

Hydrological Dynamics and Anthropogenic Pressures in Benin's River Basins (2010-2019): Implications for Integrated Water Resources Management

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Abstract: This study analyzes changes in hydrological dynamics in Benin's major river basins (Mono-Couffo, Ouémé, Niger, and Volta) over the 2010-2019 period, linking variations in flow rates to anthropogenic and environmental pressures. Daily hydrometric data from 19 stations covering 15 watercourses were used to calculate annual mean flows and characterize interannual and seasonal variability. The approach combines statistical analyses, hydrological indices, and spatial comparisons, supplemented by demographic and land-use data. The results reveal marked hydrological contrasts between the basins, with high variability in the Mono River (90 to 230 m³/s), relative stability in the Couffo (5 to 15 m³/s), heterogeneity in the Ouémé basin, and pronounced instability in the Niger's tributaries. These dynamics can be explained by a combination of rainfall variability, population growth, deforestation, and agricultural intensification. The study highlights a structural hydrological vulnerability and underscores the need to strengthen IWRM (integrated water resources management), particularly through the protection of recharge areas, the regulation of water withdrawals, and the development of appropriate hydrometric monitoring systems.

Key words: Hydrology, flow variability, anthropogenic pressures, IWRM, Benin.

1. Introduction

In Benin, the major river basins—Mono-Couffo, Ouémé, Niger, and Volta—form the country's hydrological backbone and provide most of the water-related ecosystem services: drinking water supply, irrigation, fishing, pastoralism, flood mitigation, and low-flow support. However, for several decades, these systems have been subject to a complex interplay of climatic and anthropogenic pressures that are reshaping the seasonal and interannual variability of flows, altering

base flows, and increasing the occurrence of extremes (droughts, floods) [1, 2]. At the regional scale, declining rainfall and rising temperatures (+1.8 °C over 1960-2010 in the Benin section of the Niger Basin) increase the sensitivity of runoff, particularly since rainfall is heavily concentrated in a few months (May-September) [1].

At the same time, population growth remains strong in many riverside municipalities, with intercensal growth rates exceeding both the departmental and national

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averages, which intensifies pressure on land, floodplains, and water use [3]. These changes are accompanied by rapid human impact on the landscape: the retreat of gallery forests and savannas (e.g., a 58% decline in gallery forests in Couffo between 2000 and 2011 [4, 5]), and accelerated land-cover conversion in the Niger Valley (64.43% of forest formations between 2000 and 2013 [6]). In the Ouémé region, land-use dynamics are illustrated by the rapid expansion of irrigated areas (from 755 km² in 2014 to 1,883 km² in 2022), reshaping water demand during the dry season [7, 8]. In Mono-Couffo, irrigated IR 841 (rice farming) and reliance on surface water for irrigation are increasing water withdrawals [9, 10].

In this context, the 2010-2019 period provides a useful window of opportunity to compare the dynamics of average annual flows in each basin and to examine the anthropogenic pressures that shape them. The scientific and operational challenge is twofold: (i) to document hydrographic contrasts and their recent evolution; (ii) to identify sustainable management approaches tailored to local contexts while remaining compatible with integrated governance at the basin scale [11].

The purpose of this paper is to:

- analyses trends in average annual discharge (2010-2019) in the four basins;
- characterize anthropogenic pressures and their hydrological impacts;
- propose operational implications for integrated water resources management;
- provide a cross-cutting synthesis to inform public policy and investment priorities.

2. Materials and Methods

2.1 Study Area

The study covers Benin's four main river basins: the Ouémé, the Niger, the Mono-Couffo, and the Volta, which constitute the country's largest river systems. These basins are characterized by hydroclimatic diversity: annual rainfall ranges from 900 mm in the north to over 1,400 mm in the south, while average temperatures range

from 26 °C to 29 °C [12]. This climatic variability strongly influences hydrological regimes and determines the availability of surface and groundwater.

2.2 Data Used

(i) Hydrometry (2010-2019). The data used were obtained from the national hydrometric network administered by the Directorate General for Water and illustrated in Fig. 1 [13].

The selected stations are those whose time series cover the period 2010-2019, enabling the calculation of average annual stream flows. These consist of daily records of flow rates and water levels recorded at 19 stations distributed across 15 watercourses and covering 16 municipalities (Table 1).

(ii) Climate and contextual data. For hydroclimatic contextualization and rainfall seasonality, regional summaries are available for the Ouémé and Niger regions [2, 11].

(iii) Demographics. Intercensal growth rates and municipal indicators are derived from INSAE's (National Institute of Statistics and Economic Analysis) RGPH-4 reports [3].

(iv) Land use/environment. The assessments of deforestation and forest corridors are based on Thiam et al. [4] and Togbévi and Sintondji [5]. Land-use dynamics in the lower Ouémé Valley are derived from Etèné et al. [8]. For the Volta, the evolution of cultivated areas into protected complexes is documented by Polo-Akpiisso, Kouami, and Dosseh [14]. Hydromorphic lowlands (potential/developable) are sourced from Souberou, Ahouansou, and Yabi [15].

(v) Agriculture and irrigation. Data on water sources for irrigation and the proportion of surface water in the Mono-Couffo region are based on Noumon et al. [9]. Water requirements for IR 841 rice are taken from Degnon et al. [10]. The expansion of irrigated areas in the Ouémé region is based on Ahoton et al. [7].

2.3 Analytical Methods

To achieve the study's objectives, various complementary methodological approaches were

employed to process and interpret the collected hydrological data. These methods made it possible to identify trends, characterize interannual and seasonal variability, and link the observed dynamics to anthropogenic pressures. They are as follows:

- Statistical analyses: Annual and seasonal average flows were calculated from the daily time series. Descriptive statistics (mean, variance, standard deviation) were used to identify general trends.
- Trend detection: A simple linear regression was applied to the time series for each station to identify interannual trends [16].

- Hydrological indices: Interannual and seasonal variability was characterized by analyzing minimum, maximum, and median flows, as well as by comparing wet and dry seasons.

- Spatial analysis: A comparison between stations and sub-basins highlighted the contrasts between major rivers and secondary tributaries [17].

- Link to anthropogenic pressures: the hydrological results were cross-referenced with secondary data on changes in land use (deforestation, agricultural expansion) and water withdrawals (domestic, agricultural, and industrial use).

