadequate sanitation infrastructure. The population is exposed to rainwater and groundwater flooding caused by runoff, rising water tables, and even occasional river overflows. This combination increases the complexity of flood management and control mechanisms.

Faced with these challenges, it has become imperative to design sustainable, integrated responses adapted to the realities on the ground. This article is part of an urban resilience approach through a hydrological study, and propose technical and social solutions to significantly reduce flood risks in Khar Yalla.

2. Materials and Methods

2.1. Data Collection

The data used in this study come from various sources:

a) Rainfall data: collected from the nearest weather station to Khar Yalla, covering a representative time series from **1980 to 2018**.

b) Topographic data: obtained from a Digital Terrain Model (DTM), at 2 m resolution, to characterize the morphology of the watershed and from GPS field surveys.

c) Soil data: from field observations to identify the nature of the soil, its permeability and its retention capacity as well as data collected at the Regional Soil Institute of Saint Louis (IPR).

2.2. Data Processing

The collected data were analyzed and then processed to ensure their quality and relevance for the analysis. The processing covered:

- a) Reconstruction of rainfall series and statistical analysis of rainfall heights;
- b) Khar Yalla Watershed Delineation Using ArcMap;
- c) Calculation of morphometric, hypsometric and hydrometric parameters;
- d) Integration of data into calculation models for the sizing of structures.

2.3. Topographical and Pedological Studies

Topographic studies carried out in planimetry with a high-precision survey using Lidar technology, recognized for its reliability and finesse in terrain modeling.

For soil studies, we used the ring method, an effective approach for soil charac-

terization. This technique consisted of creating models or test sections to a depth of one meter, allowing detailed observation of soil stratification and texture.

2.4. Hydrological Studies

2.4.1. Analysis of Rainfall Data

Two statistical laws were used to study precipitation:

- The **normal** (or Gaussian) law, for the analysis of average values.
- **Gumbel's** law, for extreme values such as ten-year or hundred-year rainfall.

These treatments allowed us to identify characteristic rainfall heights for different return periods (10, 20, 50 and 100 years), which will be used in flood flow calculations.

2.4.2. Description of the Watershed

➤ 1) Hydrometric characteristics of the watershed

The approach adopted in this study is inspired in particular by the methodologies recommended in FAO Bulletin 54 [1] for ungauged basins in Sahelian Africa, but also by work carried out in similar areas such as those of Faye Ibrahima [2], Degoutte & Fry [3], and BAMBARA Télado Luc [4].

➤ 2) Characteristics relating to the geomorphometry of the watershed

The perimeter and area of the watershed

These two parameters were determined automatically using the ArcGIS tool, from the Digital Terrain Model (DTM) data. They are essential for classifying the basin according to the typology proposed by Rodier [1].

The equivalent rectangle: length and width

It facilitates the comparison between several watersheds, by highlighting the effect of their characteristics on water flow [5]. Its dimensions are calculated from the following formulas.

$$L_{eq} = \frac{P + \sqrt{P^2 - 16 \times S}}{4} \quad (1)$$

$$l_{eq} = \frac{P - \sqrt{P^2 - 16 \times S}}{4} \quad (2)$$

where: L_{eq} is the equivalent length in Km; l_{eq} is the equivalent width in km; P is the perimeter (in km) and S is the area (in km²).

Gravelus compactness index

Also called the shape coefficient, it is used to assess the shape of the pelvis. It is calculated using the following formula:

$$I_{comp} = \frac{0.282 \times P}{\sqrt{S}} \quad (3)$$

An index close to 1 indicates an almost circular basin, therefore potentially more reactive to intense rain [2].

➤ 3) Watershed relief characteristics

Characteristic altitudes

The maximum and minimum altitudes (generally located at the outlet of the

basin) were extracted from the DTM on ArcGIS.

The average slope

It gives a general indication of the basin's slope. It is calculated using characteristic altitudes using the following formula:

$$I_{moy} = \frac{H_{max} - H_{min}}{\sqrt{S}} \quad (4)$$

The longitudinal slope

This slope represents the gradient along the main axis of the basin. It is obtained using the simplified GRESILION formula. According to its value, six classes of watersheds are distinguished according to the ORSTOM classification [1], current IRD. Thus it is obtained from the expression below.

$$I_{long} = \frac{0.026}{\sqrt{S}} \quad (5)$$

Cross slope: This is determined from 4 to 6 cross sections of the basin. The slope values are recorded by plotting the profiles, then the average of these slopes is calculated.

The hypsometric curve: It allows the distribution of altitudes across the entire basin to be visualized. The curve is established from the DTM and gives the altitudes corresponding to 5% and 95% of the cumulative surface [5].

The overall slope index: The overall slope index characterizes the relief of the watershed. It influences flood flows by modifying the flow rate depending on whether the slope is steep or gentle. It is calculated using the following formula:

$$I_g = \frac{\Delta H}{L_{eq}} \quad (6)$$

where ΔH is the difference in altitude between the 5% and 95% levels of the surface.

