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Comparative Study of the Morpho-Hydrological Variables of the Djibonker and Agnack Watersheds (Lower Southern Casamance, Senegal)

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ABSTRACT: The hydrological functioning of watersheds is closely linked to their physical characteristics. In this context, GIS tools are essential for the morpho-hydrological study of watersheds shaped by climatic dynamics and land-use practices. This study aims to determine the morpho-hydrological variables of the Djibonker and Agnack watersheds, to compare them descriptively, and to relate them to hydrological functioning. Because the comparison involves only two watersheds, a formal multivariate statistical treatment, such as Principal Component Analysis, was not applicable; the 20 morphometric variables were instead compared directly. The results show that the two watersheds share broadly similar dimensional characteristics (area, perimeter, altitude) but differ markedly in shape, drainage density, and network configuration. Both watersheds have a complex hydrographic network dominated by intermittent channels. Concentration times obtained from Giandotti's (1934) empirical formula are 5.12 h (Djibonker) and 5.26 h (Agnack), and flow velocities are 0.46 m/s (Djibonker) and 0.80 m/s (Agnack), consistent with the low overall slope indices and with the more elongated shape of the Djibonker basin. These morphometric contrasts help explain the marked difference in salinity dynamics between the two basins. The approach developed in this study can be useful for a better understanding of the functioning of small, ungauged rural watersheds.

Keywords: Hydrological functioning; Morphometric variables; Digital terrain model; Watersheds; Casamance

1. Introduction

The physico-geographic diagnosis, the first step in understanding watersheds, allows for the characterization of the main natural factors involved in surface runoff: orographic, morphometric, lithological, climatic, and biogeographic factors [1]. The interaction among these parameters is crucial to studying the hydrological behavior of watersheds. Analyzing these different morphometric indicators allows for a better understanding of the elements that contribute to the proper functioning of watersheds. In this sense, ref. [1] states that determining physiographic characteristics is necessary to analyze the

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hydrological behavior of a watershed (rainfall depth, discharge, water balance, *etc*.). Physiographic, morphometric [2], and social parameters are closely linked to watershed planning and development. Many authors have used linear, areal, and relief aspects for watershed prioritization in development projects [3–5]. Ref. [6] combined soil hydro-physical properties (including texture) with morphometric parameters for land-use planning in a rainfed watershed. Other researchers have reported relationships between land use/cover, morphology, slope, soil, land-surface processes, climate, hydrology, and human activities [7–9]. Morphometric analysis, which covers linear, areal, and relief parameters, is central to watershed management and hydro-geomorphological studies [10] and helps in understanding watershed evolution, topographic processes, soil properties, and erosion, as well as waterlogging, flooding, and drought [11]. Morphometric analysis is an important step in watershed prioritization, even without soil maps [12], and the hydrological response of a watershed is influenced by characteristics such as its area, shape, elevation, slope, and orientation [13].

Beyond a purely descriptive characterization of morphometric variables, this study seeks to address three more specific questions: (i) why do the Djibonker and Agnack watersheds display contrasting morphometric characteristics despite their geographic proximity and shared regional climate; (ii) how do these morphometric differences influence their hydrological response, in particular runoff generation, concentration time and flow velocity; and (iii) to what extent does watershed morphology help explain the marked contrast in salinity dynamics observed between the two basins Djibonker being strongly affected by saltwater intrusion, and Agnack remaining comparatively unaffected. Addressing these questions is particularly relevant given the scarcity of hydrometric data in these small rural watersheds, where morphometric analysis is one of the few tools available to infer hydrological functioning.

The present study, therefore, aims to determine the morphometric variables of the Djibonker and Agnack sub-watersheds using geospatial techniques and to compare them descriptively in order to relate morphometric contrasts to hydrological and ecohydrological functioning. Morphometric analysis using remote sensing and GIS techniques has been widely used for prioritizing and managing sub-watersheds [14–17] as GIS techniques offer accurate and timely spatial information for watershed planning and management [11].

2. Study Area

The Djibonker and Agnack basins (Figure 1) exhibit contrasting dynamics. In Djibonker, the stream is influenced by saltwater intrusion from the Kamobeul bolong, resulting in seasonal flow and sparse mangrove vegetation. Areas near the outlet (Darsalam, Djibonker, Brin, Katouré) are heavily affected by salt, causing the loss of numerous rice paddies. In contrast, the southern areas (Toubacouta, Bourofaye-Baïnouck, Mpack, Boffa-Bayotte) remain relatively unaffected. In Agnack, the mainstream, 15.2 km long, is perennial and highly branched. Around it, mangrove vegetation thrives and fish farming flourishes, particularly between Adéane and the areas of Agnak-Petit, Agnak-Grand, and Niabina. This basin is rich in horticultural and fish-farming production, attracting fishermen from neighbouring villages and other regions. Djibonker thus illustrates an ecological fragility linked to salinity, while Agnak offers more diversified economic opportunities.

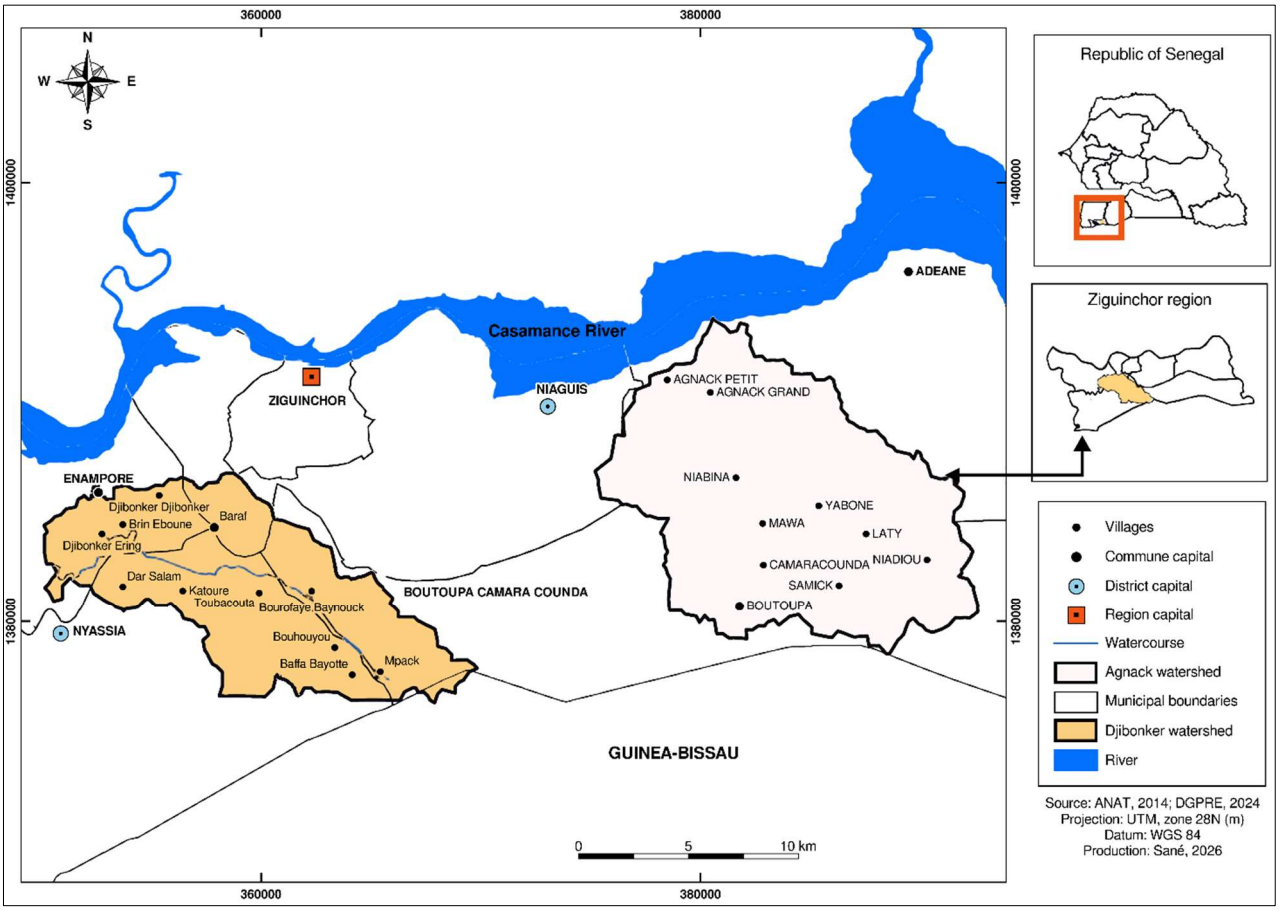


Figure 1. Location of the Djibonker and Agnack watersheds in Lower Casamance.

