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Contribution to the sustainable management of water and soil resources in North-West Benin: characterization of the watershed heads of the Ouémé and Pendjari rivers in the commune of Copargo

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Abstract

Watershed heads, which are the upstream areas where rivers originate, are crucial zones for water resource management. Defined by first- and second-order streams according to Strahler's classification, watershed heads are often overlooked in water resource planning due to limited information and knowledge about these areas. This oversight leads to anthropogenic pressures and negative impacts on water quality, soils, and biodiversity. The objective of the present study is to characterize the watershed heads of the Ouémé and Pendjari rivers within the Copargo municipality, with the aim of improving understanding of sustainable water and soil resource management in this region. For this purpose, mapping techniques and geographic information systems were employed to identify and delineate the watershed heads. Criteria related to morphometry, land use, and land cover were utilized to characterize the areas of the watershed heads. Exploratory and principal component analyses based on various characteristics of the watershed heads were conducted using the R software, which highlighted the different challenges associated with these areas. The study delineated 25 watershed heads: 14 in the Pendjari watershed and 11 in the Ouémé watershed, revealing their surface area and occupancy within the respective watersheds. The average unit area of the watershed heads is 23.6 km² in the Ouémé watershed and 21 km² in the Pendjari watershed. Across all watershed heads, the Gravelius compactness index ranges from 1.2 to 1.5, while slopes vary from 1.5% to 4.5%. Most watershed heads in Copargo are characterized by high proportions of agricultural land, moderate forest cover, and low levels of urbanized area. The high proportion of agricultural land has significant implications for water and soil resources. The results of this study provide valuable data for decision-makers and reveal the vulnerability of watershed heads to anthropogenic pressures. With a view to assessing the impact of anthropogenic pressure on the water resources of the study area, it would be beneficial in the future to proceed with the physicochemical and bacteriological characterization of these resources.

Keywords: Watershed Heads Characterization, Ouémé and Pendjari watersheds in Copargo, Integrated and Sustainable Water and Soil Resource Management

Introduction

Watershed heads (WSH), also known as headwaters or river heads, refer to the areas drained by the first watercourses in the hydrographic network (Maman, 2007). They are located upstream of the watercourses, at their source (Agence de l'Eau Loire-Bretagne, 2018). The definition of WSH varies

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depending on the approach and region. However, most definitions refer to Strahler's classification (1952), which orders watercourses in the hydrographic network from source to outlet, establishing an order of importance based on the level of confluence (Clarke et al., 2008; Wallace & Eggert, 2009). According to the Agence de l'Eau Loire-Bretagne (2020), WSH corresponds to the upstream zones of rivers, encompassing springs, diffuse flows, streams (whether temporary or permanent), and their associated watershed areas. They are defined as the catchment areas of rivers with a Strahler rank less than or equal to 2 and a slope greater than 1%. This slope criterion can be adapted locally for streams with low specific power, where there is a risk of failing to meet environmental objectives (Agence de l'Eau Loire-Bretagne, 2020). For some authors who share this perspective, WSH corresponds to the watershed areas of rivers ranked 1 and 2 in Strahler's system, i.e., small tributaries of the hydrographic network (Cirou, 2017; Clarke et al., 2008; Freeman et al., 2007; Rasmussen et al., 2013).

Situated at the interface between terrestrial and aquatic environments, WSH abounds with small streams, ponds, and wetlands, providing essential ecosystem services for the proper functioning of hydrosystems (Henner, 2013; Kagan, 2017; LE Bihan, 2017). Their distribution across a watershed makes them crucial for the water cycle. Indeed, WSH occupies 70-80% of the total surface area of a watershed, while the length of their watercourses represents 60-80% of the total length of the hydrographic network. They are also responsible for 60% of the water quality in downstream rivers (Agence de l'Eau Loire-Bretagne, 2018, 2020; Kagan, 2017; Maman, 2007). Due to their multiple functions, WSH is a major challenge for water and soil resource management. The integrity of these areas is essential for the functioning of downstream rivers, in terms of both flow and water quality.

Despite their importance, WSH watercourses are often overlooked in inventories and in the preparation of planning documents and water resource development and management schemes (Dourotimy Rachel et al., 2020). These areas, often ignored by certain socio-professional groups, are subject to increasing anthropogenic pressure, and their condition is rarely assessed (Agbanou, 2018; Barnaud, 2013; Dourotimy Rachel et al., 2020; Meyer & Wallace, 2001). Additionally, the degradation of soil fertility, linked to overexploitation of the land and climate change, is leading to a significant drop in agricultural productivity, prompting the population to seek new fertile land. Considered fertile, WSH is exploited for various purposes, including agriculture.

In northern Benin, where agriculture is the main economic activity, WSH is also subject to these anthropogenic pressures. The intensification of agriculture and livestock farming, driven by the growing demand for food products and the depletion of arable land in the valleys, is compromising the

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integrity of water and soil resources, as well as the state of biodiversity, which is becoming increasingly degraded (Gouv-Bénin, 2021). Stakeholders from all socio-professional categories are unaware of the importance and role of WSH, and riverside populations fail to recognize the need to protect and preserve these areas, often seeing them merely as spaces to exploit for immediate benefits (Dourotimy Rachel et al., 2020).

Faced with these challenges, WSH are now at the center of growing concerns, although their inclusion in water management is relatively recent (Agence de l'Eau Loire-Bretagne, 2020; CREDEL, 2019; Henner, 2013; Kagan, 2017; LE Bihan, 2017). In Benin, this is reflected in the pilot integrated management initiative for the headwaters of the Mékrou watershed, implemented in 2012 by PNE-Benin. Dourotimy (2020) also worked on identifying WSH to improve the sustainable management of water resources in the Mékrou River. The present research is therefore the second study devoted to WSH in Benin. Its originality lies in the combination of several approaches, which not only allow for the identification but also the characterization of WSH according to various criteria. This will create a database that facilitates their integration into the planning and management of water and soil resources. For WSH to be included in the planning and sustainable management of water and soil resources, it is essential to know their location, functions, importance, and vulnerability to human pressures.

In light of the above, the present study aims to characterize the WSH of the Ouémé and Pendjari rivers in the municipality of Copargo, northwest Benin, in order to contribute effectively to the integrated and sustainable management of water and soil resources in this region.

Materials and methods

Study area

Located between latitudes 9°40'50" and 10°4'31" north and longitudes 1°20' and 1°45' east, the municipality of Copargo covers an area of 876 km² and has a population of approximately 71,000. It is bordered to the northwest by Boukombé, to the north and northeast by Kouandé, to the southwest by Ouaké, to the southeast and east by Djougou, and to the west by the Republic of Togo (Figure 1).

The region experiences a Sudano-Guinean climate, moderated by the Atacora mountain range. During the dry season, the Harmattan, a cool and dry wind, blows across the area. There are two main seasons: a dry season from mid-October to mid-April, and a rainy season from mid-April to mid-October. Rainfall is unevenly distributed throughout the municipality, ranging from 800 mm to 1,300 mm, with August and September being the wettest months (Mathieu & Bernard, 2020).