The corrected slope index, when the transverse slope exceeds the longitudinal slope by 20%, the corrected slope index is calculated by applying the following formula:

$$I_{gcor} = \frac{(n-1) \times I_g + I_t}{n} \quad (7)$$

where n depends on the length of the equivalent rectangle.

The specific elevation: This parameter expresses the different relief forms of the basin. It is given by:

$$D_s = I_g \times \sqrt{S} \quad (8)$$

The reliefs can be classified according to the value of the D_s as follows

- $D_s < 50$ m: low relief;
- $50 \text{ m} \leq D_s \leq 100$ m: moderate relief;
- $D_s > 100$ m: marked relief.

3. Determination of the Project Flood Flow

The design flood corresponds to a rare and high flow, characterized by a rapid rise

in water levels in the watercourse. It has a low return frequency but a potentially significant impact. To ensure safety, the structures will be designed to evacuate the 100-year flood, *i.e.* an event with an annual probability of occurrence of 1% (or an average occurrence every 100 years).

The determination of ten-year flows is based on the ORSTOM deterministic method and the Puech and Chabi or CIEH linear regression. The hundred-year flood, the design flood, is then calculated using the GRADEX method, which applies a multiplier coefficient to the ten-year flows obtained.

3.1. ORSTOM Method of AUVREY and RODIER

It allows the estimation of the ten-year flood from climatic and morphological data of the watershed. It is based on empirical formulas adapted to ungauged watersheds in West Africa. This method has been widely used for hydrological studies in similar contexts due to its simplicity and relevance.

3.1.1. Determination of the Ten-Year Runoff Flow Rate of the Ten-Year Flood

The ten-year runoff rate (Q_{r10}) represents the volume of water runoff over the surface during a flood event with a 10-year return period. **Table 1** below gives the formula for determining the ten-year runoff rate:

Table 1. Determination of the ten-year runoff flow rate of the ten-year flood.

Formula	Settings
$Q_{r10} = 10 \times A \times P_{10} \times K_{r10} \times \alpha_{10} \times \frac{S}{T_{b10}} \quad (9)$	T_{b10} = Basic time determined by the Rodier and Auvrey charts of ORSTOM (min) S = Surface area of the BV (Km ²) α_{10} = Peak coefficient of the ten-year flood taken as 2.6 K_{r10} = Ten-year runoff coefficient P_{10} = Ten-year daily rainfall A = Reduction coefficient

Its calculation is based on several parameters described below.

3.1.2. Estimation of Ten-Year Runoff Flow Parameters (Q_{r10})

The reduction coefficient (A)

It is a correction factor that allows a single rainfall event to be transformed into an average value across the entire watershed. It decreases as the area of the basin increases, due to the spatial smoothing effect of precipitation. It is calculated using the formula shown in **Table 2**:

Table 2. Calculation of the reduction coefficient (A).

Formula	Settings
$A = \left(1 - \frac{161 - 0.042 \times P_{an}}{1000} \right) \log_{10} S \quad (10)$	P_{an} = average annual precipitation (in mm) S = Surface area of the BV (Km ²)

The ten-year runoff coefficient (K_{r10})

The ten-year runoff coefficient (K_{r10}) is estimated from an exceptional rainfall event with a ten-year return period, generally associated with a precipitation height of between 70 mm and 100 mm.

The base time (T_{b10})

The base time corresponds to the approximate duration of surface runoff during a flood, from the beginning of the water level rise until the end of runoff. Its value is determined by linear interpolation.

The ten-year peak flow (Q_{10})

Once the ten-year runoff flow (Q_{r10}) is known, the ten-year peak flow (Q_{10}) can be estimated using the ORSTOM method as described in **Table 3**.

Table 3. Calculation of the ten-year peak flow rate.

Formula	Settings
$Q_{10} = m \times Q_{r10}$ (11)	m = Increase coefficient, function of the infiltrability class of the basin and the climatic zone Q_{r10} = ten-year runoff flow rate (m ³ /s)

3.2. CIEH Method

The method is based on empirical relationships established from hydrological and meteorological observations. Developed by Puech and Chabi-Gonni (1983), it is based on the study of numerous African basins located in the Sahelian and Sudano-Sahelian zones. This basis makes it well suited to the conditions of Senegal. It is applicable to watersheds of less than 1000 km². The ten-year peak flow is estimated using a multiple regression model (FAO, 1996), according to the formula:

$$Q_{10} = a \times S^s \times P_{an}^p \times I_g^i \times K_r^k \times D_d^d \quad (12)$$

In this study, four (04) equations will be used, as they are considered the most representative for estimating the ten-year flood. Their choice is based on the combined analysis of the parameters S , I_g and K_r . These are:

Equations (11) and (12) for basins where $P_a \leq 1000$ mm, Equation (09) which is a function of the climatic division and Equation (33) for the group of countries

$$(09): 0.92 \times S^{0.745} \times I_g^{0.731} \times K_r^{0.475}$$

$$(11): 0.41 \times S^{0.524} \times I_g^{0.406} \times K_r^{0.982}$$

$$(12): 0.095 \times S^{0.643} \times I_g^{0.406} \times K_r^{1.038}$$

$$(33): 0.195 \times S^{0.471} \times I_g^{0.239} \times K_r^{1.046}$$

As a precaution, the maximum flow rate obtained from the different equations will be retained as the ten-year flood flow rate, in order to integrate the uncertainties linked to the equations.

