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Relating health benefits of water, sanitation, and hygiene services with the context of urban informal settlements: lessons from Côte d'Ivoire and Kenya

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If the purpose of urban planning is not for human and planetary health, then what is it for?

— UN-Habitat & WHO (2020, p. x)

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Abstract

As cities progressively become humankind's primary habitat, understanding how urban environments affect people's health and well-being is a pressing question. This thesis is inscribed in the recent efforts to reconnect urban planning and public health. It focused on the context of sub-Saharan African cities, for they offer invaluable lessons regarding environmental health determinants and potential solutions to address rapidly growing urban areas characterized by a high prevalence of "informal" settlements. The latter compose a heterogeneous universe of settlements inhabited by vulnerable populations and are, in fact, birthplaces of innovations to deal with social and material precarity. A major concern is that living environments in these areas often exacerbate the risk of several diseases. Indeed, disparities in spatial and socioeconomic development within cities translate into intra-urban health inequities, i.e., the inequitable distribution of the disease burden based on the place of residence.

This thesis addressed health inequities from a spatial perspective. It investigated how the material deprivations that typically affect informal settlements and shape their built environment relate to the effectiveness of water, sanitation, and hygiene (WASH) services, which are often insufficient or inadequate in these vulnerable settings. Diarrhea was the health outcome of interest, as it is directly related to the quality and accessibility of WASH services. Moreover, despite being preventable and treatable, it remains among the leading causes of death worldwide, especially in sub-Saharan Africa. Therefore, planning WASH infrastructures adapted to the specific needs of informal settlements is a global health imperative.

Today, the only consensus is that there is no one-fits-all solution to ensure access to safe WASH services. As advancement toward the United Nations' Sustainable Development Goal for clean water and sanitation (SDG 6) stalls, transitional, short-term solutions are urgently needed in low- and middle-income countries. Several alternatives have emerged in African cities in the past decades, but there is still a lack of empirical studies assessing their association with health outcomes, as well as contextual parameters related to the built environment that might affect the expected health benefits of WASH facilities.

This thesis addressed this knowledge gap. The overarching goal was to understand, in the context of informal settlements in two African countries, how the performance of WASH facilities (measured by the occurrence of diarrhea and continuity of access to such services)

related to the place where they were inserted. Hence, the thesis contextualized WASH facilities by looking beyond the single object, under the hypothesis that their sole availability is not enough to prevent diarrhea in informal settlements, as certain characteristics of their built environments are, per se, risk factors, and affect the accessibility to WASH facilities.

Methodologically, this thesis consists of a sequence of cross-sectional studies based on primary and secondary data. Multi-level analyses were conducted at: (i) a broader geographic scale based on secondary datasets (ecological analysis between city and region scales); and (ii) a local geographic scale based on primary datasets (cross-sectional analyses between individual and neighborhood scales). In this way, the study critically confronted observations of large-scale analyses (resulting from low-resolution, aggregated data) to more detailed observations (resulting from high-resolution, primary data collected at the individual level). The study focused on sites in Côte d'Ivoire and Kenya, two countries affected by significant challenges regarding the expansion of WASH services in low-income urban areas and by a high burden of diarrheal diseases. For the primary data collection, we selected four informal settlements (two in Abidjan, and two in Nairobi) having different built environment configurations, and featuring a variety of WASH services. Participating households were selected through a systematic sampling method.

We obtained secondary data from 9686 households in Côte d'Ivoire (from the Demographic and Health Surveys Program), and primary data from 1147 households in Nairobi, and 567 in Abidjan. The results suggest that the accessibility and health benefits of WASH facilities in informal settlements are interrelated with the form and composition of the built environment at different scales, from the single housing conditions to the spatial configurations of the neighborhood. At a larger scale, urban areas in Côte d'Ivoire characterized as dense and precarious were associated with a higher prevalence of diarrhea. At a local scale, in Abidjan, inadequate dwelling materials and outdoor cooking were associated with higher risks of diarrhea, even in households with access to basic WASH services. In Abidjan and in Nairobi, the form of the built environment was associated with perceived safety to access shared toilets. In Nairobi, non-networked water services (public dispensers) were associated with higher service continuity (water availability) and lower risks of diarrhea than other sources, including piped water.

Ultimately, this study provides empirical knowledge that contributes to elaborating urban planning policies to provide sustainable, safe access to WASH services in informal settlements. Some "unconventional" WASH solutions already implemented in such contexts might be viable alternatives to expand, in the short term, the coverage of these essential services. Also, the study highlights the need to consider the built environment as a potential risk factor for diarrhea, as well as a key parameter to determine the most suitable WASH facility type. More generally, the findings contribute to advancements toward SDGs 3 (good health and well-being), 6 (clean water and sanitation), and 11 (sustainable cities and communities).

Key words: Diarrhea; Informal settlements; Urban infrastructures; Urban Morphology; Water, Sanitation and Hygiene; sub-Saharan Africa.

Résumé

Cette thèse s'inscrit dans les efforts récents visant à reconnecter l'urbanisme et la santé publique. Elle s'est concentrée sur des villes d'Afrique subsaharienne, car celles-ci offrent de précieux enseignements sur les déterminants environnementaux de la santé et des solutions visant les zones urbaines en croissance rapide, caractérisées par une forte prévalence de quartiers "informels". Ces derniers constituent un univers hétérogène de quartiers habités par des populations vulnérables et qui sont, en fait, le foyer d'innovations permettant de répondre aux précarités sociales et matérielles. Toutefois, le cadre de vie dans ces quartiers exacerbe souvent le risque de plusieurs maladies. En effet, les disparités de développement spatial et social au sein des villes se traduisent par des iniquités sanitaires intra-urbaines, à savoir une répartition injuste de la charge de morbidité en fonction du lieu de résidence.

Ces iniquités en matière de santé ont été abordées d'un point de vue spatial. Elle a étudié comment les privations matérielles affectant les habitats informels et façonnant leur environnement bâti sont liées à l'efficacité des services d'eau, d'assainissement et d'hygiène (WASH), qui sont souvent insuffisants ou inadéquats dans ces milieux. L'étude s'est concentrée sur la diarrhée, car elle est directement liée à la qualité et à l'accessibilité de ces services. En outre, elle reste l'une des principales causes de décès dans le monde, en particulier en Afrique subsaharienne. La planification d'infrastructures WASH adaptées aux besoins spécifiques des établissements informels est donc un impératif de santé globale.

Aujourd'hui, le seul consensus est qu'il n'existe pas de solution unique. Alors que les progrès vers la réalisation de l'objectif de développement durable des Nations unies relatif à l'eau potable et à l'assainissement (ODD 6) piétinent, des solutions transitoires et à court terme s'imposent d'urgence dans les régions à faible revenu. Plusieurs alternatives ont vu le jour dans les villes africaines, mais il y a encore un manque d'études empiriques évaluant leur association avec les bénéfices sanitaires escomptés, ainsi que des paramètres contextuels liés à l'environnement bâti qui pourraient affecter ces bénéfices.

Cette thèse a visé à combler cette lacune. L'objectif principal était de comprendre, dans le contexte des quartiers informels de deux pays africains, comment la performance des services WASH (mesurée par l'occurrence de la diarrhée et la continuité de l'accès à ces services) était liée à l'endroit où ils étaient insérés. Ainsi, la thèse a contextualisé les équipements WASH en

regardant au-delà de l'objet unique, sous l'hypothèse que leur seule disponibilité ne suffit pas pour prévenir la diarrhée dans les quartiers informels, car certaines caractéristiques de leurs environnements bâtis sont, en soi, des facteurs de risque, et affectent leur accessibilité.

L'étude consiste en une série d'études transversales basées sur des données primaires et secondaires. Des analyses multi-niveaux ont été menées à : (i) une échelle géographique plus large basée sur des données secondaires (analyse écologique entre les échelles de la ville et de la région) ; et (ii) une échelle géographique locale basée sur des données primaires (analyses transversales entre les échelles de l'individu et du quartier). Ainsi, l'étude a confronté de manière critique les analyses à grande échelle (résultant de données agrégées à faible résolution) aux analyses plus détaillées (résultant de données primaires à haute résolution). L'étude s'est concentrée sur des sites en Côte d'Ivoire et au Kenya, deux pays affectés par de sérieux défis concernant l'expansion des services WASH et par une forte charge de maladies diarrhéiques. Les données primaires ont été collectées dans quatre quartiers informels (deux à Abidjan et deux à Nairobi) ayant différentes formes d'environnement bâti et disposant d'une variété de services WASH. Les ménages participants ont été sélectionnés par une méthode d'échantillonnage systématique.

Nous avons obtenu des données secondaires de 9686 ménages en Côte d'Ivoire (du Demographic and Health Surveys Program), et des données primaires de 1147 ménages à Nairobi, et 567 à Abidjan. Les résultats suggèrent que l'accessibilité et les bénéfices sanitaires des équipements WASH dans les quartiers informels sont liés à leur environnement bâti, à différentes échelles : des conditions du logement individuel aux caractéristiques spatiales du quartier. À plus grande échelle, les zones urbaines de Côte d'Ivoire caractérisées comme étant denses et précaires ont été associées à une prévalence plus élevée de la diarrhée. À l'échelle locale, à Abidjan, l'usage de matériaux de construction inadéquats et la cuisine en plein air ont été associés à des risques plus élevés de diarrhée, même chez les ménages ayant accès à des services WASH adéquats. À Abidjan et à Nairobi, la forme de l'environnement bâti a été associée à la sécurité perçue de l'accès aux toilettes partagées. À Nairobi, les services d'eau hors-réseau ont été associés à une plus grande disponibilité de l'eau et à des risques de diarrhée plus faibles que d'autres sources, y compris l'eau canalisée.

Cette étude a fourni des éléments empiriques contribuant à l'élaboration de politiques de planification urbaine visant à fournir un accès durable aux services WASH dans les zones d'habitat informel. Certaines solutions "non conventionnelles" déjà mises en œuvre dans ces contextes pourraient constituer des alternatives viables pour étendre, à court terme, la couverture de ces services essentiels. L'étude souligne également la nécessité de considérer l'environnement bâti comme un facteur de risque pour la diarrhée, ainsi que comme un paramètre clé pour déterminer le type d'installation WASH le plus approprié. Globalement, l'étude contribue à faire progresser les ODDs 3 (bonne santé et bien-être), 6 (eau propre et assainissement) et 11 (villes et communautés durables).

Mots-clés : Diarrhée ; Habitat informel ; Infrastructures urbaines ; Morphologie urbaine ; Eau, assainissement et hygiène ; Afrique subsaharienne.

Resumo

Esta tese se inscreve nos recentes esforços para reconectar o planejamento urbano e a saúde pública. Ela se concentrou em cidades da África Subsaariana, pois estas oferecem lições valiosas sobre os condicionantes ambientais de saúde e possíveis soluções para lidar com áreas urbanas em rápido crescimento, caracterizadas por uma alta prevalência de assentamentos "informais". Estes últimos compõem um universo heterogêneo de assentamentos habitados por populações vulneráveis e são, na realidade, o berço de inovações para lidar com precariedades sociais e materiais. Porém, os ambientes de vida nessas áreas geralmente exacerbam o risco de várias doenças. De fato, disparidades no desenvolvimento espacial e social nas cidades se traduzem em iniquidades intraurbanas de saúde, ou seja, a distribuição injusta da carga de doenças com base no local de residência.

Essas iniquidades em saúde foram tratadas sob uma perspectiva espacial. Ela investigou como as privações materiais que tipicamente afetam assentamentos informais e moldam seu ambiente construído se relacionam com a eficácia dos serviços de água, saneamento e higiene (WASH), que geralmente são insuficientes ou inadequados nesses locais. O estudo focou na diarreia, pois ela está diretamente relacionada à qualidade e à acessibilidade a esses serviços. Além disso, ela continua entre as principais causas de morte no mundo, especialmente na África Subsaariana. Portanto, planejar infraestruturas WASH adaptadas às necessidades específicas dos assentamentos informais é um imperativo de saúde global.

Atualmente, o único consenso é que não existe uma solução única. Como o avanço em direção ao Objetivo de Desenvolvimento Sustentável das Nações Unidas para água limpa e saneamento (ODS 6) está estagnado, soluções transitórias e de curto prazo são urgentemente necessárias em países de renda baixa e média. Alternativas surgiram em cidades africanas nas últimas décadas, mas ainda faltam estudos empíricos que avaliem sua associação com desfechos de saúde, bem como parâmetros contextuais relacionados ao ambiente construído que possam afetar os benefícios de saúde esperados.

Esta tese abordou essa lacuna de conhecimento. O objetivo geral foi entender, no contexto de assentamentos informais em dois países africanos, como o desempenho das instalações WASH (medido pela ocorrência de diarreia e pela continuidade do acesso a esses serviços) se relaciona com o local onde estão inseridas. Assim, a tese contextualizou as instalações WASH

olhando além do objeto único, sob a hipótese de que sua simples disponibilidade não basta para prevenir a diarreia em assentamentos informais, já que certas características do ambiente construído são, por si só, fatores de risco e afetam a acessibilidade a essas instalações.

Esta tese consiste em uma sequência de estudos transversais baseados em dados primários e secundários. Análises multi-nível foram conduzidas em: (i) uma escala geográfica ampla com base em dados secundários (análise ecológica entre as escalas de cidade e região); e (ii) uma escala geográfica local com base em dados primários (análises transversais entre as escalas de indivíduo e bairro). Assim, o estudo confrontou criticamente análises em larga escala (resultantes de dados agregados de baixa resolução) a análises mais detalhadas (resultantes de dados primários de alta resolução). O estudo se concentrou em locais na Côte d'Ivoire e no Quênia, dois países afetados por desafios significativos em relação à expansão dos serviços WASH e por uma alta carga de doenças diarreicas. Os dados primários foram coletados em quatro assentamentos informais (dois em Abidjan e dois em Nairóbi) com diferentes configurações de ambiente construído e com uma variedade de serviços de WASH. As residências participantes foram selecionadas por meio de um método de amostragem sistemática.

Obtivemos dados secundários de 9686 domicílios na Côte d'Ivoire (do Demographic and Health Surveys Program), e dados primários de 1147 domicílios em Nairóbi e 567 em Abidjan. Os resultados sugerem que a acessibilidade e os benefícios sanitários das instalações WASH em assentamentos informais estão inter-relacionados com a configuração do ambiente construído em diferentes escalas, desde as condições de moradia individual até as características espaciais do bairro. À larga escala, áreas urbanas na Côte d'Ivoire caracterizadas como densas e precárias foram associadas a uma maior prevalência de diarreia. À escala local, em Abidjan, materiais de construção inadequados e cozinhar ao ar livre foram associados a maiores riscos de diarreia, mesmo em residências com acesso a serviços básicos de WASH. Em Abidjan e em Nairóbi, a forma do ambiente construído foi associada à percepção de segurança para acessar banheiros compartilhados. Em Nairóbi, os serviços de água não ligados à rede (distribuidores públicos) foram associados a uma maior disponibilidade de água e a menores riscos de diarreia do que outras fontes, incluindo água encanada.

Este estudo fornece conhecimento empírico que contribui para a elaboração de políticas de planejamento urbano para fornecer acesso sustentável aos serviços WASH em assentamentos informais. Algumas soluções "não convencionais" já implementadas em tais contextos podem ser alternativas viáveis para expandir, a curto prazo, a cobertura desses serviços essenciais. Além disso, o estudo destaca a necessidade de considerar o ambiente construído como um possível fator de risco para a diarreia, bem como um parâmetro fundamental para determinar o tipo de instalação de WASH mais adequado. De modo mais geral, as descobertas contribuem para os avanços em direção aos ODSs 3 (boa saúde e bem-estar), 6 (água limpa e saneamento) e 11 (cidades e comunidades sustentáveis).

Palavras-chave: Diarreia; Assentamentos informais; Infraestruturas urbanas; Morfologia urbana; Água, saneamento e higiene; África subsaariana.

