Assessing transmission patterns of flood-related waterborne diseases in two urban municipalities of Côte d’Ivoire

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Abstract

Flooding increases with climate variabilities and results in health risk factors in urban settings with poor sanitation infrastructure. Expert previsions highlight that by 2030, climate change and change in land-use will increase waterborne disease transmissions. However, there are few assessments of the indirect impacts of flooding, such as waterborne pathogens and zoonoses. This research aimed at assessing flooding-related disease transmission patterns in two municipalities (Abobo and Cocody) of Abidjan in Côte d’Ivoire. The study applied a cross-sectional survey with 844 households. Overall, 200 samples of rainwater from flooded households and drainage streams were collected, followed by laboratory analyses. *Giardia lamblia* and *Vibrio cholerae* spp. concentrations were assessed using the Sodium Acetate Formalin (SAF) method and the most probable number (MPN) method, respectively. Blood and urine were sampled from 129 rodents captured in households, followed by a PCR analysis to detect *Leptospira* species. The results show no significant difference detected in household exposure to flooding associated with solid waste management. In flooded households, perceived malaria symptoms and diarrhoea are associated with education (OR = 0.8, 95% CI 0.7–0.8, p = 0.001) and waste disposal (OR = 1.4, 95% CI 1.2–1.6, p = 0.001). There was no *V. cholerae* detected in the flood water. A total of 77 cyst/ml of *Giardia lamblia* were found in the flood water in Abobo. Three species of rodents were identified (*Mus musculus*, *Crocidura*, *Rattus*), and there is no *Leptospira* spp. detected in water, blood and urine. The presence of waterborne pathogens associated with flood water highlighted mainly faecal contamination risk. Further interventions should focus on sanitation that reduce faecal contamination.

1. Introduction

The climate variability combined with the pressure of urbanization, and the poor sanitation exacerbate exposure to disease transmission and to environmental contamination in sub-Sahara African countries, which lack sustainable resilience mechanisms and reliable management strategies (Hinz, Frickmann, & Krüger, 2019). Most of the urban settings of these countries are facing pollution by urban runoff and open sewage channels, which are the main sources of pathogen transfer patterns. Furthermore, in most of the cases, the surface water is contaminated by animal and human feces from septic tanks, open dumped wastes or sewage discharges (Bastaraud, Cecchi, Handschumacher, Altmann, & Jambou, 2020). Concerning urbanization aspects, the growing population density contributes to an increasing number of outbreaks of water-related infectious diseases (Castro et al., 2021; Haikerwal & Saxena, 2020). Discharge of pollutants and wastes openly dumped during flooding are associated with disease outbreaks. This very often is exacerbated by climate conditions, particularly during flooding. For example, the precipitation could influence the breeding habitats of mosquitoes, causing malaria. The vector-borne diseases of Japanese encephalitis and Ross River are linked to the alteration of weather and climatic conditions, due to seasonal changes or extreme weather events (Hinz et al., 2019). One should also mention the poor environmental sanitation conditions that favour the proliferation of rodents. These are natural reservoirs of some pathogens and are accountable for Lassa fever and leptospirosis outbreaks (Gravinatti, Barbosa, Soares, & Gregori, 2020). Previsions highlighted that climate change, by 2030, and
land-use change will increase waterborne disease transmissions to 10% (Ntajal, Falkenberg, Kistemann, & Evers, 2020). There is a critical need to improve water and sanitation management strategies and access to basic infrastructures to cope with flooding effects through the increase of the access to clean water, secure sanitation and hygiene in urban areas because the urban population worldwide is estimated at 54% in 2020, and projected to be 60% by the 2030 (Lal, 2020). Strengthening the implementation of the United Nations Agenda 2030 needs multi-sector engagement and evidence-based research. Especially to achieve the Sustainable Development Goals (SDG 3) for good health and well-being, SDG 6 for clean water and sanitation, SDG 13 for climate and adaptation actions, providing relevant data on health risks related to climate change and sanitation to policy makers in due time is important (Ramutsindela & Mickler, 2020).

Studies addressing the link between floods, sanitation infrastructure and health are limited in developing countries. In the context of climate variability, settings with poor sanitation infrastructure and inadequate waste management are the most affected by severe floods, with direct impacts on people’s health (Douglas et al., 2008). Therefore, there are few assessments of indirect impacts of flooding, such as waterborne pathogens and zoonoses. Furthermore, there are not in-depth assessments of infectious disease outbreaks following natural disasters including floods in sub-Saharan Africa (Kakalou & Tsiamis, 2021). These countries are experiencing a drastic climate variability, where extreme rainfall and annual precipitation are declining; Côte d’Ivoire, Nigeria and Ghana are particularly affected (Hounguè, Lawin, Moumouni, & Afouda, 2019). Most of these countries are suffering from severe erosion, flooding and environmental pollution (Croitoru, Miranda, & Sarraf, 2019). In Burkina Faso, for example, in 2009, rainfall from water runoffs and floods, lead to 180’000 severely affected people, 41 deaths, with 33,172 destroyed houses (Dos Santos, Peumi, & Soura, 2019). In Accra (Ghana), flooding annually since 1990 has had huge consequences on life, property and the environment (Mensah & Ahadzie 2020). In 2015, the flood’s disaster led to the death of over 150 individuals in Ghana, with important economic losses and environmental damages (Atanga, 2020).