3.3. GRADEX Method

The project's 100-year flood flow is determined from the 10-year floods and the multiplier coefficient C . This coefficient, greater than 1, makes it possible to link

the 10-year flood to the 100-year flood, taking into account the excess rainfall compared to the 10-year flood. The relationship used is as follows:

$$Q_{100} = C \times Q_{10} \quad (13)$$

The method used for calculating this coefficient is that of Gradex, as defined by Grésillon *et al.* (1977), and is widely applied in West and Central Africa. This approach was used in the studies [6], for the construction of the Lantaga dam in the northern region of Burkina Faso, and of I. FAYE [2], for the rehabilitation of the Aghor pond in Mauritania.

3.4. Determination of the Flood Hydrograph

This is a graph that shows the flow rate over time during a flood period. This graph depends on the base time as well as the time required for the water to rise. The peak flow, combined with the recession flow, constitutes the recession curve of the hydrograph. The expression for the discontinuity flow is shown in **Table 4**.

Table 4. Calculation of discontinuity flow.

Formula	Settings
$\frac{Q}{Q_{\max}} = \frac{2}{\alpha_{10}} \times \frac{T_{b10} - \alpha_{10} \times T_{m10}}{T_{b10} - 2 \times T_{m10}} \quad (14)$	T_{b10} = Base time (hour)
	T_{m10} = Ten-year rise time (min)
	Q = Discontinuity flow rate (m ³ /s)
	Q_{\max} = Project flow rate (m ³ /s)
	α_{10} = Ten-year peak coefficient

4. Study of the Reservoir

Reservoir design is essential for flood management and the design of hydraulic structures such as retention basins and dikes. It helps determine the characteristics of water storage structures, such as retention basins or protective dikes, and size structures to ensure their capacity to handle extreme events. This study is based on the analysis of several criteria, such as storage capacity, evaporation losses, infiltration, and overflow risks.

The methods used here include the work [1], which served as the basis for several recent studies, including those of Faye [2] and OUEDRAOGO [6].

4.1. Estimation of Liquid Intake

Estimating the volume of water from the watershed is an essential step in verifying the reservoir's filling capacity. Thus, the volume of inputs (V) is determined from the following relationship see **Table 5**:

Table 5. Estimation of liquid intake.

Formula	Settings
$V = K_e \times S \times P \quad (15)$	V : volume of water flowing at the outlet
	K_e : flow coefficient
	S : area of the watershed
	P : average annual rainfall

The COUTAGNE method

This method is based on empirical relationships linking climatic parameters, in particular rainfall and average annual temperature, to the water flow in a watershed. According to COUTAGNE, the parameters necessary for estimating annual inputs are listed in **Table 6**.

Table 6. The parameters necessary for estimating annual contributions.

Formula	Settings
$L_e = P - D$	T : average annual temperature ($^{\circ}\text{C}$)
$D = P - \lambda P^2$	D : Annual flow deficit (mm)
$\lambda = \frac{1}{0.8 + 0.14 \times T}$ (16)	P : average annual rainfall (mm)
	L_e : Water flow (mm)

The correlations presented by ONBAH (Harouna Karambiri and Dial Niang, 2011) [5] make it possible to estimate the annual contributions in dry years (five-year and ten-year dry) from the average flow coefficient K_e , defined by the following relationship:

$$K_e = \frac{L_e}{P} \quad (17)$$

The flow coefficients in the dry five-year period (K_{e5}) and dry ten-year period (K_{e10}) are then determined from the average coefficient, according to the following formulas: their expression is below in **Table 7**.

Table 7. Flow coefficients in dry five-year (K_{e5}) and dry ten-year (K_{e10}).

$K_{e5} = 0.7 \times K_e$ (18)	$K_{e10} = 0.5 \times K_e$ (19)
--------------------------------	---------------------------------

The RODIER method: The approach consists of identifying a typical basin representative of the watershed studied, specifying its area of influence. The distribution curve of the water blades, plotted as a function of the cumulative frequencies of non-exceedance, then makes it possible to determine the flow coefficients as well as the associated volumes for the five-year and ten-year return periods. These results are obtained after adjusting the rainfall data according to the normal law. By analyzing the morphological parameters of the watershed, it appears that it is linked to the Oued Djajibine typical basin, attached to the Oued Ghorfa system in Mauritania. This typical basin is characterized by a drainage density of 2.02 km/km² and a specific elevation difference of 25 meters.

4.2. Study of Losses

Loss assessment is an essential step in ensuring the effectiveness of flood protection structures, such as dikes and retention basins. It focuses on assessing water losses through evaporation, infiltration, and the accumulation of solid deposits. These losses, by reducing the useful storage capacity, can compromise the perfor-

mance of the structure. It is therefore essential to estimate them accurately in order to correctly size the reservoir and ensure optimal flood management.