3. Materials and Methods

A digital terrain model (DTM) is a digital representation of a given region using an elevation field, either as a scatter plot of characteristic points or as a regular grid of square cells (a raster) [18]. This technique was used to delineate the two watersheds and to calculate their area and perimeter simultaneously, and it enables the automatic extraction of parameters characterizing the terrain.

Land-cover units and the phenomenon of rising groundwater or major floods can influence the actual boundaries of watersheds. The streams of the Djibonker and Agnak watersheds function as both tributaries and outlets; delineating them at their natural outlets would therefore lead to an overestimation of their flow. The morphometric parameters computed for the watersheds are: area, perimeter, length and width, compactness coefficient, elevation, average slope, overall slope index, and specific elevation. These parameters were obtained from the 2016 DEM (Digital Elevation Model).

3.1. Data Sources

Data were obtained from the USGS Earth Explorer platform (http://earthexplorer.usgs.gov/, accessed on 12 April 2026) a source of free, publicly accessible, high-resolution data offering GDEM TIFF images at various scales and dates.

ASTER GDEM (Global Digital Elevation Model), part of the ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) program, is a digital terrain model covering the entire world between 83° North and 83° South [13]. The model used here has a resolution of 30 m in the WGS84 projection. The morphometric variables obtained from this DEM are listed in Table 1.

The 30 m resolution of ASTER GDEM is generally considered acceptable for watersheds of about 100 km^2, such as those studied here; however, this resolution can limit the accuracy with which first-order streams are extracted. Stream network extraction was performed by applying a flow-accumulation threshold to the DEM-derived flow-accumulation raster, above which a cell was classified as belonging to the drainage network. Drainage density and stream order are both sensitive to this threshold, so the DEM-derived network and morphometric parameters should be interpreted as being conditional on this choice.

Table 1. Morphometric variables calculated.

Watershed	Area (km^2)	Perimeter (km)	KG	Length (km)	Width (km)	H5% (m)	H95% (m)	Elevation Gain (m)	Ig (m/km)	Specific Elevation
Djibonker	107.8	60.3	1.62	22.8	7.2	42	8.5	33.5	1.46	15.16
Agnack	115.8	51.7	1.34	16.7	9.0	41	2.5	38.5	2.30	24.75

3.2. Comparative Approach Used for the Morphometric Variables

Statistical analysis allows for a better understanding of the relationships between variables or individuals. The choice of processing approach depends on the number of variables to be analysed, the type of data available, and the expected results.

Principal Component Analysis (PCA) is a widely used multivariate statistical technique [12,19,20]. However, PCA requires the number of observations (n) to be substantially larger than the number of variables (p) (commonly $n > 5p$, and preferably $n > 10p$) for the resulting axes and correlations to be statistically meaningful. In the present study only two individuals (the Djibonker and Agnack watersheds) are compared across 20 morphometric variables ($n = 2$, $p = 20$), a configuration for which PCA is not statistically valid: with only two observations, any two-variable PCA necessarily explains the totality of the variance on a single axis, regardless of the underlying data, so that the resulting eigenvalues and correlation loadings carry no statistical meaning. PCA was therefore not applied in this study. Instead, the 20 morphometric variables were compared directly between the two watersheds and grouped descriptively into dimensional variables (related to watershed size and shape: area, perimeter, altitude, compactness coefficient, equivalent rectangle) and network/flow variables (drainage density, hydrographic density, stream frequency, torrentiality coefficient, flow velocity). This comparison is descriptive: no inferential statistical test, confidence interval, or significance level is reported, consistent with the sample size of two. A statistically valid multivariate analysis would require subdividing each watershed into a larger number of sub-basins so that the sample size satisfies the assumptions of multivariate statistics; this is identified as a direction for future work.

The 20 variables considered are: area (A), perimeter (P), compactness coefficient (Kc), altitudes (Hmax, Hmin, and Hmoy), specific elevation difference (Ds), equivalent rectangle length (Lrec), equivalent rectangle width (lrec), mean basin slope (Ibv), main thalweg length (L), mean slope of the main stream (Icp), overall slope index (Ig), drainage density (Dd), hydrographic density (F), stream confluence ratio (Rc), stream length ratio (RL), torrentiality coefficient (Ct), flow velocity (Ve), stream frequency (Fr), and stream stability constant (C). These are extracted from the 30 m resolution ASTER DEM.

4. Results

4.1. Watershed Hypsometry

The hypsometric curve provides a synthetic view of watershed slope and represents the distribution of watershed area according to altitude [21]. The shape of the hypsometric curve is characteristic of the maturity stage of the landform (young, mature, or old) and of its erosive capacity [21,22], it characterizes the erosion cycle of the current landform under study [23] (Figure 2). Low elevations are observed over

more than 80% of the total basin area. Topographic irregularities are more pronounced in the Agnack basin; the lowest elevations are found on its western slope (Samick, Niabina, and the Bissine plateau), where significant irregularities in relief occur alongside generally low elevations.

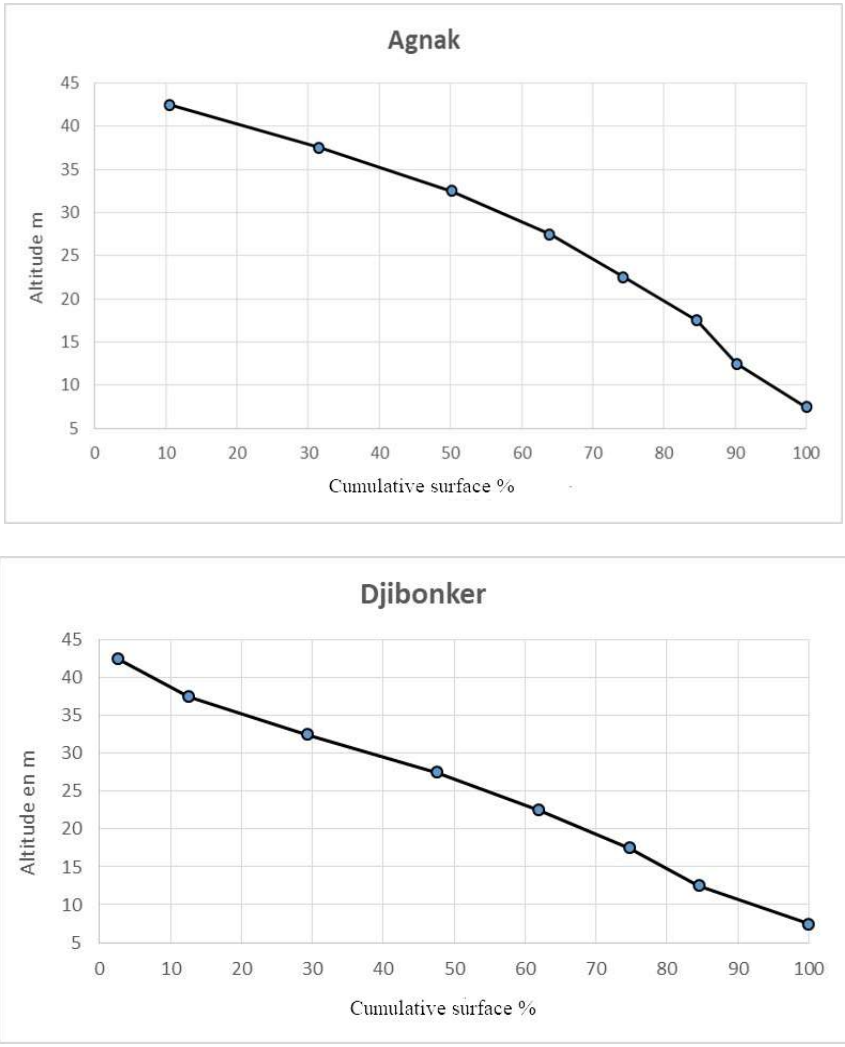


Figure 2. Hypsometric curves of the Djibonker and Agnack watersheds.

