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Escherichia coli in the Niger River: Links to environmental variables and anthropogenic activities in Niamey city, Niger

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ABSTRACT

Study region: Middle Niger River, upstream to downstream of Niamey city, Sahel, West Africa.
Study focus: Understanding surface water pollution dynamics and identifying its main drivers is particularly important in regions where surface waters are largely used without proper treatment. This study is focused on the Niger River water and assesses *E. coli* numbers, and physicochemical parameters upstream and downstream of Niamey. Data collected over three years, supplemented by occasional campaigns, aimed to determine the spatial and temporal variability of water quality.
New hydrological insights for the region: SPM and *E. coli* showed high values during the rainy season, peaking before the Red flood. *E. coli* increased from the first rainfall events in Niamey with a peak occurring before SPM peak. Distinct sources play an important role on their seasonal dynamics; *E. coli* mainly originates from urban areas along the Niger River, while SPM comes from right-hand tributaries upstream of Niamey. Downstream of Niamey, *E. coli* were significantly higher than upstream, highlighting the city's substantial contribution to fecal contamination through wastewater discharges, particularly on the left bank. No significant differences between upstream and downstream were observed in the other physicochemical parameters analyzed. Considering spatial distribution in *E. coli* sources and environmental parameters such as rainfall and SPM is of major and global importance for understanding and addressing fecal contamination in urban environments.

1. Introduction

In 2019, diarrheal diseases caused the death of 1.53 billion people around the world (GBD, 2019). African Sub-Saharan countries were the most impacted areas with 593 213 deaths (GBD, 2019). Diarrheal diseases represented the main cause of malnutrition and the

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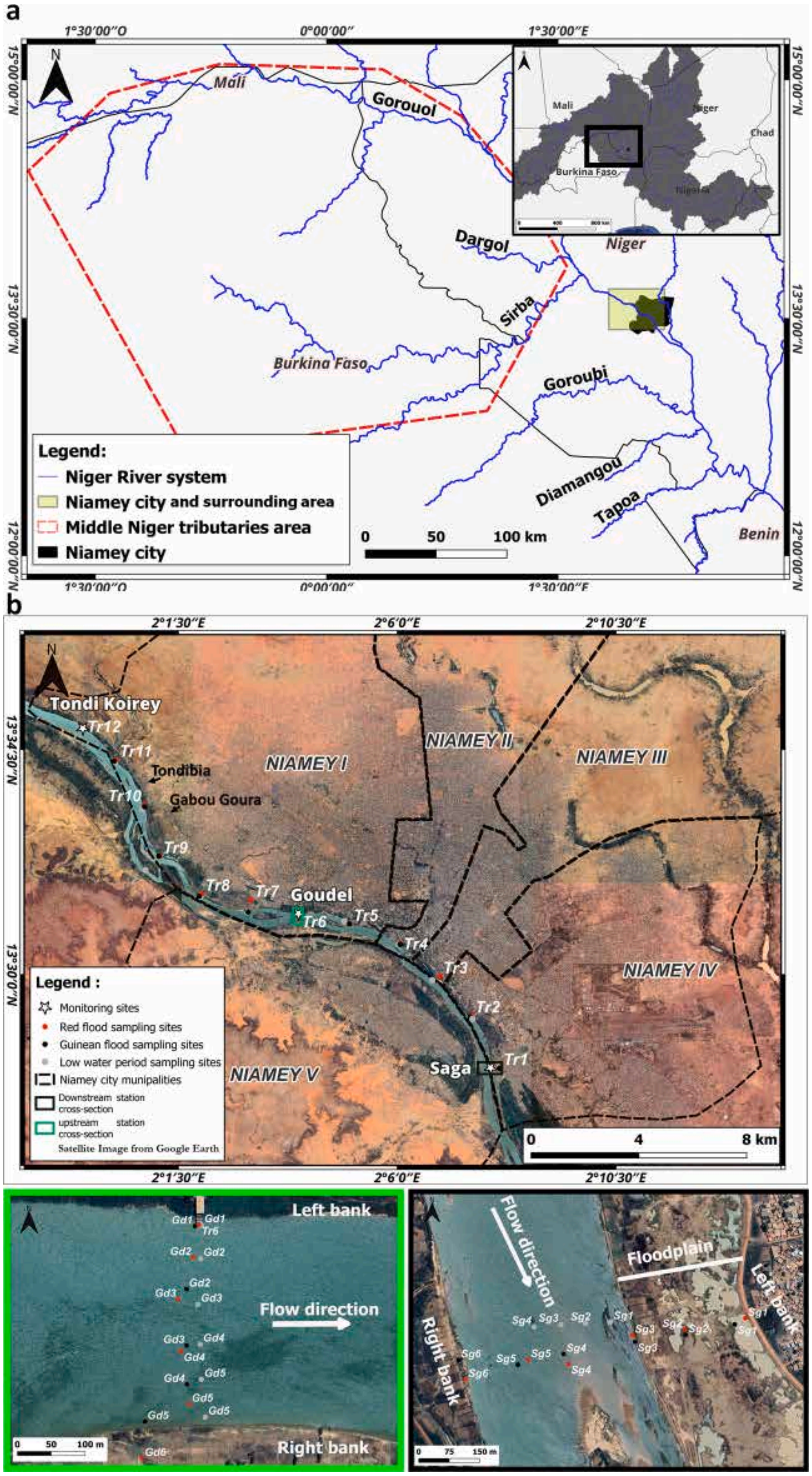

Fig. 1. a) Niger River basin and zoom on the middle Niger River basin; b) Top: study area and sampling points location between the upstream and downstream stations (Tr1 to Tr12). Bottom left-side: site of Goudel (Gd1 to Gd5–6) cross-section sampling points location. Bottom right-side: site of Saga (Sg1 to Sg4–6) cross-section sampling points location during the Niger River hydrological episodes (Gray dots = Low water period = 28/05/2020, Red dots = Red flood = 16/08/2020, Black dots = Guinean flood = 22/03/2021). Satellite Image from Google Earth.

second cause of child mortality (under five years old) with around 360 000 deaths in 2019 (GBD, 2019). Niger is one of the most impacted countries with 500 deaths for 100 000 children in 2015, even if a 17 % decrease has been observed between 2005 and 2015 (Troeger et al., 2017). In 2019, diarrheal diseases still represented one of the first causes of death in this country (Murray et al., 2020). Diarrheal diseases are generally the results of a lack of sanitation in addition to consumption of water contaminated with pathogenic bacteria, viruses, parasitic organisms spread mostly by human and animal faeces (GBD, 2019). *Shigella spp.* and entero-invasive *Escherichia coli* (*E. coli*) are the second leading cause of diarrhea in Sub-Saharan Africa (Oppong et al., 2020; Krumkamp et al., 2015). The high prevalence of diarrheal diseases in Sub-Saharan Africa countries is due to the fact that a large part of the population relies on surface waters for their daily use (for reasons of cost, distance, pump inoperability, Schweitzer et al., 2013; Robert et al., 2021), does not have access to sanitation (3 out of 4 people, UNICEF and WHO, 2022), and has poor knowledge of water quality (Brou et al., 2018; Karambiri et al., under review).

Surface water quality is mostly impacted by human activities in watersheds (Peters and Meybeck, 2000). Cecchi et al. (2020) highlighted a strong correlation between population density and suspended particulate matter (SPM) load in small water bodies in Burkina Faso. Additionally, water body banks are used by domestic animals for grazing areas and for open defecation by a part of the population. The latter is a direct consequence of the low access to adequate sanitation infrastructure that ultimately leads to higher pathogen concentrations in surface waters (Hickling and Bevan, 2010; UNEP, 2016).