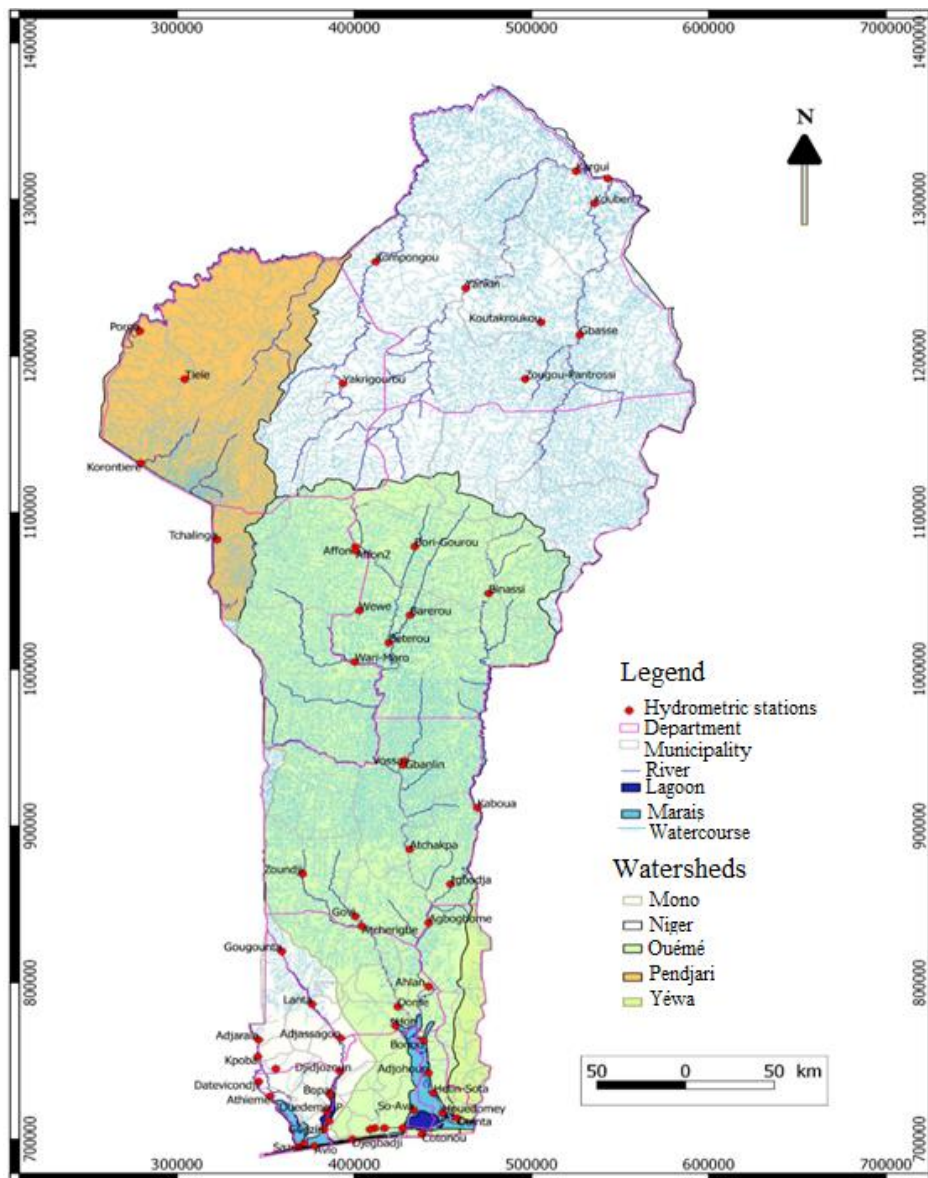


Fig. 1 Map of Benin's hydrometric network [13].

Table 1 Hydrological stations.

Hydrological basin	Watercourse	Station	Municipality	Latitude (° N)	Longitude (° E)
Mono-Couffo	Couffo	LANTA	Klouékanmey	07°06'43'' N	01°52'43'' E
	Mono	ATHIEME	Athiémé	06°34'44'' N	01°39'53'' E
	Sota	KOUBERI	Malanville	11°44'13'' N	03°19'32'' E
Niger	Niger	MALANVILLE	Malanville	11°52'48'' N	03°23'45'' E
	Mékrou	YAKRIGOUROU	Kérou	10°41'44'' N	02°01'39'' E
		AHLAN	Zangnanado	07°12'52'' N	02°28'29'' E
	Ouémé	ATCHAKPA	Savè	08°00'41'' N	02°22'47'' E
		BETEROU	Tchaourou	09°11'56'' N	02°16'00'' E
		BONOU	Bonou	06°54'35'' N	02°26'59'' E
	Affon	AFFON	Djougou	09°45'03'' N	02°05'46'' E
Ouémé	Zou	ATCHERIGBE	Dassa Zoumè	07°33'44'' N	02°07'58'' E
		DOME	Zogbodomey	07°05'53'' N	02°19'01'' E
	Yérou Maro	BAREROU	Tchaourou	09°21'33'' N	02°22'37'' E
	Alpouro	BORI-GOUROU	N'dali	09°45'18'' N	02°23'59'' E
	Térou	COTE	Tchaourou	09°05'16'' N	02°05'35'' E
	Beffa	VOSSA	Ouessè	08°29'40'' N	02°20'29'' E
	Wéwé	WEWE	Djougou	09°23'06'' N	02°06'58'' E
Volta	Pendjari	PORGA	Matéri	10°59'37'' N	00°58'39'' E
	Magou	TIELE	Tanguiéta	10°43'02'' N	01°12'41'' E

3. Results

3.1 Changes in River Flow Rates and Anthropogenic Pressures in Each Basin

3.1.1 Mono-Couffo Basin

The main waterways in the Mono Basin are the Couffo and Mono Rivers. Their average annual discharge rates are shown in Fig. 2.

An analysis of the average annual flows of the basin's rivers reveals a marked disparity between the Mono and the Couffo. At Athiémé, the Mono River exhibits very marked interannual variability: after a significant decline in 2012, estimated at approximately 90 m³/s, the flow rate rose significantly in 2013 to nearly 170 m³/s, before falling again in 2014 to about 95 m³/s. However, starting in 2016, a continuous upward trend has taken hold, peaking at over 230 m³/s in 2019.