4.1.1. Average Altitudes of the Basins

Watershed altitudes were calculated from morphometric variables and measurement data. Altitudes range from 7 to 45 m across the study watersheds (Table 2).

Table 2. Median altitudes, partial areas, and average altitude of the Agnack watershed.

Altitude Class (m)	Hi-Mid-Altitude (m)	Partial Area (km^2)	Weighted Altitude
5–10	7.5	16.64	1.16
10–15	12.5	10.61	1.23
15–20	17.5	13.75	2.23
20–25	22.5	15.55	3.25
25–30	27.5	19.66	5.01
30–35	32.5	17.98	3.34
35–40	37.5	10.73	3.73
40–45	42.5	2.81	1.11
-	-	Hmoy=	21.06

4.1.2. Surfaces and Perimeters

The Djibonker and Agnack basins have surface areas of 107.8 km^2 and 115.8 km^2, respectively. Surface area and perimeter are two important parameters used to calculate the other morphometric characteristics shown in Table 1. Since a watershed is the area that receives rainfall and feeds watercourses, flow rates are partly related to its surface area; theoretically, the larger the catchment area, the greater the flow rate, although specific discharge tends to change inversely with increasing surface area. Unlike surface area, the perimeter represents the irregularities of the watershed boundary, defined as the line joining all the highest points [12].

4.1.3. Shape Index (Kc), Length, and Width

Characterizing the shape of a watershed is important in hydrology, as it helps explain how the watershed responds to a hydrological event (runoff, flooding). The index generally used by hydrologists to characterize watershed shape is the Gravelius compactness index (1914) [23], the ratio of the watershed perimeter to that of a circle of equal area:

$$KG = (0.28 \times P)/\sqrt{A} \quad (1)$$

with P = 60.3 km (Djibonker) and 51.7 km (Agnack); A = 107.8 km^2 (Djibonker) and 115.8 km^2 (Agnack).

Following the ORSTOM classification, a KG value close to 1 indicates a near-circular watershed, while values above 1 indicate progressively more elongated watersheds. The values obtained are 1.62 (Djibonker, elongated) and 1.34 (Agnack, intermediate). Both watersheds, therefore, have elongated shapes, Djibonker being the more elongated of the two.

The shape of a watershed influences flow across its different sections and directly impacts the hydrograph's response at the outlet. For an equivalent rainfall event, an elongated shape produces lower peak flows because of the longer travel time of water to the outlet, whereas a small, near-circular watershed generates a more rapid flood response [24]. Many factors, including socio-economic activities and current climate dynamics, also contribute to changes in the hydrological characteristics of these basins, and several impacts of territorial development may persist or emerge.

The equivalent rectangle is a rectangle with length L and width l that has the same perimeter and area as the watershed (P = 2 × (L + l); A = L × l) [25]; it allows watersheds to be compared from a runoff perspective. It can also be derived from the compactness coefficient (Kc):

$$L = (Kc\sqrt{A}/1.12) \times [1 + \sqrt{(1 - (1.12/Kc)2)}] \quad (2)$$

$$l = (Kc\sqrt{A}/1.12) \times [1 - \sqrt{(1 - (1.12/Kc)2)}] \quad (3)$$

The results are given in Table 3. The equivalent-rectangle length of the Djibonker watershed (25.81 km) is greater than that of Agnack (19.94 km).

Table 3. Morphometric parameters of the study basins.

Watershed	Length (km)	Width (km)	Area (km^2)	Perimeter (km)	KC
Agnack	19.94	5.79	115.8	51.7	1.34
Djibonker	25.81	4.20	107.8	60.3	1.62

4.1.4. Specific Elevation Gain

The specific elevation difference is another characteristic of watershed shape, calculated from the elevation difference (H5% − H95%), and is related to the overall slope. The ORSTOM classification (1964) provides thresholds for this index [25]; both basins fall in the low to moderately low relief classes (Table 4).

Table 4. Classification of relief types according to ORSTOM.

Class	Description	Ds < 10
R2	Very slight relief	10 < Ds < 25
R3	Low relief	25 < Ds < 50
R4	Fairly low relief	50 < Ds < 100
R5	Moderate relief	100 < Ds < 250
R6	Fairly strong relief	250 < Ds < 500
R7	Strong relief	500 < Ds

4.2. Relief of the Djibonker and Agnack Watersheds

Topographic profiles were extracted using the "Swath Profiler" ArcGIS extension, which analyses surface elevation and topography (mean, minimum and maximum elevation, quartiles, local relief and hypsometry) within a strip of defined width [26,27]. Studying topography is essential because the dynamics of water flow are intrinsically linked to the shape of the landform (slope, degree of incline). The hydrological response of a basin depends on flow factors related to its shape and landscape (geology, soils, vegetation, topography) [12,28,29], and slope shape indicates the duration of runoff. Topography best reflects the division of the basin between upper reaches (highlands) and middle reaches (mid-relief areas) [30].

The relief can be summarized by the overall slope index:

$$Ig = D/L \quad (4)$$

where D is the elevation difference (H5% − H95%, in m) and L is the watershed length reported in Table 1 (km). The values obtained are 1.46 m/km (Djibonker) and 2.30 m/km (Agnack), indicating relatively gentle slopes in both basins; according to the ORSTOM classification, a relief is considered steep only above 20 m/km. These gentle slopes are consistent with a low flow velocity in both basins and help explain the deep intrusion of the sea into the Casamance basin [31].

Both basins show generally low elevations (Figure 3), consistent with the monotonous relief of the Casamance region described by [31,32], where elevations generally do not exceed 50 m. In the Agnack basin, the only notable landforms occur on the southeastern and eastern plateaus of Camaracounda, Samick, and Niadiou (30–38 m). The villages of Mawa, Niabina, Agnak-Grand, and Agnak-Petit lie on the lower western slope (13–20 m), on hydromorphic soils of relatively fine texture; the Agnak-Petit depression, the largest in the basin, has a comparatively steep slope with numerous gullies and alluvial deposition along the minor bed during high water. A deeper depression (1–20 m) is frequently waterlogged, with clay soils and silt from sedimentary deposits.

Comparing topographic profiles (Figure 4) reveals greater heterogeneity in the Agnack basin. Agnack has a lower maximum altitude (41 m) than Djibonker (42 m) but an almost homogeneous relief with slight variations; minimum elevations near 5 m are found within 6 km along the transect, while elevations above 25 m require more than 15 km upstream from Sindon. The Agnack relief resembles a meandering river with concave valley shapes, possibly reflecting fluvial input and land-development activities. In the Djibonker basin, the topography is similarly monotonous, with the highest elevations (30–42 m) on the Brin, Djibonker, and Boffa-Bayotte plateaus. The villages of Darsalam, Katouré, and Bourofaye-Baïnouck lie at the foot of the main valley, which includes the Mpack and Binako valleys; significant flooding occurs there during the rainy season, and five water-control structures have been installed, with the upstream villages (Mpack, Boffa-Bayotte, at about 35 m) affected by the resulting water-management issues.