During rainfall events SPM and bacteria are carried into surface waters, thus degrading their quality (Ribolzi et al., 2016; Manini et al., 2022). Water suspended particulate matter may increase bacteria survival by providing them attachment support, nutrients and organic matter essential for their growth. SPM also offer significant protection from the antiseptic effects of sun UV rays (Rochelle-Newall et al., 2016; Amalfitano et al., 2017). Previous work has shown how environmental and climatic variables impact bacterial concentrations in surface waters (Islam et al., 2021). For instance, rainfall events may impact the concentration of bacteria through sediment re-suspension or by dilution (Funari et al., 2012; Hofstra, 2011). Stream temperature, pH and Dissolved Oxygen (DO) can also affect bacteria numbers by facilitating their decay (An et al., 2002). High stream temperature could also indirectly favor the growth of bacteria (Valenca et al., 2022). However, the majority of these studies have been carried out in temperate ecosystems. Much less work has been conducted in tropical regions and notably in semi-arid regions such as in Sub-Saharan Africa where it is anticipated that the environmental characteristics of such regions question the applicability of the results obtained in temperate ecosystems.

Sahelian surface waters are characterized by very high SPM concentrations especially during the rainy season (Robert et al., 2016, 2017; Abdourhamane Touré et al., 2016; Moussa et al., 2022) with high water and air temperatures year-round (Guichard et al., 2015) and ubiquitous pollution sources, especially in urban areas (Alhou et al., 2009). These characteristics suggest favorable conditions for bacterial growth (Garzio-Hadzick et al., 2010; Pachepsky and Shelton, 2011). However, while hydrological aspects have been widely addressed (Amogu et al., 2010; Descroix et al., 2018; Massazza et al., 2021; Moussa et al., 2022), less work has focused on the physicochemical and microbiological quality of surface waters in these areas and on the environmental factors that may impact water quality. Studies carried out in the Niger River at Niamey city, based on punctual measurements of some physicochemical and microbiological parameters revealed significantly degraded water quality (Amadou et al., 2011; Alhou et al., 2016). Working in the Bagré Lake, Burkina Faso, Robert et al. (2021) showed a strong correlation between SPM and *E. coli*, with both peaking during the rainy season. Despite these studies, the survival, transport, and growth of pathogens as well as their relationships with human activities, natural processes and their impact on human health still remain poorly known in the tropical zones (Rochelle-Newall et al., 2015).

The main objective of this work was to document the spatial and temporal dynamics of the physicochemical and microbiological quality of the Niger River water in the Niamey city area and to analyze the links between these parameters in relation with the hydrological cycle and anthropogenic activities. We collected water samples to determine the *E. coli* counts and the SPM concentration along with in situ measurements of physicochemical parameters. These measurements were carried out at three different sites on the Niger River, upstream, in the middle and downstream of the city of Niamey, during three years.

2. Material and methods

2.1. Study site

Niamey city, located south-west of Niger (Fig. 1a), is characterized by a Sahelian semiarid climate with a rainy season that lasts from June to September. Annual rainfall was on average 527 mm between 1970 and 2017 (Hamadou Younoussa et al., 2020). As in other west African cities, Niamey has undergone rapid population growth, from 35 000 in 1960 to 1 335 700 persons in 2021 (worldpopulationreview, 2023). Despite this, the city does not have an adequately dimensioned sanitation system (Alhou et al., 2009). This lack of sanitation is widespread all over Niger. Moreover, non-sealed latrines that overflow during the rainy season are common in urban areas (Wassenaar et al., 2023). Open defecation is also widespread: 10 % of urban population and 86 % of rural population were concerned by this option in 2020 (MHA rapport, 2020). The Niger River banks are used for open defecation and also for livestock grazing. In addition, large quantities of untreated water from Niamey city are discharged into the Niger River from industrial, hospital and domestic productions. Amadou et al. (2011) reported 3 048 m^3. d^{-1} discharged in the Niger River from industrial and hospital sources and 12 868 m^3. d^{-1} from domestic activities. The major portion of this waste is discharged in the Niger River without any treatment because of the absence of a wastewater treatment plant. According to a survey in the early 2000 (Maiga et al., 2002) only 0.5 % of the population of Niamey city was connected to the sewer system. Moreover, the sewer system is characterized by a lack of efficiency which leads to the stagnation of sewer water and peaks of pollution after rainfall events (Alhou, 2007).

Hydrologically, the Niger River at Niamey is characterized by a low water period (between April and May) and two distinct discharge peaks: The Red flood and the Guinean flood (Moussa et al., 2022). The Red flood occurs between June and September and corresponds to the local rainy season (Amani and Nguetora, 2002). This flood is the result of rainfall events and surface water contributions from tributaries located in the middle part of the Niger River basin (Fig. 1a). The Guinean flood occurs between October and March at Niamey (Olivry, 2002) and is the result of rainfall events occurring between June and November in the upper part of the Niger River watershed. Water fluxes follow the hydrographic network of the Niger River and arrive at Niamey after passing through the Inner delta. The Inner delta is characterized by slow water drainage due to high amounts of vegetation, and low slope and flow velocities (0.3 and 0.6 $m.s^{-1}$) (Mahé et al., 2002), thus explaining the delay of that discharge peak as compared to that of the Red flood. Over the last 50 years the Red flood peak has greatly increased as a consequence of large hydrological changes related to the increase of surface runoff in Sahelian watersheds (Descroix et al., 2018) and endorheism breaks (Mamadou, 2012; Amogu et al., 2010).

2.2. Measurements, sampling sites and data acquisition

The physicochemical and microbiological characteristics of Niger River water from upstream, middle and downstream of Niamey were analyzed. Three monitoring stations, located on the left bank according to the flow direction, were sampled at:

- The site of “Goudel” located in the middle of Niamey city on the Niger River, from 8th of July 2018 to the 27th of September 2021;
- The site of “Saga” located downstream of Niamey, from 20th of April to 16th of August 2020 and from 13th of March to 12th of August 2021;
- The site of “Tondi Koirey” located upstream of the Goudel site, from 20th of April to 16th of August 2020 (Fig. 1b).

An additional site referred as “Saga right bank”, located downstream but on the right bank, was monitored from 13th of July to 15th of August in 2019.

In addition, specific measurements were performed at key moments of the Niger River hydrological cycle: the low water period (2020), the Red flood (2020) and the Guinean flood (2021). Twelve sites with a 2 km spacing were sampled on the river transect (Tr) along the left bank from the position of Tondi Koirey to the position of Saga. Four to six positions were sampled along the river cross-sections at the site of Goudel (Gd) and at the site of Saga (Sg) (Fig. 1b).

Water samples (0.5 L) were collected 5 m away from the bank at a depth of about 20 cm and kept in an isothermal bag prior to laboratory analyses. The time between sampling and laboratory analyses did not exceeded two hours. *E. coli* bacteria most probable number (MPN) was determined using the standardized MUG/EC microplate® method (ISO 9308–3) (Robert et al., 2021; Nakhle et al., 2021) and suspended particulate matter (SPM) concentration determined by the filtration of 50 mL of water with a 0.7 µm porosity Whatman fiberglass filter (Moussa et al., 2022).

Water physicochemical parameters such as pH, temperature, Electrical Conductivity (EC) and Dissolved Oxygen (DO) were measured in situ using multiparameter analyzers: the YSI™ multi-parameter 556 MPS and the WTW Multi-parameter portable meter MultiLine® Multi 3620 IDS SET G. The probes were calibrated every day before field measurements. Electrical Conductivity and pH probes were calibrated at the laboratory with a standard solution at 1 000 $\mu s.cm^{-1}$ and two standard solutions at pH equal 4.1 and 7.1, respectively. The DO probe was calibrated *in situ* before measurements.