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The highest average monthly maximum temperature occurs in March, reaching around 36°C, while the lowest average minimum temperature is recorded in August at 32°C.

The vegetation in the area is primarily composed of wooded and grassy savannas. Common shrub species include shea, *Parkia biglobosa*, mango, and caïlcédrat. There is also a classified forest covering 1,091 hectares along with gallery forests scattered across the region (République du Bénin, 2019).

The commune's topography is dominated by the Atacora mountain range, with its highest point at 654 meters above sea level, located in the Tanéka-Koko area in the western part of the municipality. The remaining area consists of vast wooded plains interspersed with valleys and basins, which are often wet and conducive to agriculture. These wetlands are concentrated in the northwestern part of the commune, at elevations ranging from 329 to 396 meters (Mathieu & Bernard, 2020).

Copargo is traversed by a dense hydrographic network, with several rivers, the main ones being the Ouémé and Pendjari. The Pendjari has a seasonal flow, while the Ouémé flows year-round toward the Atlantic Ocean (République du Bénin, 2019).

Soils in Copargo are primarily unconcreted and indurated tropical ferruginous leached soils, found mainly on the summits and slopes. Lighter soils with low water retention capacity are predominantly found in the arrondissements of Anandana and Singré (Gnonhoue, 2020; Mathieu & Bernard, 2020).

Geologically, the region is characterized by formations ranging from the Atacorien series (which extends into Togo and Ghana) to the earliest outcrops of the Dahomeyan or Benino-Togolese basement, composed of very ancient volcanic rocks. These are followed by layers of quartzites, schists, micaschists, and deposits from the Buem series (UNEP/GEF/Volta/NR Benin, 2010). The water resources in Copargo include both groundwater and surface water.

The local economy is largely based on agriculture, fishing, hunting, trade, manufacturing, and other industries. The population is predominantly agricultural, with farming as the main economic activity, employing over 90% of the working population. The three primary sectors contributing to the local GDP are yam (80.12%), maize (14.95%), and cashew nuts (7.43%). Other crops that could further contribute to local economic growth include chili peppers, rice, and cotton.

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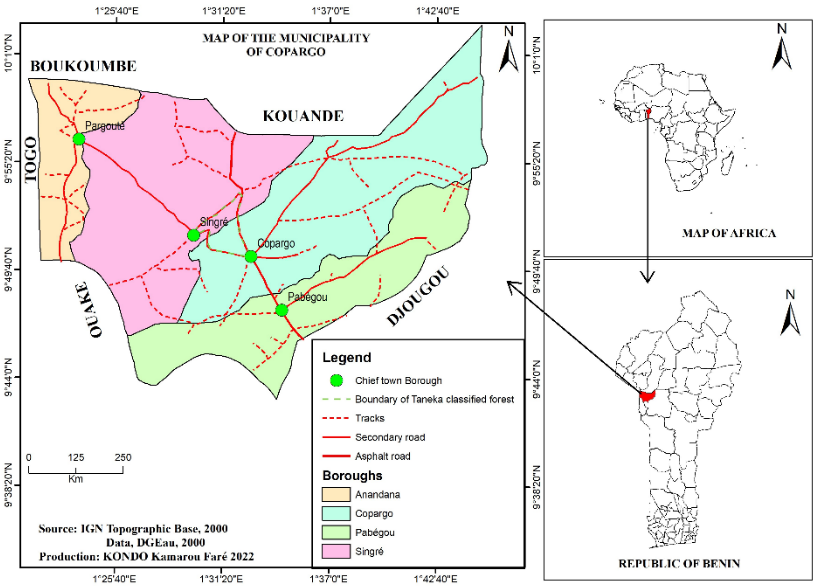

Figure 1: Geographical location of the study area

Method for delimiting and characterizing watershed heads

Understanding the concept of watershed heads

The definition of Watershed Heads (WSH) varies depending on the approaches and regions around the world. However, most definitions refer to Strahler's (1952) classification or ordination. This method classifies watercourses based on their significance from the source to the outlet of a watershed, assigning ranks that increase from upstream to downstream. The Strahler ordination method, summarized in Figure 2, follows these rules: a) the watercourse at the source is assigned rank 1, b) any watercourse without tributaries is of order 1, c) the confluence of two watercourses of order n results in a watercourse of order n+1, and d) any watercourse that receives a tributary of a lower order retains its original order (Strahler, 1952). For some authors, WSH corresponds to watersheds delineated by watercourses of ranks 1 and 2 according to Strahler (Clarke et al., 2008; Freeman et al., 2007; Rasmussen et al., 2013). Others extend the definition to include rank 3 or, in some cases, restrict it to rank 1 (Krecek & Haigh, 2006; Wallace & Eggert, 2009). WSH can also be defined based on the width and discharge of the watercourses, considering them as upstream areas devoid of fish (Wipfli et al., 2007).

According to the Agence de l'Eau Loire-Bretagne (2018), in its Water Development and Management Master Plan (2016-2021), WSH is "watersheds delineated by watercourses of Strahler rank equal to or less than 2 (Figure 3) and having a slope greater than 1%." This slope criterion may be

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adapted locally for watercourses with low specific power, which present a risk of failing to meet environmental objectives.

In Benin, in her study on the identification of WSH in the Mékrou River, Dourotimy (2020) defines WSH as the watersheds of watercourses with a Strahler rank less than or equal to 2 and a slope greater than 1%. However, this slope criterion is often contested in the delineation of watershed heads for several reasons (Henner, 2013; LE Bihan, 2009).

In the context of this study, the slope criterion was not retained for the following reasons: a) applying the slope criterion would exclude fragile watercourses from WSH; b) the 1% slope criterion is not substantiated in the scientific literature; c) applying this criterion results in the exclusion of meandering watercourses; d) within the same WSH, slopes can vary both above and below 1%, leading to inconsistencies (LE Bihan, 2017); e) the slope criterion is not relevant and can be counterproductive, as it overlooks environments vulnerable to anthropogenic pressures and fails to address lowland and plateau watersheds adequately (Agence de l'Eau Loire-Bretagne, 2018; LE Bihan, 2009); f) mapping rivers according to Strahler's ordination method shows that the watercourses in the WSH are not necessarily located upstream of the entire hydrographic basin.

For this reason, this study defines and delimits WSH as the small watersheds drained by watercourses of Strahler ranks 1 and 2. Thus, in the present study, WSH are considered as the areas drained by the watercourses of order 1 and 2 according to the Strahler classification.

Figure 2: Strahler hydrographic network classification
(Agence de l'eau Loire-Bretagne, 2020)

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Figure 3: Hydrographic network showing watershed heads
(Agence de l'eau Loire-Bretagne, 2020)

Cartographic and GIS Tools

The delineation of WSH requires a cartographic approach (Cirou, 2017; Dourotimy Rachel et al., 2020).