In contrast, at Lanta, the Couffo is characterized by low and relatively stable flows, generally ranging between 5 and 15 m³/s, which reflects increased vulnerability to climate hazards and local anthropogenic pressures.

In fact, this trend stems not only from fluctuations in rainfall but also from a combination of factors. Population growth in the municipalities along the Mono River exerts particularly strong pressure, with intercensal growth rates reaching 4.87% in Athiémé, 5.82% in Comè, and 6.01% in Lokossa between 2002 and 2013—levels higher than the departmental average of 5.17% [3]. This trend is driving both the demand for agricultural land and water withdrawals. Agriculture is another key factor. Irrigation of individual farms relies primarily on surface water, which accounts for 78.81% of water supply, more than half of which is drawn directly from the Mono River and nearly one-fifth from its tributaries [9]. Irrigated rice cultivation, particularly the IR 841 variety, clearly illustrates this pressure: it requires an average of 129 m³/ha/day for 120 days, or approximately 15,500 m³/ha per cycle, with massive withdrawals concentrated in the Mono and Couffo rivers [10].

Added to all this is deforestation, which contributes to the degradation of ecosystems: forest cover in the basin declined by nearly 11% between 2010 and 2020, representing an estimated loss of 26,400 hectares, while

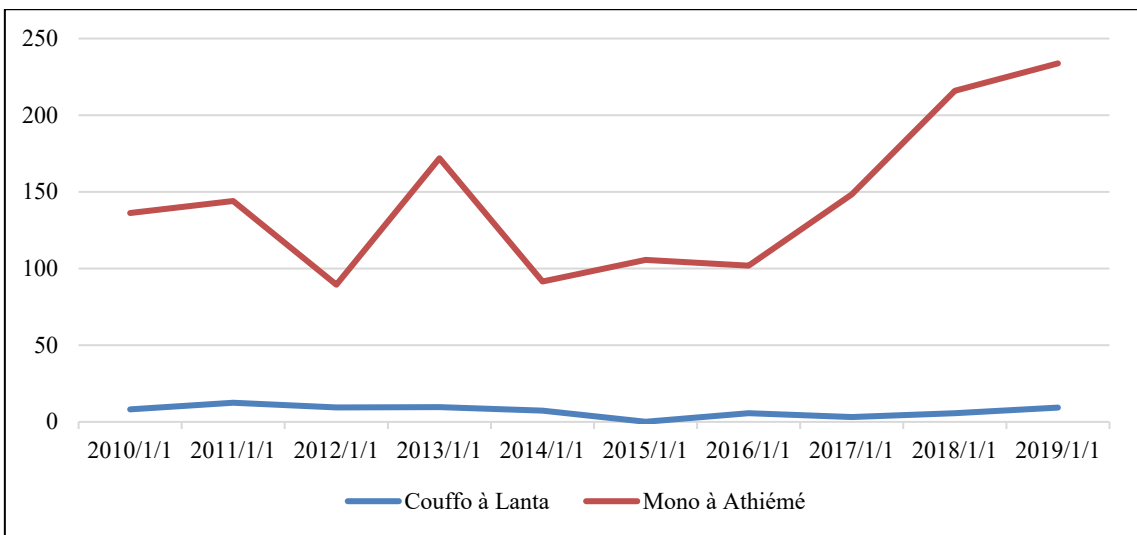


Fig. 2 Average annual flow of the main rivers in the Mono-Couffo basin (m³/s).

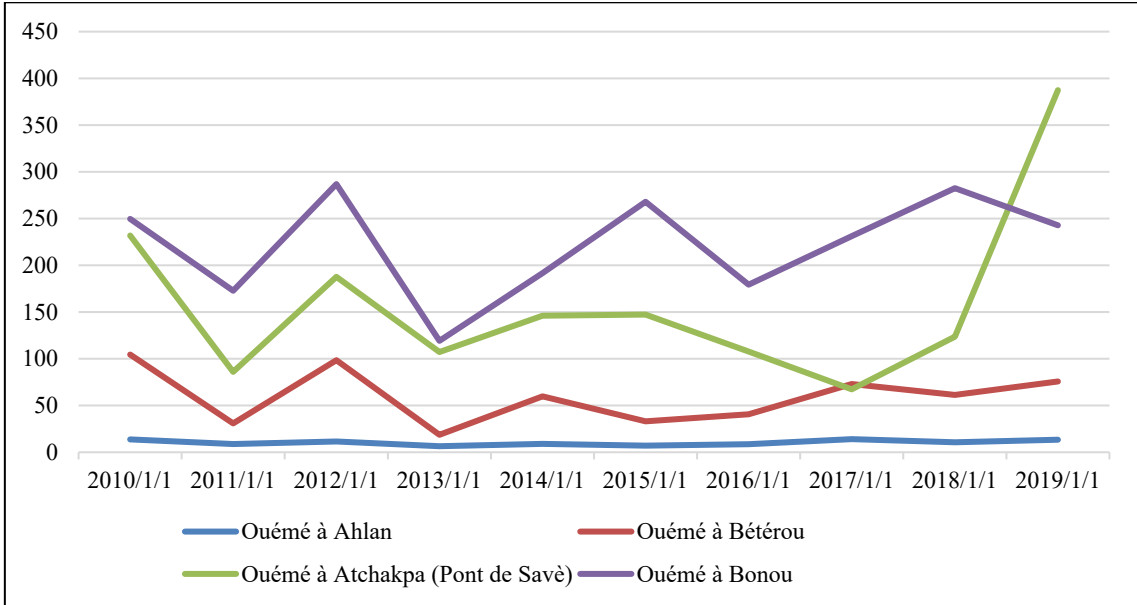


Fig. 3 Average annual flow of the main rivers in the Ouémé basin (m³/s): Ouémé river.

the Couffo gallery forest had already decreased by 58% between 2000 and 2011, confirming a sustained process of degradation [4, 5].

3.1.2 Ouémé Basin

The main watercourses in the basin are the Ouémé and Zou rivers and the Affon, Yérou Maro, Alpouro, Térrou, Beffa, and Wéwé rivers. Their average annual flows are shown in Figs. 3, 4, and 5.

The trend in the average annual discharge of the Ouémé River (Fig. 3) reveals a varied pattern across the different monitoring stations. At Ahlan, discharge

levels remain generally high, ranging between 150 and 300 m³/s. After a decline in 2011, a peak was recorded in 2012, followed by a decrease in 2013. A recovery began in 2014 and continued through 2018, before a slight decline in 2019.