The amount of daily rainfall was obtained from the IMERG product (NASA/GPM_L3/IMERG_V06; Huffman et al., 2019) through Google Earth Engine from 1st of January 2018 to 31st of August 2021. Average precipitations were calculated for two different areas:

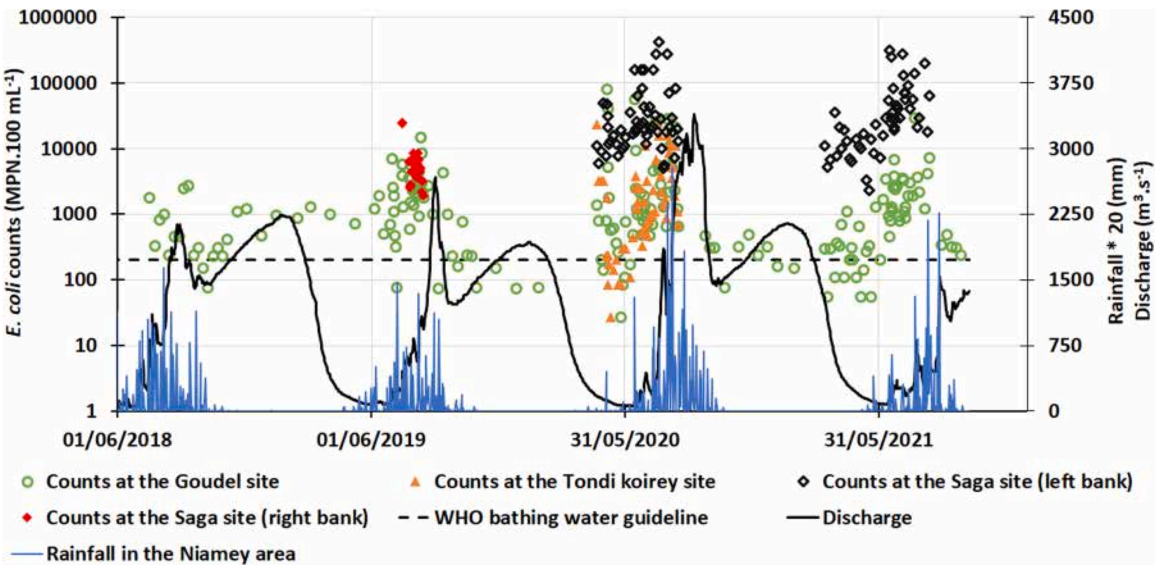

Fig. 2. Spatial and temporal dynamics of the Niger River *E. coli* counts at the four sampled sites in the Niamey area.

the middle Niger River tributaries watersheds upstream of Niamey and Niamey city and its surrounding area (see the corresponding polygons in Fig. 1a).

The dataset can be accessed with the following link: https://doi.org/10.5281/zenodo.13907826.

3. Results

3.1. *Spatio-temporal dynamics of E. coli counts in the Niger River upstream and downstream of Niamey city*

Given the *E. coli* counts followed a log-normal distribution, the following analysis was performed using geometrical means and logarithmic (Log_{10}) *E. coli* values for linear regressions.

3.1.1. *E. coli dynamics at the monitoring sites*

The Niger River *E. coli* counts ranged between 27 and 81 000 MPN.100 mL^{-1} at the site of Goudel from 17th of July 2018 to 27th of September 2021 (Fig. 2). *E. coli* counts were characterized by a significant seasonal and inter-annual variability: low values were measured from October to May during the dry season and high values during the wet season (June to September). Highlighting the inter-annual variability, the geometrical mean of the *E. coli* counts at the Goudel site was 530 MPN.100 mL^{-1} during the 2018 – 2019 dry season (October to May). During 2019 – 2020 and 2020 – 2021 dry seasons the geometrical mean was respectively 228 and 214 MPN.100 mL^{-1}. The highest *E. coli* levels were recorded during the rainy seasons, with geometrical means on average six times higher than in the dry seasons. The geometrical mean of *E. coli* counts for the 2020 rainy season, equal to 1 722 MPN.100 mL^{-1}, was highest (in 2019 and 2021 rainy seasons it was equal to 1 582 and 1 505 MPN.100 mL^{-1}, respectively). The *E. coli* levels during the dry season appeared to be independent of those recorded during the previous rainy season: *E. coli* levels in the 2020 – 21 dry season were the lowest, whereas this period followed the rainy season with the highest *E. coli* pollution. According to the hydrological cycle of the Niger River, the *E. coli* dynamics at the site of Goudel (Fig. 2) were characterized by:

1. Very high values during the rising limb of the Red flood. The greater was the Niger River discharge during the Red flood, the greater was the *E. coli* contamination. Thus, when the maximum of the Red flood reached ~3 300 and 2 700 $m^3.s^{-1}$ in 2020 and 2019, the geometrical mean of *E. coli* counts was respectively 2 393 and 1 889 MPN.100 mL^{-1};

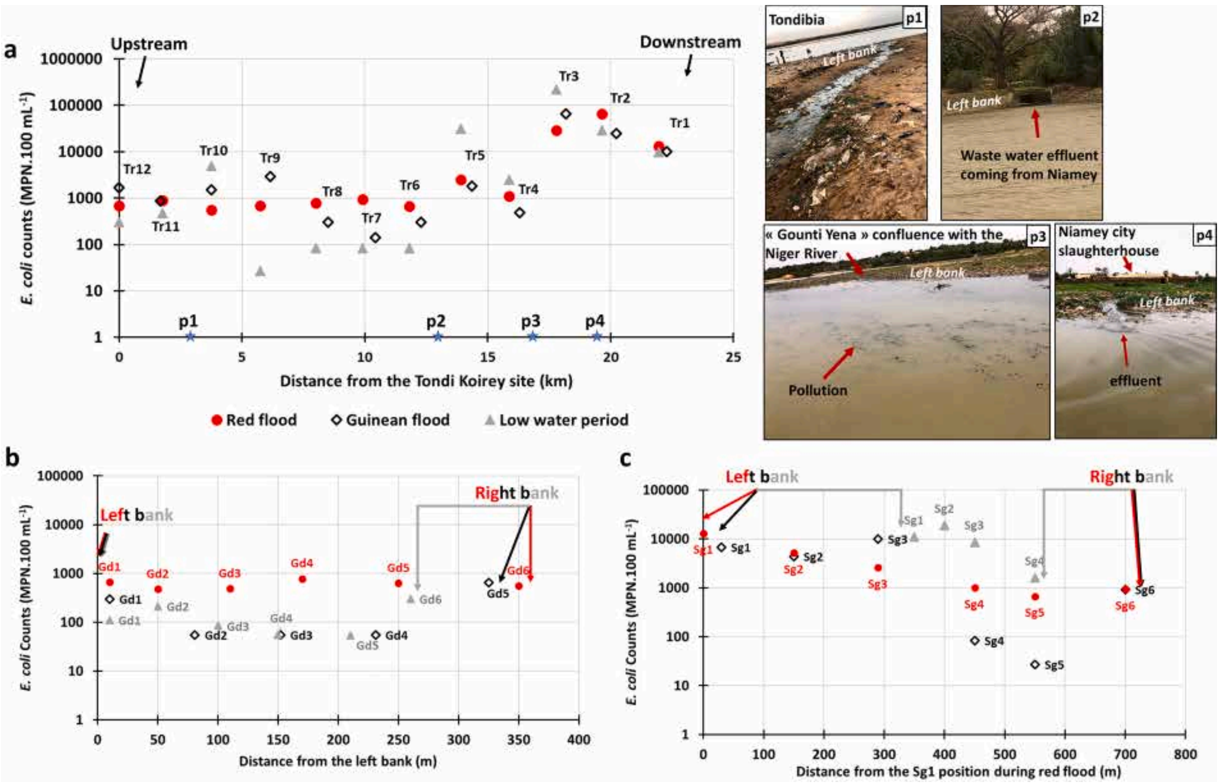

Fig. 3. a) *E. coli* counts along the transect measurements sites during different hydrological episodes; Tr12 = Tondi Koirey site; Tr6 = Goudel site; Tr1 = Saga site; p1 to p4 represent identified wastewater discharges from Niamey city to the Niger River; E. counts along the cross-section sampling sites: b) site of Goudel = upstream site; c) = site of Saga = downstream site. (Red flood = red dots; Guinean flood = black dots; low water period = grey dots).