In Côte d’Ivoire, projections state that the high increase of cumulative intensity of precipitation combined with an amplification of extreme precipitation (Yapo et al., 2020). A study showed that Abidjan, the economic capital of Côte d’Ivoire, is heavily exposed to flooding risks, where eight municipalities out of thirteen, are considered as being at a high risk of flooding (Danumah et al., 2016). The critical rainfall and flooding time period occurred at 75 percent from the 27th of May to the 22nd of June (Konaté et al., 2016). In June 2018, most of cities of the country suffered from heavy rains leading to considerable material damage, and the destruction of several buildings and bridges, which had fatal consequences for the people living in Abidjan (WHO, 2018). The uncontrolled urbanization in Abidjan has led to important environmental changes in habitats of various vectors of diseases, such as mosquitoes (Silué et al., 2022). Additionally, while some risk factors related to climate variability have been investigated in Côte d’Ivoire, there is still a missing link addressing the environment-animal-human interface in relation to climate variabilities and waterborne disease transmissions. Evidence has shown that in some contexts, among emerging diseases’ transmission patterns, climate variability, environmental degradation and shortcomings and the level of sanitation infrastructure are likely to contribute to the increase in the
prevalence of cholera, malaria, and typhoid fever (Kumar, Haikerwal, & Saxena, 2020). Communicable
diseases' transmission during disaster risk factors are associated with access to water services,
sanitation infrastructures and hygiene, the public health system, the environment, mass population
displacement, and the economy (Hammer, Brainard, & Hunter, 2019). The example of cholera outbreaks is
known to originate from the complex interaction with environmental drivers and reservoirs. Bacteria
causing cholera persists in various aquatic systems, such as lakes and rivers. During an outbreak, V. 
cholerae could be associated with the environment through human excretions and municipal wastewater
effluent (Gwenzi & Sanganyado, 2019). Cholera transmission associated with rainfall has diverse
pathways, mainly the increase of exposure to contaminated water by freshly excreted bacteria due to
washout of open-air defecation sites (Lemaitre et al., 2019). In Abidjan, since 2009, overall since 1985,
there have been confirmed cholera cases with 64 deaths (OCHA, 2021). The effects of climate variability
and related flooding on the transmission of zoonoses, such as Leptospirosis, in urban environments are
poorly understood. A survey conducted on 124 patients in the Yopougon municipality of Abidjan
estimated at 4% the seroprevalence of Leptospirosis (Bonfoh, Mwachui, Akpatou, & Zinsstag, 2014; Koffi
et al., 2018). Leptospirosis, a zoonosis transmitted by rodents, is probably the most zoonotic disease in
tropical countries, while floods have recently been documented as a contamination source thereof
(Hooshyar, Rostamkhani, Arbabi, & Delavari, 2019). Although cholera has been well documented, the
interaction with leptospirosis in the context of climate variability and floods is relatively new, and
understanding is yet limited. This study will contribute to filling the knowledge gap by analysing the
environment-animal-human nexus in relation to floods and waterborne disease transmissions. This
research aimed at assessing the interaction of flooding-related diseases (V. cholera, protozoa
and Leptospirosis) transmission patterns in two vulnerable urban settings in Abidjan.

2. Material And Methods

2.1 Study site

This study was conducted in Abidjan, located in southern Côte d'Ivoire, between 5°10 – 5°30 North
latitudes and 3°45 – 4°21 West longitudes (Fig. 1). The study area covers 57,735 ha including 8’981 ha of
the lagoon (16% of the total area). Five municipalities out of thirteen in Abidjan are well known to be at-
risk of flooding. In Abidjan, annual precipitation ranges from 1,500 to 2,500 mm, with averages around
1,784 mm, and the average temperature is 26.6°C. Two of these municipalities have been considered in
this study, namely Abobo and Cocody, because of their different sanitation contexts and flooding
experiences. The municipality of Abobo is a vast territory divided into 28 sectors and 72 neighbourhoods.
The population was estimated at 1,030,658 inhabitants in 2014 (INS, 2014). In terms of spatial
distribution, housing covered 23% of individual standing housing, 7% of grouped housing of companies,
66% of courtyard housing and 4% of precarious housing. Cocody municipality is a residential area,
relatively well-built and well-structured. However, due to poor urbanization there are some shortcomings in
sanitation infrastructures (e.g. rainwater and drainage systems) that increase the risk of flooding during
the rainy season. The population of Cocody municipality is estimated at 447,055 inhabitants.
2.2 Study design

This study applied an interdisciplinary approach to better understand the epidemiology of the selected diseases in the environment and humans in relation to floods in the study area (Fig. 2). The research framework investigated the transmission patterns of flood-related waterborne diseases by assessing environmental risk factors for zoonotic diseases, including sanitation infrastructure, solid waste management, flood water, vectors (*V. cholerae*, *G. lamblia*, and *Leptospira* spp.) and potential reservoirs, such as rodents. Four types of activities were undertaken, mainly a research co-design workshop with stakeholders, household surveys, rainwater sampling and laboratory analyses of blood samples from rodents. Key indicators investigated were *G. lamblia*, *V. cholerae*, and *Leptospira* spp.

A one-day co-design workshop was organized with 35 stakeholders, on 15 November 2016 at the Centre Suisse de Recherches Scientifiques en Côte d’Ivoire (CSRS) and included key persons from local government (municipalities of Abobo and Cocody); administrative authorities (Abidjan District); governmental agencies (public health, water and sanitation; environment, national meteorological service); communities (associations, local authorities); researchers (academics, Leading Integrated Research for the Agenda 2030 in Africa project team members) and other civil society organisations. Based on the research priorities and interests, stakeholders were selected to explain the project and to have a common understanding of the research questions related to access to health services and water, sanitation, and hygiene infrastructure. This activity contributed to validating the study objectives and to having more engagement of the key partners in the implementation of the study. This approach also ensured the integration of local knowledge and the tailoring of the final study design for the needs of the population.