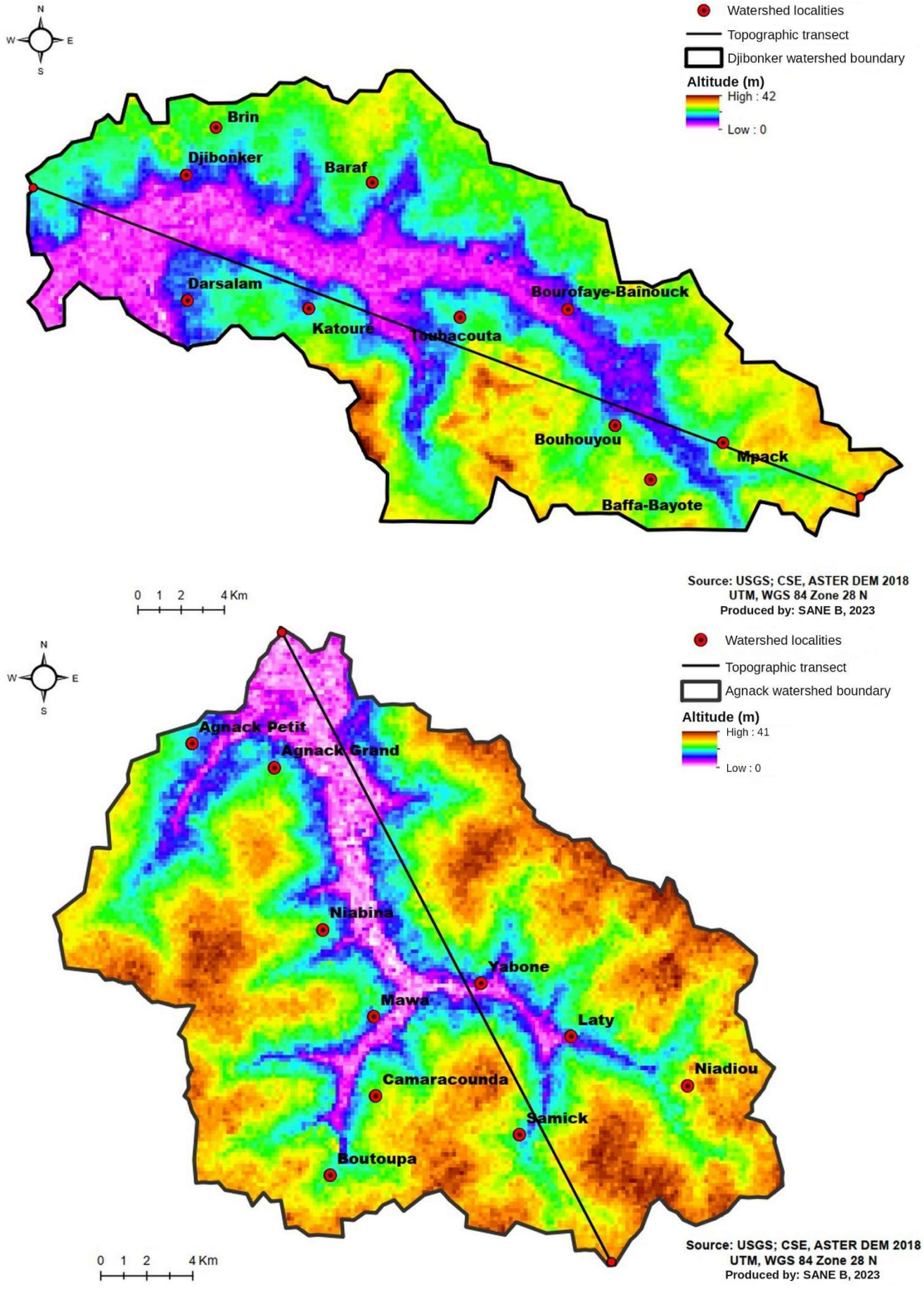


Figure 3. Relief characteristics of the Djibonker and Agnack watersheds.

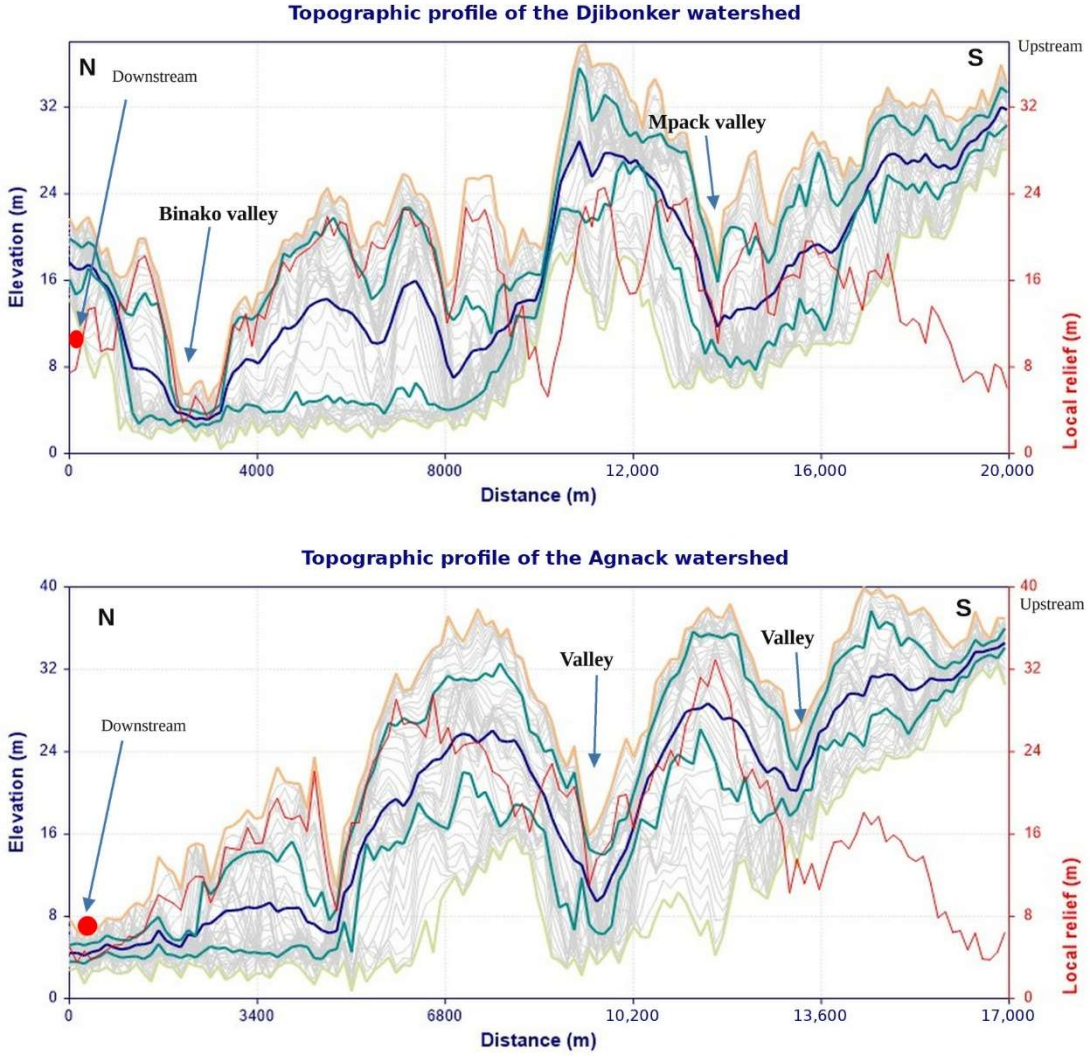


Figure 4. Topographic transects of the Djibonker and Agnack watersheds.

Slope Indices

Slope values were derived from the DTM for both basins (Figure 5, reference classes in Table 5). Following Rodier's classification, two slope classes are identified: shallow slopes (0–3%), covering about 70% of the watershed area, and moderate slopes (4–7% and above), covering about 30%, located mainly in the northern part at the base of the slopes, where cash crops are more widely cultivated. In the Agnack catchment, moderate slopes occur upstream of the Sindon terroirs and in the Laty, Yabone, Niadiou, and Samick terroirs.