2. Lower values during the falling limb of the Red flood compared to the rising limb, but still high. The difference of *E. coli* count between the rising and the falling limbs of the Red flood was the greatest in 2020, when the discharge reached very high values;
3. Lower values during the rising and falling limbs of the Guinean flood compared to the Red flood, but with no clear trends. Indeed, during the hydrological cycles of 2019 – 2020 and 2020 – 2021, the rising limb of the Guinean flood presented *E. coli* counts with geometrical means higher than during the falling limb. In 2018 – 2019, the opposite situation was observed with the Guinean flood falling period presenting *E. coli* levels higher than during the rising limb;
4. During the low water period, *E. coli* count did not show any definite trend. However, the geometrical mean of *E. coli* count in 2020 was higher than during the Red flood rising limb, probably due to the early start of the rainy season in the Niamey area.

E. coli counts from 20th of April to 16th of August 2020, at the Tondi Koirey site, further upstream than Goudel, showed values ranging between 27 and 25 000 MPN.100 mL^{-1} (Fig. 2). These values had similar ranges and dynamics to those recorded at the Goudel station for the same period (from 20th of April to 16th of August 2020). On the contrary, *E. coli* at the site of Saga located downstream on the left bank, ranged from 1 900–420 000 MPN.100 mL^{-1} between July 2020 and August 2021 (Fig. 2). The geometrical mean of *E. coli* counts recorded at the site of Saga was twenty-two times higher than those measured at the upstream sites (Goudel and Tondi Koirey). *E. coli* measured at the downstream site, but on the opposite bank to the Saga site (on the right bank), from 13th of July to 15th of August 2019, showed similar values as those of the Goudel site (Fig. 2).

None of the *E. coli* values measured at the four sites were below the MPN method detection limit, which is 27 MPN.100 mL^{-1}, meaning that the Niger River water is inappropriate for human consumption, without an adapted treatment, according to the WHO drinking water standard for the presence of fecal indicator bacteria (Fig. 2). In comparison to WHO bathing water standard (200 *E. coli*.100 mL^{-1} corresponding to a good bathing water quality) (WHO, 2021): 86 % of the *E. coli* values recorded at the Goudel site were above the guideline, of which 7/10 of them were measured during the rainy season. 85 % of the values measured at the site of Tondi Koirey and 100 % at the site of Saga were above that guideline as well.

3.1.2. E. coli counts along the upstream-downstream transect

E. coli measurements along the Niger River transect between Tondi Koirey and Saga showed three parts with different levels of fecal contamination (Fig. 3a). Such observations were duplicated for each sampling date during the hydrological periods observed: the Red flood, the Guinean flood and the low water period. From upstream to downstream, the first part (Tr12 to Tr9; ~6 km) was characterized by intermediate values with a geometrical mean of 741 MPN.100 mL^{-1}; the middle part (Tr8 to Tr6; ~4 km), which includes the pumping site of the Goudel water drinking plant (Tr6), was characterized by lower fecal contamination with a geometrical mean of 249 MPN.100 mL^{-1} and the downstream part (Tr5 to Tr1; ~8 km) was characterized by the highest fecal contamination with a geometrical mean of 13 447, fifty-four times higher than the middle part. This part includes the downstream monitoring station (the site of Saga) and numerous wastewater effluents discharges to the Niger River (Fig. 3a). The measurements between Tondi Koirey and Saga also highlight *E. coli* hotspots that were specifically at "Tr3", "Tr5" and "Tr10" localized downstream of untreated wastewater discharges described in the presentation of the study area. "Tr3" is located downstream of the Gounti Yena confluence (P3 point in the Fig. 3, wastewater discharge from left bank), the main tributary of the Niger River at Niamey that drains wastewater from the city into the river, "Tr5" is located downstream of a gutter draining wastewater from government ministries (P2 in the Fig. 3, wastewater discharge from left bank); whereas "Tr10" is located downstream of the artisanal slaughterhouse of the Tondibia satellite village (P1 in the Fig. 3**,** wastewater discharge from left bank).

3.1.3. E. coli counts between the two banks of the Niger River

The E. coli counts along the Goudel site cross-section showed different patterns depending on the hydrological episode concerned (Fig. 3b). Indeed, the Guinean flood and the low water period were characterized by higher *E. coli* counts on the banks compared to the middle of the river. The values measured on the two banks were two to eight times higher than those measured in the middle of the river stream. During the Red flood period, the *E. coli* counts across the Goudel site section showed similar values from one bank to the other, probably due to the high-water discharge and associated mixing that characterize the Niger River during Red flood measurements. Indeed, the Niger River discharge at Niamey was 2 740 $m^3. s^{-1}$, 900 $m^3. s^{-1}$, 61 $m^3. s^{-1}$ during the Red flood, the Guinean flood and the low water period, respectively (Fig. 3b).

For the site of Saga cross-section, the measurements were taken at 4 positions during the low water period instead of six positions during the Red flood and the Guinean flood due to reduced river width during this part of the hydrological cycle (Fig. 3c). Over the three different periods of measurements, the *E. coli* counts on the left bank were up to seven times higher than in the middle of the river. Even though fecal pollution is higher close to the two banks, the sampling sites near the left bank showed *E. coli* counts six, seven and fourteen times higher than those near the right bank during the low water period, the Guinean flood and the Red flood, respectively. Moreover, unlike at the Goudel cross-section, which showed higher values during the Red floods, the maximum *E. coli* count at the Saga cross-section was measured during low water period (19 000 MPN.100 mL^{-1}) and the minimum was obtained during the Guinean flood, with 27 MPN.100 mL^{-1} at Sg5 (Fig. 3c).

3.2. Physicochemical parameters of the Niger River water at the sampling sites

SPM at Goudel were characterized by seasonal dynamics with very low values (around 0.1 g. L^{-1}) from October to May and very high values (about 15 times higher) the rest of the year as described by Amogu (2009); Alhou et al. (2016) and Moussa et al. (2022). The SPM concentrations at the three sites on the left bank were similar and presented the same temporal dynamics (Pearson correlation coefficient r between SPM measured at Goudel and Tondi Koirey = 0.88; Goudel and Saga = 0.93; Tondi Koirey and Saga = 0.79) (Fig. 4a).

The pH varied between 5.9 and 8.8 and was on average 6.9 at the three monitoring sites, with values in line with the optimal values recommended by WHO drinking water guideline. The temporal dynamics of pH were similar at the three sites and showed increasing trends during the falling limb of the Guinean flood and an important decreasing trend during the rising limb of the Red flood, going from 8.5 to 6.5 (Fig. 4b).