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List of abbreviations

AOR - Adjusted Odds Ratio
CAR - Covered Area Ratio
CBD - Central Business District
CI - Confidence Interval
CSRS - Centre Suisse de Recherches Scientifiques en Côte d'Ivoire
DHS - Demographic and Health Surveys Program
EPFL - École Polytechnique Fédérale de Lausanne
GIS - Geographic Information Systems
GPS - Global Positioning System
JMP - WHO/UNICEF Joint Monitoring Program for Water Supply, Sanitation, and Hygiene
KEMRI - Kenya Medical Research Institute
LJC - Local Join Count
LLR - Likelihood Ratio
MAUP - Modifiable Areal Unit Problem
MLR - Multiple Logistic Regression
NCD - Non-Communicable Disease
NCWSC - Nairobi City Water and Sewerage Company
OECD - Organisation for Economic Cooperation and Development
SDG - United Nations' Sustainable Development Goal
SSA - Sub-Saharan Africa
UN - United Nations
UN-Habitat - United Nations Human Settlements Program
UNICEF - United Nations Children's Fund
VIF - Variance Inflation Factor
WASH - Water, Sanitation, and Hygiene
WHO - World Health Organization

Foreword

This thesis was part of the SNSF Sinergia project "African contributions to global health: Circulating knowledge and innovations," a research consortium with principal investigators based at the University of Basel, the École Polytechnique Fédérale de Lausanne, and the Swiss Tropical and Public Health Institute. The consortium also included invaluable partnerships in several African countries: Burkina Faso, Côte d'Ivoire, Kenya, Mali, Tanzania, Togo, and Zambia. This large project developed a transdisciplinary perspective on health and innovation from an Africanist viewpoint by bringing together urban planners, historians, and health professionals.

As a sub-project of the consortium mentioned above, this thesis aimed to situate urban planning in the global health agenda. There has been much debate on the actual definition of "global health," which has blurred boundaries as a field of study, overlapping with the fields of "public health" and "international health." Based on the work by Koplan et al. (2009, p. 1995), "global health" here was defined as "an area for study, research, and practice that places a priority on improving health and achieving equity in health for all people worldwide. Global health emphasizes transnational health issues, determinants, and solutions; involves many disciplines within and beyond the health sciences and promotes interdisciplinary collaboration; and is a synthesis of population-based prevention with individual-level clinical care." Therefore, from the urban planner's perspective, if equity in health is to be achieved as set by the global health agenda, then inequitable urban development (given by the spatial distribution of essential infrastructures and services) becomes a most pressing issue, as it inevitably results in an inequitable distribution of the burden of disease.

In this regard, African cities certainly offer relevant case studies – not exactly for the social (and spatial) equity challenges currently faced, but especially because of recent innovations aiming to expand access to basic services that deserve further scientific attention. Such experiments may be relevant to promote health equity in other contexts, effectively consisting in African contributions to global health. Indeed, other regions with rapidly growing cities, notably in the global south, may learn invaluable lessons from these African experiences.

1 Introduction

Urbanization is a ubiquitous process. Although the "urban age" declaration by the United Nations Human Settlements Program (UN-Habitat) has been contested for the lack of consistency in the definition of what "urban" is (Brenner & Schmid, 2014; Vo, 2016), we can argue that today the global population tends to live in cities (UN-Habitat, 2022). As they progressively become humankind's primary habitat, understanding how urban environments affect people's well-being is a global health question.

Such concern is certainly not new. Throughout history, the relatively high demographic densities in cities facilitated the spread of deadly infectious diseases such as tuberculosis or cholera (Dobson & Carper, 1996). To prevent these diseases, a consensus emerged during the 19th century around the necessity of interventions in the built environment, notably through constructing well-ventilated spaces and water and sanitation infrastructures (Njoh, 2016; Peterson, 1979). For example, in 1848 in England, The Times described cholera as "the best of all sanitary reformers" (Museum, 2019), alluding to the Public Health Act that launched a series of critical urban reforms to expand water and sanitation infrastructures. It was precisely during the sanitary movement of the 19th century that the so-called "modern" urban planning and public health fields emerged, sharing common goals. Both fields rose to address, in a "scientific" way, the structural socioeconomic and spatial changes of that time (i.e., industrialization and increasing demographic densities in cities) and the health challenges that came with them (Benevolo, 1963; Corburn, 2004).

During the 20th century, however, these two fields were progressively disconnected. Globally, urban planning became increasingly determined by capital accumulation and reproduction (Harvey, 2003; Rolnik, 2015; Slater, 2017) and, especially after World War II, the housing sector started playing a major role in economic growth worldwide (R. Harris & Arku, 2006). At the same time, public health efforts progressively focused on microbiology and individual-level healthcare based on a curative approach while paying less attention to environmental and other determinants of health (M. Susser & Susser, 1996a).

It is only in the last decades that a renewed interest in reconnecting urban planning with public health has appeared (Barton & Grant, 2006; M. Susser & Susser, 1996b; UN-Habitat & WHO, 2020), while scholars have promoted the integration of concepts and tools used in different disciplines to address the spatial and socio-ecological dimensions of health (Corburn et al., 2019; Utzinger et al., 2011). Also, governments have raised the need to shift from a curative approach to a preventive, more holistic approach to health. For instance, the Kenyan national government acknowledged that "a disproportionate share of spending has focused on curative, hospital-based health care", which led to a "cost-ineffective health care delivery system which allows people to fall sick, then tries to cure them" (Government of Kenya, 2013, p. 14). Urban planning certainly has a role in this preventive approach, and urban health studies are a useful source of empirical evidence to guide decision-making to promote healthier living environments in cities (Corburn et al., 2019; Galea & Vlahov, 2005).

This thesis is inscribed in these recent efforts to reconnect urban planning with public health. It focused on African settings, for they offer invaluable lessons regarding environmental health determinants in rapidly growing cities characterized by a high prevalence of "informal" settlements. Some of these vulnerable human settlements are referred to as "slums" (Davis, 2006; UN-Habitat, 2022). However, considering previous debates on the pejorative nature of this denomination (Gilbert, 2007), here, the term "informal settlements" was used instead. Based on the UN-Habitat's definition (UN-Habitat, 2017, p. 9), by "informal settlements," we refer to "settlements and areas where housing is not in compliance with current planning and building regulations (unauthorized housing)." In this broader definition, we also include "slums," i.e., areas lacking one or more of the following: access to adequate sanitation facilities; easy and affordable access to clean water; durable housing structure; sufficient living space; and security of tenure.

1.1   Context and motivation

Sub-Saharan Africa is the fastest-urbanizing region in the world (OECD & Sahel and West Africa Club, 2020). This poses considerable challenges, as the growth of human settlements largely outpaces the extension of essential infrastructures and services. In this region, more than 230 million urbanites lived in "slums" in 2020, corresponding to over half (50.2%) of the urban population (UN-Habitat, 2022). This urbanization trend, deeply marked by social and spatial disparities, materializes in "planned" and "informal" areas. In turn, these disparities translate into urban health inequities, as we will see.

Many cities in sub-Saharan Africa had their spatial and social configurations historically affected by colonial urban planning, which enforced, from early-stage, spatial patterns of social segregation through strict laws on land use and social control. For example, in addition to the functional segregation established by the Athens Charter's zoning model, residential segregation was established based on ethnicity under public health pretexts: Europeans lived in areas separated from all other populations, which were (erroneously) considered "dangerous

classes" more likely to be sick and transmit diseases (Greenwood & Topiwala, 2020; Steck, 2005). Of relevance, the residential areas allocated to Europeans were usually better served in terms of urban infrastructures like water and sanitation (Njoh, 2016). This inequitable distribution of infrastructures was patent from their very concept and design; for example, the estimated daily water demand of Europeans could be the double of the estimated quantity for "natives" (Nilsson, 2016). Also, from a topographic perspective, Europeans occupied areas better protected from environmental hazards and with lower risks of vector-borne diseases (Achola, 2001).

Even after the independence movements, socio-spatial segregation persisted. Only this time through inflexible building laws, still largely based on standards elaborated in Europe and North America that are incompatible with the reality on the ground (Chenal, 2013; Parnell & Pieterse, 2014). This inadequacy of building and urban planning regulations "swept" low-income urbanites away from formal housing markets and fostered the development of informal settlements (Watson, 2009). Indeed, rigid regulations such as minimum plot sizes or lengthy approval processes, combined with limited access to housing finance schemes and lack of "pro-poor" land use policies, have reduced the affordability of formal housing markets to low-income populations (Buckley et al., 2016; Hammam, 2014). For instance, in Kenya, only 10% of housing units were provided by the formal construction industry in 2019, targeting mostly higher income groups (Gardner et al., 2019). In addition, public housing programs in most African countries have been either inexistent, unaffordable to the lowest incomes, or failed to meet the size of the demand (Majale et al., 2011).

Therefore, informal settlements are a predominant characteristic of African cities (Parnell & Pieterse, 2014). These settlements are commonly referred to as a single group, which omits the fact they are very heterogenous, varying across regions and within cities. From a social perspective, there is a large variety of socio-demographic characteristics between and within informal settlements (Jankowska et al., 2011). From a morphological perspective, the spatial disposition of buildings (i.e., their proximity, street alignment, and size) also varies greatly in place and time (Kraff et al., 2020).

In particular, "slums" and informal settlements are, inevitably, birthplaces of multiple solutions to deal with precarity in socioeconomic and material dimensions (Bolay et al., 2016), which are reflected in the composition of their built environment. The predominance of incremental, auto-construction practices that often characterize dwellings in those areas is, in fact, a bottom-up response to the lack of affordable housing in the formal markets and to financial limitations impeding to afford, at once, the construction of a finished structure (Angélil & Malterre-Barthes, 2016; J. F. Turner, 1978). Also, faced with the insufficient pace of expansion of urban infrastructures like electricity, water, or sewerage networks, the provision of these essential services has been made through a variety of non-networked systems that have been progressively adapted to the social and spatial conditions of these settlements (Kasper & Schramm, 2023; Lawhon et al., 2018) – this topic was further elaborated in Chapters 4 and 5. Of course, the extra-legal nature of informal settlements has led to social struggles and tensions

between their residents, who claim better access to basic services (and who otherwise have to recur to illegal solutions), and local authorities, who may neglect these claims due their a hesitation to engage with "informality" (Kimari, 2021; Roy, 2005).

Even though they compose a heterogenous universe, informal settlements in sub-Saharan Africa often face common challenges, most notably low housing quality and significant health hazards (Majale et al., 2011). Ezeh et al. (2017) argue that, beyond socioeconomic aspects, human health also has spatial determinants, i.e., specific factors of the built environment that exacerbate the risk of disease. The authors put forward how urban "slum" dwellers are exposed to "neighborhood effects," making them disproportionally vulnerable to both infectious and non-communicable diseases, as compared to "non-slum" dwellers – even presenting, in some cases, worse health outcomes than low-income populations in rural areas. These findings support previous arguments raising the need to address the built environment and the urban context in general as key health determinants (Galea & Vlahov, 2005). One must note that improving the living conditions in "slums" is a public health concern that is not limited to their own residents, as there is an "interconnectedness" between the different parts of a city (Obrist et al., 2006). Although infrastructural deprivations may be local, the health penalties of these urban planning deficiencies are dispersed through the pollution of ecosystems and communicable diseases.

Therefore, urban planners have the responsibility to understand the links between the built environment and health outcomes. There is a global need to tackle health inequities in cities through the urban form and the adequate design and distribution of infrastructures. Indeed, with over one billion people living in "slums" today (UN-Habitat, 2022), urban planners have an important role to play in addressing global health challenges by implementing a more "just" spatial development (Soja, 2010) that reduces urban health inequities due to the place of residence.

Such health inequities, however, may be dissimulated depending on how one processes data. Since the sanitary movement, economic and urban growth have been associated with better health outcomes (based on aggregated urban and rural mortality data), what has been called the "urban advantage" (Ompad et al., 2017; Rydin et al., 2012). While this urban advantage may be observed with data aggregated at the city level, the same data disaggregated at the intra-urban level (e.g., by neighborhood) might not support this idea anymore as discrepancies between different areas and populations become evident (Elsey et al., 2016; Kuddus et al., 2020; WHO, 2010). For example, in Nairobi (Kenya), city-level data from the Global Burden of Disease Study showed that non-communicable conditions, namely, malnutrition and hypertension were the two main contributors to the disease burden in 2016, while unsafe water, sanitation, and hygiene services and air pollution represented considerably smaller risks (Achoki et al., 2019). However, such conclusions did not address intra-urban disparities. In fact, in Nairobi's informal settlements, although non-communicable diseases are on the rise, in 2012, the three leading causes of adult deaths were, by order of relevance, tuberculosis, injuries, and HIV/AIDS (Mberu et al., 2015). In addition, Mberu et al. (2016) found that the mortality rate of children

younger than five years living in such settlements in 2012 was much higher than the city-level estimates (Nairobi) or even rural areas in Kenya (respectively, 79.8, 22.0, and 56.0 per 1,000). These findings explicitly illustrate the health inequities resulting from disparities in social and spatial development while they raise the question of whether the urban advantage applies to all – notably those living in low-income urban areas.

1.1.1   Diarrheal diseases: a persisting health challenge

As their cities and economies grow, low- and middle-income regions must face at the same time the rise of non-communicable diseases (NCDs) related to the living conditions in cities and the persistence of infectious diseases associated with the formation of "pockets" of extreme urban poverty (Garenne, 2010). The geography of health is hence very complex, varying greatly between and within cities, which may blur the interpretation of urban health data. Such complexity is notable when speaking of epidemiological transition, that is, when the burden of NCDs progressively takes over the burden of infectious diseases. For some decades now, it has been acknowledged that this transition is neither unidirectional nor continuous (Wahdan, 1996). In the context of African cities, although NCDs inflict an increasingly high burden, one must not forget that infectious diseases still pose a significant challenge to public health and, indeed, to urban planning (Boyce et al., 2019; Larson, 2019). In this regard, the Coronavirus-2019 crisis emphasized the disproportionate vulnerability of low-income populations living in overcrowded settings and with limited access to safe water and hygiene, among other basic needs (Bhowmick et al., 2020; UN, 2020).

This thesis focused on diarrhea as the health outcome of interest because, even though it is preventable and treatable, it remains among the main causes of death worldwide, especially in sub-Saharan Africa, with the most vulnerable age groups being children under-5 and adults older than 70 (Troeger et al., 2018). In fact, in 2016, out of the 446,000 estimated deaths of children younger than five years caused by diarrhea worldwide, 290,724 (65%) occurred in sub-Saharan Africa, corresponding to the highest mortality rates in the world (Troeger et al., 2018). Moreover, diarrhea is directly related to urban planning and the quality of infrastructures accessible by the population: it is the main component of the global disease burden from unsafe water, sanitation, and hygiene (WASH) services, with 828'651 deaths (44% of the total attributed to inadequate WASH) and over 49 million disability-adjusted life-years (40% of the total DALYs) in the sole year of 2016 (WHO, 2019b).