Table 5. Reference values for the classification of watershed slopes.

Class	Values	Nature of the Slope
A	0 to 3%	Weak
B	3 to 12%	Moderate
C	12 to 20%	Steep
D	20 to 35%	Very steep
E	>35%	Extreme

Source: [33].

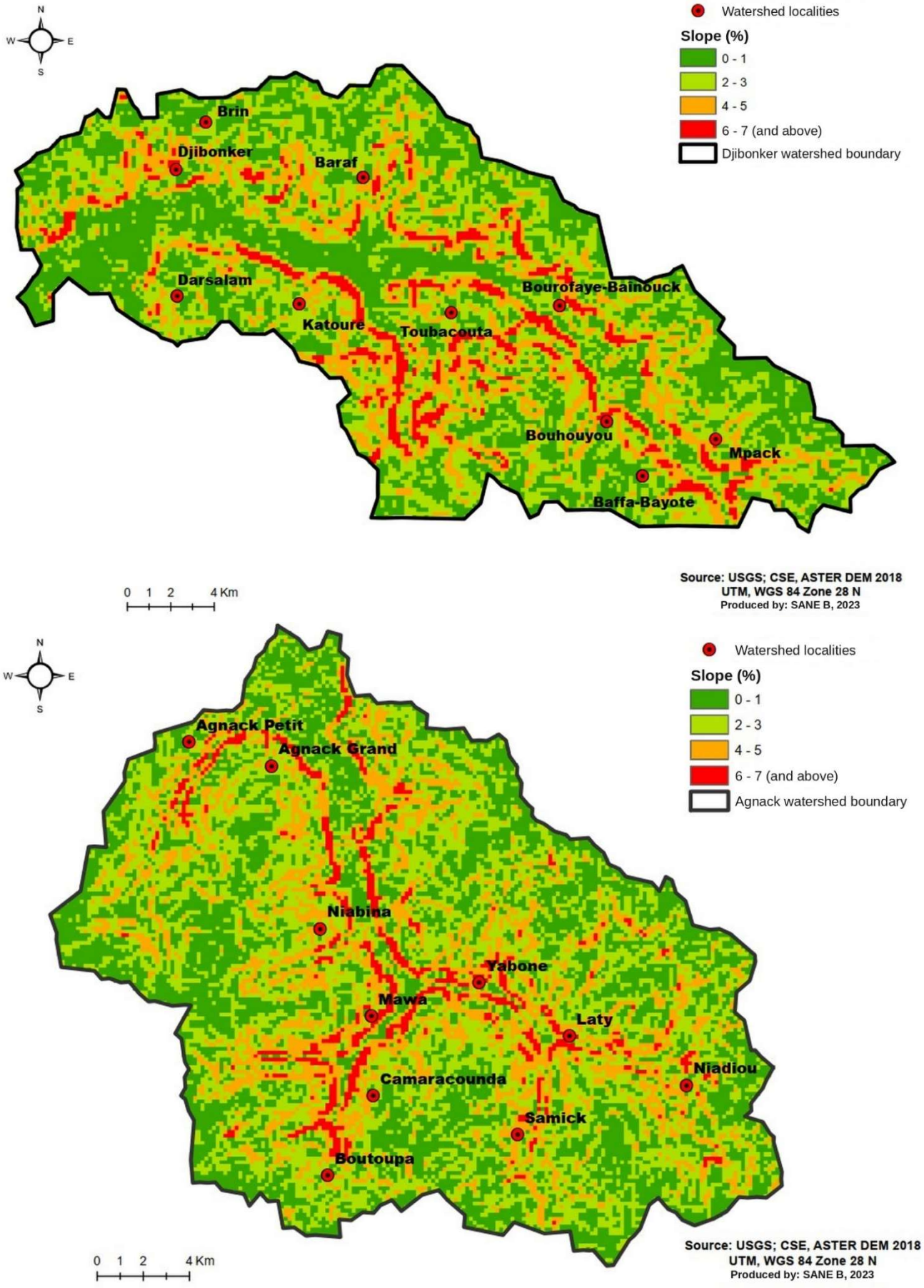


Figure 5. Slope classes (%) of the Djibonker and Agnack basins.

4.3. Complex Hydrographic Network

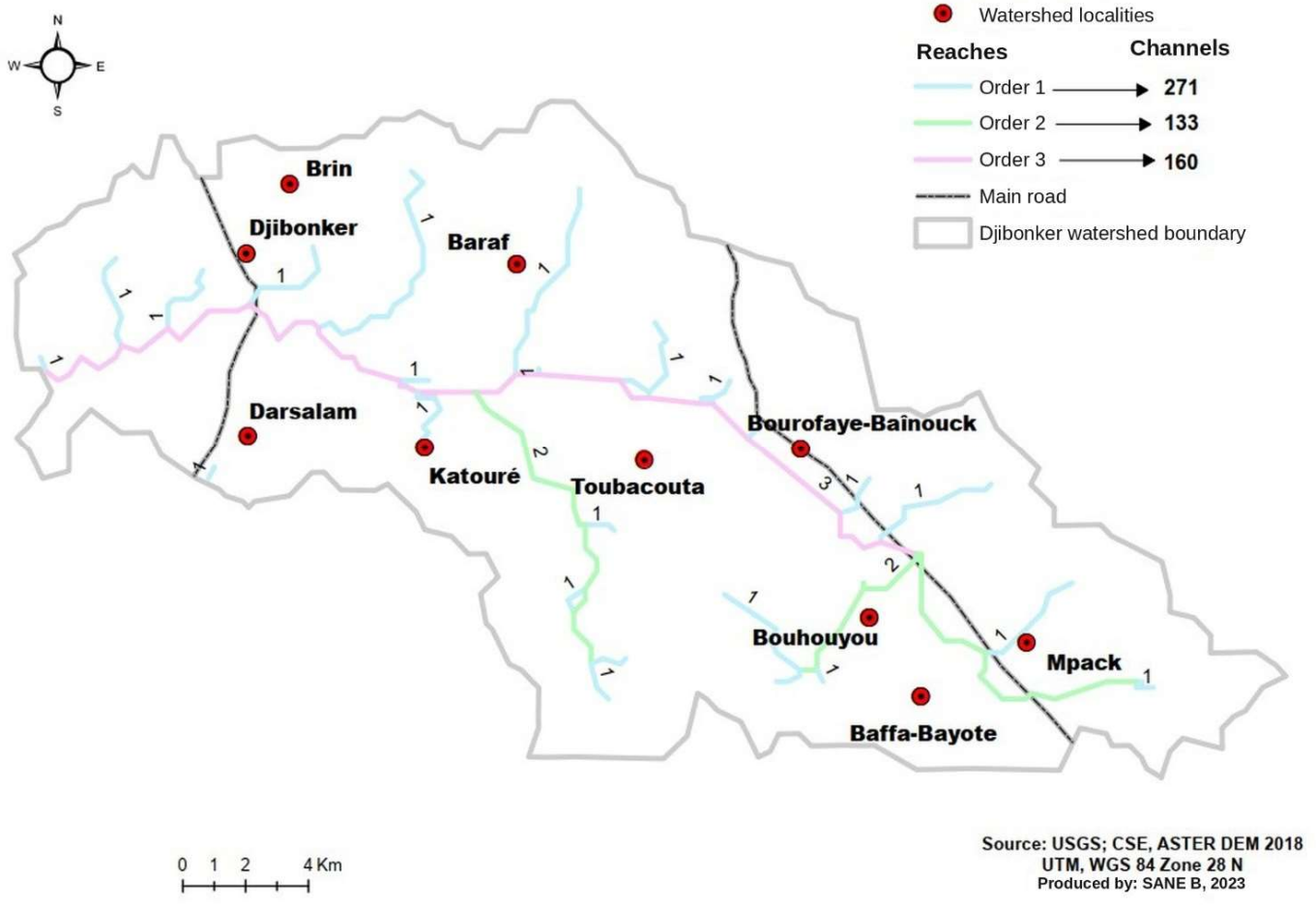
The hydrographic network is the set of channels (tributaries, sub-tributaries, and drains) belonging to the same river, and can be characterized by its hierarchy, its development (number and length of watercourses), and its longitudinal profile [25].