Estimation of evaporation losses

Rainfall data collected at the Saint Louis station made it possible to assess evaporation losses. Within the framework of the planned structures, particularly the dissipation basins and spillways, these losses remain limited compared to the volumes mobilized during floods. They are nevertheless taken into account to ensure the effectiveness of the flood protection system.

Estimation of infiltration losses

The Khar Yalla area (Saint-Louis) is located below sea level according to the visualization with Google Earth, the 2 m resolution DTM and the topo surveys, which suggests a basin topography.

Estimation of spatial losses due to solid deposits

Runoff water, especially during heavy rainfall, carries solid materials (sand, silt, organic debris) that end up being deposited in retention areas, such as dissipation basins, upstream of dikes or around spillways. These deposits gradually reduce the storage capacity and can disrupt the hydraulic efficiency of flood protection structures. In the Khar Yalla catchment, characterized by a basin-shaped topography, the reduced flow velocity promotes settling and accumulation of sediment. It is therefore essential to take these losses into account from the design stage, in order to correctly size the structures and ensure their long-term effectiveness. To estimate these solid losses at the project scale, several recognized empirical formulas were used, including those of Grisillon, Gottschalk and the modified formula of Professor Karambiri [5], adapted to the hydrological conditions of the region. **Table 8** includes all the formulas proposed by various authors to estimate spatial losses due to solid deposits.

Table 8. Estimation of spatial losses due to solid deposits.

Authors	Formulas
GRISILLON	$D = 700 \times \left(\frac{P}{500} \right)^{-2.2} \times S^{-0.1}$
GOTTSCHALK	$D = 260 \times S^{-0.1}$
KARAMBIRI	$D = 137 \times \left(\frac{P}{500} \right)^{-2.2} \times S^{-0.05} \times [0.25 + 1.13 \times (h + r)]^{1.15} \quad (20)$

D: Annual specific degradation (m³/Km²/year)
P: Average annual rainfall (mm)
S: Area of the watershed (Km²)
V: Annual volume of sediment input (m³)
h: Anthropogenic parameter (*h* = 0.3) for a watershed containing small towns/villages or located near them (FAO, 1996)
r: Morphological parameter (*r* = 0.2) for a slightly uneven, pronounced relief (FAO, 1996)

The annual volume of solid inputs can then be determined using the following relationship:

$$V = D \times S \quad (21)$$

4.3. Study on the Relocation of Populations Affected by Flooding in the Khar Yalla Neighborhood

The social study was conducted through a participatory field survey in the most exposed areas of the neighborhood. A semi-structured questionnaire was administered to a representative sample of affected households (31 households) using the SurveyMonkey tool, allowing the collection of their feelings, fears, living conditions, and level of acceptability regarding the relocation option. The qualitative analysis focused on:

- Experiences of recurrent flooding;
- Perceptions of the proposed solutions (infrastructure works, relocation);
- Level of trust in the authorities and the project;
- Emotional, economic, and social barriers to a potential relocation.

5. Results and Discussion

5.1. Topographic Studies

The topographic analysis of the study area is based on a high-resolution (2-meter) Digital Elevation Model, supplemented by a ground survey carried out by the Parar Consulting consultancy firm. The recorded altitudes range between -1.17 m and 2.82 m, with a large portion of the Khar Yalla district located below sea level. This basin-like configuration, characterized by a very low drop, prevents efficient gravity flow and increases vulnerability to flooding. **Figure 1** below represents the surface height curve.

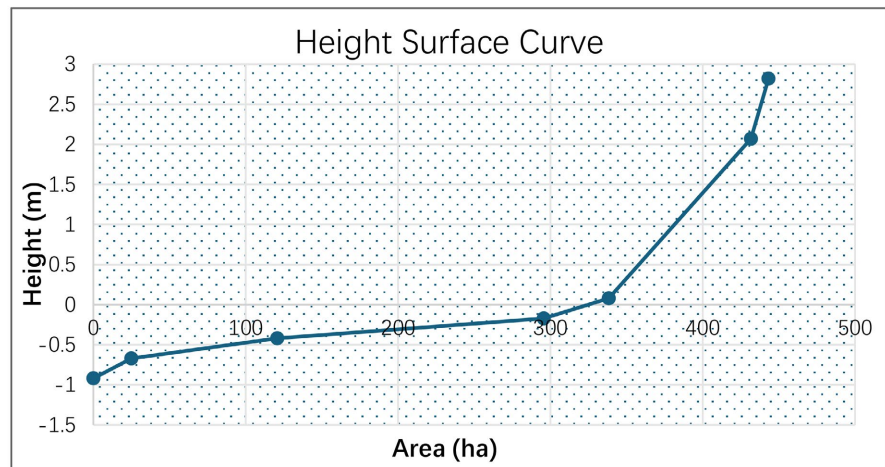


Figure 1. Height surface curve.

This curve shows the evolution of the flooded area as a function of water height. Up to about 300 hectares, the growth is gradual, then accelerates significantly. This reflects the sudden opening of the basin in its upper parts, where a slight rise in level leads to a large spatial extension.