An important transmission pathway of pathogens causing diarrheal diseases is the fecal-oral route (Kang et al., 2014; Prüss et al., 2002), which, as the "F-Diagram" shows (Fig. 1.1), can be interrupted at different levels through the safe provision of well-managed WASH services. Despite their crucial role in preventing diarrheal diseases, WASH facilities are often insufficient or inadequate in informal settlements worldwide (Kim et al., 2022; Parikh et al., 2020; UN-Habitat, 2022). More generally, the routes illustrated in the F-Diagram are deeply related with the characteristics of the physical environment - not only the man-made, "built environment"
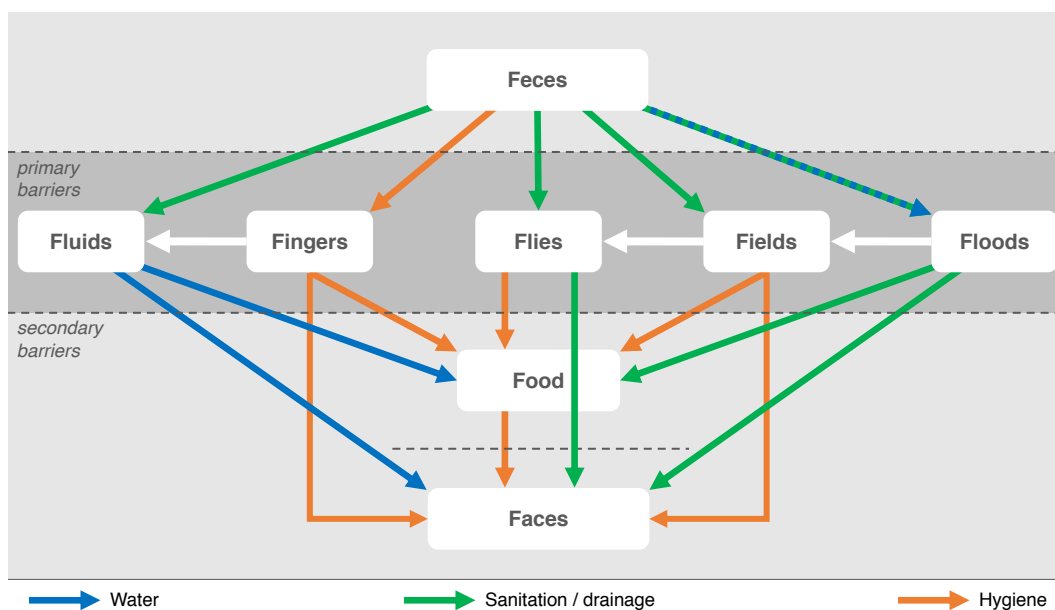
Figure 1.1: The "F-Diagram" shows the transmission pathways of the fecal-oral route (relations with water, sanitation, and hygiene services are shown here by colored arrows, with one color attributed to each service group). Adapted from Reed et al. (2012).

(which comprises WASH infrastructures), but also the natural environment, e.g., water bodies and green areas that might be reservoirs of pathogens (Medgyesi et al., 2019). Nevertheless, this thesis deliberately focused on the built environment and WASH infrastructures (see definitions in section 1.3.3), as it sought to identify solutions adapted to the contexts of urban informal settlements (see section 1.2).

1.1.2 Need for transitional WASH solutions

WASH services impact directly or indirectly numerous health conditions beyond diarrhea, including HIV or malnutrition (Kang et al., 2014; West et al., 2013; WHO, 2019b). In the context of peri-urban areas in Africa, besides diarrhea, vector-borne diseases such as Dengue have emerged due to insufficient access to adequate WASH (Gainor et al., 2022). According to the World Health Organization (WHO), a total of 1.9 million deaths and 123 million disability-adjusted life-years (DALYs) were attributed to inadequate WASH worldwide in 2016 (WHO, 2019b). Ensuring universal access to WASH services is, hence, indispensable for global health.

Surely, "access" to any given service is a multi-faceted concept. In their theory of access to healthcare, Penchansky and Thomas (1981) argue that it must be addressed at different dimensions, including not only geographic measures but also other practical aspects such as people's actual predisposition to use the services in question (e.g., socioeconomic adequacy and cultural acceptance). Similarly, this study refers to "access" to WASH services as not only their physical availability or proximity but also their conformity with local cultural and

socioeconomic needs. These notions have been incorporated by the Joint Monitoring Program for Water Supply, Sanitation and Hygiene (JMP), led by the WHO and the United Nations Children's Fund (UNICEF). The JMP defines "accessible" facilities as "facilities that are close to home that can be easily reached and used when needed" (Thomas et al., 2018) – which, although implicitly, allude to their conformity to the specific social, economic, and spatial conditions.

Transitional and more affordable solutions are urgently needed to expand access to WASH, especially in cities marked by high poverty levels and informal urbanization (Larsen et al., 2016; Parkinson et al., 2014). The choice of WASH services must consider macroeconomic limitations, especially in the case of low- and middle-income countries. Not surprisingly, in such countries, the universal provision of "safely managed" water and sewerage services, as determined by the United Nations' Sustainable Development Goal (SDG) 6, is economically challenging in the short-term, as it requires a substantial (and practically impossible) increase to current investments on the sector (Hutton & Varughese, 2016). In these situations, transitional solutions may include non-"conventional" technologies, independent of centralized networks or shared by more than a single household.

Implementing alternative solutions that could be more adapted to the reality on the ground may be hampered by normative definitions of WASH services, like those given by multilateral agencies, that are far from consensual. Indeed, such normative issues are not trivial, as they can be highly influential on policy-making at the national level and have practical impacts on urban planning decisions (Clasen, 2016). In this regard, the new service ladder proposed by the JMP brought important innovations by disaggregating the binary classification of "improved"/"unimproved" facilities (see section 1.3) previously used in the Millennium Development Goals (Thomas et al., 2018). There are, however, controversies on the criteria to define what should be considered an adequate WASH technology. For instance, the fact that both the "safely managed" and even "basic" sanitation categories (see details in section 1.3) indistinctively exclude any amenity used by more than one family has been challenged (Buckley & Kallergis, 2019; Meili et al., 2022).

At present, the only consensus is that there is no one-size-fits-all solution to define WASH standards. In the context of informal settlements, there is still a lack of clear parameters regarding the design, spatial configuration, and distribution of WASH facilities to optimize their accessibility and health benefits (prevention of diseases). As previous studies suggest, different settlement "types" (defined simultaneously by physical, socioeconomic, and cultural aspects) require different WASH technologies (Parkinson et al., 2014; Reymond et al., 2016). In other words, the number of WASH technologies implemented should be as varied as the number of settlement "types" addressed.

Cities in sub-Saharan Africa offer a fertile ground for research and policy discussions on this topic, for they are composed of diverse settlement types with distinct spatial and social characteristics (Chenal, 2013; Rahbaran et al., 2014), and they feature a variety of WASH

services (e.g., networked-based and on-site systems) operating both in the "formal" and "informal" sectors. Most importantly, recent attempts to adapt "formal" services to the needs of informal settlements in this region deserve particular attention from the scientific community, as they may effectively consist in African contributions to global health questions.

1.2   Research gaps and needs: contextualizing WASH

By "contextualizing" WASH facilities, this study means to understand how their accessibility and expected health benefits (i.e., association with a lower risk of diarrhea) might be affected by the place where they are inserted, which remains a major research gap. In this sense, the geographic scale of the analyses is a crucial aspect that has been neglected. Previous studies on WASH have often focused on the facility type and socioeconomic conditions of the household without adding to the analyses a more global perspective that includes the surrounding physical environment – particularly housing conditions, urban morphology, and the specific spatial disposition of WASH services.

This thesis addressed this gap by conducting a multi-scale analysis (see section 1.4.2). It assessed how, at constant access to WASH services, specific spatial configurations and material deprivations that typically affect informal settlements were associated with diarrhea. The underlying question was to understand the policy and design implications to effectively address the contextual characteristics of informal settlements in order to enhance, simultaneously, the accessibility and health benefits of WASH services. Indeed, if their design fails to address the spatial and socioeconomic configurations of informal settlements, WASH facilities' ability to prevent diarrhea may be compromised. For instance, water distribution systems relying on a centralized network may be less efficient in areas affected by shortages, where autonomous systems with storage capacity might provide more constant access to water (Kasper & Schramm, 2023). At the same time, the sole availability of WASH services may not be enough to reduce the burden of diarrhea if the built environment, per se, exacerbates exposure to pathogens or physically hampers access to these services.

Those interrelations remain unexplored, as the efficacy of WASH facilities has most often been assessed separately, either in terms of technical (design) adequation or health impacts, by studies that have had their scope and methods limited by the epistemological borders of their own disciplines. From the perspective of spatial planning, including environmental and architectural engineering studies, there is a natural tendency to focus on the socioeconomic and cultural acceptance (Guma & Wiig, 2022; Lawhon et al., 2018; Meili et al., 2022) or technical aspects of WASH facilities (Parkinson et al., 2014; Tilley et al., 2014), while not directly measuring their health impacts. Conversely, from the public health perspective, numerous studies have estimated the health impacts of different WASH technologies, notably on diarrhea (Pickering et al., 2019; Prüss-Ustün et al., 2014; Wolf et al., 2014). However, such studies have mostly focused on the sole presence or absence of these facilities, using the JMP normative definitions as proxy indicators of quality (Hutton & Chase, 2016) and limiting the scale of

the analysis to the household. Although prominent WASH scholars have advanced more comprehensive methods to assess access to WASH and its health benefits at the community scale (French et al., 2021; Wolf et al., 2022), the proposed framework still excludes important features of the built environment, like housing conditions or where specifically the facilities are located.

Recently, longitudinal studies conducted in several developing countries have shown mixed effects of WASH interventions on diarrhea, pointing to the need to investigate other potential risk factors and relevant interventions than the sole improvement of facility types (Pickering et al., 2019). Although these findings did not deconstruct the consensus on the importance of WASH facilities in preventing threatening diarrheal diseases (Cumming et al., 2019), they certainly raised the need for diarrhea studies to look beyond the facilities themselves by addressing contextual elements, which include the built environment.

1.2.1   Bringing in the spatial dimension: the built environment as a key exposure

A relevant question is whether the built environment interferes with WASH facilities' capacity to prevent infection. For example, there may be spatial determinants of accessibility to these facilities; even if they are physically available in a nearby location and well-functioning, in practice, their usage by the target population might be hampered by spatial conditions that affect either their safety (protection from environmental hazards) or their convenience. If there is no adherence by the target population, then the potential health benefits of such facilities – such as the prevention of diarrhea – are critically undermined, as the population may recur to alternative and often hazardous solutions (Winter et al., 2018). Moreover, the spatial and material configurations of housing and the overall built environment (as defined in section 1.3.3) are susceptible to becoming "environmental reservoirs" for diarrheal pathogens (Julian, 2016). This aspect may be especially relevant in low-income settings where construction materials are improvised and indoor spaces are exposed to external elements like water and dirt.

To date, this relationship between the built environment (which comprises WASH facilities but not only) and the risk of diarrhea remains a significant research gap, particularly in informal settlements (Weimann & Oni, 2019). Against this background, considering the built environment as a key variable of exposure to assess the risk of diarrhea can be an insightful complement to current WASH and diarrhea studies. This spatially explicit approach is necessary to understand how housing conditions (e.g., the durability of dwelling materials or overcrowding) and settlement morphology (e.g., the spatial disposition, density, and entropy of built structures) interfere with the expected health benefits of WASH facilities.

1.2.2   Health benefits of different WASH services in informal settlements

As mentioned previously, there is a pressing need for affordable, transitional WASH systems that simultaneously meet social, spatial, and public health needs. At the same time, there is no universal consensus on the normative definitions of the different WASH facility types – particularly what a "basic" facility should be. In view of transitional solutions, there is a fine balance to be found between the financial and spatial capacities to build new facilities in the short-term and their compliance to current norms advocated by multi-lateral organizations such as the United Nations and funders like the World Bank.

In this regard, several alternative solutions have been implemented in sub-Saharan cities. For example, in Nairobi, several WASH innovations have been tested, from shared sanitation systems based on community entrepreneurship and circular economy (Auerbach, 2016) to non-networked water distribution points, sometimes called "water ATMs" (Sarkar, 2019b). These interventions have been implemented relatively recently (since the 2000s) and, while several studies already assessed their adequacy to the local populations' needs (O'Keefe et al., 2015; Sarkar, 2019b), there is still a lack of empirical studies focusing on their association with health outcomes.

If they prove to bring concrete health benefits, these innovative WASH services can be relevant contributions to global health, rising as cost-efficient, transitional solutions for low-income human settlements. As mentioned previously, the health benefits of WASH are multiple, contributing to reduce the burden of several diseases. In this study though, we focused on diarrhea as a proxy outcome for the wider health benefits of these services. In this sense, the associations between the different WASH services and diarrhea were an indirect way to "measure" their health benefits.

1.3   Conceptual framework and definition of terms

This thesis explored the potential of geographic information systems (GIS) and spatial analyses to directly relate the occurrence of diarrheal diseases (as defined in section 1.3.2) with specific characteristics of the built environment (as defined in section 1.3.3). In this sense, diarrhea was considered as the outcome of interest (hence, the dependent variable in the statistical models used), while a selection of features of the built environment, including the different types of WASH facilities, were considered as the exposures of interest (hence, the candidate explanatory variables in the statistical models used).

1.3.1   Thesis goal and research objectives

The overarching goal was to understand, in the context of informal settlements in two African countries, how the performance of WASH services (measured by the occurrence of diarrhea and continuity of access to such services) related to the place where they were inserted. Hence,

the thesis contextualized WASH facilities by looking beyond the single object, under the hypothesis that their sole availability is not enough to prevent diarrhea in informal settlements, as certain characteristics of their built environments are, per se, risk factors, and affect the accessibility to those facilities. This overarching objective was decomposed into four specific objectives:

1. To assess, at a broader geographic scale, whether different "urban landscapes" (cf. section 1.3.3) are associated with different risks of diarrhea;

2. To assess, at a local scale, whether different "housing conditions" (cf. section 1.3.3) in informal settlements are associated with different risks of diarrhea;

3. To assess whether access to shared sanitation facilities in informal settlements is associated with their "morphology" (cf. section 1.3.3) and how it relates to diarrhea;

4. To assess whether different "water distribution systems" (cf. section 1.3.3) in informal settlements are associated with different risks of service disruption and diarrhea.

With the first objective (1), this study started from a broader geographic scale and universe (including any urban settlement, not only "informal") and used a landscape ecology approach (see section 1.3.3). This first objective was, hence, to assess the very idea that the built environment can be, in itself, a determinant risk factor for diarrhea. With the second objective (2), this study assessed the same concept, but this time at a higher level of detail (at a local scale, between the household and the neighborhood) and in the specific context of informal settlements. The outputs of this multi-scaled approach allowed us to confront observations of large-scale ecological analyses resulting from low-resolution, aggregated data to detailed analyses based on data collected at the individual level.

Finally, while the first two objectives focused on the research gaps explained in section 1.2.1, the third and fourth objectives (3 and 4) focused on the research gaps described in section 1.2.2 by assessing the efficacy of different water and sanitation solutions in the context of informal settlements. These systems are both part of the built environment (e.g., pipes and water distribution points) and determined by it, as they need to adapt to the local spatial conditions (i.e., the physical space available to insert new services). With the last two objectives, hence, this thesis assessed the performance of "non-conventional" sanitation facilities and water distribution systems in the context of informal settlements. This was done in view of exploring alternative systems that, although they are not always endorsed by normative references such as the JMP service ladder and might even be extralegal, could be efficient transitional solutions to mitigate the current lack of access to safely managed water services.

1.3.2 Outcome of interest: diarrhea

By "diarrheal disease," we referred to any disease having diarrhea (i.e., the passage of three or more loose or liquid stools within 24h) as a symptom (WHO, 2017). Diarrhea has been widely

used as a quality indicator of WASH infrastructures (Clasen et al., 2014). Here, it was more broadly utilized as a quality indicator of the living environment in general, a proxy indicator of the lack of adequate WASH infrastructures and other essential services that ensure dignified living conditions.

1.3.3   Exposure variables: spatial characteristics of the built environment

According to Weich et al. (2001, p. 284), "the built environment includes many characteristics of places [. . .], such as housing form, roads and footpaths, transport networks, shops, markets, parks and other public amenities, and the disposition of public space." In this study, we focused on its physical aspects, that is, the urban form resulting from the spatial disposition of built structures (any building or urban infrastructure, including WASH facilities), their density (land occupation), and their materiality (building materials).

There are multiple ways to extract quantitative variables from the built environment. Common solutions include the calculation of "landscape metrics" (M. G. Turner & Gardner, 2015) and "urban morphology" indicators (Dibble, 2016). The former is a widely used method in the field of landscape ecology, based on "patches" defined by land cover categories; indeed, landscape metrics are the quantitative indicators that describe the form (including shape complexity and perimeter) and the extent of these land cover patches (Bosch, 2019). Urban morphology, on the other hand, constitutes a field of study offering methods to extract indicators describing the urban form based on more granular data. These indicators are based on the spatial disposition, density, and entropy of specific features of the built environment, notably buildings and roads. They can be elaborated at different geographic scales, from the single object level (e.g., building shape) to aggregated block- or city level indicators (Schirmer & Axhausen, 2015).