4.3.1. Description of the Hydrographic Network

The hydrographic network of the study catchments consists of streams and rivers with intermittent flow. The Djibonker stream, 8.46 km long and perennial, flows into the Kamobeul bolong, a major tributary of the Casamance River; two water-retention structures have been built downstream to support rice cultivation, and a mangrove forest occupies the left bank near the outlet, upstream of Darsalam and downstream of Djibonker village. The Agnack stream, 15.2 km long, is also tide-affected and flows into the Casamance River upstream of Sindom village. Both perennial courses ensure regular drainage of most of the two watersheds through their smaller, intermittently flowing tributaries. Flow is concentrated during the rainy season (August–October), while some reaches experience low water or complete drying between March and June. Both basins have relatively extensive, meandering hydrographic networks.

4.3.2. Hierarchy of the Hydrographic Network

Following Strahler's method (1957) [22], stream reaches were classified by order, first-order streams being those without tributaries; the main channel of each basin is fed by successive lower-order tributaries. The hydrographic network of the Djibonker catchment comprises three orders (Figure 6), while that of Agnack comprises four.



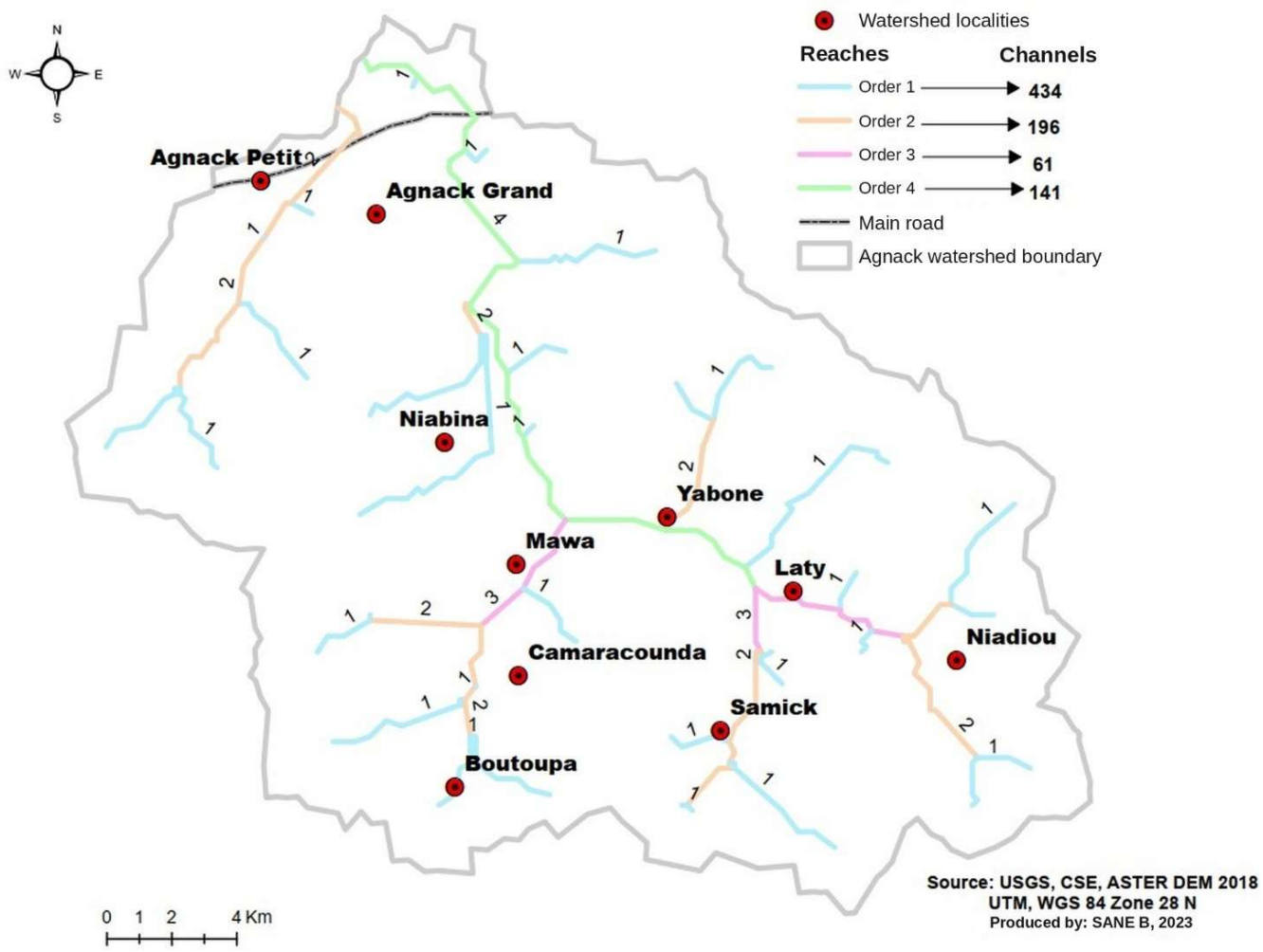


Figure 6. Branches of the hydrographic network of the Djibonker and Agnack watersheds.

4.3.3. Length of the Main Watercourse

The length of the main watercourse (L) is the curvilinear distance from the outlet to the drainage divide, following the highest-order segment at each branch (or the segment draining the larger area, in case of equal order) [13]. The lengths obtained are 15.21 km (Agnack) and 8.46 km (Djibonker).

4.3.4. Drainage Density

Drainage density ($Dd = \Sigma Li/A$) is the ratio of the total length of watercourses of any order to the basin area (km/km^2) and indicates a basin's capacity to drain water to the outlet; it is classified into five classes: very coarse (<1.2), low (1.2–2.4), moderate (2.4–3.6), high (3.6–4.8) and very high (4.8–6). Following Strahler (1964), a high drainage density generally indicates lower infiltration capacity, sparse vegetation, and rugged terrain, whereas a lower density indicates higher infiltration capacity.

The drainage densities obtained are 0.53 km/km^2 (Djibonker) and 1.09 km/km^2 (Agnack) (Table 6); both fall in the "very coarse" class, indicating a comparatively under-developed drainage network in both basins, consistent with their low relief and gentle slopes. Agnack's higher value, relative to Djibonker, points to a somewhat more developed network and, correspondingly, a lower relative infiltration capacity.

Table 6. Drainage densities of watercourses classified according to Strahler (1957).

Agnack-Order	Length Ni (km)	Density	Djibonker-Order	Length Ni (km)	Density
1	60.73	0.52	1	33.06	0.30
2	29.59	0.25	2	17.42	0.16
3	15.64	0.13	3	8.46	0.07
4	15.21	0.13	-	-	-
Total	121.2	1.09	-	58.94	0.53

4.3.5. River Stability Constant

Following [34], the inverse of drainage density gives a stream-stability constant:

$$C = 1/Dd \quad (5)$$

The values obtained are C = 1.88 km^{-1} (Djibonker) and 0.91 km^{-1} (Agnack).

4.3.6. Hydrographic Density

Hydrographic density (F = ΣNi/A) describes the number of watercourses per unit area, giving insight into the hierarchy and distribution of the network. The values obtained are 0.26 (Djibonker) and 0.46 (Agnack) (Table 7). Relative to Djibonker, Agnack's denser network is associated with somewhat greater drainage efficiency, which can promote surface runoff, whereas Djibonker's lower density corresponds to a less-branched network more consistent with infiltration. Given the low relief of both basins and the absence of direct soil or geological data, these are relative rather than absolute characterizations.