Delineation of Watershed heads (WSH)

The delineation of the WSH in Copargo was carried out using a cartographic approach. To achieve this, it was first necessary to inventory and validate the watercourses by referencing those surveyed in the field. Subsequently, the watercourses were classified, followed by the delineation of the WSH based on the Strahler classification.

a. **Inventory of streams (watercourses) of the watershed heads of Copargo**

This involved a series of operations to identify the hydrographic network, from the main rivers to the smaller creeks and streams in the Copargo municipality. Using the Digital Elevation Model (DEM), raster layers were generated, and through vectorization, linear layers representing the hydrographic networks of the Ouémé and Pendjari rivers in Copargo were obtained. The chosen discretization threshold was 350, which provided the maximum level of detail for the hydrographic networks. Additional fieldwork was also conducted to validate the hydrographic network that was generated.

b. **Ordination of the hydrographic network according to the Strahler method**

Using the Strahler method, each watercourse in the hydrographic network was assigned a rank based on its order of significance, from source to outlet. In this process, watercourses at the source, as well as those without tributaries, were assigned rank 1. The confluence of two rank 1 watercourses resulted in a rank 2 watercourse. Similarly, the confluence of two rank 2 watercourses resulted in a rank 3 watercourse, and the confluence of two rank

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3 watercourses produced a rank 4 watercourse. Watercourses receiving tributaries of a lower rank retained their original rank. As a result, at the end of this ordination process, the hydrographic network was classified into four ranks according to Strahler classification

c. Delineation of the Watershed heads of Copargo

Based on the definition of WSH adopted in this study (areas drained by and delineated by watercourses of Strahler ranks 1 and 2), the delineation process involved identifying the outlets of the rank 2 watercourses across all watersheds. From each of these outlets, the WSH was delineated by aggregating the areas across all the watersheds.

Watershed head characterization

The characterization aimed to describe the WSH based on several criteria, with the goal of contributing new knowledge about their morphometric characteristics and enhancing understanding of the condition of the WSH.

Criteria relating to the physical and geographical context

These criteria pertain to general morphological characteristics, as well as specific elevation and altitude at the crest and downstream.

General morphology index

The general morphology index of the WSH includes area, perimeter, the linear extent of the watercourses within the WSH, the Gravelius compactness index (KG), the density of channels, the density of the low point network, and the time of concentration.

Area and Perimeter

The area and perimeter are directly determined from the watershed head map using GIS software.

Gravelius Compactness Index (KG)

The Gravelius compactness index provides information about the shape of the WSH and indicates its responsiveness following a rainfall event. The Gravelius compactness index is calculated using the following formula:

$$\text{KG} = \frac{Perimeter\ of\ the\ watershed\ head}{2\sqrt{\pi(Area\ of\ watershed\ head)}} \quad (1)$$

KG = Compactness Index

If KG is close to 1, the WSH has a diffuse (or irregular) shape, resulting in a strong hydrological response.

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If KG is greater than 1, the WSH takes on an elongated shape, which results in a weaker hydrological response (Gravelius, 1914).

Average slope of the watershed head

The average slope can provide insights into the topography of the valley (whether it is more or less rugged) within the WSH. A pronounced slope may also correspond to increased runoff. In this study, the slope is derived from a slope raster of each WSH through the processing of the DEM of the municipality of Copargo. The resulting values thus represent the average slope.

Time of concentration (Tc)

The time of concentration is the time it takes for a raindrop, falling at the furthest point of a watershed, to reach the watershed outlet. In other words, it is the maximum time needed for runoff, generated by uniform rainfall, to reach the outlet. This parameter is crucial in hydrology, as it helps estimate a watershed's response time to precipitation, thereby influencing flood forecasting and stormwater management (Critchely & Siegert, 1991; Giandotti, 1934; Kirpich, 1940; McCuen, 2004; Te Chow et al., 1988). In this study, the time of concentration was calculated using the following formula:

$$Tc = 0{,}108 \frac{\sqrt[3]{WSH\ area\ (km2) * lLength\ of\ the\ longest\ flow\ path\ (km)}}{\sqrt{Slope\ of\ the\ longest\ flow\ path}}\ \text{(hour)} \quad (2)$$

Density of inventoried channels

The density of inventoried channels allows for estimating the importance of the surface area in contact with terrestrial environments, where potential functional hyporheic zones (areas where groundwater and surface water mix, contributing to self-purification processes) may exist (Meyer et al., 2007). The density is calculated using the following formula:

$$Dens\_IC = \frac{Extent\ of\ the\ Watercourse\ )}{watershed\ head\ area\ (ha)} \quad (3)$$

Density of low point network

The low point network density indicates the density of identified thalwegs within the WSH. A higher density reflects a favorable context for runoff, as more low points facilitate the movement of water. The low point network density is calculated using the following formula (Cirou, 2017):

$$Dens\_Lpn = \frac{Length\ of\ the\ low-point\ network}{Watershed\ head\ area\ (ha)} \quad (4)$$

Dens_Lpn = Density of low point network

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Specific relief, crest elevation, and downstream elevation

Specific relief, crest elevation, and downstream elevation are determined directly from the map using GIS tools. The specific relief classifies the WSH relief into seven categories (DGEAU, 2013) (Table 1, summarized below).

Table 1: Classification of watershed heads relief

Specific relief	**<10**	**10-25**	**25-50**	**50-100**	**100-250**	**250-500**	**>500**
Class	R1	R2	R3	R4	R5	R6	R7
Relief	Very weak	Weak	Fairly strong	Moderate	Relatively low	Strong	Very strong

Risk and Stake Criteria

The risk and stake criteria adopted in this study include land use criteria (such as agricultural, and urban areas), land cover criteria (such as forests), as well as criteria specific to wetlands.

Land use and land cover

Land use and land cover, representing the different activities in the study area, required calculating the percentage of land by typology (urban areas, agricultural land, forested areas). The study of land use in the WSH was conducted using remote sensing via Google Earth Engine, employing a supervised classification with the ESA WorldCover classifier (Zanaga et al., 2022). In this context, the percentage of land occupation for each typology in the WSH was calculated using the following formula:

$$\%Land\_Use = \frac{Typological\ area}{Watershed\ head\ area} \times 100 \quad (5)$$

Wetlands density

The wetland density (W-Dens) within the WSH, defined as the proportion of wetland area relative to the total area of the watershed, is calculated using the following formula (Cirou, 2017):

$$W\_Dens = \frac{Wetland\ area}{Watershed\ head\ area} \times 100 \quad (6)$$

Statistical analysis

Data processing resulting from the characterization and statistical analysis was performed using Excel 2013 and R software. Excel was used for performing various calculations, as well as for producing tables and graphs. Multivariate statistical analysis was carried out using R software (Husson et al., 2010; Lê et al., 2008). Using the compiled database that includes all characterization criteria, exploratory analyses were conducted to classify and differentiate the WSH based on their functions and associated issues. A Principal Component Analysis (PCA) was performed to examine the

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distribution of the WSH according to their morphological characteristics. Additionally, a Hierarchical Ascending Classification (HAC), based on the PCA results, was used to identify groups of WSH exhibiting similar morphological traits. The morphological criteria were then used to characterize each group, with the objective of testing whether the mean of each group differed significantly from that of the overall population. An Analysis of Variance (ANOVA) was performed at the 0.1% significance level, assuming homoscedasticity (equal variances across groups).