Water temperature at the different sites ranged between 24.5°C and 37.6°C with an average of 29.8°C. The temporal dynamic was similar at the three sites and followed the same pattern as pH (Fig. 4c).

The Electrical Conductivity values were between 32 and 170.6 μS.cm^{-1} at the three sites, within the WHO drinking water guidelines (EC less than 400 μS.cm^{-1}). Niger River water EC also showed increasing trends from the site of Tondi Koirey to the site of Saga (upstream to downstream of Niamey) that could be linked to wastewater effluents from the city. EC at the three sites was characterized by an increasing trend during the falling limb of the Guinean flood (2021). The highest values were measured during the low water period and a decreasing trend was observed during the rising limb of the Red flood (2020) (Fig. 4d).

The Dissolved Oxygen values ranged between 3.15 mg/L (critical level) to 11.95 mg/L (saturation level) but were within the recommended range for drinking water (Fig. 4e). On average, DO values decreased from the site of Tondi Koirey to the site of Saga, probably as a consequence of the high concentrations of organic matter in wastewater discharges coming from Niamey. DO was quite high during the low water period, probably because of photosynthetic activity, and exhibited a decreasing trend during the rising limb of the Red flood, which may be attributed to degassing phenomena and lower photosynthetic activities or by the decomposition of organic matter brought by fertilizer runoff from farm fields.

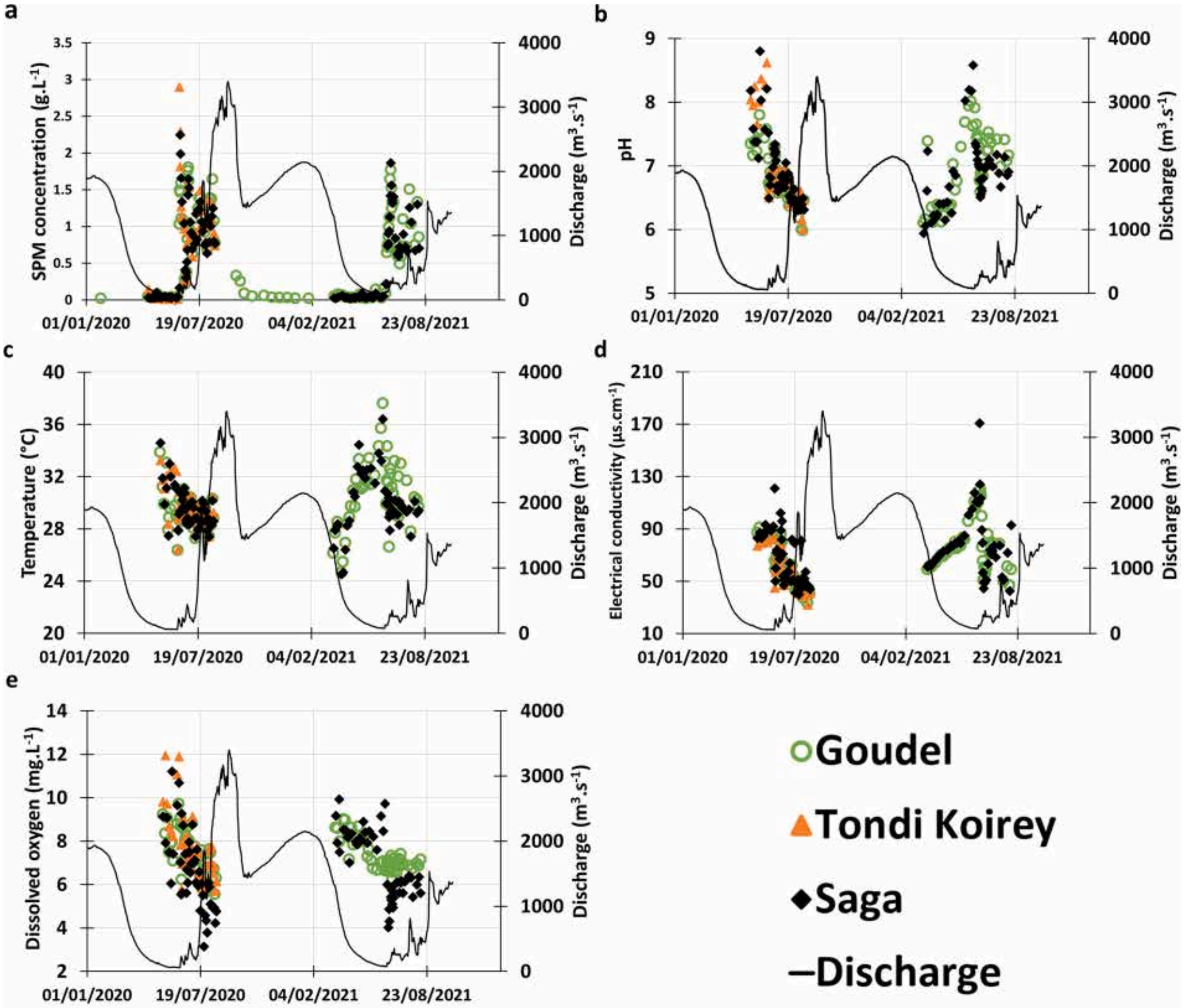

Fig. 4. Niger River water physicochemical parameters spatio-temporal dynamics at the three monitoring sites. a) SPM concentration b) pH, c) Temperature, d) Electrical Conductivity, e) Dissolved Oxygen.

3.3. Relationship between E. coli counts, rainfall and physicochemical parameters

Log_{10} *E. coli* counts showed significant correlations with daily rainfall recorded the same day (Table 1). The dynamics of the *E. coli* count showed peaks after rainfall events, particularly at the beginning of the rainy season. Globally, Log_{10} *E. coli* counts at the three sites were better correlated to the daily rainfall events occurring in the Niamey and its surrounding area than to rainfall occurring in the middle Niger River tributaries area located upstream of the city (Table 1). After rainfall events in the Niamey area, *E. coli* counts followed two different scenarios (Fig. 5):

1. The initial rainfall events were followed by a significant increase of the *E. coli* counts. For example, the rainfall event of the 29th of June 2019 (20 mm) was followed, at the Goudel site, by an increase of around 10 times higher counts than before the event. A similar scenario was observed in 2020 for the rainfall of the 04th of May (22 mm). *E. coli* counts were multiplied by 8, 101 and 6 at Tondi Koirey, Goudel and Saga, respectively, after the rainfall event. The days following the rainfall events, the *E. coli* counts decreased and remained approximately the same as before the events, especially when these rainfall events were followed by dry periods (absence of rainfall events, Fig. 5).
2. Some rainfall events were not systematically followed by an increase in *E. coli* counts. These cases were particularly observed in the core of the rainy season (Fig. 5).

Generally, Log_{10} *E. coli* counts were positively correlated to SPM concentration at the monitoring sites (Fig. 6a). Nevertheless, the correlation between these two parameters showed a decreasing trend from the site of Tondi Koirey (upstream Niamey) to the site of Saga (downstream Niamey). Indeed, SPM and *E. coli* temporal dynamics displayed three different situations:

1. A period when the two parameters were characterized by their lowest values. According to the hydrological cycle of the Niger River, SPM and *E. coli* counts were at their lowest during the falling limb of the Guinean flood and during the low water period.
2. A second period when the *E. coli* counts were high while the SPM concentrations were still low; this is the case at the end of the low water period with the first rainfall events.
3. And a third period when the two parameters exhibit increased trends reaching their highest values. Compared to the hydrological cycle of the Niger River, this period coincides with the rising limb of the Red flood.