The analyses conducted here used both landscape metrics and urban morphology indicators, but separately, depending on their geographic extent (Fig. 1.2). Landscape metrics were used for analyses covering larger areas (between city- and region scales, see Chapter 2). For analyses covering smaller areas (between household- and neighborhood scales, see Chapters 3-5), indicators derived from urban morphology and housing conditions were used instead.

In both cases, the analyses were based on common "areal units", i.e., buffers generated from centroids corresponding to the point location of the household data (approximate location in the case of secondary data). The areal units were used as the reference surface to spatially aggregate landscape metrics or urban morphology indicators (more details are given in section 1.4).

The terminology proposed here to describe specific aspects of the built environment - which was employed in the study objectives and in Chapters 2-5 - reflects this multi-scale approach, as described below.
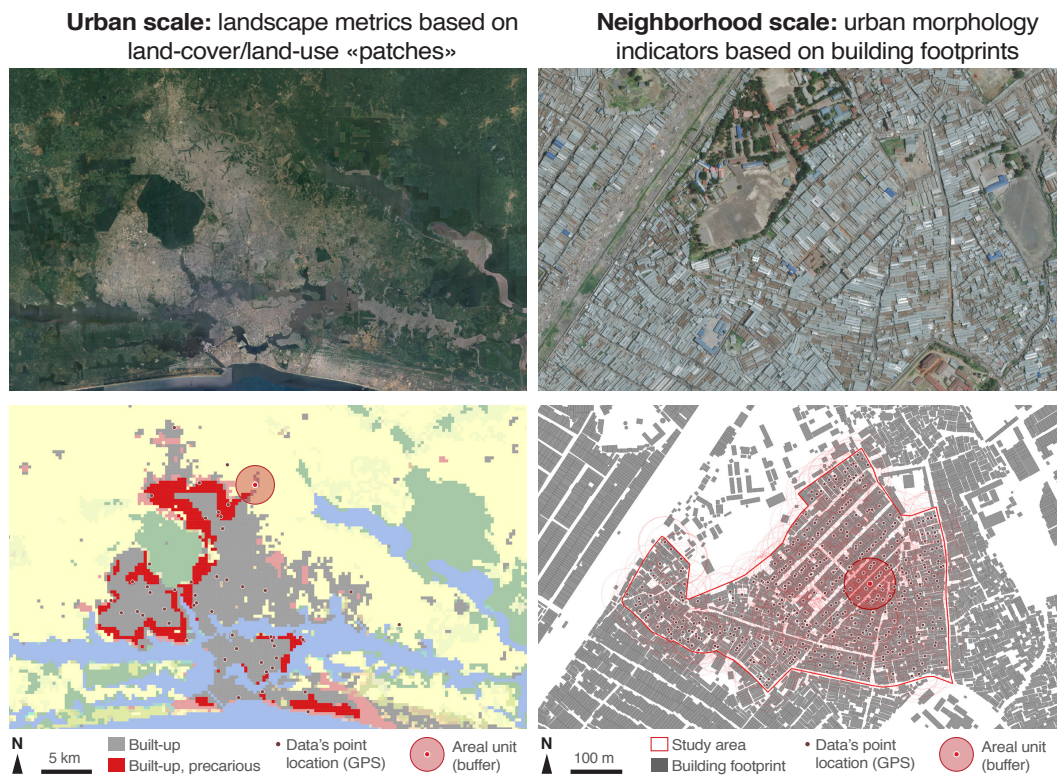
Figure 1.2: Spatial features of the built environment: landscape "patches" (bottom-left) and building footprints (bottom-right). Elaborated from Google Earth (Google, n.d.); Maxar (2020); ESA (2017) ©ESA Climate Change Initiative—Land Cover led by UCLouvain 2017; Ecopia Tech Corporation (2021) ©2021 Ecopia Tech Corporation, Imagery ©2021 DigitalGlobe, Inc.

- **"Urban landscapes"** is a term deliberately used in the plural, referring to the various spatial arrangements that materialize into diverse urban habitats. They are characterized by landscape metrics describing the extent and shape of the different landscape "patches" (Forman & Godron, 1981) that are found within a predefined areal unit (Fig. 1.2). The spatial definition of these patches is based on land cover categories (built-up or natural surfaces) and intensity of land use (measured by population density).

- **"Settlement morphology"** refers to the urban form resulting from the spatial agency and distribution of built-up structures (Kraff et al., 2020); it is described through urban morphology indicators based on the building footprints that are found within a predefined areal unit (Fig. 1.2).

- **"Housing conditions"** refer to the living conditions inside a single dwelling. Based on UN-Habitat's definition of "slum" households (UN-Habitat, 2017), these conditions are described in terms of access to WASH facilities, the durability of materials (whether the dwelling's floor, walls, and roof are adequately built), and crowding (whether there are sufficient rooms for the household members).

- **"Water distribution systems"** refer to the different ways to distribute water, considering the existing heterogeneity of "post-networked" infrastructures available in informal settlements (Kasper & Schramm, 2023). They are described in terms of facility type (as defined by the WHO/UNICEF JMP service ladder, explained below), connectivity (whether connected to a network or not), and location (whether water is obtained within premises or not).

At the local level, the exposure variables related to the built environment were given by the housing conditions (including the specific water distribution system used) and the settlement morphology. At a larger geographic level, those exposures were determined by the urban landscape. Because the exposure was based on the residence location, individuals living in the same household were considered to be exposed to the same built environment characteristics. We acknowledge this simplification can be a limitation when establishing exposures, as eventual gender and age differences are not considered (see section 6.3.1). Based on the Guide to DHS Statistics (Croft et al., 2018), we defined a "household" as "a person or group of related or unrelated persons who live together in the same dwelling unit(s), who acknowledge one adult male or female as the head of the household, who share the same housekeeping arrangements and who are considered a single unit."

In addition to the terms explained above, another set of definitions was crucial to this study: the normative definitions of WASH facility types given by the WHO/UNICEF JMP (WHO & UNICEF, 2021). They provide a common framework for policy-making at regional and national levels amongst United Nations Member states. To monitor advancements toward SDG 6, the JMP defined a "service ladder" building on the definitions of "improved" and "unimproved" infrastructures (table 1.1) and determined different categories of WASH infrastructures.

Table 1.1: Definitions of types of WASH facilities. Adapted from WHO and UNICEF (2021)

	Drinking Water	Sanitation
Improved facilities	**Piped supplies** - Tap water in the dwelling, yard or plot - Public stand posts **Non-piped supplies** - Boreholes/tube wells - Protected wells and springs - Rain water - Packaged water, including bottled water and sachet water - Delivered water, including tanker trucks and small carts	**Networked sanitation** - Flush and pour flush toilets connected to sewers **On-site sanitation** - Flush and pour flush toilets or latrines connected to septic tanks or pits - Ventilated improved pit latrines - Pit latrines with slabs - Composting toilets, including twin pit latrines and container-based systems
Unimproved facilities	**Non-piped supplies** - Unprotected wells and springs	**On-site sanitation** - Pit latrines without slabs - Hanging latrines - Bucket latrines
No facilities	Surface water	Open defecation

Based on the definitions given in Table 1.1, the JMP set the following "service ladders" for WASH:

- The **"drinking water ladder"** is divided into (a) SAFELY MANAGED, i.e., "drinking water from an improved water source which is located on-premises, available when needed and free from fecal and priority chemical contamination"; (b) BASIC, i.e., "drinking water from an improved source, provided collection time is not more than 30 minutes for a roundtrip including queuing"; (c) LIMITED, i.e., "drinking water from an improved source for which collection time exceeds 30 minutes for a roundtrip including queuing"; (d) UNIMPROVED, i.e., "drinking water from an unprotected dug well or unprotected spring"; (e) SURFACE WATER, i.e., "drinking water directly from a river, dam, lake, pond, stream, canal or irrigation canal."

- The **"sanitation ladder"** is divided into (a) SAFELY MANAGED, i.e., "use of improved facilities which are not shared with other households and where excreta are safely disposed in situ or transported and treated off-site"; (b) BASIC, i.e., "use of improved facilities which are not shared with other households"; (c) LIMITED, i.e., "use of improved facilities shared between two or more households"; (d) UNIMPROVED, i.e., "use of pit latrines without a slab or platform, hanging latrines or bucket latrines"; (e) OPEN DEFECATION, i.e., "disposal of human feces in fields, forests, bushes, open bodies of water, beaches and other open spaces or with solid waste."

- The **"hygiene ladder"** is divided into (a) BASIC, i.e., "availability of a handwashing facility on premises with soap and water"; (b) LIMITED, i.e., "availability of a handwashing facility on premises without soap and water"; (c) NO FACILITY, i.e., "No handwashing facility on premises."

1.4   Methodology

This section explains the general outlines of the study design implemented. The specific, detailed methods and tools utilized to attain the four study objectives are described separately in the following Chapters (see Chapters 2-5), each focusing on a single objective. Notably, the specific variables derived from the built environment (that were related to diarrhea) are described in detail in Chapters 2-5.

1.4.1   Geographic scope

This research focused on cities in two African countries: Côte d'Ivoire and Kenya. In both countries, cities have followed a similar pattern of rapid demographic growth coupled with considerable challenges in providing safe access to WASH services (Fig. 1.3). According to WHO and UNICEF (2023), between 2000 and 2020, access to "at least basic" water services in urban areas stagnated at around 87% in Kenya. In Côte d'Ivoire, access to these services has actually decreased from 91% to 87%, suggesting that urban growth there is not being followed by basic water infrastructures. As for sanitation services, in urban areas in Kenya, the proportion of people with access to "at least basic" sanitation services was limited to 39% in 2020. In Côte d'Ivoire, this number increased from 38% in 2000 to 50% in 2020 – still leaving, though, half of the urban population without access to basic sanitation services. According to the UN-Habitat (2022), the urban population living in "slums" in 2020 was estimated to be 53% in Côte d'Ivoire and 51% in Kenya.

Moreover, according to the 2019 Global Burden of Disease Study, diarrheal diseases were among the top-five main causes of death and disability combined in Côte d'Ivoire and Kenya (Vos et al., 2020). In Côte d'Ivoire, the prevalence of diarrhea among children under five years old was 11.4% in 2021, with 9.9% in urban areas against 12.9% in rural areas, and it was the highest in the Abidjan District, where it attained 17.2% (de la Statistique-INS & ICF, 2023). In
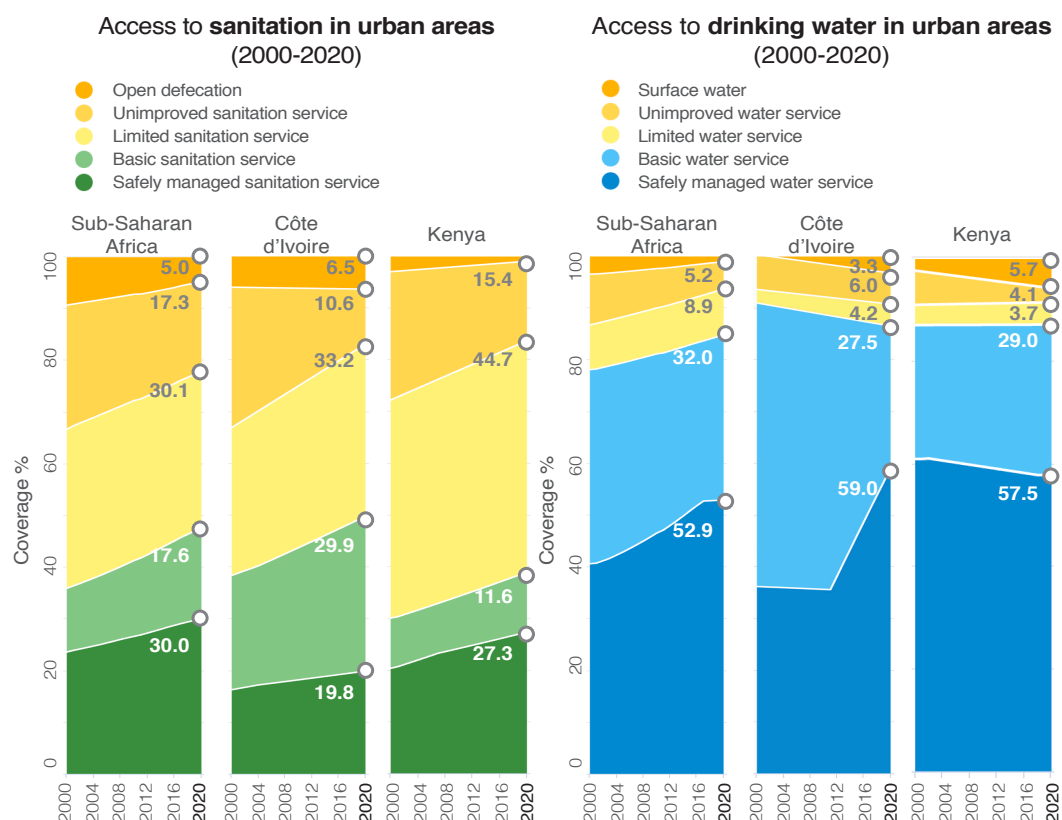
Figure 1.3: Access to water and sanitation services in sub-Saharan Africa and selected countries. Adapted from WHO and UNICEF (2023)

Kenya, this prevalence was 14.3% in 2022, with 14.8% in urban areas against 14.0% in rural areas, and it was the highest in Wajir County (north-eastern region), where it attained 27.3% (KNBS & ICF, 2023). In Nairobi county, the prevalence of diarrhea was 15.0%.

This situation illustrates the current challenges related to expanding access to basic WASH infrastructures in cities in these two countries. At the same time, several innovative solutions and promising sectoral reforms have taken place in their largest cities, namely, Abidjan and Nairobi, and deserve further attention. These two cities have similar population sizes and are representative of the "urban revolution" taking place in Africa (Parnell & Pieterse, 2014), as they experienced extremely rapid, spatially concentrated, and mostly informal urbanization processes. In 2019, there were 4,397,073 inhabitants in Nairobi, accounting for almost 10% of the country's population (Government of Kenya, 2019a), and nearly 70% of the city's residents lived in one-room units in informal settlements or tenements (Mwau et al., 2020). As for Abidjan, in 2014, there were 4,707,404 inhabitants, accounting for 21% of the total Ivorian population (INS Côte d'Ivoire, n.d.). In 2019, the annual demand for housing in Abidjan was estimated at 25,000 units, while only a few thousand were provided by the formal market, and only 43% of homeowners had a legal title (Nana et al., 2019).

In both cities, there is much to be explored regarding innovative WASH solutions and service schemes that could be implemented in other locations facing similar challenges in urban development, thus contributing to reducing the burden of diarrheal diseases in low-income settings. For instance, in Nairobi, value-chain strategies have been applied to sanitation systems to ensure sustainable and safe maintenance of amenities (Auerbach, 2016; O'Keefe et al., 2015). Also, the utilities responsible for water distribution in both cities have implemented tailored interventions to extend water services to the urban poor. The Nairobi City Water & Sewerage Company created the Informal Settlements Department in 2009 and, in 2015, assigned it a full Commercial Region status. This facilitated the elaboration of service strategies targeting people living in slums that reduced the share of nonrevenue water while they improved access to sanitation in these areas (Drabble et al., 2018). In Abidjan, the Société de Distribution d'Eau de la Côte d'Ivoire has implemented cross-subsidy schemes that have facilitated the connection of low-income households to the water distribution network (Adopo et al., 2018).

Finally, the choice of study areas located in different regions of sub-Saharan Africa aimed to address eventual differences in terms of the usage and health impacts of WASH facilities based on geography. In fact, the same facility type may have very different health impacts depending on its geographic and cultural context. In Africa, particularly, these differences are visible in the associations between shared sanitation and diarrhea, which vary greatly between African regions (Fuller et al., 2014). To address these contextual diversities, this study was conducted in two countries formed by distinct urban and cultural colonial backgrounds, one in West Africa and the other in East Africa.

1.4.2   General study design

This thesis consists of observational, cross-sectional studies based on primary and secondary data. Secondary health data is usually much less granular (and available) than secondary settlement data (Friesen et al., 2020), which limits the design possibilities of ecological studies. Indeed, for confidentiality reasons, geo-referenced health data is usually only available at coarse spatial resolutions from secondary sources. Therefore, the general study design also included analyses with primary health datasets collected at a very high spatial resolution (at the individual level, geo-referenced to the residence location with a 5-meter horizontal precision).