Results

Inventory of watercourses

The results of the watercourse inventory conducted in the municipality of Copargo are shown in Figure 4 below. The figure illustrates that the hydrographic networks of both the Pendjari and Ouémé rivers consist of minor streams, secondary brooks, and main watercourses.

Ordination of the hydrographic network and identification of watershed heads

Figure 5 presented below illustrates the hydrographic networks of the Ouémé and Pendjari rivers classified according to Strahler's method. The figure shows that, within the municipality of Copargo, the hydrographic networks consist of watercourses of orders 1, 2, 3, and 4 according to Strahler's classification. In this study, the identified WSH correspond to small watersheds drained by order 1 and order 2 watercourses. Specifically, these small watersheds have outlets defined by either the confluence of two order 1 watercourses or the confluence of one order 1 and one order 2 watercourse.

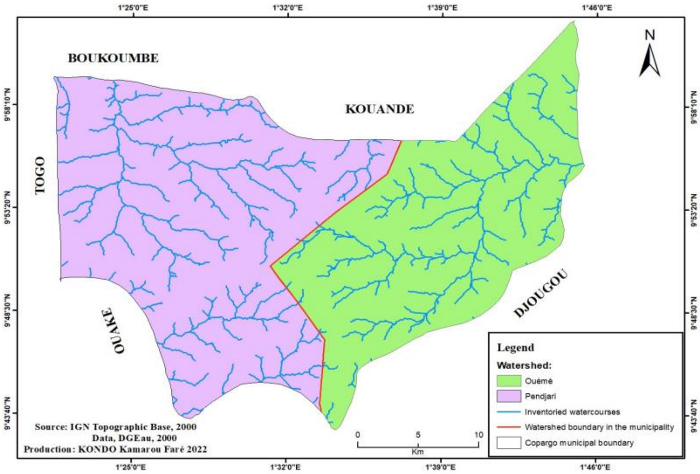

Figure 4: Map of the watercourses inventoried at the watershed heads within the municipality of Copargo

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Delineation obtained for the Ouémé and Pendjari watersheds

Figure 6 below illustrate the various WSH delineated in the municipality of Copargo. A total of 25 WSH have been identified and delineated. Of these, 11 are located in the Ouémé watershed, and 14 in the Pendjari watershed. Each of these WSH has an outlet defined by either the confluence of two order 1 watercourses or the confluence of one order 1 and one order 2 watercourse, according to Strahler's classification.

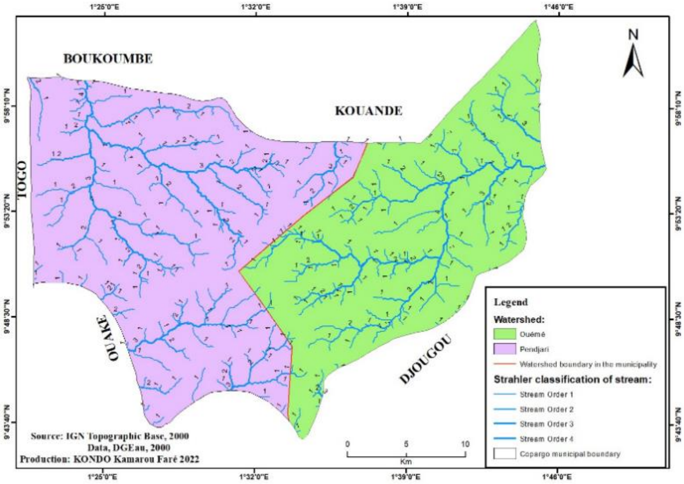

Figure 5 Ordination of the hydrographic network of Copargo according to Strahler's method

Characteristics of the watershed heads
Morphometric characteristics
Surface area

The areas of the delineated WSH in the municipality of Copargo are shown in Figure 7. The data reveals that the size of the WSH in the Ouémé watershed ranges from 9.3 km² (930 hectares) to 44.4 km² (4,440 hectares). In the Pendjari watershed, the WSH areas range from 7.1 km² (710 hectares) to 42 km² (4,200 hectares). The largest WSH is located in the Ouémé watershed.

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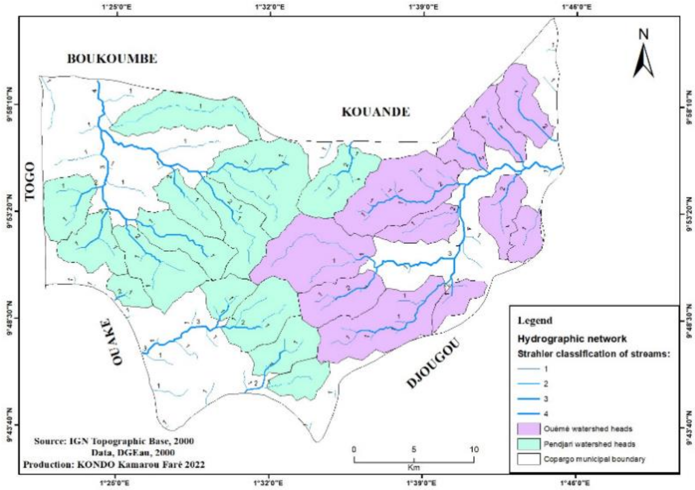

Figure 6: Map of the delineated watershed heads of the Ouémé and Pendjari rivers in the municipality of Copargo

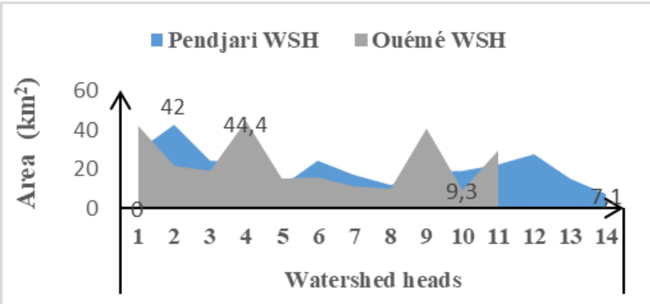

Figure 7: Surface area of the Pendjari and Ouémé watershed heads in Copargo

Perimeter

Figure 8 below shows the perimeter of each WSH, ranging from 14.8 km to 31.7 km for the Ouémé watershed and from 11.3 km to 31 km for the Pendjari watershed.