The explanation of the decreasing values of correlation between log_{10} *E. coli* and SPM from the upstream to the downstream may be the distinct sources of the two parameters accentuated by the influence of the city of Niamey. Thus, when the rainfall events were localized on Niamey city and its surrounding areas, they were followed by an important increase in *E. coli* counts compared with SPM concentration (Fig. 7a and b). This is particularly true for the site of Saga which is under the influence of the Niamey city and downstream of the major wastewater discharges. In contrast, when rainfall events occurred in the middle Niger River tributaries watersheds located upstream of Niamey, they were followed by an important increase of SPM concentration at Niamey compared to the *E. coli* counts (Fig. 7c and d). In other words, the high value of correlation between SPM and Log_{10} *E. coli* at the site of Tondi Koirey (Pearson R score = 0.63; p-value < 0.00001; Fig. 6) compared to the two other sites (Goudel and Saga) may result from the semi-urban context of the Tondi Koirey site (see Fig. 1b).

The Log_{10} *E. coli* counts in the Niger River at the monitoring sites presented significant correlations with some of the physico-chemical parameters measured with the probes (pH, temperature, EC, DO, Fig. 6). Globally, EC and DO showed a significant negative correlation with the Log_{10} *E. coli* counts at the monitoring sites except for the site of Saga where EC were positively correlated to Log_{10} *E. coli* (Fig. 6). pH and temperature were also negatively correlated to Log_{10} *E. coli* for the site of Tondi Koirey. Globally, pH, temperature, EC and DO were characterized by higher values during the falling limb of the Guinean flood and the low water period when *E. coli* values were lower. During the rising limb of the Red flood (rainy season), the opposite situation was observed (Fig. 6). As highlighted for SPM, correlation between Log_{10} *E. coli* and physicochemical parameters also showed a decreasing trend from the site of Tondi Koirey to the site of Saga, during the common period of measurements (from 14th of May to 16th of August 2020) at the three stations.

Table 1
Relationship (Pearson R score) between the Niger River water Log_{10} [*E. coli* count] and rainfall events.

Rainfall	Tondi Koirey	Goudel	Saga (left bank)
Daily rainfall on the Niamey area	**0.43**** (n = 55)	**0.32****** (n = 196)	**0.44****** (n = 107)
Daily rainfall on the middle Niger River tributaries area located upstream of Niamey	**0.35**** (n = 55)	**0.33****** (n = 196)	**0.37***** (n = 107)

**** = p < 0.00001
*** = p < 0.001
** = p < 0.005
* = p < 0.01; **Bold**: Pearson R score.

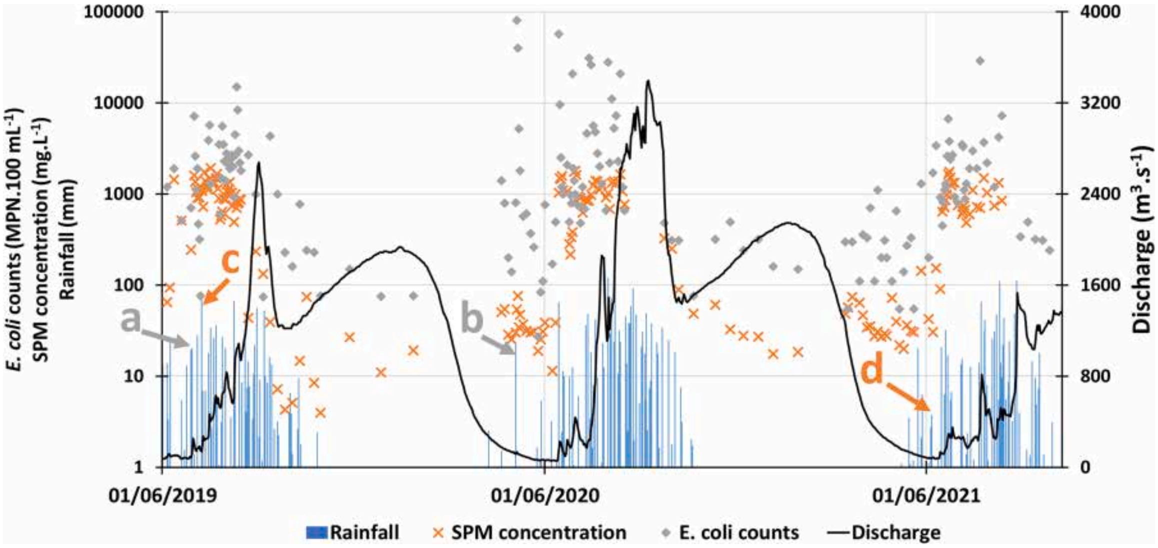

Fig. 5. *E. coli* counts and SPM concentration at Goudel site. Niger River discharge and daily rainfall in Niamey and the surrounding area are also provided. a, b, c, d represent rainfall events for which the effects on *E. coli* count and SPM concentration at Niamey were studied. The spatial distribution of these events can be seen in Fig. 7.

4. Discussion

Monitoring of the microbial quality of Niger River water at Niamey city revealed a permanent contamination by *E. coli*, the fecal indicator bacteria recommended by the WHO. The measured counts at the three monitoring sites were 100 % and 91 % higher than the guideline values given by the WHO for drinking and bathing waters, respectively (WHO, 2017; WHO, 2021). *E. coli* counts assessed at the two upstream sites (Goudel and Tondi Koirey) were slightly higher at the Goudel site. This suggests that the Goudel site, although located in the upstream part of Niamey city, is nevertheless under the influence of a peri-urban environment. Indeed, this area includes former villages such as Tondi Koirey, Tondibia and Gabou Goura that are now part of the city of Niamey, albeit less urbanized than the downstream part. The significantly higher *E. coli* counts at the site of Saga and on the left bank compared to the right bank clearly highlight the impact of Niamey city on the microbiological quality of the Niger River. Moreover, outside of the rainy season, wastewater from Niamey does not immediately mix across the Niger River width, which is coherent with the water color pattern linked to SPM, that comes from the tributaries as documented by Moussa et al. (2022). Nevertheless, despite the reported high levels of fecal contamination, Niger River water at Niamey can be used as a drinking water resource if appropriate potabilization treatments are applied. Indeed, Niger River waters at Goudel are used to supply drinking water to Niamey, after passing through the Goudel potabilization station.

Measurements along the Niger River transect between the sites of Saga and Tondi Koirey confirm the results of long-term measurements at the three monitoring sites. They highlight the significant pollution of the Niger River by the Niamey urban area and, in addition, they identify several hotspots of *E. coli* contamination at sampling positions located directly downstream of wastewater discharges in the Niger River (Fig. 3a). The left bank of Niamey concentrates four of the five municipalities that compose the city, as well as numerous sites producing untreated effluents such as the National Hospital of Niamey and the industrial zone with its agri-food factories. These findings are in line with the work of Alhou et al. (2009) who identified the presence of permanent pollution sources as the main cause of the water quality degradation in the Niamey area. Microbiological contamination sources on the Niger River are mainly due to the urban area activities, domestic animal grazing and open defecation on the riverbanks (Abia et al., 2015; Islam et al., 2017). Niamey city leather tanning area and slaughterhouse also contribute to that contamination through their effluents (P4 in the Fig. 3**,** wastewater discharge from left bank).