2.3 Household survey

To assess the health conditions and practices associated with flooding in the study area, a household survey was conducted in two selected vulnerable areas of Abobo and Cocody municipalities to gather quantitative data on flooding risk factors and disease occurrences (e.g. cholera, malaria, typhoid, diarrhoea and disease symptoms). The study addressed the major issue of malaria risk during flooding. In addition, the effect of poor flooding water management on diarrhoea transmission (as one symptom pathogen injection) was investigated. Furthermore, other variables were addressed, mainly socio-demographic characteristics, such as gender (female or male), housing conditions, water and sanitation access, solid waste management, and education.

The sample size was calculated with a precision of 5% and a 95% confidence interval (Taro, 1967), using the census for the population in each municipality and the published tables approach. Municipal authorities in Abobo and Cocody contributed to selecting at-risk flooding areas, where the survey was conducted. Overall, 844 households were surveyed in Abobo and Cocody from the 4th to 12th August 2017 by nine well trained research assistants, including four females and five males. Simple random sampling was used to select households to be investigated. This consisted of selecting households at
random locations in identified vulnerable areas. Each sampling point has the same probability of being selected. An approximative distance of 100 m was considered between selected households.

### 2.4. Water, urine, and blood sampling

Water samples and rodent blood samples were collected, according to the guidelines of the US Environmental Protection Agency standards, during the flooding period in Abobo and Cocody municipalities (Charles, Ngumbu, Toe Sr., & Sangodoyin, 2020). Rainwater and wastewater samples were taken from households' drainage. Additional *in situ* parameters were collected to understand chemical risk factors associated with the samples. Overall, 200 water samples were collected between June 2017 and July 2019, during the rainy seasons. Flood water samples were stored in plastic bottles and placed in an ice-packed cooler, according to the “Rodier Guidelines for Sampling and Water Quality in Environment Monitoring” (reference method: FD T90-523-1 of 2008, T90-523-1) (Rodier, Broutin, Chambon, & Champsaur, 1996). Water samples were collected and transferred to the CSRS laboratory for analysis.

Rodent urine and blood samples were collected after those animals were trapped and captured in the households. Overall, 129 rodents were trapped using conventional traps with the assistance of a specialist. Two trapping campaigns of eight days were conducted in selected sites in Abobo and Cocody, from 14–17 August and 18–21 August 2017, respectively. Samples were identified with labels, mainly sample type (blood or urine), date, location, trap number, identifier ID, order, genus, species, and weight. Traps were used because they are known for their effectiveness with trapping small mammals. Traps were baited with peanut butter and fish powder and placed in houses. Twenty-four houses were selected for trapping per site; there were four sub-neighbourhoods per site on a regular basis with approximately 100 m between trapping points. Geographic coordinates were taken at each trapping site using a Global Position System (GPS) device. Each trapping station consists of four coded traps. On each plot, the twelve trapping stations were arranged on two lines with an interval of 100 m. Each line consisted of six trapping stations separated by regular distances. Four trap lines were positioned, covering all twenty-four trapping stations. Four traps were placed in each dwelling, for a total of 84 traps at each site. Traps were visited each morning and the captured rodents were extracted and transported to the laboratory of zoology and animal biology of the University of Félix Houphouët-Boigny in Abidjan. A biologist involved in the research team conducted traps and biological analyses on rodents.

### 2.5 Microbiological analyses of pathogens in flooding water

Three pathogens were investigated in this research namely, *G. lamblia* and *V. cholerae* spp. and *Leptospira* spp. Pathogen *G. lamblia* cysts were analysed, according to the SAF technique (Lora-Suarez, Rivera, Triviño-Valencia, & Gomez-Marin, 2016). After decantation of diluted flooding water samples, the sediment was collected and diluted in 10 ml of SAF solution prior to centrifugation for 500×g for 10 min. The cysts were identified and counted with an optical microscope equipped with a × 50 magnifier. Levels of *V. cholerae* in water samples were determined with the three-tube most-probable-number (MPN) method and ranged from < 0.3 to > 110 MPN/ml. The detection of *V. cholerae* was carried out in three successive stages, mainly the enrichment in a selective medium, isolation of agar cultures and
presumptive identification, and confirmation by biochemical tests (Waturangi, Pradita, Linarta, & Banerjee, 2012). The isolation of *V. cholerae* spp. was made from water inoculated plates containing alkaline buffered peptone water. A standardized identification system for Enterobacteriaceae (API 20E) was used as an alternative to traditional tube media for biochemical testing. A positive sample appears as a very well-defined transparent area without red blood cells around the colony and multiple concentric rings.

Blood and urine samples were transported to the laboratory of CSRS for the analysis of *Leptospira* spp. for bio-molecular analyses using the Polymerase chain reaction (PCR) method. Blood and urine from rodent samples were conserved and stored for PCR using a simple and rapid DNA extraction (ZR Kit), a product from (Zymo Research, California, USA) (Ahmed et al., 2012). Indeed, for genomic DNA extraction, a beta-mercaptoethanol reagent was added to the genomic Lysis Buffer to obtain a final dilution of 0.5%. Fresh samples (1 ml of blood) were taken up into a 30 ml syringe attached with a ZRC GF filter in order to push the sample completely through the filter into an appropriate waste container. Genomic Lysis Buffer (1 ml) was collected with the 30-ml syringe and put in the collection Tube of a Zymo-spin IC Column through the filter. Centrifuge at $\geq 10,000 \times g$ for 1 minute. A 200 µl DNA Pre-Wash Buffer was added to the spin column and centrifuged at $\geq 10,000 \times g$ for 1 minute. G-DNA Wash Buffer (500 µl) was added to the column and centrifuged at $\geq 10,000 \times g$ for 1 minute. After 1 minute, the column was centrifuged at $> 10,000 \times g$ for 1 minute and the collected solution was used to perform PCR purification. Primers were used for the amplification with oligonucleotide sequences of Lep F, Lep R, Lau01, and Lau02 used for the mPCR amplification of the *Leptospira* species Ahmed et al. (2001). The detection limits and sensitivity of the mPCR were determined using a serial dilution of leptospiral DNA mix and by urine-spiking experiments.