At Savè (Atchoupa Bridge), discharge rates, ranging between 100 and 200 m³/s, experienced a gradual decline between 2010 and 2013, followed by relative stability from 2014 to 2017, before a marked recovery in 2018 that peaked in 2019 with a record value exceeding 350 m³/s. At Bétérou, flow rates appear more

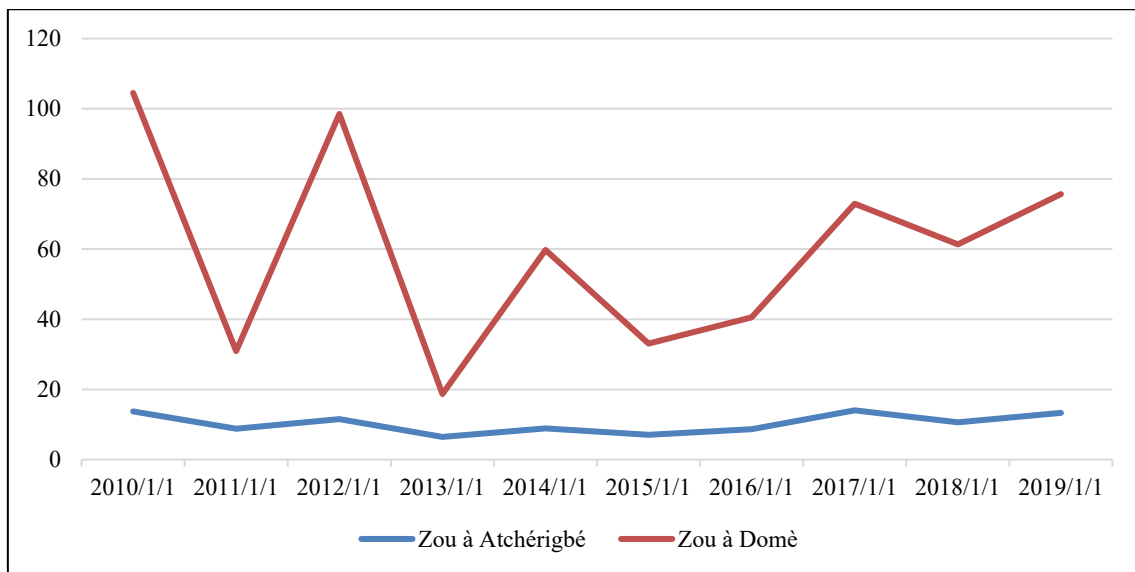


Fig. 4 Average annual flow of the main rivers in the Ouémé basin (m³/s): Zou river.

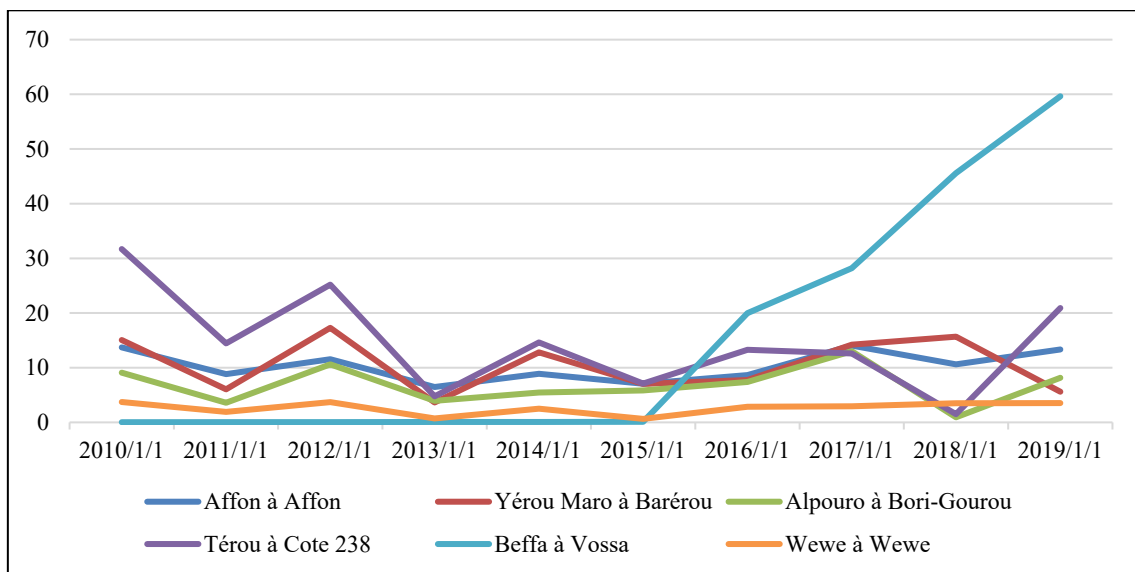


Fig. 5 Average annual flow of the main rivers in the Ouémé basin (m³/s): Affon, Yérou Maro, Alpouro, Térou, Beffa, Wéwé.

modest, ranging between 20 and 100 m³/s, with lows recorded in 2013 and 2016 and highs in 2012 and 2019. Finally, at Bonou, flows remain low, often below 30 m³/s, and relatively stable, with a slight upward trend toward the end of the period. These contrasts reflect significant heterogeneity between the upstream and downstream sections, where flows are modest, and the intermediate sections, where variability is much more pronounced.

The Zou River (Fig. 4), the main tributary, also exhibits contrasting patterns. At Domè, flows range

from 20 to over 100 m³/s. After a peak of nearly 105 m³/s in 2010, a sharp drop occurred in 2011 to around 35 m³/s, followed by alternating increases and decreases, with lows recorded in 2013 and 2015. Starting in 2016, a gradual recovery was observed, reaching nearly 80 m³/s in 2019. In contrast, the Atchérigbé station shows significantly lower flow rates, ranging between 8 and 15 m³/s, and remaining relatively stable throughout the entire period.

The secondary tributaries (Fig. 5) also exhibit varied dynamics. The Affon reached a peak of nearly 30 m³/s

in 2010, followed by a drop to less than 5 m³/s in 2013, and then returned to values between 10 and 20 m³/s by the end of the series. The Yérou Maro shows moderate variability, with flows ranging from 5 to 18 m³/s and a gradual upward trend through 2018. The Alpouro remains low and relatively stable, fluctuating between 2 and 7 m³/s, while the Térou rarely exceeds 5 m³/s. The Beffa is an atypical case, with initially very low flows but spectacular growth after 2015, reaching nearly 60 m³/s in 2019. Finally, the Wéwé remains modest, with flows of 3 to 10 m³/s and a slight increase recorded starting in 2016.