Compared to our results, similar *E. coli* temporal dynamics, with higher values during the wet season rather than during the dry season, were also reported at the Bagré Lake in Burkina Faso (Robert et al., 2021), in mountainous China subtropical zone (Xue et al., 2018) and in the Mekong River watershed (Nakhle et al., 2021). Such differences in *E. coli* counts between the dry and wet seasons demonstrate the importance of rainfall and runoff in the process of leaching bacteria from reservoir surfaces and of transporting pollutants to rivers (Niger River) and water bodies. In addition, the *E. coli* levels in the Niger River showed significant increases after the first rainfall events. The same trends were observed at the Raccoon River in the Mississippi basin, marked by intense rainfall between May and June, following a peak in discharge (Schilling et al., 2009). Heavy rainfall events at the beginning of the rainy season are known to be major contributors of *E. coli* to surface waters (Effler et al., 2001). Rainfall events in our area increase the *E. coli* count, which then decreases a few hours/days later (Fig. 5). Daily rainfall in the Niamey area showed significant correlations with the *E. coli* counts at the three sampling sites on the Niger River. However, such correlations do not explain all the fluctuations of *E. coli* counts as several factors impacting bacterial counts were not considered here, such as the state of bacteriological contamination of surfaces

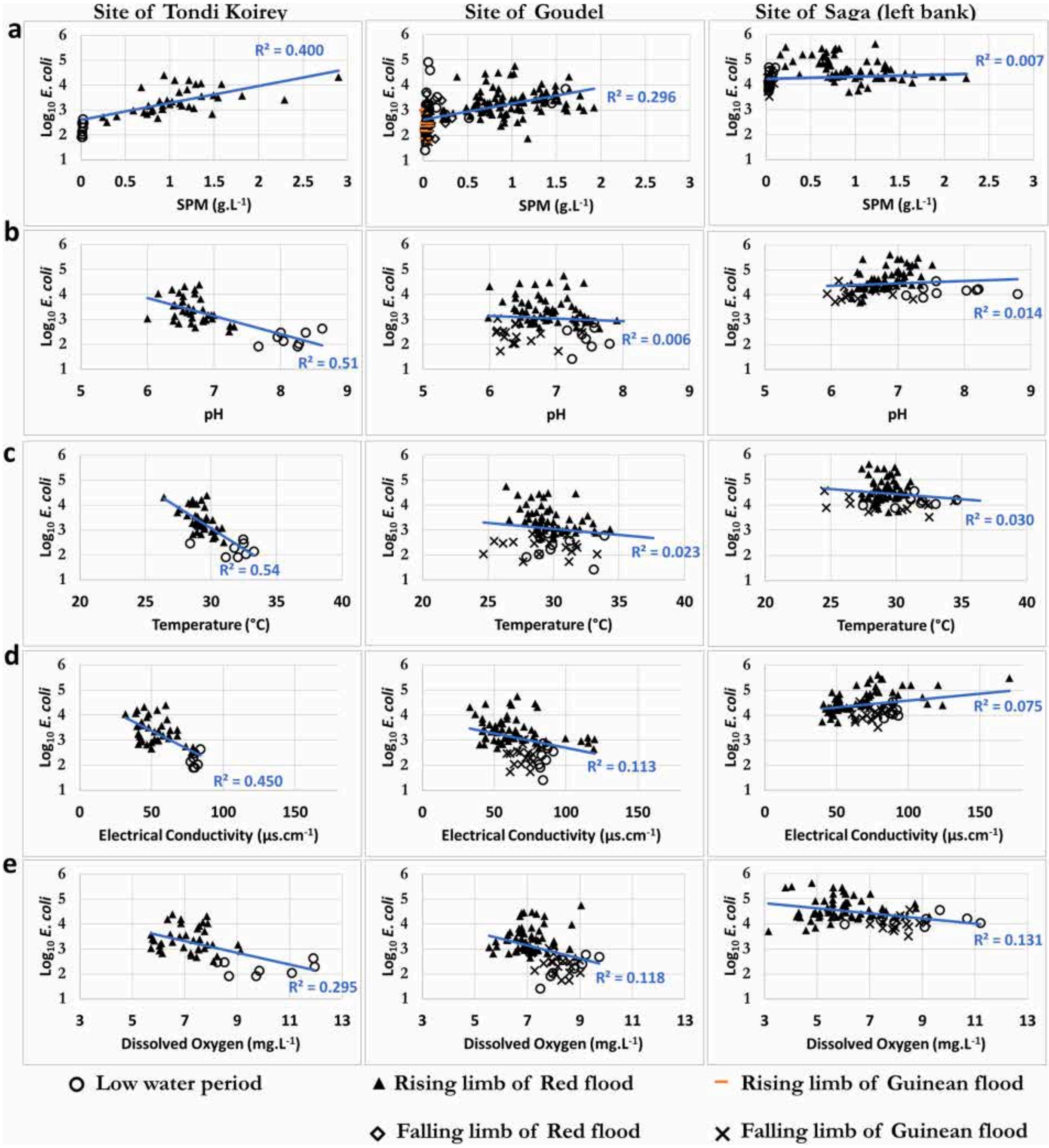

Fig. 6. Relationships between and Log_{10} *E. coli* counts and physicochemical parameters for different hydrological periods.

before rainfall events, land-use and associated anthropogenic activities (McCarthy et al., 2012).

The physicochemical parameters of Niger River measured at our three sampling sites are in line with previous measurements carried out on the Niger River water at Niamey (Alhou et al., 2009; Soumaïla et al., 2022). The temporal dynamics of the Niger River physicochemical parameters showed the preeminent role of rainfall events onto the pollution of surface water bodies with for instance the Niger River DO which was about the level of saturation during the low water period and then became a critical environment during the Red flood due to local rainfall. Similar to some of our results (pH, EC, DO and temperature), several studies have also shown significant correlations between *E. coli* counts and stream water physicochemical parameters in tropical zones (Nakhle et al., 2021; Hathaway et al., 2010; Herrig et al., 2019). However, the observed correlations are not necessarily causal and may be due to the fact that the *E. coli* counts and physicochemical parameters simultaneously respond to the runoff occurring after rainfall events. Relationships between *E. coli* counts and stream water physicochemical parameters measured at our sampling stations, have shown that