Table 7. Summary of hydrographic densities of the studied watercourses.

Agnack-Order	N° Waterways	Density	Djibonker-Order	N° Waterways	Density
1	130	1.12	1	54	0.50
2	21	0.18	2	18	0.17
3	17	0.15	3	14	0.13
4	5	0.04	-	-	-

4.3.7. Confluence and Length Ratios

Following [34,35], the confluence ratio (Rc = Ni/Ni + 1) and the stream-length ratio (RL = Li/Li + 1) describe the homogeneity of the drainage network across the two basins (Table 8).

Table 8. Summary of confluence and length ratios of the studied watercourses.

Agnack-Order	Li	Ni	Rc	RL	Djibonker-Order	Li	Ni	Rc	RL
1	60.7	130	-	-	1	33.06	54	-	-
2	29.6	21	6.19	2.05	2	17.42	18	3.00	1.89
3	15.6	17	1.23	1.89	3	8.46	14	1.28	2.05
4	15.2	5	3.40	1.02	-	-	-	-	-

4.3.8. Frequency of Watercourses

Stream frequency (the ratio of the number of first-order streams to the watershed area) provides insight into network density and the concentration time of surface water. The values obtained are 1.12 km^{-2} (Agnack) and 0.50 km^{-2} (Djibonker). Agnack's higher value indicates a denser network with greater relative drainage capacity (favouring surface runoff but also erosion risk), while Djibonker's lower frequency indicates a less-branched network more consistent with infiltration and groundwater recharge, though at the expense of readily available surface water.

4.3.9. Torrentiality Coefficient

The torrentiality coefficient (Ct = Dd × F, where F is the hydrographic density defined in Section 4.3.6) was found to be low for both basins (0.15 for Djibonker and 0.58 for Agnack), indicating a weakly hierarchical hydrographic network in both cases. These low values indicate that neither watershed is strongly optimized for rapid runoff generation, which is consistent with the low relief and gentle slope indices reported above. Relative to one another, however, Agnack's higher drainage and hydrographic densities point to comparatively lower infiltration capacity and higher runoff potential, while Djibonker's lower densities are more consistent with comparatively higher infiltration capacity. This relative distinction, rather than an absolute characterization of either basin as "permeable" or "impermeable", should be confirmed against local geology, soil, and vegetation data, which were not available for this study.

4.3.10. Concentration Time

Concentration time estimates the time taken for a raindrop falling on the watershed to reach the outlet, after losing part of its volume to infiltration, evaporation, or runoff, and provides insight into the watershed's response to rainfall. It depends not only on surface area but also on lithology, rainfall, and topography [36]. It was estimated from the main thalweg length (L, km), mean altitude (Hmoy, and minimum altitude Hmin, both in m above sea level), and watershed area (A, km^2) using Giandotti's (1934) formula [37]:

$$Tc = (4(A + 1.5L)0.5)/(0.8(Hmoy - Hmin)0.5) \quad (6)$$

The concentration times obtained are 5.12 h (Djibonker) and 5.26 h (Agnack). Giandotti's formula was originally developed for small to medium mountainous Italian catchments; its direct applicability to flat, tide-influenced tropical coastal watersheds such as Djibonker and Agnack has not, to our knowledge, been locally validated against observed hydrographs, discharge, or water-level records. The resulting concentration times should therefore be treated as indicative order-of-magnitude estimates rather than as locally validated values, pending comparison with field observations.

Concentration time also depends on lithology (permeable formations favour infiltration over runoff, delaying concentration at the outlet), rainfall intensity (higher intensity shortens concentration time regardless of soil type), and topography [28]. The similarity observed between the two basins may partly reflect their shared geographic setting and generally monotonous topography.

4.3.11. Water Flow Velocity

Flow velocity is given by:

$$Ve = L/Tc \quad (7)$$

where L is the length of the main thalweg (m), and Tc is the concentration time (s). Using L = 8460 m and Tc = 5.12 h = 18.432 s for Djibonker, and L = 15.210 m and Tc = 5.26 h = 18.936 s for Agnack: Ve (Djibonker) ≈ 0.46 m/s; Ve (Agnack) ≈ 0.80 m/s. These values fall within the typical range reported for lowland rivers with gentle slopes (about 0.2–2 m/s) and are consistent with the low overall slope indices computed for both basins (Ig = 1.46 m/km for Djibonker, 2.30 m/km for Agnack). They are also consistent with watershed shape: the more elongated Djibonker basin (Kc = 1.62) shows a lower flow velocity than the less elongated Agnack basin (Kc = 1.34), in agreement with classical hydrological theory, which associates elongated basin shapes with longer concentration times and lower flow velocities [24].

4.4. Comparison of the Morphometric Variables Between the Two Watersheds

As explained in Section 3.2, the small number of individuals (two watersheds) precludes the use of multivariate techniques such as Principal Component Analysis, for which the number of observations must

considerably exceed the number of variables ($n > 5p$ to $10p$ is recommended; here $n = 2$, $p = 20$). The main morphometric and hydrological variables computed for the two watersheds are therefore compared directly in Table 9, without any inferential statistical test.

Table 9. Summary of the main morphometric and hydrological variables compared between the two watersheds.

Variable	Djibonker	Agnack
Area, A (km^2)	107.8	115.8
Perimeter, P (km)	60.3	51.7
Compactness coefficient, Kc	1.62	1.34
Equivalent rectangle length, Lrec (km)	25.81	19.94
Equivalent rectangle width, lrec (km)	4.20	5.79
Overall slope index, Ig (m/km)	1.46	2.30
Specific elevation difference, Ds	15.16	24.75
Main thalweg length, L (km)	8.46	15.21
Drainage density, Dd (km/km^2)	0.53	1.09
Hydrographic density, F	0.26	0.46
Stream frequency, Fr (km^{-2})	0.50	1.12
Torrentiality coefficient, Ct	0.15	0.58
Stream stability constant, C (km^{-1})	1.88	0.91
Concentration time, Tc (h)	5.12	5.26
Flow velocity, Ve (m/s)	0.46	0.80

Two broad patterns emerge from this comparison. First, the dimensional variables describing overall watershed size area, perimeter, and equivalent-rectangle dimensions are of similar order of magnitude in the two basins, reflecting their comparable extent and their shared position on the generally flat topography of the Casamance region. Second, the variables related to watershed shape and network configuration (the compactness coefficient, specific elevation difference, drainage and hydrographic densities, and flow velocity) differ more markedly between the two basins and appear to underlie their contrasting hydrological behaviour. Because only two individuals are compared, these patterns should be read as descriptive observations rather than as statistically validated correlations.

5. Discussion

Because this study compares only two watersheds, the relationships highlighted below should be read as descriptive patterns and working hypotheses for future research involving a larger number of comparable sub-basins, rather than as statistically validated correlations.

The compactness index (KG) shows that Djibonker is an elongated watershed (1.62) while Agnack is intermediate (1.34). This distinction matters because shape directly influences hydrological response: an elongated watershed tends to produce lower and delayed peak flows compared with a more circular watershed, which generates more rapid floods, corroborating [24]. The specific elevation difference (Ds) 15.16 (Djibonker) and 24.75 (Agnack) places both basins in the low to moderately low relief classes of the ORSTOM classification (1964), consistent with [11], who show that quantitative morphometric analysis helps to understand erosion, flooding, and drought processes linked to topography and vegetation cover.

Both basins have a complex hydrographic network dominated by intermittent channels, consistent with [7,8], who highlight the close relationship between morphology, slope, land cover, and hydrology. The relatively higher drainage and hydrographic densities of Agnack, compared with Djibonker, are consistent with a somewhat more responsive network, while Djibonker's lower densities are more consistent with a network favouring infiltration; as noted in Sections 4.3.9 and 4.3.11, these are relative, descriptive distinctions that would benefit from confirmation against local geology and soil data.