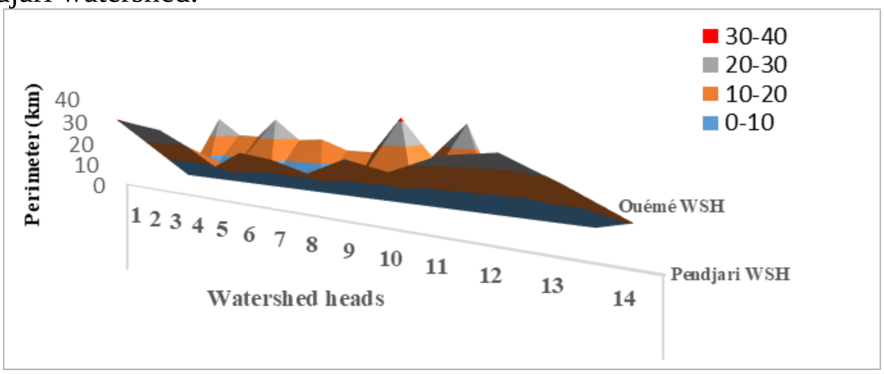

Figure 8: Perimeter of the Pendjari and Ouémé watershed heads in Copargo

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Gravelius compactness index (KG)

The Gravelius compactness index, calculated for each WSH, is greater than 1. It ranges from 1.2 to 1.5 for the Ouémé watershed, while it fluctuates from 1.1 to 1.6 for the Pendjari watershed.

Linear of watercourses at the watershed heads

In Copargo, the watercourses of the Ouémé watershed extend over 132 km, accounting for 83.5% of the total length of the Ouémé hydrographic network. In contrast, the watercourses of the Pendjari watershed extend over 293.7 km, accounting for 59.4% of the total length of the Pendjari hydrographic network.

Average slope and area of watershed heads

Figure 9 below shows the variation in slope with respect to the area of the WSH. The slope varies between 1.5% and 4.2%. Relatively higher slopes are generally observed in the smaller WSH of the Ouémé watershed.

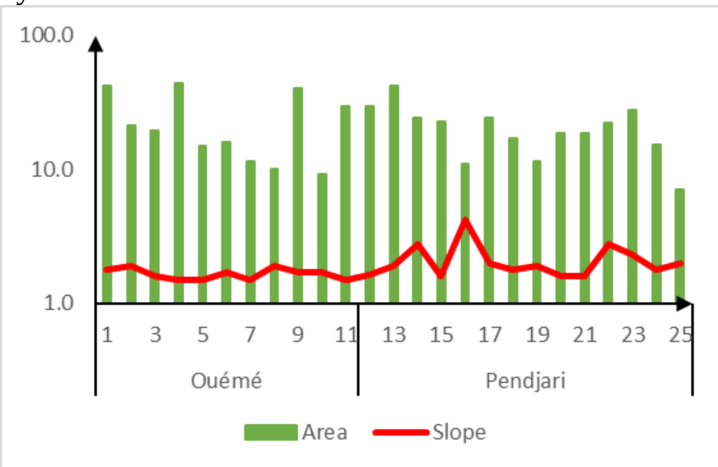

Figure 9: Area and average slope of watershed heads

Crest and downstream elevation

The elevations of the crest and downstream of the WSH are presented in Figure 10 below. In the Ouémé watershed, the crest elevation ranges from 432 m to 543 m, while the downstream elevation spans from 375 m to 453 m. In the Pendjari watershed, the crest elevation varies from 431 m to 644 m, and the downstream elevation ranges from 342 m to 432 m.

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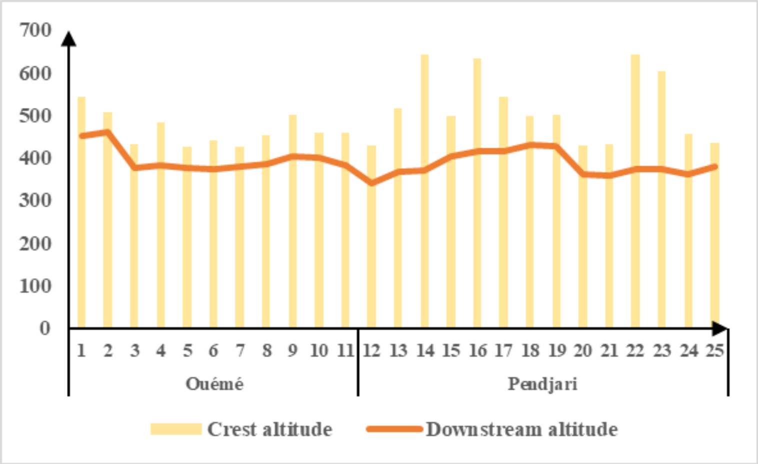

Figure 10: Crest and downstream elevation of Copargo watershed heads

Specific relief and average slope of the watershed heads

As shown in Figure 11 below, significant specific relief in the Ouémé WSH is typically associated with steeper slopes. A similar pattern is observed in the Pendjari WSH, where average slopes correspond to variations in specific relief.

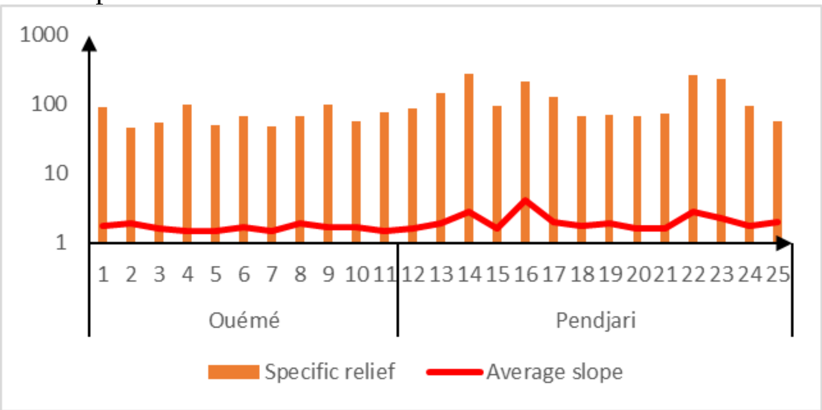

Figure 11: Specific relief and average slope of the Copargo watershed heads

The specific relief values allowed the classification of the WSH relief into four categories: R3, R4, R5, and R6. According to Figure 12, 64% of the WSH in Copargo exhibit moderate relief (R4), 8% show strong relief (R6), 20% exhibit fairly strong relief (R5), and 8% have relatively low relief (R3).

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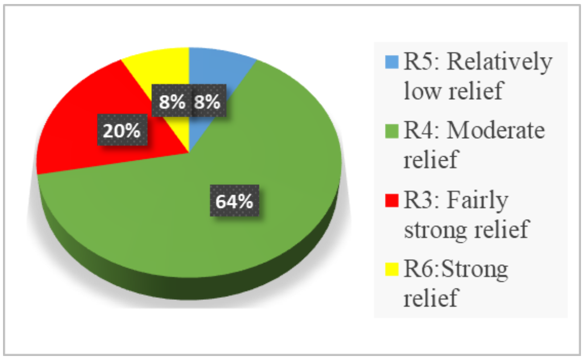

Figure 12: Relief classes of Copargo watershed heads

Specific relief and size of watershed heads

According to Figure 13, which illustrates the variation of specific relief of the WSH based on their size, it is the larger WSH that exhibit the highest specific relief. This trend is observed for both the headwaters of the Ouémé and those of the Pendjari.