As soon as the water exceeds a certain threshold (around 0.08 m), the flooded area increases very rapidly. This behavior highlights the vulnerability of certain areas of the neighborhood, which can be submerged in a short time if no regulation measures are implemented.

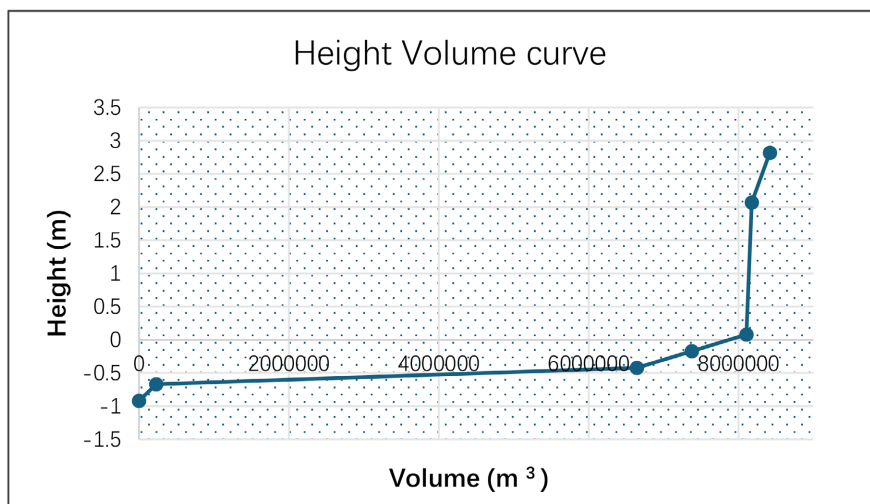


Figure 2. Height volume curve.

The height-volume curve highlights the relationship between the water height in the basin and the stored volume. There is a slow increase in volume up to approximately 8,000,000 m³, followed by a marked increase. This break reflects the slight slope in the lower areas, where water accumulates without generating large volumes, followed by a more rapid filling as the level rises. This confirms the basin shape of the retention area (Figure 2).

Water storage begins slowly, which means that the first flooded areas become saturated quickly without providing much capacity. This phenomenon increases the risk of flooding during the initial heavy rains.

5.2. Soil Studies

The results of soil surveys carried out at several strategic points in the study area reveal a strong presence of clay in the surface layers, to an average depth of one meter. This dominant texture gives the soil very low permeability, limiting water infiltration and promoting surface stagnation.

5.3. Hydrological Studies

The hydrological analysis made it possible to characterize the Khar Yalla watershed, to better understand the rainfall regime and to estimate extreme rainfall events that could lead to flooding. It is based on local rainfall data and the application of statistical methods according to different return periods.

Analysis of rainfall data. The rainfall data used come from stations close to the study area. They were subjected to statistical analysis using HYFRAN+ software,

with adjustment according to Gumbel and Gauss laws. This analysis made it possible to estimate the rainfall quantiles associated with different return periods, which helps anticipate extreme episodes (Table 9).

Table 9. Rainfall data from the Saint-Louis station from 1980 to 2018.

Descriptive characteristics of rainfall data from the Saint-Louis from 1980 to 2018		
Station	Saint-Louis	
Nature	Average annual rainfall	Maximum daily rainfall
Size	39	39
Average (m)	255.77	127.45
Standard deviation (6)	98.36	59.18
Maximum	593.6	320.1
Minimal	58.6	33.1
Median	261.3	126.8
Confidence interval (%)	95	95

Table 10 below represents the summary of the adjustments to the rainfall data.

Table 10. Summary of rainfall data from the Saint-Louis station from 1980 to 2018.

Summary of rainfall data adjustments						
Quantile	NORMAL Law			GUMBEL's Law		
Summary of rainfall data adjustments						
	Return period	q = F(xi) probability of non-exceedance	Ui: variable reduced by GAUSS	Rain (mm)	Ui: reduced variable	Rain (mm)
Dried	100	0.01	-2.33	26.95	-1.527	36.19
	50	0.02	-2.05	53.76	-1.364	43.71
	10	0.1	-1.28	129.72	-0.834	68.18
	5	0.2	-0.84	172.99	-0.476	84.71
Median	2	0.5	0	255.77	0.367	123.6
	5	0.8	0.84	338.56	1.5	175.92
Humid	10	0.9	1.28	381.83	2.25	210,556
	50	0.98	2.05	457.78	3902	286.79
	100	0.99	2.33	484.6	4.6	319.02

The results reveal a logical progression of rainfall heights with increasing return period, reflecting an increase in risk in the event of exceptional events.

The results reveal a logical progression of rainfall heights with increasing return periods, reflecting an increased risk in the event of extreme events. The fittings using probability distributions showed good agreement with the Gaussian and Gumbel distributions, with over 90% of the data falling within the confidence in-

tervals. This validates the relevance of these distributions for modeling rainfall data in the study area.