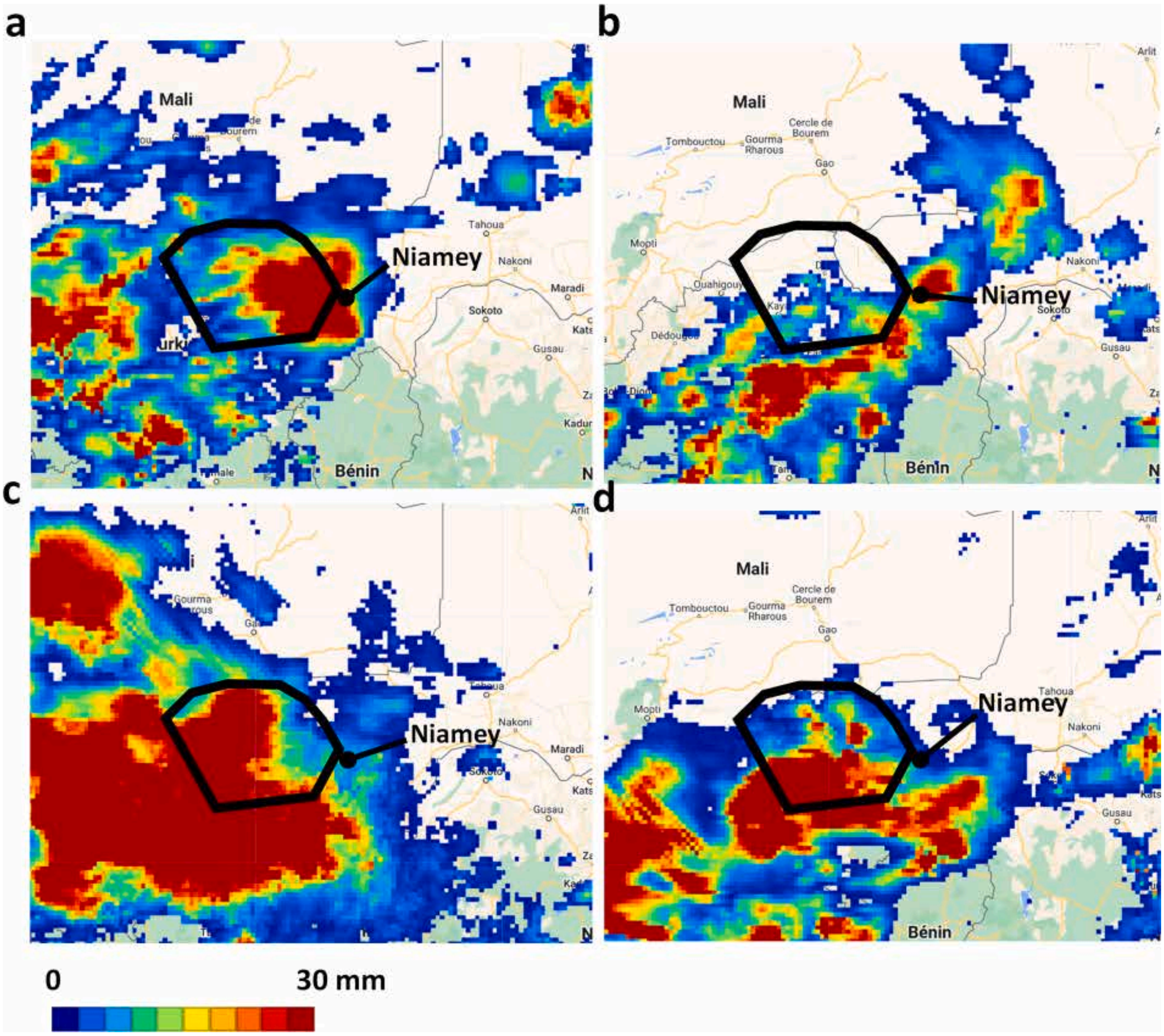

Fig. 7. Location of rainfall occurring in the middle Niger watershed (daily average between 0 and 30 mm). a: rainfall event 29th of June 2019 followed by peak of SPM and *E. coli*; b: rainfall event 04th of May 2020 followed by peak of *E. coli* only; c and d: rainfall event 09th of July 2019 and 06th of June 2021 respectively, followed by peak of SPM only. Black polygons represent the watershed of the middle Niger River tributaries area.

the most important changes in both *E. coli* and physicochemical parameters are observed during the rising limb of the Red flood (Fig. 6). Indeed, Cano-Paoli et al. (2019) showed in the Vermigliana Alpine creek, Italy, that the increase of the discharge is followed by a significant decrease of the EC. Likewise, Du et al. (2020) in the Elbow River, Canada, showed that stream temperature decreases when the streamflow increases.

Both SPM concentration values and *E. coli* counts increased at the three sampling sites after the first rainfall events and showed a significant correlation on a longer time series. These results are in line with many studies that have shown positive correlations between fecal indicator bacteria and turbidity / total sediment load, parameters that are related to the water SPM concentration (Weller et al., 2020; Nakhle et al., 2021; Robert et al., 2021). SPM in surface waters are known to contribute to bacterial survival (Jeng et al., 2005; Chu et al., 2011; Rochelle-Newall et al., 2015). Moreover, correlation between Niger River *E. coli* counts and SPM concentrations at the city of Niamey exhibited decreasing values from the upstream to the downstream. A possible explanation is that SPM and *E. coli* have different sources. Thus, the site of Saga, located downstream the city and under the influence of the city's microbial contamination, renders this relationship less strong at this location. Whereas rainfall events in the Niger River watershed are the main factor impacting the temporal dynamics of these two parameters, its influence on SPM and *E. coli* depends on the location of the rainfall events. *E. coli* counts in the river at the beginning of the rainy season increase following bacteria transport from surface stores (open fecal areas, latrine overflows, gullies…) by rainfall events. In contrast, we also showed that Niamey city is not an important source of SPM to the Niger River. Indeed, the SPM measured at Niamey comes from SPM transported, through erosion, into the river during rainfall events that occur upstream of the city in the middle Niger River tributaries. Amani and Nguetora (2002) have shown that the

Sirba river, the main tributary of the middle Niger River contributes to 80 % of the water supply at Niamey; Moussa et al. (2022) also recently showed that significant SPM contributions come from the Sirba at the early beginning of the rainy season. Thus, rainfall events around the middle Niger River tributaries, located upstream of Niamey, are the reason for an increase in SPM concentrations measured at Niamey. In contrast, rainfall events on Niamey and its surrounding areas, which is the major source of fecal pollution, explain the increase of Niger River *E. coli* counts at Niamey (***Graphical Abstract***). This result has not been reported elsewhere, but it may well explain why lower correlations are observed between *E. coli* and SPM counts in other urban areas worldwide. Indeed, in contrast to our study, previous studies on the influence of rainfall events on *E. coli* counts and SPM have not focused on the spatial variability of precipitations but on their intensity and duration within the study area (Wu et al., 2011; Chen and Chang, 2014).

5. Conclusion

This study aimed at reducing the important information gaps regarding surface water quality, *E. coli* counts and physicochemical parameters, in the Niger River water. Fecal contamination (estimated from *E. coli* counts) was significant throughout the year with 91 % of the measurements higher than the WHO bathing water standard value. The rainy season was the most polluted period of the year. *E. coli* in Niger River at Niamey city can represent a strong risk of gastro-intestinal diseases as well as severe respiratory failures for the populations who use untreated river water for their domestic needs. Continuous and episodic measurements showed that Niamey city is an important source of fecal contamination thus suggesting that human activities are the main source of fecal bacteria. Indeed, if the physicochemical parameters are similar at the measurement positions along the Niger river, *E. coli* counts are significantly higher at the downstream position. We also showed, like previous studies, that there is significant correlation between fecal contamination and suspended particulate matter of the Niger River at Niamey, but with an important decrease of the correlation values from the upstream to downstream. In addition to the urban context of the study, this result is due to the presence of distinct sources of SPM and *E. coli*. While SPM is brought by rainfall events occurring on the upstream tributaries, the *E. coli* sources are more localized in the city of Niamey and its surrounding areas. These results suggest an urgent need in improving knowledge of the different sources responsible for the surface water quality degradation in the Niamey area, especially in the context of environmental and demographic changes. This will be particularly important for the establishment of water use and treatment regulations.

CRediT authorship contribution statement

Rochelle-Newall Emma: Writing – review & editing, Methodology, Data curation. **Ribolzi Olivier:** Writing – review & editing, Methodology. **Mamane Aliko:** Data curation. **Robert Elodie:** Writing – review & editing, Methodology, Data curation, Conceptualization. **Kergoat Laurent:** Writing – review & editing, Methodology, Formal analysis, Conceptualization. **Lartiges Bruno:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation. **Abdourhamane Toure Amadou:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Conceptualization. **Boubacar Moussa Moussa:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Grippa Manuela:** Writing – review & editing, Visualization, Validation, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

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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Data availability

The dataset can be accessed with the following link: http://doi.org/10.5281/zenodo.13907826.

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