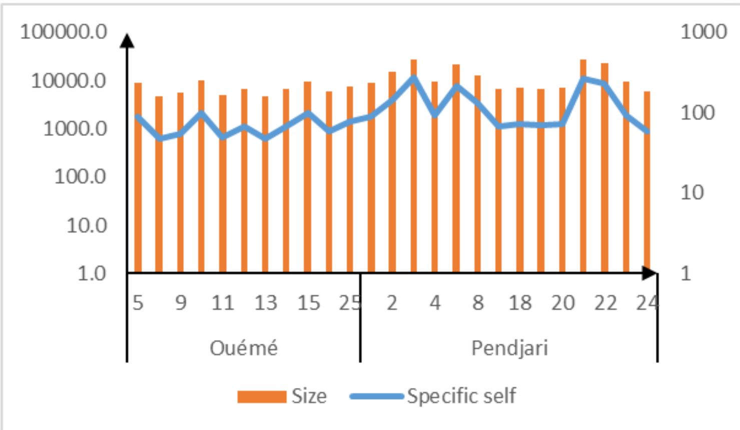

Figure 13: Size and specific elevation change of Copargo's watershed heads

Average morphometric characteristics of watershed heads by watershed

Table 2 summarizes the main average morphometric characteristics of the delineated WSH. The average area of the WSH in the Ouémé watershed is 23.6 km², while in the Pendjari watershed it is 21 km². The average unit perimeter is 22.3 km in the Ouémé watershed and 21 km in the Pendjari watershed. The total area of the WSH in the Ouémé watershed is 259.4 km², representing 69.4% of the total area of the Ouémé watershed. In contrast, the total area of the WSH in the Pendjari watershed is 293.7 km², corresponding to 59.4% of the total area of the Pendjari watershed.

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Table 2: Morphometric characteristics of watershed head by watershed in Copargo

	Ouémé watershed	**Pendjari watershed**
Number of watershed heads	11	14
Min-Max area	9.3 – 44.4 km^2	7.1 - 42 km^2
Average area	23.6 km^2	21 km^2
Total area	259.4 km^2 (69.4%)	293.7 km^2 (59.4%)
Compactness index (KG)	1.2 – 1.5	1.1 – 1.6
Average perimeter	22.3 km	21 km
Length of hydrographic network	132 km (83.5%)	198 km (85.7%)

Relationship between the morphology of the watershed heads and their delineation

Figure 14 presents the results of the Principal Component Analysis (PCA) performed on the morphometric characteristics of the WSH. This analysis reveals that the first two dimensions of the correlation circle account for 57.83% of the total variance. The first dimension (Dim 1: 31.87%) is primarily positively influenced by the mean slope and specific relief. The second dimension (Dim 2: 25.96%) is driven, in its positive section, by density channel and, in its negative section, by the Gravelius compactness index and WSH area. This indicates that density channel is negatively correlated with both the Gravelius compactness index and WSH area.

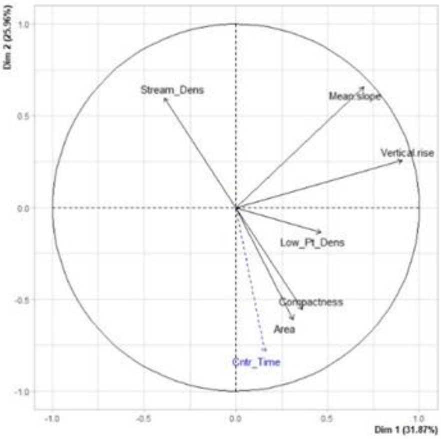

Figure 14: Graph of variables representing dimensions 1 and 2 of the PCA on the morphology of the WSH

Grouping of watershed heads into homogeneous morphology classes

Figure 15 shows the graph of the overlap between the WSH and the morphometric variables, illustrating those whose characteristics most contribute to the formation of the first two dimensions of the PCA. The graph reveals three distinct groups or classes of WSH. Morphological class 1 (MC1) consists exclusively of WSH from the Ouémé watershed (4%). Morphological class 2 (MC2) includes 32% of WSH from Ouémé and 48% from Pendjari.

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Morphological class 3 (MC3) is made up of 8% of WSH from both Ouémé and Pendjari (table 3).

Table 3: Classes of watershed heads morphology based on their respective watersheds

Morphological class	Watershed	
	Ouémé	Pendjari
MC1	4%	0%
MC2	32%	48%
MC3	8%	8%

The statistical trends characterizing each class based on morphological criteria are summarized in Table 4. The mean values of each morphometric characteristic are provided for each morphological class. If a characteristic does not show a significant difference from the overall mean of all WSH, it is marked as 'NS' (Not Significant).

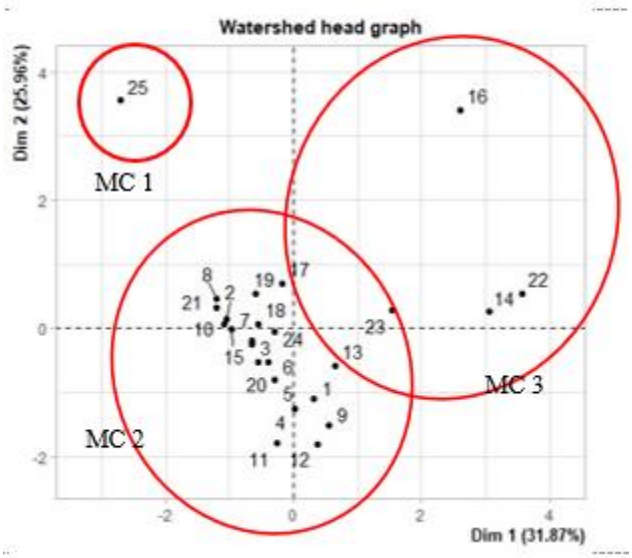

Figure 15: Graph of individuals representing dimensions 1 and 2 of the PCA on the morphology of the WSH

Table 4: Description of morphology classes by morphology criteria

		Area	**Compactness**	**Dens_Ch**	Dens_Lpn	**Tc**	**Average slope**	**Vertical rise**
MC1	Mean	2969,68	1,53	2,85	1,18	0,50	0,015	77,00
	σ	0,00	0,00	0,00	0,00	0,00	0,000	0,00
MC2	Mean	2304,06	1,30	6,24	2,25	0,42	0,019	NS
	σ	868,13	0,10	2,42	0,50	0,11	0,004	51,03
MC3	Mean	1564,86	1,34	4,56	1,38	0,33	0,019	112,50
	σ	612,01	0,01	0,28	0,34	0,07	0,002	58,75
Total	**Mean**	**2212,42**	**1,32**	**5,84**	**2,07**	**0,42**	**0,019**	**105,84**
	σ	859,59	0,09	2,00	0,55	0,10	**0,004**	50,80

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The information provided by the different morphology classes in Figure 15, Tables 3 and 4 is summarized below in table 5.