6. Watershed characterization

6.1. Geo-Morphometric Characteristics

The watershed that feeds the study area covers an area of 44.4 km², with a total perimeter of 101.85 km. According to the Rodier classification (FAO Bulletin 54), it is a medium-sized basin ($40 \text{ km}^2 < S < 1000 \text{ km}^2$). Its morphology is elongated, as evidenced by its high compactness index of 4.31. With reference to the typology proposed by Rodier and Auvrey (FAO Bulletin, 1998), it is classified in category P3 or RI, which indicates low permeability of the watershed. The results of the geomorphometric characteristics are shown in **Table 11**.

Table 11. Geomorphometric characteristics.

Setting	Value	Unit	Interpretation
Area (S)	44.4	Km ²	Middle basin
Perimeter (P)	101.85	Km	-
Gravelius compactness index or (Shape index)	4.31	-	Elongated shape
Equivalent length (L_{eq})	50.04	Km	Elongate
Equivalent width (l_{eq})	0.89	Km	Very narrow
Undercover Class	RI (P3)	-	Relatively waterproof

In summary, the basin has an elongated shape and low permeability, increasing the risk of rapid runoff towards the outlet.

The set of geomorphometric, hypsometric, topographic, and hydrographic characteristics of the Khar Yalla watershed reveals an area with high hydrological vulnerability. The combination of an elongated shape, gentle slopes, depressed relief, and low permeability promotes rapid runoff while limiting the natural drainage of water. Despite a relatively high drainage density, the efficiency of the hydrographic network remains compromised by the nearly flat topography. These factors fully justify the implementation of flood protection structures, adapted to a context of low natural hydrodynamics.

The hypsometric curve

The analysis of the hypsometric curve allows us to assess the altitudinal distribution of the basin. The altitudes vary from -1.17 m to 2.82 m , which reflects a very low topographic amplitude.

- **H 5%** $\approx 2.82 \text{ m}$: 5% of the basin is located at this high altitude

H 95% $\approx -1.17 \text{ m}$: 95% of the basin is below this threshold, confirming the basin topography of Khar Yalla, with more than 60% of the basin located between $+0.5 \text{ m}$ and -1.0 m . This altimetric structure, consistent with the results geomorphometric, explains the difficulties of natural water evacuation: the gentle slopes limit the gravitational flow, while the negative altitudes compared to the sea level

favor the rise of the water table and flooding by submersion or saturation. This configuration justifies the need for suitable hydraulic structures to compensate for the absence of natural drainage and to protect the area sustainably.

Figure 3 represents the hypsometric curve.

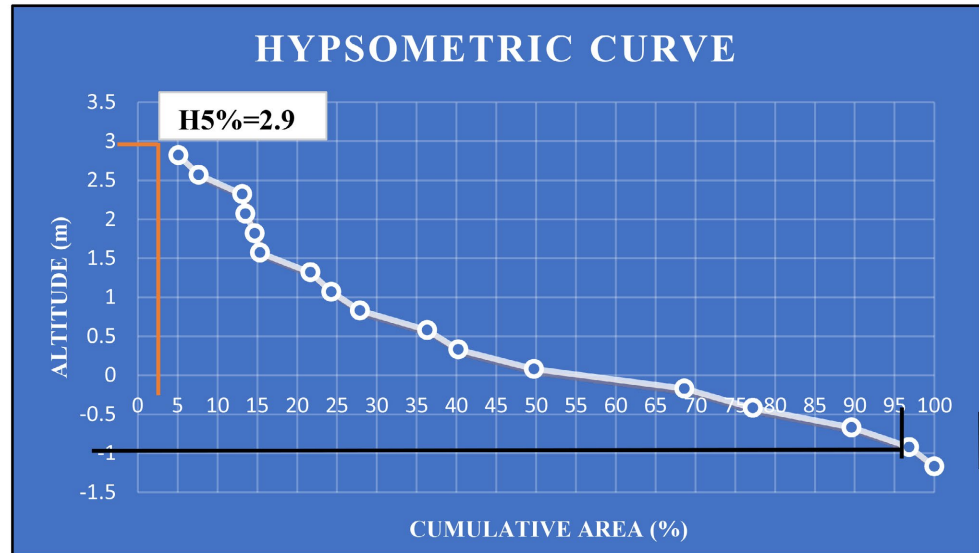


Figure 3. Hypsometric curve.

The hypsometric curve confirms the bowl-shaped topography of Khar Yalla, with over 60% of the watershed located between +0.5 m and -1.0 m. This altimetric structure, consistent with the geomorphometric results, explains the difficulties in natural water drainage: the gentle slopes limit gravitational flow, while the negative elevations relative to sea level favor groundwater rise and flooding due to inundation or saturation. This configuration underscores the need for suitable hydraulic structures to compensate for the lack of natural drainage and to sustainably protect the area.

Watershed relief characteristics

Table 12 below represents the characteristics relating to the relief of the watershed.

Table 12. The characteristics relating to the relief of the watershed.