### 2.5 Ethical considerations

Before conducting the fieldwork in the study area, the project was approved by the national clearance committee in Côte d’Ivoire (Ref. 112//MSHP/CNER/-km, IORG00075, 2017). The ethical approval covered the household survey investigation and rodent capture and laboratory analyses in the study. For the quality of the data, surveyors were trained prior to the investigation. Informed consent was obtained from all individual participants included in the study. We understand that the importance of rodent welfare for obtaining good experimental results added value to our results and their acceptance to the scientific community. In this context, the ethical clearance has integrated this issue in terms of access to suitable shelter and appropriate capture methods to guarantee the welfare of rodents during data collection.

### 2.6 Data analyses

The data was entered into EpilInfo version 3.5.1 (Centers for Disease Control and Prevention; Atlanta, GA, USA) and exported for statistical analyses into Microsoft Excel (Microsoft Corporation; Office 365 version 2016, New York; USA). Statistical analyses were conducted using R software version 3.0.1 (R Development Core Team; Vienna, Austria) for survey characteristics and microbiological parameters. Descriptive statistics were performed to assess proportions and 95% confidence intervals (CIs) of the main characteristics of the study population, stratified by the municipality. Logistic regression analysis
was used to test for differences between households with flooding experience and without flooding experience. Logistic regression analysis, adjusting for clustering effects (municipalities), was used to test for differences between households with malaria or diarrhoea and without malaria or diarrhoea. Each variable was tested for presence vs. absence.

3. Results

3.1 Demographic characteristics

Overall, 844 households participated in the survey conducted in Abobo and Cocody municipalities and were considered as experiencing flooding events in the city of Abidjan in 2019. Participants ages ranged from 18 to 60 years. Participants were composed of 41.7% (N = 348) male and 58.3% (N = 496) female. In terms of education, about a quarter (24.6%; N = 197) of the respondents by household were totally illiterate, 7.1% (N = 57) attended Koranic school, 19.6% (N = 157) completed primary school, while 26.7% (N = 214) and 22.0% (N = 176) had a secondary and a high level of education, respectively. For housing conditions, 13.7% (N = 116) lived in high standard residential habitats, 48.4% (n = 410) in medium standard habitats and the other 38.0% (N = 322) of participants lived in common courtyards considered here as low standard habitats.

3.2 Assessment of household’s exposure to flooding events

Table 1 summarizes the results of exposure factors linked to flooding risks in the study area. The results from the household surveys described affected households per variable characteristics in the study area. In Abobo, there was no significant difference regarding whether or not households were affected by the flooding based on socio-economic characteristics. The only access to sewerage variable showed a statistically significant high risk of flooding (OR = 1.4, 95% CI 0.6–3.1, p = 0.033). In Cocody, the following variables were significantly associated with a higher risk for flooding, such as residential habitats (OR = 1.6, 95% CI 1.0–2.6, p = 0.035), medium (OR = 1.6, 95% CI 0.4–0.8, p = 0.002), access to septic tanks (OR = 0.5, 95% CI 0.3–0.7, p = 0.001), and tap water (OR = 0.3, 95% CI 0.1–0.9, p = 0.038). When comparing the status of solid waste management system on flooding occurrences, results showed that there was no statistically significant difference detected between households in Abobo and Cocody municipalities.
Table 1
Characteristics of affected households by flooding in Abobo and Cocody

<table>
<thead>
<tr>
<th>Variables</th>
<th>Affected in Abobo</th>
<th></th>
<th>Affected in Cocody</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N (%)</td>
<td>OR</td>
<td>95%CI</td>
<td>p-value</td>
</tr>
<tr>
<td><strong>Sex</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sex</td>
<td>171 (42.1)</td>
<td>1.056</td>
<td>(0.7–1.6)</td>
<td>0.79</td>
</tr>
<tr>
<td><strong>Education</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>None</td>
<td>97 (23.9)</td>
<td>1.1</td>
<td>(0.7–1.8)</td>
<td>0.645</td>
</tr>
<tr>
<td>Confessional School</td>
<td>34 (8.4)</td>
<td>1.5</td>
<td>(0.7–3.1)</td>
<td>0.259</td>
</tr>
<tr>
<td>Primary</td>
<td>82 (20.2)</td>
<td>0.9</td>
<td>(0.5–1.4)</td>
<td>0.521</td>
</tr>
<tr>
<td>Secondary</td>
<td>113 (27.8)</td>
<td>1.1</td>
<td>(0.7–1.6)</td>
<td>0.815</td>
</tr>
<tr>
<td>High School</td>
<td>64 (15.8)</td>
<td>0.8</td>
<td>(0.5–1.4)</td>
<td>0.465</td>
</tr>
<tr>
<td><strong>Habitat</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residential</td>
<td>15 (3.7)</td>
<td>3.0</td>
<td>(1.0–10.6)</td>
<td>0.072</td>
</tr>
<tr>
<td>Economic</td>
<td>217 (53.4)</td>
<td>0.8</td>
<td>(0.5–1.2)</td>
<td>0.28</td>
</tr>
<tr>
<td>Common courtyard</td>
<td>28 (6.9)</td>
<td>0.6</td>
<td>(0.3–1.4)</td>
<td>0.265</td>
</tr>
<tr>
<td>Traditional</td>
<td>NA</td>
<td>0.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Income Per Month (USD)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Below 25</td>
<td>32 (7.9)</td>
<td>0.9</td>
<td>(0.4–1.8)</td>
<td>0.342</td>
</tr>
<tr>
<td>25 to 85</td>
<td>87 (21.4)</td>
<td>1.3</td>
<td>(0.8–2.0)</td>
<td>0.92</td>
</tr>
<tr>
<td>85 to 150</td>
<td>82 (20.2)</td>
<td>1.0</td>
<td>(0.6–1.7)</td>
<td>0.388</td>
</tr>
<tr>
<td>150 to 1000</td>
<td>74 (18.2)</td>
<td>1.3</td>
<td>(0.8–2.1)</td>
<td>0.989</td>
</tr>
</tbody>
</table>
### 3.3 Risk factors influencing waterborne disease transmission during floods