Although ecological studies have the advantage of being low-cost and allowing to explore associations between population-level exposure to environmental risk factors and disease, they are prone to the "ecological fallacy," that is, assuming that associations found for a group of people are also found at individual-level (Gordis, 2014; Levin, 2006). We mitigated this problem by testing the same associations – i.e., between diarrhea and specific features of the built environment – at varying geographic scales and levels of detail, from the urban scale to the single household. In practice, we implemented a multi-level study with analyses conducted:

(i) at a broader geographic scale when using secondary datasets (ecological analysis between city- and region-scales); and (ii) at a local geographic scale when using primary datasets (cross-sectional analyses between individual- and neighborhood-scales). This approach also sought to address the Modifiable Areal Unit Problem (Openshaw, 1984), i.e., when the spatial resolution of the analysis impacts statistical associations between variables.

Of relevance, although the geographic scope of this study includes sites in two cities, this was *not* a comparative study. In fact, the objective was not to systematically analyze similarities and differences of the same phenomenon and/or facts in the two cities but to explore, in general terms, interrelations between the built environment, access to WASH, and diarrhea. The selection of case studies in Côte d'Ivoire and Kenya was justified on the basis of their current challenges to expand access to WASH and on the exposures of interest (specific features that we sought in WASH facilities and in the built environment, as explained further in this chapter). Most importantly, as mentioned in the previous section, the necessity of conducting this research in different African regions is due to cultural differences that may affect the way in which people use WASH facilities in similar social and built environments. Geographic location was, hence, a control variable proxying culture.

Ecological analyses with secondary data

Aiming to maximize the reproducibility of our ecological study design, we used health and settlement data from open sources only (see Chapter 2). Combining datasets from different sources and with varying spatial and temporal resolutions required pre-processing steps to harmonize health and settlement data (Fig. 1.4). The first step was to obtain health and settlement datasets corresponding to the same collection period (in this case, the same year). Then, the next step was to "spatialize" diarrhea by measuring its occurrence within predetermined areas through spatial aggregation. This process required the definition of a common "areal unit" of data aggregation – a common area used to calculate both the occurrence of diarrhea and a selection of variables derived from the physical environment.

The areal units were defined using fixed-distance buffers generated from the point coordinates of the approximate residence location, given by the centroid of the cluster of surveyed households. This point location was approximate because secondary health data could only be obtained with a "geographic blur," that is, a random translation of the original coordinates of the surveyed cluster (Perez-Heydrich et al., 2013). This impacted the spatial resolution of the analysis, as the buffer distance used to define the areal units was determined by the geographic blur's amplitude (2-5 km), following the methodology of previous ecological studies that also used secondary demographic and health data (Grace et al., 2019). Given the relatively low spatial resolution of the health data available and their lack of statistical representativity for intra-urban analysis (too few observations in single cities and with a geographic blur making them unsuitable for granular analyses), this study was conducted at a broader geographic scale, covering all urban settlements in Côte d'Ivoire.

Once the areal units were defined, the occurrence of diarrhea could be directly related to the built environment. This was done by calculating, for each areal unit, the prevalence of diarrhea (dependent variable) and a series of landscape metrics (candidate explanatory variables, see Chapter 2). In addition to the dependent and explanatory variables, each areal unit also featured a selection of control variables to account for potential confounders. In this case, access to basic WASH facilities and socioeconomic status (levels of education and wealth) were included as control variables, for they have been associated with diarrhea in previous studies (Manesh et al., 2008; Mulatya & Ochieng, 2020).
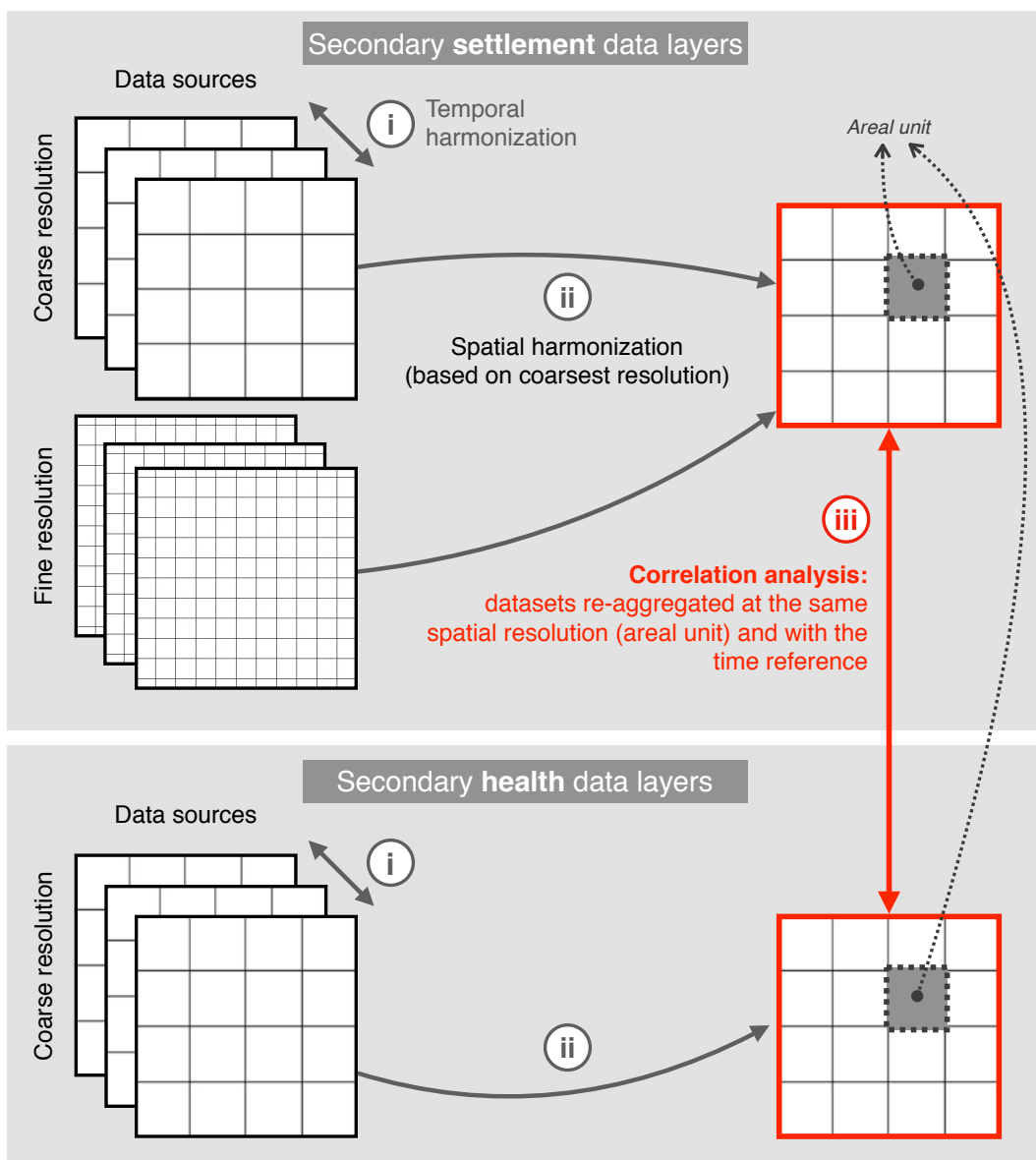
Figure 1.4: Harmonization of secondary datasets to find correlations between settlement features and the health outcome of interest. Adapted from Friesen et al. (2020)

Cross-sectional analyses with primary data (household surveys)

The exercise of contextualizing WASH services and understanding their potential associations with the built environment and expected health benefits required an in-depth comprehension of the reality on the ground, which would not have been possible with secondary data only. Therefore, this research included analyses based on household surveys conducted in close collaboration with partners in the selected study areas (see Chapters 3-5). We counted on the invaluable inputs and support from research peers, the local government, and civil society. In Côte d'Ivoire, we worked with the Centre Suisse de Recherche Scientifiques en Côte d'Ivoire (CSRS), and community leaders from the selected informal settlements. In Kenya, we worked with the Kenya Medical Research Institute (KEMRI), the Nairobi City County Government, and community leaders from the selected informal settlements.

Household data were collected through a structured questionnaire that included individual- and household-level questions (see Appendix 1.1). The sample size calculation and selection criteria are explained further below. This questionnaire was adapted from the Demographic and Health Surveys (DHS) template for their 8th phase (DHS, n.d.). To validate the adapted questionnaire, we tested it through "mock" surveys with academic partners and stakeholders in Côte d'Ivoire and Kenya. Thus, several pilot tests were conducted with public health and planning experts, as well as with the enumerators (all of which knew well the research sites). Based on the pilot tests, several questions were rephrased to ensure their intelligibility by the target public (dwellers of informal settlements), while some items listed in the multiple answer options were adapted to the local contexts. All enumerators spoke the relevant local languages (Swahili and English in Nairobi, and Ébrié and Franch in Abidjan). The pilot tests of the questionnaire were conducted in both languages.

As explained in section 1.3.2, the outcome of interest was diarrhea. Hence, the questionnaire included a specific question on that matter, allowing us to quantify the occurrence of diarrhea at the individual level (this question was asked for each household member). A "case" was defined as an individual having had diarrhea in the two weeks preceding the survey. This corresponds to the recall period used by the DHS (n.d.) and the African Population and Health Research Center (2014) in their previous studies. Although a two-week recall period is relatively long compared to other cross-sectional studies on diarrhea and may lead to some recall bias (Arnold et al., 2013), reducing this period would have substantially decreased our study's power.

To relate the collected health and socioeconomic data with the built environment, the surveys were geo-referenced to the household location. Hence, all household data were collected digitally, with tablets (Galaxy Tab A 8.0 2019, Samsung, Suwon-si, South Korea), using the mobile application KoboCollect 1.30.1 (Kobo, Cambridge, USA). To support on-site data collection and the geo-referencing of participating households, the enumerators were equipped with a digital map of the surveyed area, showing their live location through the Global Positioning System (GPS) integrated into the tablet. The maps provided a precise spatial description of the streets,

building footprints, and public spaces, as well as the enumerator's respective survey area. They were produced using the software QuantumGIS 3.10.4 (Free Software Foundation, Boston, USA) and were based on georeferenced satellite imagery (30 cm resolution) obtained from Digital Globe's open data portal, as well as vector data provided by Ecopia Tech Corporation (2021).

Selection of informal settlements for primary data collection

In each country, two informal settlements were selected to conduct household surveys. This selection was based on two criteria, i.e., the presence of: (1) varying types of WASH facilities (e.g., networked/non-networked, as well as shared/not-shared); and (2) varying settlement morphologies (e.g., varying patterns of street layout, land-use, and buildings' size, orientation and density). These criteria were based on the study objectives, which required variations in the exposure variables (settlement morphology and facility types). Besides these two criteria, the selection also depended on the residents' acceptance to participate and the availability of local leaders who could act as facilitators so that access to these communities was, in practice, guaranteed. Furthermore, the total area of each settlement was limited to 10 hectares. This limitation was based on previous household surveys conducted in informal settlements elsewhere (Santos et al., 2023).

Four informal settlements were identified during site visits in 2019 and 2020, two in Abidjan (Côte d'Ivoire) and two in Nairobi (Kenya). Their locations and spatial characteristics are shown in Figure 1.5. In each city, we selected one settlement with a more regular settlement morphology (i.e., street alignment close to orthogonality and flat topography) and another with an irregular settlement morphology (i.e., nonaligned built structures and complex topography). All settlements had different types of WASH facilities. Notably, in Nairobi, they featured innovative technologies such as water "ATMs" and Sanergy's Fresh Life toilets.

Household survey design and sampling methods

The precise study perimeter of each informal settlement was defined during on-site visits, with the participation of local community leaders. In these areas, the inclusion criteria for participating in the household surveys were: (1) the place of residence, which had to be located within the defined study perimeter; (2) the informed consent (Appendix 1.2) of the respondent, which each enumerator obtained before starting the survey; and (3) the respondents needed to be adults (older than 18 years). A single respondent answered on behalf of the household members, eventually consulting them (in the case of individual-level data). The enumerators were instructed to contact the head of the household, or another adult who could answer the questionnaire (preferably the caregiver if there were children). The definition of the "head" of the household was done on-site, during the questionnaire. To ensure an even spatial distribution of the surveys, the selected informal settlements were subdivided into survey areas with an equivalent number of built structures - this was based on the building footprints extracted from aerial images. Each survey area was allocated a group between two and three enumerators, who were accompanied by a community volunteer.
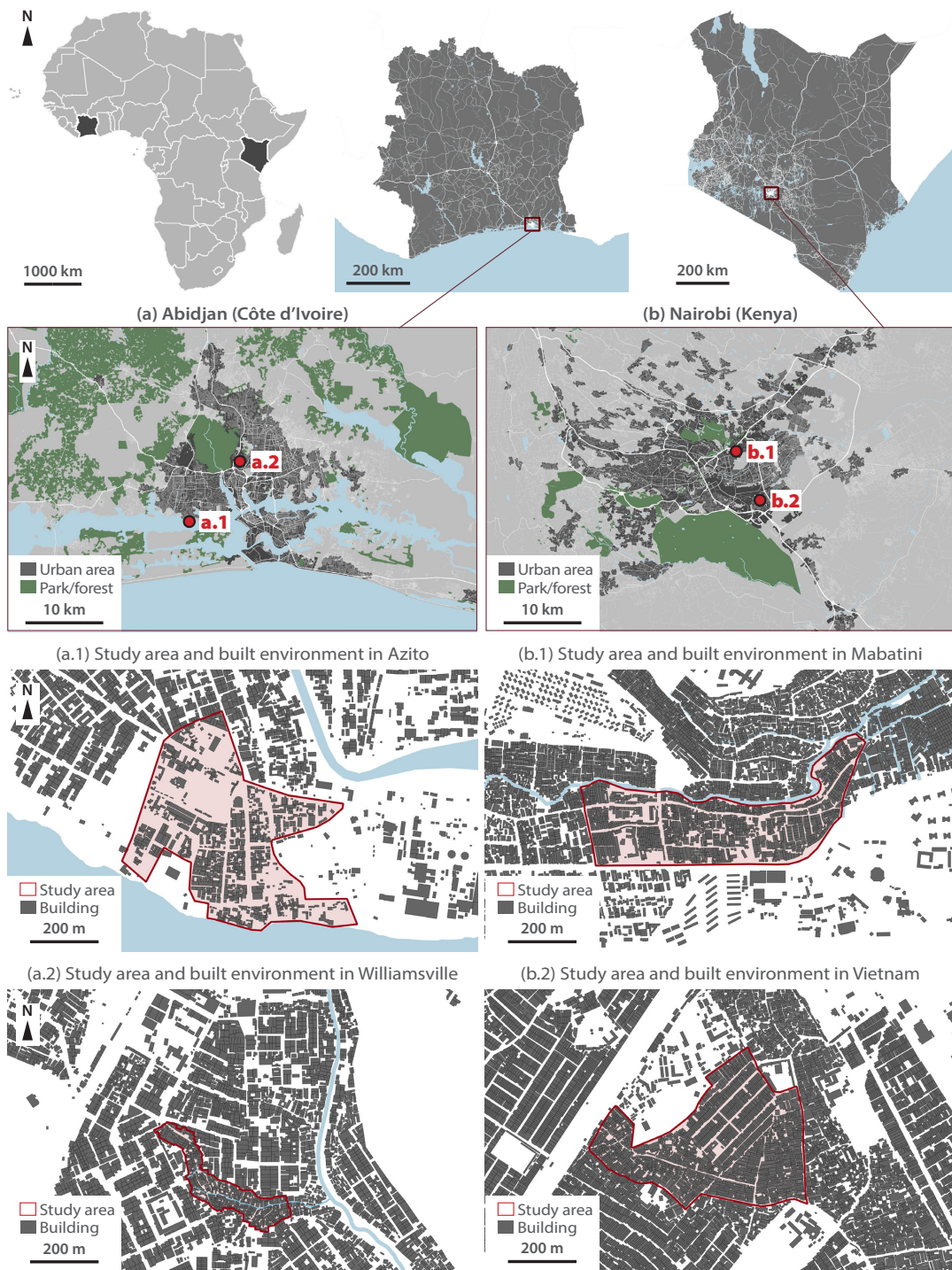
Figure 1.5: Maps showing the selected study areas (countries and specific informal settlements). From Pessoa Colombo et al. (2023); elaborated from GADM; OpenStreetMap; Ecopia Building Footprints ©2021 Ecopia Tech Corporation, Imagery ©2021 DigitalGlobe, Inc.