Table 5: Summary description of watershed heads morphology

Class	Description
MC1	Profile of an elongated WSH with a low average slope and elevation change, exhibiting a high concentration time.
MC2	Profile of a WSH with a steep slope, high watercourse density, and the presence of thalwegs.
MC3	Profile of small WSH with a less elongated shape, low concentration time, and significant slope and elevation change.

Environmental characteristics of the watershed heads

Direct observation and field analysis of the WSH in Copargo reveal several environmental characteristics. These include various crops such as maize, cotton, yam, beans, and soybeans. Fallow agricultural areas are also present in the WSH. Water infrastructure, such as wells and boreholes, is found at various locations within the WSH. The non-cultivated areas within the WSH are well forested. Crops, particularly maize, soybeans, millet, and sorghum, are found near watercourses. Rice cultivation is observed in the low-lying areas and wetlands. The area supports various types of vegetation, including trees, shrubs, tree-shrub-herbaceous associations, and herbaceous plants.

Classification of watershed heads according to their stakes

Specific stakes related to morphological classes

The different morphological classes are characterized by varying degrees of erosion and sedimentation risks. Class M1 is characterized by significant vertical transfer risks, particularly in terms of time of concentration, and a predominance of agricultural land use. In contrast, Class M2 is distinguished by a higher density of wetlands, especially thalwegs, lower erosion risk, and less urbanization. Finally, Class M3 is distinguished by its forested context and lower horizontal transfer risks, resulting from its low time of concentration.

Land use profile and associated stakes

The distribution of land use coverage percentages across the main categories is shown in three classes in Figure 16. As shown in the figure, Class 1 is dominated by agricultural land, Class 2 by urban areas, and Class 3 by forests. The histograms show that the majority of WSH (12 WSH) have a high proportion of agricultural land, while only a few WSH exhibit a low proportion (Class 1). The opposite trend is observed for forested areas, which dominate in Class 3. Class 2, which includes only a few watershed heads, has a relatively

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high proportion of urbanized land, though it rarely exceeds 20% of the total area of the watershed head (Figure 16).

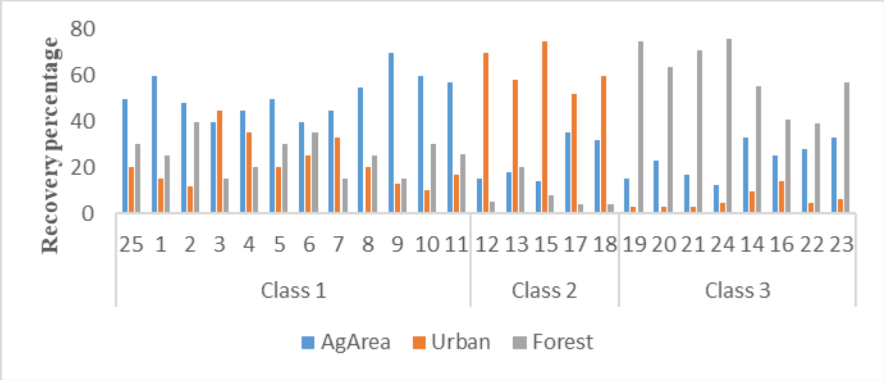

Figure 16: Distribution of the percentages of coverage of the main land uses of the watershed heads in Copargo

The PCA was performed on all WSH based on the three main types of land use. Based on the dendrogram, three classes were selected. The classification explains approximately 80% of the variance. This allowed us to categorize the WSH according to their predominant land use profile (agricultural, urban, or forestry), as shown in Table 6.

Table 6: Land use profiles obtained and associated land use percentages

	Class 1: Ag		Class 2: Ur		Class 3: Fr		**Total**	
Profile	Agricultural		Urban		Forestry			
Number of watershed heads	12		5		8		25	
	Mean	**σ**	**Mean**	**σ**	**Mean**	**σ**	**Mean**	**σ**
Agri	51,66	7,27	22,8	8,56	23,27	6,45	32,58	0,75
Urb	22,08	8,27	63	7,6	6,05	3,01	30,37	2,19
Forest	23,28	6,45	6,05	3,01	59,79	11,71	31,16	2,75

Discussion

Delineation obtained and morphometric characteristics

The municipality of Copargo is divided between two watersheds: the Ouémé and the Pendjari. In Copargo, WSH (watershed heads) account for 69.4% of the area of the Ouémé watershed and 59.4% of the Pendjari watershed. The minimum and maximum areas of WSH in the Ouémé watershed are 930 hectares and 4,440 hectares, respectively, while in the Pendjari watershed, they range from 710 hectares to 4,200 hectares. The streams associated with the WSH of the Ouémé extend over 132 km, representing 83.5% of the total length of the hydrographic network in this watershed. For the Pendjari, the streams of the WSH total 198 km, or 85.7% of the hydrographic network length. These results corroborate findings from the literature, which indicate that the drainage network of WSH often constitutes more than two-thirds (66.66%) of the total hydrographic network (Choucard, 2011; Marchand, 2018). Various studies have reported that WSH represent between 60% and 85% of the area of watersheds (Agence de l'Eau Loire-Bretagne, 2020; Alban, 2014), while other research estimates their coverage at around 50%, with streams accounting for 48% of the hydrographic network length (Choucard, 2011). However, in comparison to the results obtained by Dourotimy et al. (2020) in their study on the identification of watershed heads for sustainable water resource management in the Mékrou River, our findings appear significantly higher. In their study, they identified 415 watershed heads with minimum and maximum areas of 22.5 hectares and 2,421 hectares, respectively. The total area of the WSH in their study area was 2,472.064 km², representing 30% of the area of the Mékrou sub-watershed. Furthermore, the length of streams within the WSH in their study area was 1,963.59 km, accounting for 22% of the hydrographic network length. These differences underscore the importance of WSH in the hydrological context of Copargo and highlight the regional variability of watershed characteristics. The observed differences and variations can be attributed to disparities in the definition of WSH. Indeed, the conceptualization of WSH varies across regions and depends on the methods employed for their delineation. Among the criteria influencing the extent and number of streams within a WSH, slope plays a predominant role. Incorporating slope as a criterion can significantly reduce the area of a WSH. Additionally, the decision to include or exclude streams of order greater than two has a notable impact on the characteristics of WSH, thereby affecting the results of hydrological analyses. These methodological variations highlight the need for a clear and uniform definition of WSHs to ensure the comparability of studies in the field of hydrology.