When asked about the access to sanitation in Abobo municipality, more than half (57.9%) of the households used septic tanks, 36.5% used latrines, and 28% reported using the sewerage system. In Cocody municipality, 41.6%, 36.0% and 21.5% of households reported using septic tanks, latrines, and
sewerage system, respectively. To understand health risk factors and impacts of sanitation infrastructure during the flooding periods, the study revealed that practices of open defecation could contribute to an increase in waterborne disease transmission through runoff. Open defecation was reported by a minority of study participations (0.5% in Abobo, 3.4% in Cocody). However, our observations show that open defecation and urination are very common in surrounding neighbourhoods.

For the health concerns, globally the results of the surveys screened potential diseases contracted during the flooding event in the study area, with 7.3% for Typhoid, Cholera (1.2%), Malaria (61.1%), and Leptospirosis (0.4%). The main disease symptoms indicated by participants were fever (61.7%), vomiting (17.5%), diarrhoea (3.1%), and miscarriage (0.3%). Specifically to each municipality, in Abobo, the investigation showed 8.1% of Typhoid, Cholera (1.5%), Malaria (61.6%), and no leptospirosis case. When asked for symptoms observed in this municipality, participants reported fever (62%), diarrhoeas (2.9%), and vomiting (15%). In Cocody, for the same diseases, the respondents reported 6.2% for Typhoid, Cholera (0.9%), Malaria (60.7%) and no case of leptospirosis. In terms of symptoms, participants indicated 61.4% of fever, diarrhoeas (3.2%), miscarriage (0.2%) and 19.9% of participants for vomiting cases. There is no case of jaundice that would attest to the presence of Leptospirosis reported from the survey in this study. Furthermore, when asked whether households are critically affected by flooding events, the study showed that about two-thirds (65%) of the children are affected in Abobo and Cocody due to migration, causing absenteeism in the schools.

Table 2 presents the results of risk factors influencing malaria and diarrhoea during flooding events. When asked whether flooding water can cause malaria and diarrhoea in households, the results of analyses highlighted many variables as risk factors. Participants attending Koranic school (OR = 1.8, 95% CI 1.8–1.9, p = 0.001) and those with no school education (OR = 1.7, 95% CI 1.4–2.1, p = 0.001) were associated with high risks of malaria. Diarrhoea cases were statistically significant, as there is an association with several risk factors including primary school (OR = 0.8, 95% CI 0.7–0.8, p = 0.001) and high-level school (OR = 0.3, 95% CI 0.1–0.7, p = 0.001), medium habitat (OR = 0.6, 95% CI 0.5–0.7, p = 0.001), access to sewerage sanitation (OR = 1.4, 95% CI 1.3–1.6, p = 0.001), and latrines (OR = 1.3, 95% CI 1.0–1.6, p = 0.04). Wastewater disposal in the bag (OR = 1.4, 95% CI 1.2–1.6, p = 0.001) was also associated with a risk of diarrhoea compared to other mode of disposal.
Table 2
Malaria and diarrhoea affections during flooding events in the study area

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Malaria</th>
<th>Diarrhoea</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N (%)</td>
<td>OR</td>
</tr>
<tr>
<td><strong>Sex</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>156 (39.8)</td>
<td>1.0</td>
</tr>
<tr>
<td>Female</td>
<td>139 (37.2)</td>
<td>0.7</td>
</tr>
<tr>
<td><strong>Education</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>None</td>
<td>138 (26.7)</td>
<td>1.7</td>
</tr>
<tr>
<td>Koranic School</td>
<td>42 (8.1)</td>
<td>1.8</td>
</tr>
<tr>
<td>Primary</td>
<td>89 (17.2)</td>
<td>0.8</td>
</tr>
<tr>
<td>Secondary</td>
<td>126 (24.4)</td>
<td>0.9</td>
</tr>
<tr>
<td>High School</td>
<td>91 (17.6)</td>
<td>0.6</td>
</tr>
<tr>
<td><strong>Habitat</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residential</td>
<td>61 (11.8)</td>
<td>0.7</td>
</tr>
<tr>
<td>Medium</td>
<td>246 (47.7)</td>
<td>0.9</td>
</tr>
<tr>
<td>Common courtyard</td>
<td>86 (16.7)</td>
<td>2.143</td>
</tr>
<tr>
<td><strong>Income Per Month (USD)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Below 25</td>
<td>45 (8.7)</td>
<td>1.0</td>
</tr>
<tr>
<td>25 to 85</td>
<td>121 (23.4)</td>
<td>1.6</td>
</tr>
<tr>
<td>85 to 150</td>
<td>88 (17.1)</td>
<td>0.978</td>
</tr>
<tr>
<td>150 to 1000</td>
<td>84 (16.3)</td>
<td>0.9</td>
</tr>
<tr>
<td>Above 1000</td>
<td>9 (1.7)</td>
<td>1.147</td>
</tr>
<tr>
<td><strong>Sanitation Access</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Malaria</th>
<th>Diarrhoea</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N (%)</td>
<td>OR 95%CI</td>
</tr>
<tr>
<td>Collective sanitation</td>
<td>74 (14.3)</td>
<td>1.0</td>
</tr>
<tr>
<td>Septic tanks</td>
<td>243 (47.1)</td>
<td>0.8</td>
</tr>
<tr>
<td>Pit</td>
<td>70 (13.6)</td>
<td>1.0</td>
</tr>
<tr>
<td>Latrine</td>
<td>133 (25.8)</td>
<td>1.6</td>
</tr>
<tr>
<td>Open air</td>
<td>13 (2.5)</td>
<td>2.093</td>
</tr>
<tr>
<td>Solid Waste management</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trash can</td>
<td>356 (69)</td>
<td>1.4</td>
</tr>
<tr>
<td>Garbage bag</td>
<td>102 (19.8)</td>
<td>0.8</td>
</tr>
<tr>
<td>No equipment</td>
<td>22 (4.3)</td>
<td>2.0</td>
</tr>
</tbody>
</table>