The selection of participating households was made on-site through "random walks" (Johnston, 2011); that is, a systematized sampling method based on predefined paths and an estimation of existing households. In practice, a dwelling was selected for every given number of dwellings within the predefined walking path. For example, given a minimum sample size of 100 households in an area with 500 dwellings, one of every five dwellings in the predefined walking paths would be selected. In this same example, in the case of a refusal to participate, or absence, the enumerators would skip the household and look for the next fifth dwelling within their walking path. In case of a short absence (less than a day), enumerators could return to the selected dwelling to apply the questionnaire. Because we did not have updated baseline data on the number of households in each study area, we calculated estimates considering that one built-up structure unit corresponded to one household. This simplified estimation does not address cases where several families live in a single shack (which may happen in informal settlements). Also, although the sampling method was systematic, we acknowledge it was not randomized, as we did not have a comprehensive, accurate list of all households in the study sites (which is needed to run a proper random sampling). Still, this household estimation and sampling methods were the best alternatives given our resources, as the most updated data we had were very high resolution aerial imagery (30 cm).

The sample size was determined by the expected prevalence of the health outcome of interest, i.e., diarrhea. The calculation of the minimum number of household surveys necessary for this study was based on the manual on sample size determination in health studies by Lwanga and Lemeshow (1991). Given that this was a prevalence study of diarrhea in informal settlements, we used the formula given by Equation 1.1:

$$n_0 = \frac{Z^2_{1-\alpha/2} \times P \times (1-P) \times D_{eff}}{e^2} \tag{1.1}$$

where n_0 is the unadjusted sample size (total number of people required for the survey); $Z_{1-\alpha/2}$ is the critical value for the standard normal distribution corresponding to a Type I error rate of α (here, we followed standard practice using $\alpha = 0.05$, hence, $Z_{1-\alpha/2} = 1.96$); P is the expected prevalence rate in the targeted population; D_{eff} is the "design effect" of cluster sampling (African Population and Health Research Center, 2014; Lwanga & Lemeshow, 1991); and e is the margin of error to be tolerated at 95% level of confidence (here, $e = 0.05$). The prevalence of diarrhea is usually higher among children under the age of five than among older individuals, which impacts the sample size definition. To ensure a sample size adequate for all age groups, we used the expected prevalence amongst children under-five as the parameter P. In Abidjan, the P value ($P = 15\%$) was based on the work by Koné et al. (2014). As for Nairobi, the expected diarrhea prevalence was 20%, based on previous cross-sectional surveys conducted in informal settlements in Nairobi (African Population and Health Research Center, 2014). This same study was used as a reference to establish the design effect parameter ($D_{eff} = 1.50$) adjusting the minimum sample sizes in Abidjan and Nairobi.

Table 1.2: Estimation of minimum sample sizes in Nairobi and Abidjan.

Parameter	Nairobi	Abidjan
$Z_{1-\alpha/2}$ (95% level of confidence)	1.96	1.96
Expected prevalence rate (P)	0.20	0.15
Design effect (D_{eff})	1.50	1.50
Margin of error (e)	0.05	0.05
Unadjusted sample size (minimum number of individuals)	**369**	**294**
Proportion of children under the age of 5 years	0.12[1]	0.15[2]
Number of people needed given the proportion of children under 5 years	3073	1959
Average household size (number of individuals)	3.0[1]	4.5[2]
Expected valid response rate	0.9	0.9
Adjusted sample size (minimum number of households)	**1138**	**484**

[1] Parameter obtained from the 2019 Kenya Population and Housing Census

[2] Parameter obtained from the 2014 Population and Housing Census of Côte d'Ivoire

In Equation 1.1, the sample size (n_0) corresponds to an estimated number of people needed for the survey. Given that the basic unit of the survey was the household, this sample size needed to be adjusted and counted in terms of households. On this basis, we adjusted the initial sample (n_0) by a composite factor given by: (1) the proportion of the targeted population (% of children younger than five years in the general population); (2) the average household size (number of household members); and (3) the expected valid response rate (proportion of questionnaires duly answered to, and without data entry errors). The proportion of children under five years old and the average household size was obtained from the latest census data at the time of the study design, i.e., 2019 for Kenya and 2014 for Côte d'Ivoire (Government of Kenya, 2019b; INS Côte d'Ivoire, n.d.). Given those parameters, the minimum sample size was estimated at 1,138 housholds in Nairobi, and 484 in Abidjan (Table 1.2)

Preparation of household surveys and training of enumerators

The preparation for the household surveys comprised communication campaigns led by the investigators in collaboration with local community leaders. The goal of these campaigns was twofold: to sensitize the communities to the study and to gauge the community's acceptance to participate. This process allowed us to solidify the geographic definitions of the study sites. During the survey preparation period, the investigators and respective leaders identified residents who could assist the enumerators during the data collection. In addition, the enumerators followed a 4-day training before they went to the field. This was done to ensure all of them were familiarized with the household questionnaire and the mapping tools used to geo-reference data. An average number of surveys per day was established for each site so that all enumerators had a clear quantitative goal – this number ranged between 8 to 10 surveys per day (each survey took 30 to 45 minutes).

Summarized statistics of primary data

In total, we obtained 567 valid household surveys in Abidjan (2498 individuals), and 1147 in Nairobi (3786 individuals). The observed prevalence of diarrhea in Abidjan was 14.5% (95% CI: ±3.67%) for the general population, and 24.6% (95% CI: ±10.2%) for children younger than five years old. In Nairobi, the observed prevalence was 12.0% (95% CI: ±3.0%) for the general population, and 25.9% (95% CI: ±7.6%) for children under-five. The Python notebooks with detailed, descriptive data of the surveyed population (total counts by age group and sex, and housing conditions) can be found in the the following Github page (go to "notebooks" folder):

https://github.com/ceat-epfl/household-surveys-thesis-vpc

1.4.3   Ethical considerations

Because this was an observational study, the risks to research subjects and investigators were minimal, limited to confidentiality issues that could be adequately addressed with data protection arrangements. All study staff and investigators were appropriately trained and conducted the study ethically, in accordance with the principles of Good Clinical Practice. In Switzerland, ethical opinions were obtained from EPFL's Human Research Ethics Committee (HREC, decision n° 068-2020). In Kenya, ethical clearance was obtained from the Kenya Medical Research Institute (KEMRI/RES/7/3/1) and authority to conduct research from the National Commission for Science, Technology & Innovation (NACOSTI/P/21/10921). In Côte d'Ivoire, ethical clearance was obtained from the National Health and Life Sciences Ethics Committee (Comité National d'Éthique des Sciences de la Vie et de la Santé, ref. n° 005-22/MSHPCMU/CNESVS-km).

KEMRI was the initial data recipient for the primary data collected in Kenya, while the CSRS was the initial data recipient for the primary data collected in Côte d'Ivoire. All personal data were safely stored in secured servers in KEMRI, CSRS, and EPFL. Non-anonymized individual data from Kenya was not accessible by the Ivorian partners; conversely, non-anonymized individual data from Côte d'Ivoire was not accessible by the Kenyan partners. All participants gave their informed consent (Appendix 1.2) for their data to be collected, stored in a safe place, and processed strictly by the study investigators. They were informed about the research goals and how and where their data was stored and processed. In addition, when applicable, information about child health was only obtained with the consent of the child's caregiver, who needed to be an adult.

Finally, the investigators shared the relevant research findings with the participating communities and local governments. These meetings aimed to display and discuss the results with the main stakeholders (residents, community-based organizations, local project partners, and public authorities). More particularly, this was a way to sensitize the population about hygiene practices and identify possible ways to address current challenges while drawing attention to decision-makers regarding the limitations of the implemented WASH policies.

1.5   Outline

The remainder thesis was organized into five Chapters, with one Chapter for each study objective described in section 1.3.1 (Fig. 1.6) and a last Chapter that concluded the work. They were structured as follows:

Chapter 2 set the foundations of the present thesis with an ecological study that tested the idea that different "urban landscapes" (as defined in section 1.3.3) are associated with varying risks of diarrhea, hence addressing the first study objective. By doing so, this study tested the critical working hypothesis of the thesis: that, beyond WASH infrastructures, a more comprehensive perspective of the built environment should be included in diarrhea studies, looking at the general urban landscape as a potential determinant of the risk of diarrheal diseases. Given the exploratory nature of this first ecological analysis, it was based on a large-scale dataset covering different regions of Côte d'Ivoire, with a sample sufficiently varied in terms of participants and locations to be representative of the country's overall population and regions.

Chapter 3 gave continuity to the analysis in Chapter 2, as the study was also conducted in Côte d'Ivoire – but this time, increasing the level of detail with at a higher spatial resolution of the data and with more specific exposures being assessed. It investigated associations between "housing conditions" (as defined in section 1.3.3) and diarrhea in Abidjan, the largest Ivorian city. This Chapter addressed, hence, the second study objective. A cross-sectional study based on 567 household surveys was conducted at household and neighborhood scales, with a focus on the dwellings' construction materials and food-handling spaces (considered critical for hygiene). Although the exposures of interest here were the housing conditions, the study also included descriptive analyses at the neighborhood scale, thus contextualizing the cases of diarrhea with their immediate built environment.

While Chapters 2 and 3 tested direct associations between the built environment and diarrhea, Chapter 4 explored indirect associations, with a focus on the role that the urban form has on the perceived safety to access sanitation facilities. This Chapter addressed, hence, the third study objective. A cross-sectional study based on 1,714 household surveys conducted in Abidjan and Nairobi tested whether access to shared sanitation facilities in informal settlements was associated with the "settlement morphology" (as defined in section 1.3.3) and how it related to diarrhea. The focus on two cities from distinct African regions aimed to address eventual effects of cultural differences on the health benefits (or risks) of shared sanitation, as explained at the end of section 1.4.1. Also, this study connected the two research gaps raised in sections 1.2.1 and 1.2.2 by analyzing both the eventual relations between the built environment and diarrhea and the health benefits of "non-conventional" (shared) sanitation facilities in informal settlements.

Chapter 5 examined, at the household scale and with individual-level data, associations between different "water distribution systems" (as defined in section 1.3.3) in informal settlements in Nairobi with the occurrence of diarrhea. In this way, this Chapter addressed the fourth (and last) research objective. The analysis focused on Nairobi because of the variety of

water distribution systems available in informal settlements there, with a range of networked and non-networked systems that include innovations such as the water "ATMs". The study was based on a cross-sectional survey including 1,147 household surveys conducted in two informal settlements that observed not only cases of diarrhea, but also the level of service continuity (i.e., continuous water availability) associated with each type of system. This approach allowed to determine which systems were most reliable in the context of informal settlements, both in terms of health safety and service continuity, in view of identifying a solution that could potentially be transposable to other locations facing similar challenges.

Finally, Chapter 6 synthesized the key findings of Chapters 2-5, emphasizing their scientific significance. Based on the key findings, this last Chapter advanced policy recommendations regarding access to WASH services in informal settlements in sub-Saharan cities and provided an outlook for future research.
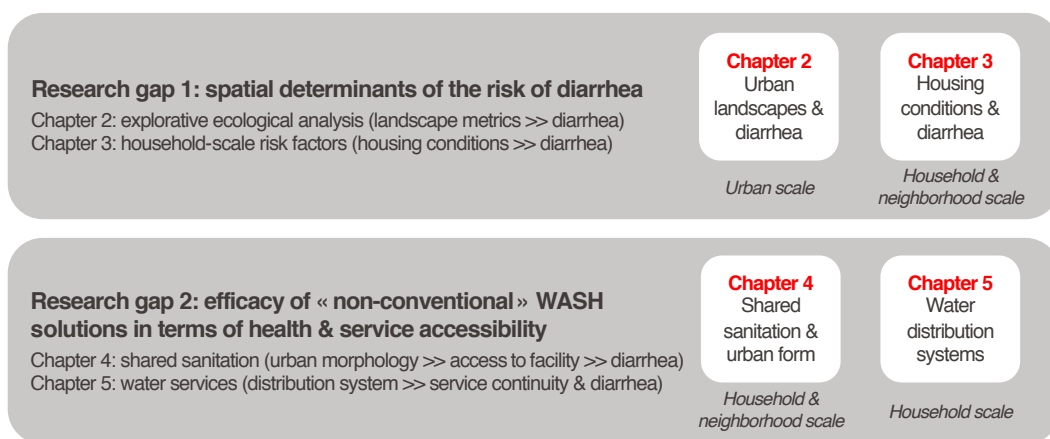
Figure 1.6: Outline of the four Chapters addressing the two research gaps advanced here and the four specific thesis goals (one by Chapter)

2 Using open-access data to explore relations between urban landscapes and diarrheal diseases in Côte d'Ivoire

Abstract

In contexts of rapid urbanization and changes in the physical environment, urban planners and public health managers could benefit from a deeper understanding of the relationship between landscape patterns and health outcomes. We conducted an ecological analysis based on a large ensemble of open-access data to identify specific landscape features associated with diarrhea. Designed as a proof-of-concept study, our research focused on Côte d'Ivoire. This analysis aimed to (i) build a framework strictly based on open-access data and open-source software to investigate diarrhea risk factors originating from the physical environment and (ii) understand whether different types and forms of urban settlements are associated with different prevalence rates of diarrhea. We advanced landscape patterns as variables of exposure and tested their association with the prevalence of diarrhea among children under the age of five years through multiple regression models. A specific urban landscape pattern was significantly associated with diarrhea. We conclude that, while the improvement of water, sanitation, and hygiene infrastructures is crucial to prevent diarrheal diseases, the health benefits of such improvements may be hampered if the overall physical environment remains precarious.

Reference

Pessoa Colombo, V., Chenal, J., Koné, B., Bosch, M., & Utzinger, J. (2022). Using open-access data to explore relations between urban landscapes and diarrhoeal diseases in Côte d'Ivoire. International Journal of Environmental Research and Public Health, 19(13), 7677. https://doi.org/10.3390/ijerph19137677

2.1   Background

Diarrheal diseases still pose a considerable public health problem. Although diarrhea is preventable and treatable, it remains one of the main causes of death worldwide, especially among young children and the elderly in sub-Saharan Africa (Troeger et al., 2018). With over 800,000 deaths attributed to inadequate water, sanitation and hygiene (WASH) in 2016, diarrhea is the main component of the disease burden from unsafe WASH (WHO, 2019b).

It is widely acknowledged that safe access to well-managed WASH services is key to interrupting the transmission pathways of pathogens causing diarrheal diseases (Koné et al., 2014; Prüss et al., 2002; Wolf et al., 2014). Nonetheless, important research gaps remain, notably regarding the potential risk factors related to the physical environment. For example, although previous studies have explained the relevance of understanding spatial patterns of diarrhea (Reiner et al., 2020; Thiam et al., 2019), little is known about the impact of landscape patterns—i.e., the form and composition of the physical environment—on the occurrence of diarrheal diseases. Besides socio-economic and biological factors, the physical environment can also be considered as a key health determinant (Ezeh et al., 2017; Galea & Vlahov, 2005). Moreover, understanding the relationship between diarrhea and the spatial characteristics of human settlements becomes even more relevant in the case of child health, considering that the main exposure pathway for toddlers is hand-to-mouth contamination (Mattioli et al., 2015), which relates directly to the living environment.

In this study, we adopted a landscape ecology perspective (M. G. Turner & Gardner, 2015) to deepen the current knowledge on risk factors for diarrhea, by advancing "urban landscapes" as the key exposures. We purposively refer to urban landscapes in the plural, positing that they result from specific, local socio-spatial arrangements that come to bear in different forms. Indeed, cities are "patchy" ecosystems (Collins et al., 2000), formed by different types of land use and occupation that materialize into extremely diverse urban habitats—arguably, with some of these habitats being more healthy than others. In this sense, landscape ecology methods are instrumental to analyze the form and composition of urban habitats, by addressing landscape as spatial mosaic of discrete land use/land cover "patches" (Bosch et al., 2019; Forman & Godron, 1981; M. G. Turner & Gardner, 2015).