The dynamics of the Ouémé basin are not solely the result of rainfall variability. They are strongly influenced by population growth and changes in land use. Between 2002 and 2013, the Ouémé department recorded an intercensal growth rate of 3.69%, with particularly high rates in riverside municipalities such as Sèmè-Kpodji (6.00%), Aguégoués (4.65%), Adjarra (4.37%), Bonou (3.63%), and Dangbo (3.40%) [3]. This demographic pressure is accompanied by a rapid transformation of agricultural areas and alluvial plains. In the lower Bonou Valley, plantations increased by 6.98% between 2000 and 2013, urban areas by 2.65%, and crop-fallow mosaics by 8.92%, reflecting accelerated human impact on the riverbanks and an

intensification of runoff and erosion risks [8]. These changes are occurring against a backdrop of climate deterioration that began in the late 1960s, marked by a significant decline in average annual flow rates. Between 1960 and 2011, the Bétérou and Bonou stations recorded decreases of 44% and 40%, respectively [2].

Added to these changes is growing agricultural pressure. The area of irrigated land in the Ouémé basin increased from 755 km² in 2014 to 1,883 km² in 2022, representing an increase of nearly 149%. This rapid expansion, particularly pronounced in the central and southern areas, reflects an intensification of agricultural use and exacerbates competition between irrigation withdrawals, domestic needs, and the river's environmental functions [7].

3.1.3 Niger Basin

The main watercourse is the Niger River. However, there are several other rivers, including the Mékrou and the Sota. Their average annual flows are shown in Figs. 6 and 7.

An analysis of the average annual flows in the Benin section of the Niger River basin (Fig. 6) reveals sharp contrasts between the main stem and its tributaries. At Malanville, the Niger River has very high flows, ranging from 800 to 1,300 m³/s.

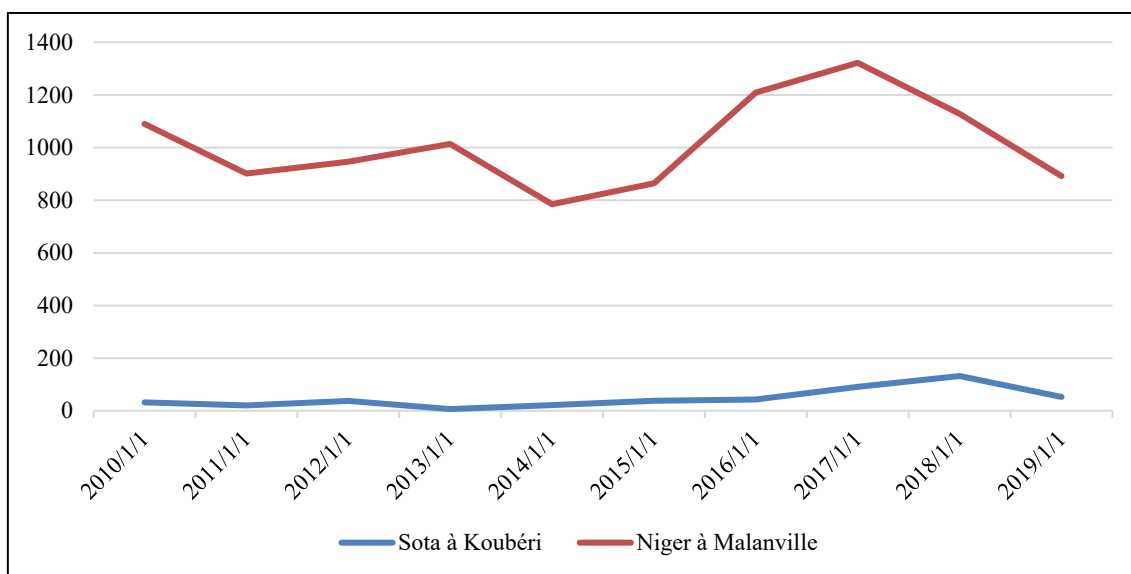


Fig. 6 Average annual flow of the main rivers in the Niger basin (m³/s): Sota, Niger.

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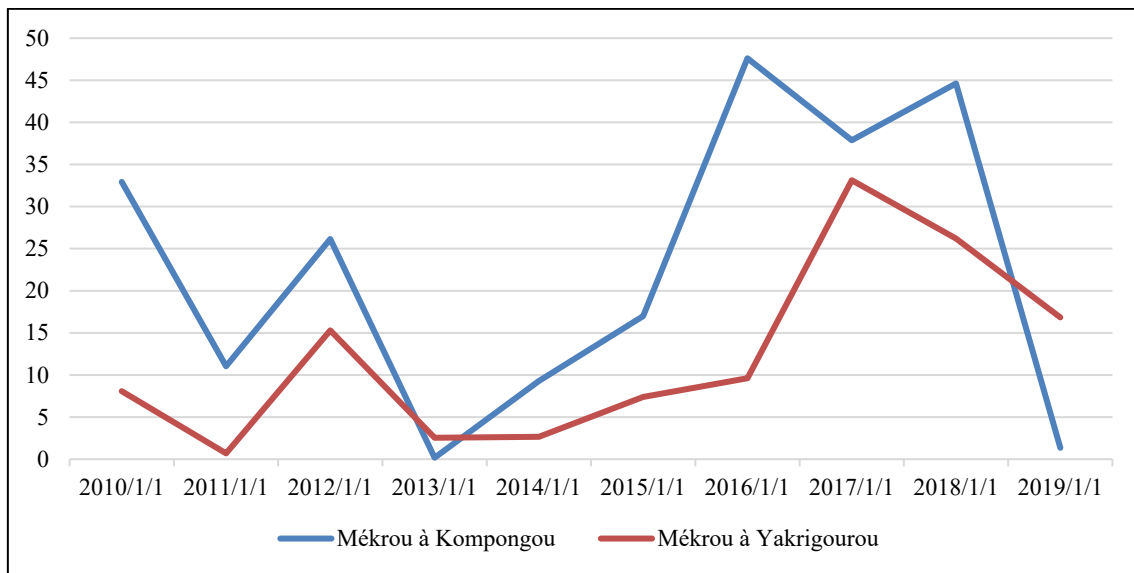


Fig. 7 Average annual flow of the main rivers in the Niger basin (m³/s): Mékrou.