Setting	Value	Unit	Interpretation
Average slope (I_{moy})	1.37	-	Low slope
Longitudinal slope (I_L)	3.90	m/km	Gentle
Average cross slope	4.69	m/km	-
Global slope index (I_g)	0.08	-	Flat
Corrected slope index	1	-	Flat (confirmed)
Specific elevation (D_s)	6.65 ($D_s < 50$ m)	m	Low relief (FAO Bulletin)

The very low relief prevents efficient natural flow, which promotes water stagnation and increases the risk of flooding.

Characteristics relating to the hydrographic network

The characteristics relating to the hydrographic network are listed in **Table 13**.

Table 13. Characteristics relating to the hydrographic network.

Setting	Value	Unit	Interpretation
Total network length	101.91	Km	Large network
Number of orders	8	-	Prioritization confirmed
Drainage density (D_d)	2.30	Km ⁻¹	Very dense network

Although drainage density is high, reflecting a network that is potentially favorable for water evacuation, its actual effectiveness remains limited by the relief. In the absence of sufficient slope, the flow remains slow and poorly structured, reducing drainage capacity during heavy rains and increasing the risk of flooding.

6.2. Determination of the Project Flood Flow

The **design flood** corresponds to a rare and high flow, characterized by a rapid rise in water levels in the watercourse. It has a low return frequency but a potentially significant impact. To ensure safety, the structures will be designed to evacuate the 100-year flood, *i.e.* an event with an annual probability of occurrence of 1% (or an average occurrence every 100 years).

The ten-year flood is estimated using the ORSTOM and Puech & Chabi (CIEH) methods. The hundred-year flood, retained as the design flood, is then deduced using the GRADEX method, via a coefficient applied to the ten-year flows obtained.

ORSTOM de AUVREY and RODIER method

Table 14 below shows the results of the ten-year flood according to ORSTOM.

Table 14. The results of the ten-year flood according to ORSTOM.

Maximum daily rainfall per hundred years	P_{100} (mm)	313
Maximum daily rainfall per ten years	P_{10} (mm)	204
Annual ten-year rainfall	P_{am10} (mm)	380
Reduction coefficient (A)	HAS	0.75
Ten-year runoff coefficient	K_{r10}	33.6
Basic time	T_b (mn)	300
Peak coefficient of a ten-year flood	α_{10}	2.60
Ten-year runoff flow rate	Q_{r10} (m ³ /s)	19.83
Ten-year peak flow	Q_{10} (m ³ /s)	20.82

CIEH method

Table 15 below shows the results of the ten-year flood according to CIEH.

Table 15. The results of the ten-year flood according to CIEH.

Linear regression equation number	Value of Q_{10} in m^3/s
Q_9	95.82
Q_{11}	94.34
Q_{12}	45.16
Q_{33}	48.28
Average Q	70.90

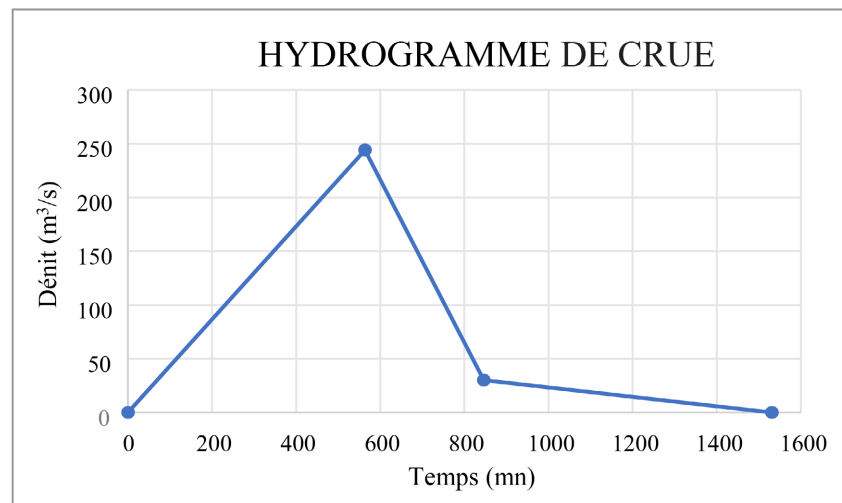
From these two methods, we obtained the centennial flood using the multiplier coefficient of the gradex method as shown in **Table 16**.

Table 16. The results of the 100-year flood.

Method	ORSTOM	CIEH	GRADEX C coefficient	Q_{100} retained (CIEH)
Value in m^3/s	48.26	164.30	2.32	164.30

The flood hydrograph

The flood hydrograph shows the different curves occurring during a flood period. **Figure 4** shows its appearance in the study area.

**Figure 4.** Simulated flood hydrograph of the study area.

The simulated flood hydrograph illustrates the evolution of discharge over time during a critical rainfall event in the Khar Yalla catchment. It is broken down into three distinct hydrological phases:

Rising phase: from the initial state to the design flow $Q_p = 244.02 m^3/s$. This rapid rise reflects a strong reaction of the basin, linked to the impermeability of the soil and the basin topography. **The Recession phase:** from the flood peak to the discontinuity flow $Q_d = 30.13 m^3/s$. The gentler slope reflects a progressive evacuation of the runoff volumes. **And the drying-up phase:** final phase bringing

the flow back to zero, marking the end of the flood episode.