Thanks to advances in geospatial technologies and access to georeferenced health data, spatial patterns of disease have been extensively studied (Baptista & Queiroz, 2019; Reiner et al., 2020), while mathematical models have been developed to analyze and predict the spatiotemporal spread of infectious diseases (Arino, 2017). However, most studies conducted at large geographic scales (e.g., national, or metropolitan scales) focus only on disease clustering, and inadequately address space as an abstract, homogenous entity. In fact, variables related to the physical environment (e.g., entropy levels of the built environment, density or land-use) are rarely integrated in large-scale studies—exceptions occur when both health and settlement data are available at a high spatial resolution, or are collected directly by the investigators (Araujo et al., 2015; Rossi et al., 2018).

The lack of high-resolution data systematically collected over large areas constitutes a barrier to ecological studies that aim to explore risk factors derived from the physical environment (WHO, 2010), especially in low- and middle-income countries (Elsey et al., 2016). Such research barriers are being overcome with rapidly growing open-access data portals (e.g., OpenStreetMap and Humanitarian Data Exchange) and the increased contribution of open science projects that freely share their data. There is a high potential to combine these openly accessible datasets to deepen the understanding of how the physical environment relates to health. Yet, there is a paucity of studies that use open-access data to investigate this relationship at a large geographic scale. Such analyses could provide a useful framework, given their low cost and high reproducibility.

Moreover, understanding how the physical environment affects health is key for decision-making, notably in contexts marked by high levels of socio-spatial segregation that lead to disparate health outcomes (Ezeh et al., 2017). Indeed, in cities characterized by inequitable spatial development, the spatial dimension of disease must be addressed to properly identify priorities and to tailor targeted interventions. In sub-Saharan Africa, given the dynamics and intensity of recent urbanization trends (OECD & Sahel and West Africa Club, 2020), decision makers would benefit from a deeper understanding of the relations between urban landscape patterns and diarrheal diseases.

The purpose of this study was to explore the possible relations between urban landscapes and diarrhea, addressing the hypothesis that specific, spatial patterns of urban settlements can be associated with the prevalence of diarrhea. In this way, the spatial characteristics of the physical environment were defined as key variables of exposure. At the same time, our study put forward an analytical framework that was strictly based on open-access data and open-source software.

2.2   Materials and methods

2.2.1   Geographic scope

We focused on Côte d'Ivoire, a West African country that faces considerable challenges related to rapid urbanization and has a high burden of diarrheal diseases, which are among the country's top 10 causes of death (Vos et al., 2020). In addition, Ivorian cities are marked by contrasting landscapes, as economic growth has failed to keep pace with the rapid urban and demographic growths (Fall & Coulibaly, 2016), while transposed town planning models have failed to address local socio-economic needs (Chenal, 2013). Notably, access to water and sanitation services remain a great challenge. Between 2000 and 2020, access to basic water services in Ivorian cities decreased from 91 to 85%, while 52% of the urban population still lacked access to basic sanitation in 2020 (WHO & UNICEF, 2023). The concentration of demographic growth around a few cities ("urban primacy") has certainly exacerbated the issues related to the lack of basic services, as these cities have become saturated and witnessed

the emergence of precarious, informal settlements (Fall & Coulibaly, 2016). In 2020, over half of the urban population in Côte d'Ivoire lived in "slums" (UN-Habitat, 2022), i.e., deprived settlements where the physical environment itself exacerbates the risk of several illnesses, including diarrheal diseases (Ezeh et al., 2017; Mberu et al., 2016).

2.2.2 Datasets

This cross-sectional, ecological study combined open-access data on health, land cover, and basic infrastructures, readily obtained from different sources (Table 2.1). Geo-spatial data on the occurrence of diarrhea among children under the age of five years was obtained from the Demographic and Health Surveys (DHS) program in vector format (DHS, 2023). The DHS provides anonymized survey data at the individual and household levels that include cases of diarrhea that had occurred in the 2 weeks preceding their survey. The DHS also provides data on access to WASH facilities and education, which were relevant to the current analysis. DHS data can be georeferenced by linking the observations to the point locations of survey clusters. To ensure anonymity, these locations do not correspond to the precise locations of participating households, but rather to the mean location of households belonging to a same cluster – i.e., for every cluster of surveyed households, there is one single GPS position that is attributed to all households belonging to the same cluster. For the datasets used in this analysis (INS Côte d'Ivoire and ICF International, 2013a, 2013b, 2013c, 2013d), there were 351 clusters distributed across Côte d'Ivoire, for a total of 9686 surveyed households. These clusters contained a median number of 27 households, or 134 people.

Table 2.1: List of open-access datasets used to explore relations between landscape and diarrhea in Côte d'Ivoire.

Data Layer	Source	Description	Available Years	Spatial resolution	Type
Geolocation of DHS cluster	DHS	Cluster location with a geographic blur of 2 to 5 km	1998/1999 2011/2012	2 to 5 km	Vector (shp[1])
Cases of diarrhea	DHS	Cases of diarrhea (under-5), geocoded to cluster location	1998/1999 2011/2012	2 to 5 km	Vector (table)
Access to water and sanitation	DHS	Type of facility used by household, geocoded to cluster location	1998/1999 2011/2012	2 to 5 km	Vector (table)
Education attainment	DHS	Education attainment of women (15–49 years), geocoded to cluster location	1998/1999 2011/2012	2 to 5 km	Vector (table)
Climatic conditions	Terra-climate	Accumulated precipitation and mean temperature	1958–2020	1/24th degr. (~4 km)	Raster
Night illumination	NASA	Intensity of night illumination	2012 & 2016	500 m	Raster
Land use	ESA Land Cover CCI	Discrete categories of land cover	1992–2019	300 m	Raster
Population density	WorldPop	Estimated demographic densities (WorldPop's model)	2000–2020	100 m	Raster
Roads	OpenStreetMap	Surveyed roads and pathways	2019	5 to 20 m	Vector (shp[1])

[1] shapefile format

Regarding the urban environment, land cover data was obtained in raster format (300 × 300 m) from the European Space Agency's Land Cover Climate Change Initiative Project (ESA Land Cover CCI) (ESA, 2017). Population estimates at high spatial resolutions were obtained from WorldPop (Stevens et al., 2015), also in raster format (100 × 100 m). Night illumination was used as a proxy for the presence of urban infrastructures, and was obtained in raster format (500 × 500 m) from the National Aeronautics and Space Administration's (NASA) Earth Observatory (NASA, 2022). Vector data on mobility infrastructures was obtained from OpenStreetMap. Finally, modelled estimates of weather conditions were obtained from Terraclimate in raster format, at a spatial resolution of 4 × 4 km (Abatzoglou et al., 2018). We included these data in our study because climatic conditions have been associated with diarrhea (Carlton et al., 2016).

2.2.3   Data pre-processing

Combining health and environmental data is often a challenge, considering the differences in terms of the spatial and temporal resolutions of openly available data (Friesen et al., 2020). In this study, the areal units used to aggregate data were based on the geolocations of DHS clusters, which had the coarsest spatial resolution. All data processing steps were done in Python language, using the Jupyter computing environment. The following packages were used to process and visualise the data: PyLandStats 2.3.0 (Bosch, 2019), rasterstats 0.15.0 (Perry & others., 2020), rasterio 1.2.9 (Gillies & others., 2013), earthpy 0.9.2 (Wasser et al., 2019), Fiona 1.8.20 (Gillies & others., 2011), pandas 1.3.4 (McKinney, 2010), geopandas 0.9.0 (Jordahl et al., 2021), numpy 1.20.3 (C. R. Harris et al., 2020), statsmodels 0.13.0 (Seabold & Perktold, 2010), pysal 2.5.0 (Rey & Anselin, 2007), matplotlib 3.4.3 (Hunter, 2007), and seaborn 0.11.2 (Waskom, 2021).

The different data layers were harmonized spatially and temporally based on the buffer areas generated from DHS clusters, hereinafter called "spatial units". Based on previous studies (Grace et al., 2019), we generated circular buffer zones originating from each cluster centroid, with radii based on the geographic blur determined by the DHS data anonymization protocol: urban clusters had a buffer radius of 2 km, while rural clusters had a buffer radius of 5 km (Figure 2.1). The different data layers were aggregated at the cluster level: environmental data were aggregated based on the respective buffer areas, while DHS survey data were aggregated based on the clusters' unique identifiers. In this way, for each spatial unit we obtained the following: (i) a the cluster's prevalence of diarrhea among children under the age of five; (ii) the proportion of the cluster's population with access to at least "basic" water and sanitation, as defined by the World Health Organization (WHO) and the United Nations Children's Fund (UNICEF) Joint Monitoring Program (WHO & UNICEF, 2021); (iii) the proportion of the cluster's female population who never attended school; (iv) local climatic conditions; and (v) a list of landscape metrics derived from remotely sensed data (NASA and ESA Land Cover CCI), hybrid models (WorldPop), and volunteered geographic information (OpenStreetMap). Table 2.2 shows the variables obtained from this pre-processing in more detail.
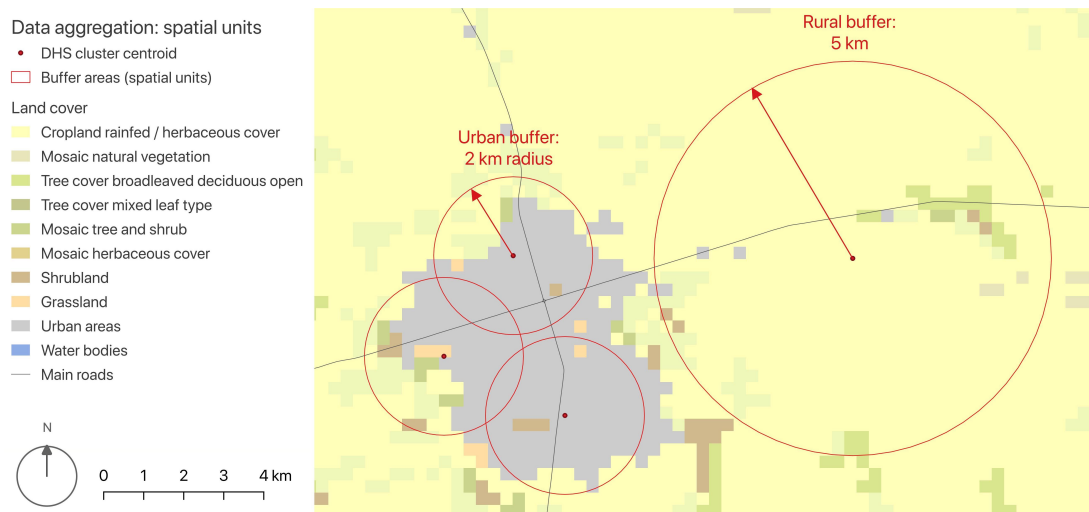
Figure 2.1: Buffer areas (red circles generated from clusters' centroids) were used to calculate landscape metrics. Elaborated by the authors with QGIS, from: DHS (2023) and ESA Land Cover CCI (ESA, 2017). ©ESA Climate Change Initiative—Land Cover led by UCLouvain (2017).

Landscape metrics have been widely used to quantify and describe spatial patterns of "patches" of similar land cover categories (M. G. Turner & Gardner, 2015), and thus are useful to analyze spatial patterns of urban settlements. These metrics were key features to our study, allowing us to relate the prevalence of diarrhea (dependent variable) to indicators describing the form and composition of urban settlements (independent variables). We used the Python package PyLandStats (Bosch, 2019) to calculate a series of landscape metrics for each land cover class contained within each spatial unit's perimeter (Table 2.2), based on the data provided by ESA's Land Cover Climate Change Initiative Project (ESA, 2017). The metrics employed here—i.e., the proportion, edge and shape index of land cover patches—were based on previous studies that referred to land cover data to analyze spatial patterns of urban settlements (Bosch et al., 2019) and environmental determinants of disease (Rossi et al., 2018).

We added a level of detail to our landscape metrics by reclassifying patches originally categorized as "urban", based on the levels of night illumination and demographic density (Figures 2.2 and 2.3). Our study used the intensity of night illumination as a proxy for the presence of urban infrastructures—or, in other words, for the "quality" of urbanization. Moreover, the quality of illumination affects the use of WASH amenities, especially by females (UNICEF and WaterAid and WSUP, 2018), and thus may impact the risk of diarrhea. We defined "precarious" and "regular" urban areas, building on the hypothesis that, if basic infra-structures are present, the level of illumination follows the level of demographic density. In this sense, urban pixels were considered "precarious" if they presented a high demographic density but a low (or relatively low) intensity of night illumination; on the other hand, "regular" urban patches had night illumination levels that matched the demographic density. This categorization was done based on quantiles (Appendix 2.1): for each urban pixel, if its density value was situated in a higher quantile than its night illumination value, it was considered "precarious".

Table 2.2: List of variables calculated for each spatial unit (variables aggregated by buffer area).

Variable	Role in analysis	Aggregation operation
Prevalence of diarrhea among children under five years	Dependent variable	$\dfrac{N_{\text{cases}}}{N_{\text{pop. under-fives}}}$
% access to basic water	Control variable	$\dfrac{N_{\text{pop. with basic wt.}}}{N_{\text{total pop.}}}$
% access to basic sanitation	Control variable	$\dfrac{N_{\text{pop. with basic s.}}}{N_{\text{total pop.}}}$
% women (15-49 years) lacking access to education	Control variable	$\dfrac{N_{\text{pop. women no ed.}}}{N_{\text{pop. women}}}$
Edge of land cover patch	Independent variable	Total perimeter (m) of given land cover category
Area-weighted mean of fractal dimension of land cover patch	Independent variable	$\dfrac{\sum_{i}^{n} Patch_{\text{area}}^{i} \times Patch_{\text{frac. dim.}}^{i}}{N_{\text{total patches}}}$
Proportion of land cover patch	Independent variable	$\dfrac{N_{\text{pixels given land cover}}}{N_{\text{total pixels}}}$
% of urban areas categorized as dense	Independent variable	$\dfrac{N_{\text{urban pixels w/ density > median}}}{N_{\text{total urban pixels}}}$
% of urban areas categorized as precarious	Independent variable	$\dfrac{N_{\text{precarious urban pixels}}}{N_{\text{total urban pixels}}}$
Density of roads	Independent variable	$\dfrac{\text{Length roads}_{km}}{\text{total urban area}}$

Another indicator of the quality of urbanization was the presence of roads, for which we calculated two indicators: road availability (km of roads per ha of built-up area) and linearity (ratio between edge length and linear distance between the two vertices of the same edge). The latter also served as an indicator of the urban form.