The 2010-2011 period was marked by a notable decline, from approximately 1,100 m³/s to 900 m³/s, followed by a gradual recovery through 2013, reaching around 1,000 m³/s. In 2014, flows dropped to a low of nearly 780 m³/s, before rising significantly to a peak of nearly 1,300 m³/s in 2017.

A downward trend then set in, bringing flows back down to around 900 m³/s in 2019. In contrast, the Sota River at Koubéri records significantly lower flow rates, ranging from 20 to 120 m³/s, but with marked interannual variability: low values between 2010 and 2014 (often below 40 m³/s), followed by a recovery peaking in 2018 at nearly 150 m³/s before another drop in 2019.

The Mékrou sub-basin (Fig. 7) also exhibits significant hydrological instability. At Kompongou, flows are generally higher than at other stations, but highly variable: a peak in 2010 (~33 m³/s), dropping to 12 m³/s in 2011, a near-zero minimum in 2013, then recovering to nearly 48 m³/s in 2016. After a slight decline in 2017, flows rose again in 2018 (45 m³/s), before another sharp drop in 2019. At Yakrigourou, flows remain modest (2-33 m³/s) but follow a parallel trend: a gradual increase through 2012 (~15 m³/s), a low point in 2013, a recovery through 2017 (>30 m³/s), followed by a decline in 2018-2019. These results

reflect extreme hydrological sensitivity to rainfall conditions and local inflows.

In fact, in the Alibori department, where Malanville and Karimama are located, the intercensal growth rates between 2002 and 2013 reached 4.58% and 4.68%, respectively—figures higher than the national average—thereby increasing pressure on floodplains and ecosystem services [3].

In terms of climate, the Benin section of the Niger River basin has experienced a prolonged decline in rainfall and an increase in average temperatures of approximately 1.8 °C between 1960 and 2010. This trend is accompanied by an increased frequency of dry years and marked seasonality, with nearly 88% of annual rainfall concentrated between May and September. These trends increase the sensitivity of runoff to extreme events and strongly influence infiltration, evaporation, and surface runoff [1].

At the same time, land use is undergoing rapid change. Between 2000 and 2013, riparian forest areas declined by 64.43%, with a conversion rate of 65.52%, while urban areas (+21.47%), bare land (+4.43%), and crop-fallow mosaics (+24.84%) increased significantly [6]. This human impact, linked to agricultural expansion, slash-and-burn farming, grazing, and timber harvesting, increases runoff and sediment input into the

river [6]. Agriculture is, in fact, the dominant activity: in Malanville and Karimama, it accounts for 48.47% and 82% of the working population, respectively [6].

Thus, the hydrological dynamics of the Benin section of the Niger River basin result from the interplay of climatic, demographic, and land-use factors. Declining rainfall and rising temperatures exacerbate interannual variability in river flows, population growth increases pressure on floodplains, and the accelerated conversion of agricultural land promotes runoff and erosion. Together, these factors increase the frequency of floods and low flows, alter base flows, and undermine the sustainability of the basin's water resources [1, 3, 6].

3.1.4 Volta Basin

Pendjari and Magou are the two rivers identified in the Volta Basin. The trend in their average annual discharge is shown in Fig. 8.

An analysis of average annual flows in the Volta River basin (Fig. 8) reveals a marked disparity between the Pendjari River at Porga and the Magou River at Tiélé.

The Pendjari River records relatively high flows, with marked interannual variability: following a gradual decline between 2010 (~65 m³/s) and 2011 (~40 m³/s), relative stability was observed through

2013, followed by a sharp drop in 2014 (~25 m³/s). Starting in 2015, a dramatic recovery was recorded, peaking in 2016 at over 240 m³/s—the highest value in the series—before a downward trend brought flows back down to around 45 m³/s in 2019. In contrast, the Magou River at Tiélé exhibits very low flows, generally below 5 m³/s, reflecting near-stability throughout the period, with a slight increase in 2019 without, however, exceeding 10 m³/s. These contrasts highlight significant hydrological heterogeneity: the Pendjari, a major river, is subject to significant flooding, while the Magou remains structurally vulnerable with low and steady flows.

The dynamics of Benin's Volta Basin cannot be explained solely by rainfall variability. They also result from sustained population pressure and rapid land-use changes that are profoundly transforming ecosystems. Indeed, population growth and the expansion of agricultural land are leading to gradual deforestation, a reduction in natural savanna areas, and changes in water cycles [18].

In terms of land use, recent changes in land tenure reflect an intensification of agriculture, with extensive development of low-lying areas and an expansion of irrigated areas [14]. This trend increases water demand, particularly during the dry season, and alters the

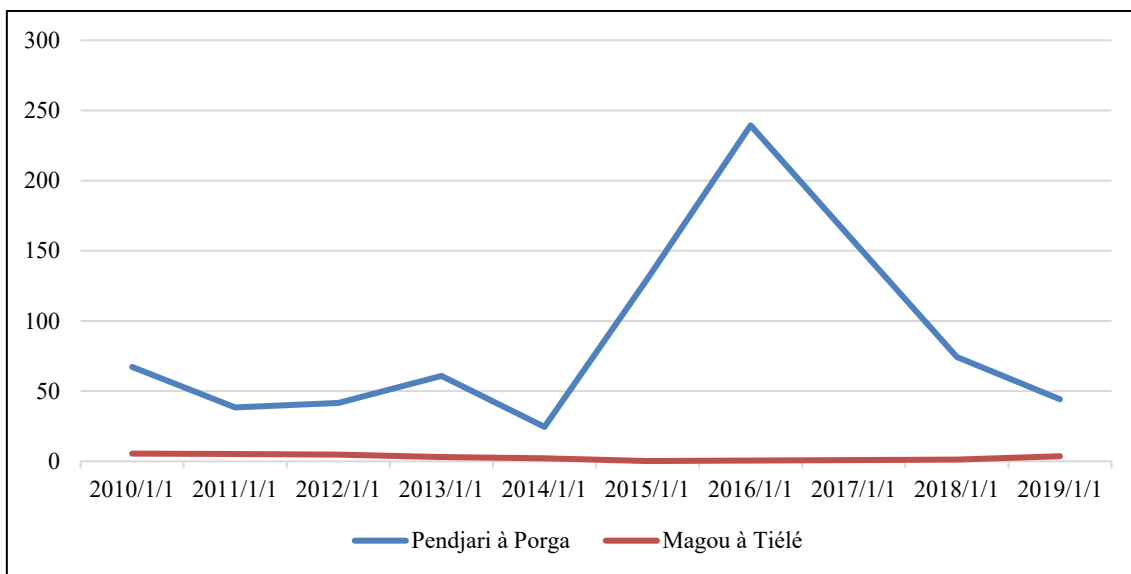


Fig. 8 Average annual flow of the main rivers in the Volta basin (m³/s).

seasonality of water withdrawals. It also contributes to landscape fragmentation and soil erosion, exacerbating the intra-annual variability of available resources [19].