❖ **The return period.**

6.3. Assessment of Contributions at the Watershed Level

This assessment aims to quantify the volumes of water generated in the basin during a rainfall episode. Two empirical methods (**Coutagne** and **Rodier**) based on regional formulas from African observations are used.

6.3.1. Estimation of Liquid Intake Using the COUTAGNE Method

The advantage of this method lies in its simplicity of application and its ability to provide a more consistent approximation from rainfall and morphological data.

The estimation based on this method made it possible to evaluate the contributions generated for different return periods. The results obtained are summarized in **Table 17**.

Table 17. Estimation of liquid intake.

Calculation parameters	Symbol	Results
Lambda	λ	0.229
Annual flow deficit	D (m)	0.241
Average annual rainfall	P_{man} (mm)	255.77
Average annual temperature	T (°C)	25.60
Annual water flow	T_{he} (mm)	14.92
Flow coefficient	$K_e\%$	5.83
Dry five-year runoff coefficient	$K_{e5}\%$	4.08
Dry ten-year runoff coefficient	$K_{e10}\%$	2.92
Annual liquid intake	V (m ³)	662036.51
Five-year liquid intake	V_5 (m ³)	463425.56
Ten-year liquid contribution	V_{10} (m ³)	331018.26

Estimation of liquid intake using the RODIER method

The results obtained are summarized in **Table 18**.

Table 18. Estimation of liquid intake.

Calculation parameters	Symbol	Results
Average annual rainfall	P_{man} (mm)	255.77
Annual water flow	T_{he} (mm)	6
Flow coefficient	$K_e\%$	2.33
Dry five-year runoff coefficient	$K_{e5}\%$	1.64
Dry ten-year runoff coefficient	$K_{e10}\%$	1.17
Annual liquid intake	V (m ³)	226197.84
Five-year liquid intake	V_5 (m ³)	186338.49
Ten-year liquid contribution	V_{10} (m ³)	133098.92

In order to ensure a safety margin in the sizing of the structures while remaining realistic, the average of the volumes obtained is retained, *i.e.* approximately 397,567 m³. This choice makes it possible to limit the deviations linked to empirical methods and serves as a reference for the rest of the hydraulic analysis.

Estimation of infiltration losses

Based on the average daily infiltration of 1 mm, retained and justified in methodology, the annual infiltrated volume is estimated at approximately m³.

6.3.2. Estimation of Spatial Losses Due to Solid Deposits

The assessment of spatial losses due to solid deposits was carried out using three empirical methods commonly used in hydro-sedimentary studies: **Grésillon**, **Gottschalk** and **Karambiri**. The results are presented in **Table 19**:

Table 19. Estimation of spatial losses.

Estimation method	Specific degradation D_s (m ³ /km ² /year)	Annual volume (m ³ /year)
GRISILION	2093.43	92877.58
GOTTSCHALK	177.94	7894.44
KARAMBIRI	820.63	36408.18
Retained value	1457.03	64642.88

6.3.3. Survey Results: Low but Informed Acceptability

The survey revealed strong resistance to the idea of relocation:

- 89% of respondents are opposed.
- 5.5% would accept temporarily leaving their homes.
- 5.5% would accept permanently leaving the neighborhood, but under very strict conditions (better living conditions, adequate support, etc.).

The reasons given are deep-rooted: attachment to the neighborhood, fear of isolation, distrust of political promises, and risk of marginalization. Nevertheless, a minority—but significant—portion recognizes that flooding is becoming unlivable and that well-managed relocation solutions could be acceptable.

Partial conclusion: Relocation in Khar Yalla should not be perceived as a failure of urban planning but as a strategic decision to optimize the project. It is technically sound, economically justifiable, and potentially socially acceptable if implemented with careful planning and sensitivity.

7. Conclusions

The Khar Yalla neighborhood, located below sea level in the city of Saint-Louis, faces a particularly acute flood risk, fueled by a combination of factors: basin-shaped topography, low permeability of clay soils, outcropping water table, and increasing urbanization without an appropriate sanitation plan. This thesis has made it possible to propose a structured response to this vulnerability by combining the implementation of adapted hydraulic structures with social reflection on the partial relocation of the most exposed populations.

The study was based on a rigorous hydrological analysis of the 44.4 km² watershed, whose annual useful inflows were estimated at approximately 597,396 m³, with a 100-year flood flow estimated at 164.30 m³/s. Based on this data, several structures were designed to meet local constraints. These include a gravity-type homogeneous clayey earth dike, 3.44 m high, 615 m long and 3 m wide at the crest, with slopes inclined at 1 V/2 H. The spillway, made of cyclopean concrete and positioned frontally, is set at a height of 3.3 m. 13.5 m long, it is designed to evacuate the design flow while ensuring an effective rolling effect. Downstream, a dissipation basin with a step reinforced by gabions arranged in a staircase helps control the flow speed and prevent erosion.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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