Notes: Characteristic: described the risk factor assessed in the study; N: Number of households exposed to flooding events; (%) Values in brackets indicate the percentage of people in the surveyed household. Significance code: * = p-value < 0.05.

3.4 Link between flooding water characteristics and exposure to diseases

Flooding water did not contain any *V. cholerae* in both municipalities. Among the three microbiological pathogens (*G. lamblia*, *V. cholerae*, and *leptospires spp.*) addressed in this study, the results revealed the presence of *G. lamblia* associated with flooding water in Abobo municipality. The study showed *G. lamblia* cysts in flooding water in two sampling points of Abobo, with a concentration from 35 to 120 cyst/ml. In Abobo municipality, the pathogen *G. lamblia* was found in water samples with lower dissolved oxygen. Flooding water in Cocody municipality was not contaminated by *G. lamblia*. Three main species of rodents (N = 129) were trapped in Abobo and Cocody municipalities: *Mus musculus*, *Crocidura*, and *Rattus*. In Cocody, a total of 35 rodents were captured, with 34% (N = 12) of *Crocidura*, 43% (N = 15) of *Mus musculus*, and 23% (N = 8) of *Rattus*. In the Abobo, overall, 94 rodents were found, with 3% (N = 3) of *Crocidura*, 89% (N = 84) of *Mus musculus*, and 7% (N = 7) of *Rattus*. The molecular analyses conducted on rodents' blood and urine using PCR revealed that there is no contamination of rodents susceptible to transfer of Leptospirosis pathogens in the flood water.
Discussion

This research applied an integrated assessment to understand how environmental risk factors (e.g. sanitation infrastructure access, and rodents) influenced flood-related waterborne disease transmission in two municipalities (Abobo and Cocody) in Abidjan, Côte d'Ivoire. We found that among the identified risk factors to disease transmission in the study area, poor access to sanitation infrastructure and open defecation are the most important. Furthermore, we showed that, though \textit{V. cholerae} and \textit{Leptospirosis} diseases were not identified in our study, the presence of rodents in the housing environment, and poor sanitation including open defecation practices could increase disease transmission risks. This investigation provides reliable knowledge on the status of flood-related exposure to \textit{V. cholerae} and \textit{Leptospirosis} and \textit{G. lamblia} infections and associated environmental risk factors in Abidjan.

\textbf{Knowledge and experience on flooding risk in the study area}

Globally (49\%) of the participants reported to having knowledge and experience about flooding risks causing temporal migrations more often. In the city of Abidjan for some decades, flood-affected populations due to many reasons including geographical locations climate variabilities, causing severe damage to infrastructure, and human loss. The critical issue of addressing flooding risk and associated negative impacts are not specific to Abidjan. Indeed, recent statistics show that floods have affected 2.3 billion people worldwide in the last 20 years and are associated with a wide range of negative health outcomes (Suhr & Steinert, 2022). A recent study confirmed that local knowledge of flooding by communities could contribute to providing a better understanding of flood vulnerability and assist in developing adaptive measures to increase people’s resilience (Membele, Naidu, & Mutanga, 2022). A meta-analysis of West Africa flood perception literature reveals that, despite the experience of a devastating flood in 2009 in Burkina Faso, there is still the need of developing a practical flood risk management plan (Schlef, Kaboré, Karambiri, Yang, & Brown, 2018).

\textbf{Understanding causative factors leading to health exposure associated with flooding risk}

The households affected by floods in the study area are statistically significant for the following socio-economic variables, namely the access to sewerage system and septic tanks and residential habitats. This result could be explained by flooding during this last decade in Abidjan, which severely damaged infrastructure and caused human loss in some municipalities (e.g. Cocody, Yopougon, Attécoubé, and Abobo), landsides, and the overflow of open drainage infrastructures. In the municipalities of Abidjan, floods are linked to habitats located in storm basins, runoff, the over flow of rain in drainage networks, and the presence of solid waste in drainage, blocking the normal flow of raining water (Rother et al., 2020). This description of flooding impacts is not specific to Abidjan, because it can affect populations with different socio-economic and cultural characteristics depending on other anthropogenic factors, such as poor urbanization, the efficiency and resilience of sanitation infrastructure, and uncontrolled climate adaptation. A study showed that flooding is among of the natural critical hazards leading to catastrophic impacts on society and urban infrastructure worldwide (Qi, Ma, Xu, Zhao, & Chen, 2022).
The analysis of health risk factors during flooding events revealed that even in the low range (range from 0.5 - 3.4%), open defecation practices contributed to an increase in waterborne disease transmission through runoff. In addition, urination is very common in surrounding neighbourhoods. Indeed, around half of the households used septic tanks, while one-third used latrines, and the remaining part go for open defecation practices and sewerage. Similar findings were reported from other settings facing flooding problems, and the authors showed that interventions on sanitation, waste management, and adequate storm drainage are necessary for developing responses to flooding risk (Mansur, Brondizio, Roy, de Miranda Araújo Soares, & Newton, 2018). Furthermore, access to reliable sanitation infrastructure is challenging in sub-Saharan African countries. For example, in Ghana where the population faces floods every year, a study has recommended the construction of modern city-wide sewerage systems to cope with the rainfall patterns (Owusu-Ansah, 2016). The problem of sanitation infrastructure in flooding occurrences is, therefore, not specific to Côte d’Ivoire.