3.2 Implications for the Sustainable Management of Water Resources

3.2.1 Mono-Couffo Basin

The high hydrological variability observed on the Mono River at Athiémé, in contrast to the relative stability of the Couffo River at Lanta, highlights a structural vulnerability in the basin. This fragility is exacerbated by sustained population growth in the riparian communities and by the gradual deforestation of the forest areas. Furthermore, agricultural pressures, particularly the expansion of irrigated rice farming, are increasing water demand and compromising the system's water balance.

In this context, several implications emerge for sustainable resource management:

- The implementation of an IWRM (integrated water resources management) program appears essential to balance competing uses—agricultural, domestic, and environmental—and to prevent conflicts over access to water.
- Protecting forest areas and promoting agroforestry are priorities for reducing erosion, improving infiltration, and restoring the basin's water regulation capacity [4].
- In the agricultural sector, the adoption of water-efficient irrigation systems and crop diversification represent appropriate solutions to limit excessive water withdrawals from the Mono and Couffo rivers. These measures would help reconcile production needs with the preservation of water resources [9, 10].

3.2.2 Ouémé Basin

The hydrological heterogeneity observed in the Ouémé River basin, characterized by contrasts between the upstream, middle, and downstream sections, highlights the complexity of this river system's functioning. This dynamic is exacerbated by population growth in the riparian communities and the rapid conversion of

agricultural land, which increase pressure on water resources. The structural downward trend in average annual flows, documented over several decades, illustrates the basin's growing vulnerability to anthropogenic and climatic pressures.

In this context, several recommendations are warranted:

- Strengthening the hydrological and climate monitoring network is essential for anticipating and managing periods of drought and flooding, given the documented recurrence of hydroclimatic extremes [2].
- Implementing coordinated management of secondary tributaries (Affon, Beffa, Yérou Maro, etc.) is necessary to preserve minimum ecological flows and avoid imbalances between upstream and downstream areas.
- Agricultural planning must incorporate measures to control the expansion of irrigated areas, which nearly tripled between 2014 and 2022, in order to limit excessive water withdrawals during the dry season [7].
- Finally, the adoption of participatory local land-use plans is essential to reduce human encroachment on floodplains and limit the risks of erosion and flooding [8].

3.2.3 Niger Basin

The Niger River at Malanville experiences high but highly variable flow rates, while its tributaries (Sota, Mékrou) exhibit significant interannual variability. These patterns reflect the basin's structural vulnerability, which is linked to declining rainfall, rising temperatures, and human pressures.

Several priority actions have emerged for sustainable management:

- Strengthening cross-border cooperation is essential, as the Niger is a shared waterway whose flow depends largely on upstream areas [1].
- The restoration of riparian forests, which declined by more than 64% between 2000 and 2013, appears to be a priority for reducing erosion and improving infiltration [6].
- The introduction of drought-adapted agricultural practices, such as supplemental irrigation or the use of

drought-tolerant varieties, would help reduce dependence on seasonal fluctuations.

- Finally, participatory governance of water use, integrating agricultural, domestic, and pastoral needs, would strengthen the resilience of riparian communities facing sustained population growth [3].

3.2.4 Volta Basin

The Pendjari's disproportionate contribution to the Volta Basin's water supply highlights the hydrological fragility of this system. Pressures from population growth, deforestation, and the expansion of cropland into wetlands are exacerbating these imbalances, while the highly seasonal nature of runoff increases vulnerability to climate extremes.

For this basin, the following implications emerge:

- The protection and sustainable management of wetlands and floodplains are a priority, in order to preserve their role as hydrological regulators. The identified potential (359,894 ha of hydromorphic areas, of which 53,588 ha are suitable for development) must be exploited in a controlled and sustainable manner [15].

- The implementation of coordinated transboundary management of the Oti-Pendjari sub-basin is essential, as this sub-basin contributes approximately 44% of the Volta River's inflow to the Akosombo Dam [20].

- Coordinated land-use plans must be developed in the Beninese municipalities bordering the Atacora River (Cobly, Matéri, Kérou, Tanguiéta) to reduce the rapid human encroachment on the floodplains [3].

- Finally, integrating protected areas (e.g., the Oti-Kéran-Mandouri complex) into a regional approach that balances conservation with socioeconomic needs would help strengthen the basin's ecological resilience [14].

3.3 Cross-Functional Overview

An analysis of the hydrological dynamics of Benin's four main river basins (Mono-Couffo, Ouémé, Niger, and Volta) reveals significant contrasts, but also common pressures that threaten the sustainability of water resources.

3.3.1 Comparative Dynamics

- Mono-Couffo: characterized by high interannual variability in the Mono (90 to 230 m³/s between 2012 and 2019) and fragile stability in the Couffo (5 to 15 m³/s), this basin illustrates the vulnerability of small rivers to climate hazards and anthropogenic pressures [9, 10].

- Ouémé: characterized by significant spatial heterogeneity, ranging from low upstream/downstream flows (Bétérou, Bonou) to higher values in the central section (Savè, Ahlan), with unstable secondary tributaries (Beffa, Affon). The structural downward trend in flows reflects the combined impact of land-use changes and reduced rainfall [2, 8].

- Niger: the high flows of the main stem (800-1,300 m³/s at Malanville) contrast with the extreme variability of its tributaries (Sota, Mékrou). This basin illustrates the dependence on transboundary inflows and the vulnerability to recurring droughts and rapid changes in land use [1, 6].