Applying Giandotti's (1934) empirical formula gives broadly similar concentration times for the two basins (5.12 h for Djibonker and 5.26 h for Agnack), suggesting a comparable order of hydrological response time despite their morphometric contrasts; this aligns with [12], who emphasizes that morphometry, combined with hydrometric data, helps predict basin response to rainfall, although, as noted in Section 4.3.10, the applicability of this formula to tidal, low-relief tropical watersheds such as these has not been locally validated. The flow velocities (0.46 m/s for Djibonker and 0.80 m/s for Agnack), in contrast, differentiate the two basins more clearly and are consistent with their contrasting shape and slope indices.

An important, and so far under-explored, dimension of these results concerns the contrasting salinity dynamics of the two basins. Djibonker's gentler slope index (Ig = 1.46 m/km), lower drainage density (Dd = 0.53), and more elongated shape (Kc = 1.62) are consistent with slower, more limited freshwater flushing, which may favour the persistence and stagnation of saline water intruding from the Kamobeul bolong, particularly during the dry season when the intermittent network largely stops draining. In contrast, Agnack's steeper slope index (Ig = 2.30 m/km), higher drainage density (Dd = 1.09), and more perennial network are consistent with more sustained freshwater discharge, which may limit saline intrusion and help support the horticultural and fish-farming activities reported in the study area. This interpretation remains qualitative and descriptive; testing it would require direct salinity and discharge measurements at both sites, which were not available for this study. If confirmed, this relationship between watershed morphology and ecohydrological vulnerability to salinization could become one of the main scientific contributions of future work building on this study.

Finally, the study highlights the ecological fragility of the Djibonker basin due to salinity, in contrast to the horticultural and fish-farming richness of Agnack. This duality illustrates the value of integrating morphometric parameters into a territorial and socio-economic approach, as recommended by [9], who stress the impact of human activities and land-use practices on hydrological dynamics.

Placing these results in a broader regional and inter-continental context helps assess whether the morphometric contrasts identified between Djibonker and Agnack reflect a general pattern in small tropical, low-relief watersheds or a more local particularity of the Casamance setting. In the south-western Ganges delta of Bangladesh, a tidally influenced, low-gradient environment broadly comparable to Lower Casamance, Joy et al. [38] report a circularity ratio as low as 0.08, a coarse drainage density, slope values below 4°, and a hypsometric index of 0.49 denoting a basin in the mature stage of geomorphic development. This combination of an elongated shape, low relief and coarse drainage network mirrors closely what is observed here for Djibonker (Kc = 1.62; Ig = 1.46 m/km; Dd = 0.53 km/km^2, "very coarse" class) and, to a lesser extent, Agnack, suggesting that the association between elongated shape, gentle slope and sparse drainage is a recurring signature of low-relief tropical deltaic watersheds rather than a feature specific to Casamance. In the Niger Delta of Nigeria, another West African tidally influenced setting, Oborie and Eteh [39] similarly show that morphometric configuration, and in particular stream frequency, governs flood response and the timing of peak discharge, reinforcing the interpretation proposed here that drainage density and network configuration, more than watershed size, condition the hydrological behaviour of these basins. By contrast, in the sixth-order watersheds of Bohol Island, Philippines, where relief is more pronounced, Torrefranca and Otadoy [40] report markedly higher bifurcation ratios (3.91–4.06) and ruggedness numbers (1.46–1.65) than those found in Djibonker and Agnack, together with a more dissected network associated with higher flood peaks; this contrast underlines that the comparatively subdued morphometric signature of the Casamance watersheds is consistent with their very low relief rather than an artefact of the method used. Taken together, these comparisons suggest that the Djibonker-Agnack contrast, modest in absolute terms but consistent across several independent indices, is of the same nature as differences documented between basins in other tropical settings, and that watershed morphometry retains explanatory value for hydrological and ecohydrological contrasts even where relief is minimal.

Limitations and Reliability of the Results

Several limitations should be kept in mind when interpreting these results. First, ASTER GDEM (30 m) provides only moderate vertical accuracy for watersheds of about 100 km^2; its influence on the extraction of first-order streams, and consequently on drainage density and related indices, has not been separately quantified here and would benefit from comparison with a higher-resolution DEM or field-surveyed cross-sections. Second, all hydrological variables in this study (concentration time, flow velocity) are derived from empirical, DEM-based formulas; no observed discharge, water-level, or salinity data were available to validate these estimates against field conditions, so the absolute values should be treated with corresponding caution even though the relative comparison between the two basins remains informative. Third, as discussed in Sections 3.2 and 4.4, the comparison of morphometric variables between only two individuals is necessarily descriptive; a statistically robust multivariate analysis would require subdividing each watershed into a larger number of sub-basins. Addressing these three limitations (DEM validation, field hydrological measurements, and a larger comparative sample) constitutes a natural next step for this line of research.

A methodologically relevant direction for that future, larger-sample or time-series-based work is offered by recent developments in the statistical treatment of hydroclimatic correlations: Koskinas et al. [41] show that cross-correlation significance tests must account for the long-range dependence (Hurst-Kolmogorov behaviour) typical of natural hydro-morphological and climatic series, consistent with the broader case for long, undisturbed observational records made within the IAHS “Panta Rhei” scientific decade [42]. Applying such persistence-aware significance tests would be the appropriate next step once a larger set of comparable sub-basins, or multi-year hydro-climatic time series for Djibonker and Agnack, becomes available.

6. Conclusions

The Djibonker and Agnack watersheds are situated on relatively flat terrain, with average elevations of around 20 m and generally gentle slopes, contributing to comparatively low runoff potential in both basins, tempered by their contrasting drainage densities. The concentration times obtained are 5.12 h (Djibonker) and 5.26 h (Agnack). The flow velocities, 0.46 m/s (Djibonker) and 0.80 m/s (Agnack), are consistent with the low overall slope indices and with the more elongated shape of the Djibonker basin, in line with classical hydrological theory. The two basins share broadly similar dimensional characteristics but differ more markedly in shape and drainage network configuration. Because the comparison involves only two watersheds, these patterns are presented descriptively rather than as statistically validated correlations, and further testing would require a larger, sub-basin-based sample. The generally monotonous relief of the Casamance region likely explains part of the overall similarity between the two watersheds. The hydrographic network identified in this study consists of a variety of channels that feed and shape the existing landforms; both watersheds lie within the alluvial and fluvio-marine zone of the Casamance basin. Beyond their hydrological interest, the morphometric contrasts identified here, particularly in slope index and drainage density, offer a plausible, though still qualitative, explanation for the marked difference in salinity dynamics between the two basins, a relationship that merits direct field validation in future work. The analysis of morphometric and hydrological characteristics presented here contributes to understanding flow patterns within small, ungauged watersheds in the context of global change.

Statement of the Use of Generative AI and AI-Assisted Technologies in the Writing Process

During the preparation of this manuscript, the authors used Claude (Anthropic) in order to assist with the final proofreading and formatting of the manuscript (renumbering of references and in-text citations, checking of figure citations, English translation of figure legends and annotations). After using this tool,

the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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Author Contributions

Conceptualization, B.S.; Methodology, B.S.; Software, B.S.; Validation, B.S., C.A.A.S.S. and T.S.; Formal Analysis, B.S.; Resources, B.S.; Data Curation, Y.S.; Writing-Original Draft Preparation, B.S.; Writing-Review & Editing, C.F. and T.S.; Visualization, B.S.; Supervision, T.S.; Project Administration, B.S.

Ethics Statement

This study is based on remote-sensing data products and does not involve human or animal subjects.

Informed Consent Statement

This study does not involve human subjects.

Data Availability Statement

The ASTER GDEM data used in this study are publicly available from the USGS EarthExplorer platform (http://earthexplorer.usgs.gov/, accessed on 12 April 2026). The morphometric results derived from these data are reported in the tables and figures of this article. The GIS layers produced in this study are available from the corresponding author upon reasonable request.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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