A secure access to sanitation infrastructure could influence the transmission of flood-related waterborne diseases in the cities of Côte d’Ivoire. Yet, there is a lack of investigation addressing flood-related diseases in Côte d’Ivoire. There have been studies conducted that analysed the necessity of sanitation improvement for reducing waterborne disease risks in the context of wastewater reuse or drinking water at school (Parfait K Kouamé et al., 2014; Parfait K. Kouamé et al., 2021). The same limitations were confirmed in Senegal through a comparing pre-and post-intervention activities showing the importance of water, sanitation and hygiene access as the main drivers to reduce disease risks at household levels. Additionally, the increase of resilience mechanisms combined with adequate sanitation services are necessary to cope with health risks regarding floods. This point of view is highlighted by a recent study showing that the surveillance of floods is essential for areas where disease clusters have already been highlighted, specifically for diarrheal diseases, cholera, hepatitis leptospirosis, and malaria (Kakalou & Tsiamis, 2021).

**Flood-related waterborne disease transmission patterns**

Our investigation revealed also that malaria infection is high (61%) in households during flooding events in the study area. In terms of symptoms observed by participants, fever, vomiting, diarrhoea, and miscarriage were noticed. Flooding water can indirectly cause malaria and diarrhoea. Particularly, diarrhoea symptoms could be associated with malaria or other diseases, such as cholera. There is not a specific plan to address the issues of malaria and diarrhoea transmission in Côte d’Ivoire, specifically for Abidjan, associated with flooding occurrences. Therefore, a study conducted in the northern part of Côte d’Ivoire showed that the strong seasonality of climate variables (10 mm of monthly precipitation) increases the number of clinical malaria episodes (M’Bra et al., 2018). Malaria infections are a broad concern in West Africa, because a recent study showed that seasonal malaria transmission is associated with the latitudinal variation of the rainfall, and the southern area of West Africa is at-risk of malaria epidemics (Diouf et al., 2022). Furthermore, this study in Abidjan showed that open defecation practices were reported despite the low percentage of open defecation reported in our study, and the effects of open defecation are figuring high globally. These practices depend on the waste management system
(e.g. open dumping or not) and could increase the occurrence of microbiological contaminants through runoffs. A similar study conducted in Ethiopia has revealed that open defecations had higher numbers of hookworm eggs in stool. These could be a source of exposure during flooding events, as is the case in Abobo and Cocody municipalities. Worldwide, open defecation affects 1 billion of people, with 842,000 annual deaths due to sanitation-related diseases (Prüss-Ustün et al., 2019). For instance, authors showed the probability of hookworm infections in flooding events are high (Anegagrie et al., 2021). In Ghana, flooding caused the displacement of people and placed them at high risk of contracting diseases, such as cholera, malaria and hepatitis (Mensah & Ahadzie, 2020).

Furthermore, the current study revealed the presence of *G. lamblia* cysts in flooding water in the Abobo municipality, with lower concentration of oxygen concentration (0.05 - 0.16 mg/l). The presence of *G. lamblia* in rainwater is an indicator of poor microbiological quality, and the potential exposure to diseases. *G. lamblia* in rainwater in Abobo could be associated with the poor sanitation conditions in this setting during the rainy seasons. The municipality of Abobo is characterized by the poor collection of solid wastes, the absence of the waste recycling infrastructures, and the lack of wastewater treatment facilities. Similar studies that have been conducted in other contexts revealed the occurrence of *G. lamblia* in rainwater, such as in Abobo municipality. For example, in Pakistan, pathogens, such as *G. lamblia* and *Cryptosporidium*, are known as faecal contamination indicators (Khan et al., 2021). In most sub-Saharan African countries, many factors are involved in the transmission of *G. lamblia*, due to open defecation and poor faecal sludge management. Indeed, *Giardia* is the foremost cause of parasitic infection in the USA with an estimated 1.2 million cases and 3581 reported hospitalizations annually (Kumar et al., 2020). A study conducted in Vietnam revealed that floodwater posed public health risks in urban setting, due to the presence of enteric pathogens (Huynh, Nguyen, Vinh, Baker, & Pathirana, 2019). Additionally, it was reported that poor individuals have unequal opportunities to cope with the shocks from flooding, where they are deprived access to water services more than wealthier households, as observed in the Abobo locality (Grasham, Korzenevica, & Charles, 2019).

Our study cannot exclusively show the link between the occurrence of *G. lamblia* and the effect of climate variabilities. However, floods caused by climate variabilities combined with the poor infrastructure quality in Abidjan and runoff of water are likely to influence the dynamic of pathogens.