- Volta: Dominated by the disproportionately large hydrological role of the Pendjari River, which contributes significantly to regional runoff, this basin is subject to pronounced seasonality and increasing agricultural pressures on floodplains and wetlands [14, 15].

3.3.2 Common Pressures

Despite their distinct characteristics, the four basins face similar challenges:

- Climate-related: a gradual decline in precipitation, rising temperatures (+1.8 °C over half a century in the Niger Basin), and a seasonal concentration of rainfall [1].

- Demographic: rapid growth of riparian populations, with rates exceeding the national average in the Ouémé, Alibori, and Atacora basins [3].

- Land use and agriculture: deforestation, expansion of irrigated areas (tripled in Ouémé between 2014 and 2022), intensification of irrigated rice cultivation in Mono-Couffo, rapid conversion of wetlands to cropland in Volta [7, 15].

- Environmental: degradation of gallery forests (-58% in Couffo between 2000 and 2011, Thiam et al. [4]), massive decline in forest cover in the Niger Valley (-64.43% between 2000 and 2013 [6]).

In summary, Benin's four basins exhibit contrasting dynamics but are subject to similar pressures. The combination of climate change, population growth, and land-use changes exacerbates the country's hydrological vulnerability.

4. Discussion

4.1 Hydrological Variability and Spatial Heterogeneity

An analysis of Benin's four river basins (Mono-Couffo, Ouémé, Niger, Volta) between 2010 and 2019 reveals marked contrasts, both between and within basins. The results show that the middle reaches (e.g., Ouémé at Savè) and major rivers (Niger at Malanville, Pendjari at Porga) exhibit the most pronounced interannual variability, with peaks exceeding 1,300 m³/s in the Niger (2017) and 240 m³/s in the Pendjari (2016). Conversely, secondary tributaries (Magou, Alpouro, Térrou, Wéwé) exhibit very low (<10 m³/s) and relatively stable flows, but are particularly vulnerable to climate hazards and local pressures. These disparities confirm that large rivers possess hydrological inertia linked to the extent of their watersheds, whereas small watercourses react more immediately to variations in rainfall and water use [20, 21].

4.2 Climate Influences and Long-Term Trends

The trends identified are part of a regional hydroclimatic pattern documented since the 1960s, characterized by a decline in rainfall, an average rise in temperatures (+1.8 °C in the Niger-Benin region between 1960 and 2010), and an increased frequency of dry years [1]. The structural declines in flow observed at certain stations (e.g., Bétérou: -44% between 1960 and 2011; Bonou: -40% over the same period) reflect the impact of this climate deterioration [2]. These results confirm that recent interannual variability (2010-2019) cannot be interpreted in

isolation but is part of a long-term trend of water scarcity, exacerbating the structural vulnerability of Benin's river basins.

4.3 Demographic Pressures and Land Use

The rapid population growth in riverside municipalities is a major contributing factor. In the Mono-Couffo region, intercensal growth rates between 2002 and 2013 reached 6.01% in Lokossa and 5.82% in Comè, levels well above the national average [3]. Similarly, in Atacora (Volta) and Alibori (Niger), annual growth rates exceeding 3% are placing increased pressure on floodplains and local resources [3]. This demographic trend is inextricably linked to land-use changes: an 11% decline in forest cover in Mono-Couffo between 2010 and 2020 [4], and the disappearance of 64.43% of riparian forests in the Niger Valley between 2000 and 2013 [6], and rapid conversion of hydromorphic floodplains into croplands in Oti-Pendjari [15]. These changes increase runoff, erosion, and sedimentation, thereby altering hydrological regimes.

4.4 Agricultural Intensification and Water Withdrawals

Irrigated agriculture is another key factor. In the Mono-Couffo region, nearly 78.81% of irrigation relies on surface water, of which 53.64% is drawn directly from the Mono river [9]. Irrigated rice cultivation (IR 841) requires approximately 15,500 m³/ha/cycle, which exacerbates local tensions [10]. In the Ouémé basin, irrigated areas increased from 755 km² in 2014 to 1,883 km² in 2022, representing a 149% increase [7]. This rapid intensification, concentrated in alluvial plains and lowlands, exacerbates competition between agricultural, domestic, and environmental uses, and undermines the ecological balance of waterways.

4.5 Implications for the Sustainable Management of Water Resources

The convergence of climatic, demographic, and agricultural factors highlights a structural hydrological vulnerability in Benin's river basins. Sustainable water

resource management must be based on an integrated approach (IWRM), combining:

- the protection and restoration of forest and riparian ecosystems to limit erosion and strengthen water regulation [4];
- the optimization of irrigation through the introduction of water-saving techniques (drip irrigation, sprinkler irrigation) and crop diversification to reduce excessive withdrawals [9, 10];
- appropriate territorial planning that integrates demographic projections and the water needs of different sectors (agriculture, energy, drinking water, environment).
- enhanced hydrometeorological monitoring to document long-term trends and prevent risks associated with droughts and extreme floods.

These guidelines are in line with the recommendations of the GWP/VBA (Global Water Partnership and Volta Basin Authority) [11], which emphasize the importance of transboundary cooperation and joint management of water uses to ensure the resilience of West African river systems.

5. Conclusion

A comparative study of the Mono-Couffo, Ouémé, Niger, and Volta River basins over the period 2010-2019 reveals marked hydrological contrasts, both between basins and within each basin. The main rivers exhibit high interannual flow variations, while several secondary tributaries remain low-flow but highly vulnerable to climatic hazards and local pressures. Beyond this variability, a structural vulnerability emerges, linked to the combination of pronounced rainfall seasonality, sustained population growth in the riverside communities, and rapid land-use change.

Three key factors stand out. First, climatic constraints—high rainfall concentration and alternating wet and dry years—exacerbate the irregularity of runoff and the frequency of extreme events. Second, demographic and urban growth intensifies water demand and the development of alluvial plains,

impacting runoff and flood risk. Finally, agricultural intensification, the expansion of irrigated areas, and the degradation of vegetation cover alter the rainfall-runoff-recharge balance, weakening baseflow during the dry season.

Operationally, these results highlight the need to integrate hydrological dynamics into public water management policies in Benin. Strengthening IWRM (integrated water resources management), protecting recharge areas, regulating agricultural uses, and developing hydrometeorological monitoring systems appear to be essential levers for improving the resilience of river basins to climate change and increasing anthropogenic pressures.

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