In the United States, a WSH is generally defined as an area not exceeding 2 km², with a minor bed measuring less than 1 meter in width (Kavage Adams & Spotila, 2005). In Japan, WSH corresponds to upstream areas dominated by sedimentation processes (Uchida et al., 2005). In many countries, however, they are defined based on Strahler's stream order theory, as is the case in Benin, where the slope criterion may or may not be considered, depending on local context and delineation objectives. These observations highlight that the extent of WSH within a basin depends heavily on the adopted definition and identification approach. Consequently, results obtained in one country cannot be universally applied, as generalizing findings to other watersheds is inherently challenging.

The Principal Component Analysis (PCA) conducted on the morphological criteria of WSH reveals a low drainage density in WSH with high compactness and large areas. The second axis of the PCA, which distinguishes WSH based on slope and relief, indicates that WSH with steep

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slopes also exhibit significant relief. Moreover, WSH with high stream density tend to have pronounced slopes, albeit to varying degrees. A notable correlation is observed between the density of low points and compactness, suggesting a strong presence of pronounced thalwegs in elongated WSH.

The Gravelius compactness index for each WSH in Copargo, which exceeds one (1), confirms their elongated shapes. This morphology directly impacts their hydrological response. After a rainfall event, water in elongated WSH takes longer to reach the outlet, resulting in a weaker hydrological response that promotes water infiltration.

Interestingly, variations in the average slopes of WSH do not seem to depend on their specific relief, which can be attributed to their elongated shapes. Based on specific relief, the WSH of Copargo can be categorized into four groups, ranging from fairly strong to strong relief.

Regarding their physical and geographical characteristics, the results obtained during the delineation align with reported values in the literature, both for the linear extent of watercourses and the corresponding areas (Alban, 2014; Clarke et al., 2008). The disparities in the area and number of WSH between the Ouémé and the Pendjari basins are attributed to differences in their characteristics, as well as geological and pedological factors. Notably, morphological classifications show that WSH of classes M1 and M2 (those with the largest areas) are predominantly found in the Ouémé basin, whereas those of class M3 (with the smallest areas and steepest slopes) are primarily located in the Pendjari basin. In both watersheds, the largest WSH are situated upstream.

Land use and associated issues

Issues related to WSH are strongly influenced by changes in land cover and land use. Land cover profiles are crucial for understanding the function and spatial organization of a watershed, as well as identifying the types of pressures that may affect it. This factor significantly impacts variations in water quality, often playing a more critical role than climate or watershed morphology (Dodds & Oakes, 2008).

The high proportion of agricultural land in the headwaters of Copargo highlights the intensity of anthropogenic pressure in the region, with notable repercussions on water and soil resources. Agriculture is a primary source of diffuse pollution, particularly affecting initial concentric flows (Kagan, 2017). From the source, an increase in nitrate concentrations can be observed. For instance, in France, 60% of the nitrate load in third-order streams originates from first-order streams (LE Bihan, 2009). The degradation of WSHs has significant consequences for the overall functioning of the watershed, with negative effects that propagate and amplify downstream.

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Alterations in land cover profiles can significantly degrade the morphology of small watercourses (Roy & Sahu, 2016). WSH are particularly vulnerable to external pressures due to their low resilience. Their small size amplifies the impacts of these pressures and limits their capacity for recovery.

The reclassification of all headwaters based on their land cover profiles revealed that the majority face agricultural challenges, with agriculture occupying 60-70% of the watersheds in Copargo. Based on these characteristics, specific vulnerability classes can be identified:

- **Ecological continuity and waterbody impacts:** These vulnerabilities broadly affect the overall health and function of aquatic ecosystems.
- **Diffuse pollution:** Class M2, which includes the largest number of headwaters (8 WSH), is of particular concern. This category represents agricultural landscapes that are highly susceptible to degradation and subject to more intensive practices, characterized by a very high proportion of cropland.

Consideration of watershed heads in the future planning

The functional importance of, and the intense pressures on, the streams and wetlands within WSH highlight the need to incorporate these areas more thoroughly into future decision-making processes. The concept of WSH has gained traction primarily due to the desire for a holistic view that encompasses their entire recharge areas, as well as the anthropogenic practices and developments they host. This also reflects the need for an integrative approach that combines diverse issues such as biodiversity, diffuse pollution, ecological connectivity, and morphology, enabling more coherent management decisions.

In terms of area, WSH cover the majority of a territory. Therefore, before implementing decisions at a broader scale, it is essential to intensify awareness efforts among managers, stakeholders, policymakers, and the public. The first step in this process is to promote an understanding of the specific characteristics of these areas, their role, the current state of degradation, and the scale of land involved. This awareness is crucial for shifting perspectives on the importance of preserving their streams and wetlands, emphasizing that despite their small size, these areas are far from insignificant. By enhancing knowledge about the condition of these WSH, the extent of certain issues can be reassessed, and management priorities may shift accordingly. Beyond planning, work on WSH must also be approached operationally. The cartographic representation of characterization data can serve as a valuable tool to assist managers in adopting an integrated approach when assessing WSH.

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Conclusion

This study has enabled the identification, delineation, and characterization of WSH in the municipality of Copargo based on morphological and land-use criteria. The characterized WSH correspond to the watersheds of first and second order streams according to Strahler‘s classification. Thus, for rivers such as the Ouémé and the Pendjari, a WSH encompasses an area defined by the watersheds of Strahler‘s first and second order streams. In Copargo, twenty-five (25) WSH have been delineated, including 14 within the Pendjari watershed and 11 within the Ouémé watershed. The delineated WSH cover more than 70% of the territory and generally exhibit elongated shapes with pronounced slopes. In Copargo, the streams of the WSH of the Ouémé represent 83.5% of the linear extent of the Ouémé river‘s hydrographic network, while those of the Pendjari account for 85.7% of the linear extent of the Pendjari river‘s hydrographic network. On the criterion of land use, majority of the WSH in Copargo are characterized by a high proportion of agricultural land, moderate forest cover, and a low proportion of urbanized areas. This predominance of agricultural surfaces has notable repercussions on water and soil resources in these hilly zones, where the slope increases vulnerability to diffuse pollution. The specific characteristics of WSH, particularly their connectivity to the entire hydrographic network, call for increased attention from managers for the sustainable management of these aquatic environments. The database created by this study thus serves as a valuable reference for current and future decision-makers. It is essential to continue efforts to deepen the understanding of these areas, where the condition of aquatic environments remains inadequately documented, either through the utilization of existing databases or through field diagnostics. This in-depth work will support a shift in practices toward a vision that more fully integrates the role of WSH and their current ecological status. In light of the results obtained, it would be beneficial to continue research to document the situation of WSH in Copargo more precisely, in order to better guide future actions for their protection and to easily identify priority intervention areas. It is in this perspective that after this characterization study based on the criteria of morphology and land use, a study will be carried out on the physico-chemical and bacteriological characterization of water resources in these watershed heads in the commune of Copargo.

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