**Environmental sanitation and flood-related zoonotic risk**

The results revealed three species of rodents in the study area: *Mus musculus*, *Crocidura*, and *Rattus*. The biomolecular analyses conducted on the blood and urine of rodents using PCR showed that there is no contamination of rodents capable of transferring Leptospirosis disease in both municipalities. There is an increased awareness that rodents in urban settings, as a reservoir of pathogens, affect emerging disease transmission patterns in the human environment. Furthermore, the occurrence of the recent SARS-CoV-2 could be an example of the critical issue regarding the contact between humans and animals (Chauha, Dessie, Noreddi, & Zowalaty, 2020). Rodents represent the largest order of mammals (40%), with 2000 species of this order (Krijger, 2020). Terrestrial mammals are scarce, therefore, there are
at least four genera of rodents: *Acomys*, *Gerbilliscus*, *Lemniscomys*, and *Mastomys* (Manthi & Winkler, 2020). These animals can be potential risk factors through poor sanitation and their contact with households, as observed in Abobo and Cocody municipalities. Similarly, a study showed that rodent reservoirs are associated with the poor management of solid wastes in Kenya (Krystosik et al., 2020). Climate change requires the sustainable management of solid waste management to prevent diseases. In Kuala Lumpur (Malaysia), authors showed the association between rodent distribution and disease transmission, and the change in climate conditions (Mackenzie & Williams, 2009; Naing, Reid, Aye, Htet, & Ambu, 2019). This correlation was also highlighted in a study conducted in the United States of America about rodent borne disease occurrences (Anstead, 2021). Other studies reported on the effect of meteorological conditions on rodent population dynamics and transmission by *Rattus rattus* sp. transmission, which increased during the period El-Nino, and from heavy rainfall found, as observed in Abidjan (Ambu, 2014). In West Africa, particularly in Nigeria, Lassa fever caused by rodent borne viral hemorrhagic fever was observed, and the authors showed that this pathogen is sensitive to population dynamics, rainfall, and flooded agricultural activities (Zhao, Musa, Fu, He, & Qin, 2020). In British India, similar observations were made, showing that when the relative humidity levels are high, outbreaks in rodents were increased in parallel (Tennant, Tildesley, Spencer, & Keeling, 2020). Although the biomolecular analyses carried out on rodent blood and urine were negative on flooding water contamination by *Leptospira* spp. in Abobo and Cocody municipalities, our investigation indicates the importance of further research to increase awareness and in-depth investigation of zoonoses transmitted by rodents in flooded urban environments in sub-Saharan Africa.

**Strengths and limitations**

This investigation is one of the first address the transmission patterns of flood-related waterborne diseases in Côte d’Ivoire. This study also has several limitations. Shortcomings in the questionnaire framing and the sampling method could lead to some indirect biases on the results. Firstly, the survey was only conducted in settings experiencing flooding events, in order to gather accurate data. Therefore, this process of having no control sites was a major limitation in the study. Secondly, the questionnaire did not have questions related to Leptospirosis as a disease because the participants have no clear idea about it. Thirdly, the sampling of rodents was carried out with traps at household level and not outside houses, in open drainage systems and open waste dumping sites. Rodents from the outside environment are more in contact with contaminants and pathogens from wastes than those in households. This limitation could explain the absence of the Leptospira vector in rodent blood and urine. Additional limitations were human urine as risk factors and the dilution effect of the flooding water.

**Conclusion**

This investigation highlighted shortcomings in sanitation infrastructure access as among key patterns that could affect the occurrences of waterborne and zoonotic diseases in Abidjan, Côte d’Ivoire. This study addressed a critical issue of waterborne disease transmissions at the animal-human-water interface and is one of the first implemented in the study area. The integrated approach used a
quantitative data combined with a questionnaire survey, flooding water sampling, rodent captures, microbiological and biomolecular analyses. Biomolecular analyses showed that there was no *V. cholerae* contamination in the rainwater in flooding water in Abobo and Cocody municipalities. Despite the presence of rodents, these mammals were not identified as a vector of Leptospires as hypothesized for this study area. Consequently, this result is well-aligned with the current health situation in Abidjan, because there is currently no official report from the Ministry of Health on the occurrences of cholera and Leptospirosis cases during the study period. The study showed that open defecation practices and poor sanitation management are key risk factors, alongside the identification of *G. lamblia*. Flooding events increase the transfer of this pathogen *G. lamblia*, which can lead to an increase in diarrhoea infections.

Due to the reported limitations of sanitation infrastructure and open defecation practices during flooding events, the achievement of SDGs 6 and 13 is hampered in Abidjan. In light of this context, the health intervention strategy plan has to be focused on *G. lamblia*. Additionally, a holistic analysis is required to integrate control sites in the study design, to extend the capture of rodents in drainage networks for in-depth analysis of Leptospirosis and should include a social component about behaviour change of people in the study area. This recommendation will strongly contribute to provide comparative data to this investigation for reducing the health risks from waterborne disease transmission in Abidjan.

**Declarations**

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**Financial interests:** The authors declare they have no financial interests.

**Conflict of interest statement**

No conflict of interest has noted by the authors in this study.

**Data availability**

The datasets generated during and analysed during the current study are available from the corresponding author on reasonable request.

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Author Contributions

We would like to thank PKK. for the study conceptualization, the methodology design, data collection and analysis and the first draft of the paper elaboration. We acknowledge P.K.K., Profs B.B., D.K. and G.F. for the support of funding acquisition, data validation, review and editing of this article for analyses supervision. We thank A.B. for biological aspects and Dr A.F.O. for statistical analyses.

Conflict of interest statement

The authors declare that there is no conflict of interest.

Ethical Approval

This study received the ethical approval for The Comité National d’Ethique et de la Recherche (CNER) in Côte d’Ivoire (Ref. 112//MSHP/CNER/-km, IORG00075).

Consent to participate

Informed consent was obtained from all individual participants included in the study.

Consent for publication

The participants have consented to the submission of this article to the Environmental Monitoring and Assessment journal.

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**Figures**
Figure 1

Location of the study area
Figure 2

Research framework, showing the study method components