A selection of features that have previously been associated with diarrhea were included as control variables. Basic water and sanitation services are key to prevent diarrhea (WHO, 2019b), and were therefore included. Access to these services was measured through DHS household data (INS Côte d'Ivoire and ICF International, 2013b). Maternal education has been associated with lower risks of diarrhea (Mulatya & Ochieng, 2020); at the same time, it has been related with reporting bias (Manesh et al., 2008). A proxy variable of maternal education (i.e., women's educational attainment) was therefore added, again based DHS data. Climatic conditions also have been associated with diarrhea (Carlton et al., 2016), but here they showed no significant correlation (see Appendix 2.2). Hence, these data were discarded (for more details, see the Computer code section at the end of this Chapter).
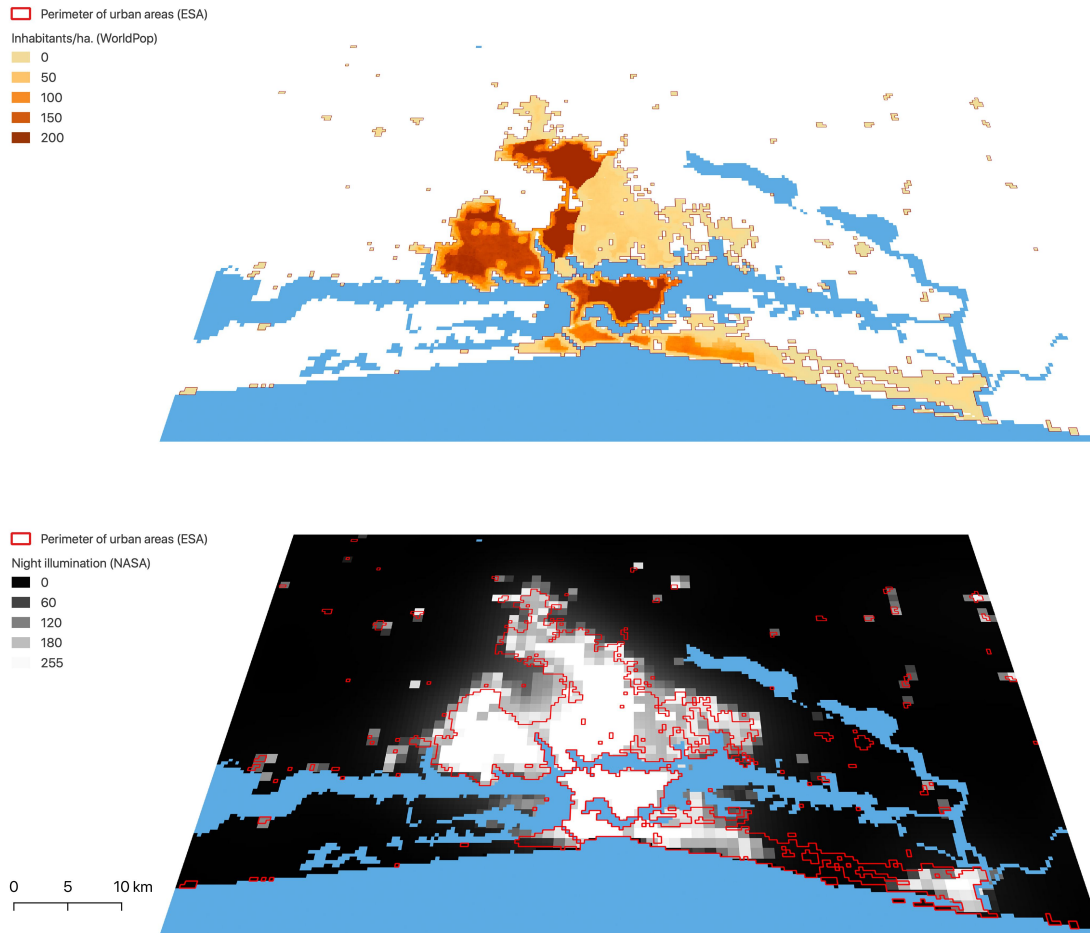
Figure 2.2: Layers used to reclassify urban patches based on demographic density and night illumination (zoom on Abidjan's metropolitan area). Elaborated by the authors with QGIS, from: NASA (2022), WorldPop (Stevens et al., 2015), and ESA Land Cover CCI (ESA, 2017). ©ESA Climate Change Initiative—Land Cover led by UCLouvain (2017).

To preserve some level of detail in the data, the variables resulting from the aggregation at the cluster level consisted of proportions (percentage) rather than simple means or medians. For example, demographic density in each spatial unit was given by the ratio between the number of built-up pixels classified as "dense" (with a value higher than the statistical series' median) and the total number of built-up pixels contained in the respective spatial unit.

By the end of the pre-processing, we obtained a geodataset with 351 spatial units. Each spatial unit had three control variables (water, sanitation, and women's educational attainment) and a total of 90 independent variables, i.e., the landscape metrics described in Table 2.2 (the full list of variables is given in the Supplementary materials section).

36
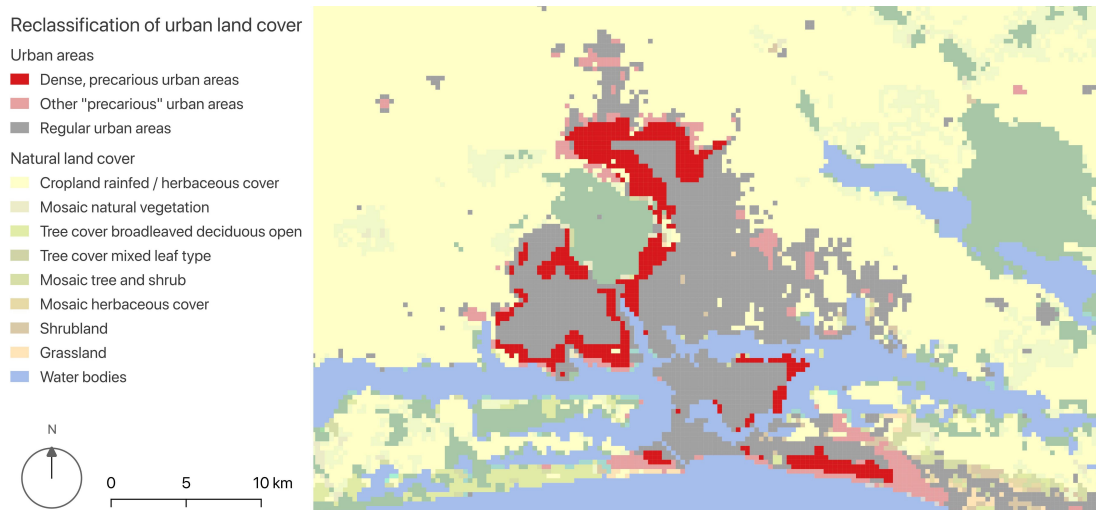
Figure 2.3: Reclassified urban patches (zoom on Abidjan's metropolitan area). Elaborated by the authors with QGIS, from: NASA (2022), WorldPop (Stevens et al., 2015), ESA Land Cover CCI (ESA, 2017). ©ESA Climate Change Initiative—Land Cover led by UCLouvain (2017).

2.2.4   Statistical models and feature selection

We used four different regression models to assess the significance of the associations between the calculated landscape metrics and diarrhea, while accounting for the effects of access to water, sanitation, and education, as well as spatial autocorrelation. The input data were standardized with a min/max scaler function, so that the effects of the different features could be compared through their coefficients.

We started by running a feature selection algorithm to identify the most important variables to be included in the regression models. Given the high number of independent variables that were derived from the landscape metrics ($n = 90$), a preliminary feature selection was necessary to avoid multicollinearity and to clarify the scope of the analysis. The feature selection algorithm was composed of two "filters". The first filter was a stepwise selection, which is a process that adds variables from a predefined list to the model, one-by-one, rechecking at each step the importance of all previously included variables (Rawlings et al., 1998). In other words, the stepwise process combines forward and backward feature selection processes, consisting of iterative linear regressions allowing to identify the "best" features based on predefined significance thresholds (maximum p-value was set to 0.1) and model performance (residual sum of squares). The second and final filter was based on Spearman's rank correlations ρ: we used the Python package statsmodels (Seabold & Perktold, 2010) to calculate bivariate correlations between each feature selected with the stepwise method and the dependent variable (i.e., prevalence of diarrhea at cluster level); only features with a p-value smaller than 0.1 were kept. We purposively opted for relative high thresholds of p-values because of the exploratory nature of this study.

Once we concluded the feature selection, we ran both weighted and unweighted regression models. First, we built an unweighted ordinary least squares (OLS) model containing the dependent, control, and independent variables, as well as a constant. Then, we built a weighted model with the same features using the cluster weights given by the DHS. In fact, when conducting country-level analyses, the DHS suggests using cluster weights to adjust for eventual biases resulting from their sampling method. Given the infectious nature of diarrheal diseases, the analysis also needed to account for spatial dependence (Nilima et al., 2018). To this end, we used the Python package pysal (Rey & Anselin, 2007) to run two models of spatial regression with the same features:, spatial lag and spatial error, as explained in the next section.

2.2.5 Addressing Spatial Dependence

Spatial dependence, or spatial autocorrelation, is the phenomenon by which values of observations are associated with each other through geographic distance (e.g., high values close to other high values) (Rey et al., 2020). Accounting for spatial dependence is essential because linear regressions assume a normal, random distribution of error terms and the absence of spatial autocorrelation in the dependent variable. We estimated the probability of spatial autocorrelation in the dependent variable by calculating the global Moran's I, which indicated whether the observed values of prevalence of diarrhea were clustered, or randomly distributed, in space. As for the error terms in the OLS regression, we detected the probability of spatial dependence through the Lagrange multiplier test for spatial error.

Contrary to an OLS model, spatial regressions can account for the spatial autocorrelation of the dependent variable (spatial lag dependence) and of the error term (spatial error dependence) (Anselin, 2009). The spatial lag model used in this study incorporates the spatial autocorrelation of the dependent variable by introducing the average values of neighbors as an additional variable into the regression specification (Equation 2.1):

$$y = \alpha + \rho W_y + \chi\beta + \varepsilon \tag{2.1}$$

where y is an N × 1 vector of observations on a dependent variable taken at each of N locations, α is the intercept, ρ is a scalar spatial lag parameter, W is an N × N matrix of weights indicating the spatial framework of neighborhood effects among the dependent variable, χ is an N × k matrix of explanatory variables, β is a k × 1 vector of parameters, and ε is an N × 1 vector of error terms. Similarly, the spatial error model used in this study also incorporates spatial autocorrelation by introducing the average values of neighbors as an additional variable into the regression specification, but this time using the values of the error terms (Equation 2.2):

$$y = \alpha + \chi\beta + u, \quad \text{given that: } u = \lambda W u + \varepsilon \tag{2.2}$$

where u is the vector of spatially autocorrelated residuals with constant variance and co-variance terms, specified by an N × N matrix of weights indicating the spatial framework of neighborhood effects among the error terms (W) and a spatial error coefficient (λ).

2.2.6   Inclusion criteria and stratification of analysis

The unit of analysis was the buffer area generated from each DHS cluster's centroid (spatial unit). Out of the 351 spatial units, 10 were excluded as they did not have valid geographic coordinates. Furthermore, because our analysis focused on human settlements, we opted to keep only those spatial units with at least 1 "urban" pixel (300 × 300 m). Hence, we excluded 74 spatial units where no human occupation was detected—including units with settlements not sufficiently large to be detected at the spatial resolution used here. In the end, 267 spatial units (out of 351) were included in our regression analyses. Details about the discarded units are given in Appendix 2.3.

To determine whether the size and proportion of urban areas affected the association between landscape features and diarrhea, the processes described in Section 2.2.4 were stratified into two levels. First, we conducted the regression analyses with all the 267 spatial units that met our inclusion criteria. Then, we conducted the same analyses with an "urban" subset, which contained 105 spatial units. The criterion for a spatial unit to be classified as "urban" was to have a proportion of urbanized area (ratio between the surface of "urban" pixels and the spatial unit's total area) that was above the average of the retained 267 spatial units. Figure 4 shows the location of the 267 spatial units included in the analysis, specified by subset.

2.3   Results

2.3.1   Overall clustering of data and need for spatial regressions

The tests for spatial dependence confirmed the need for spatial regression models when processing the data of the full dataset ($n = 267$). The global Moran's I statistics for the spatial distribution of the dependent variable showed a significant, positive spatial autocorrelation of the prevalence of diarrhea (Moran's $I = 0.11$, $p = 0.002$). Regarding the distribution of error terms in the OLS regression, a significant spatial dependence was detected by the Lagrange multiplier test ($p = 0.002$). For the urban subset ($n = 105$), however, no spatial dependence was detected. Nevertheless, we also ran spatial regressions with this subset, for the sake of comparison with the full dataset analysis, and overall coherence in the analysis.

2.3.2   Significant landscape feature: dense, precarious urban areas

One feature passed our selection filter and, hence, was retained as an independent variable: the proportion of urban patches (ratio between patch area and buffer area) that were characterized as being very dense (demographic density values situated within the last decile of the series)
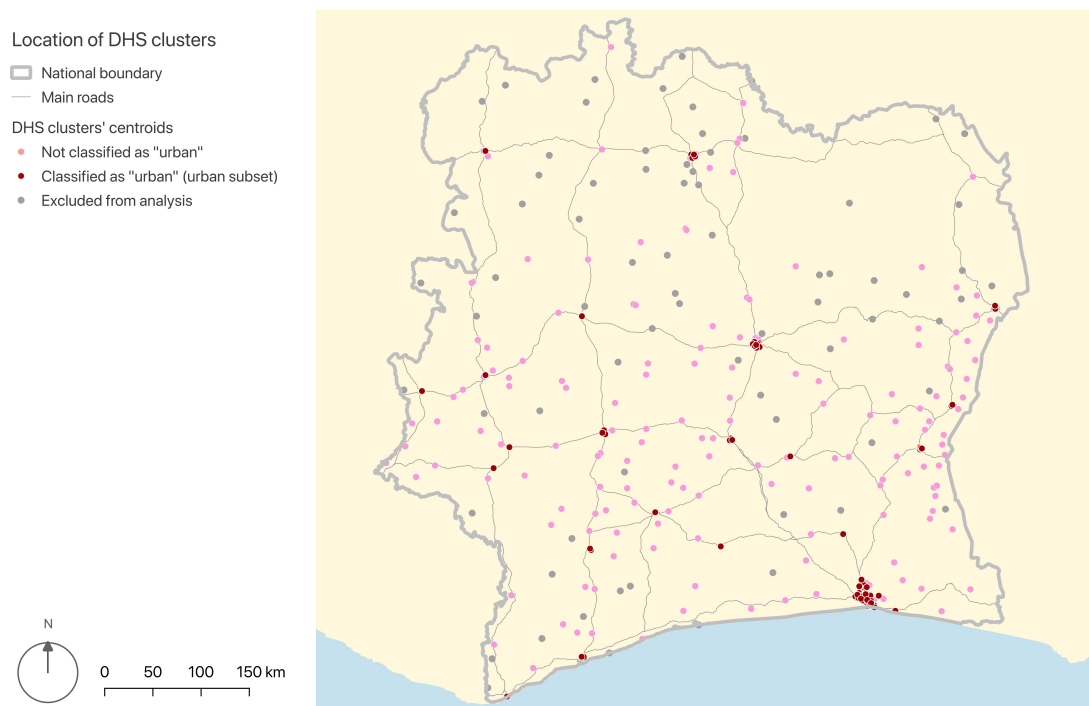
Figure 2.4: Location of DHS clusters, by subset. Elaborated by the authors with QGIS, from: DHS (2023), GADM and OpenStreetMap

and with low to medium night illumination levels (values above the median but below the last decile of the series, see Appendix 2.1). Following the rationale explained in Section 2.2, these patches correspond to "precarious" urban areas, as the level of density is higher than the illumination level. A total of 44 spatial units (all located around Abidjan and San Pédro, two large cities) had at least 1one urban pixel with these characteristics. We denominated this type of urban patch as "dense, precarious urban areas".

Tables 2.3 and 2.4 summarize the results of the different regression models used, following the stratification explained in Section 2.2.6. The proportion of dense, precarious urban areas was included as single independent variable (as it was the only significant landscape metric), while indicators of access to water, sanitation, and education were included as control variables.

For the full dataset (n = 267 spatial units), the weighted OLS regression and the spatial lag model performed better than the other two, based on their R^2 and Akaike information criterion (AIC) values. Two features consistently showed significant coefficients ($p < 0.05$): (i) proportion of the cluster population with access to basic sanitation facilities; and (ii) proportion of dense, precarious urban areas. In the four models, basic sanitation was negatively associated with diarrhea, while dense, precarious urban areas showed a positive association and had the strongest beta coefficients. The proportion of women without any education showed significant coefficients in the weighted OLS regression model and, globally, was negatively associated with the prevalence of diarrhea. There was no significant association between

Table 2.3: Regression results of four models for the full dataset ($n = 267$ spatial units), by model type.

Included features	Variance Inflation Factor	Unweighted OLS $R^2 = 0.06$ AIC= −50.4 JB [2]: 12.020 (p = 0.003) BP [3]: 4.880 (p = 0.300)			Weighted OLS $R^2 = 0.129$ AIC= 21.75 JB [2]: 10.676 (p = 0.005) BP [3]: 2.881 (p = 0.578)			Spatial Lag Pseudo $R^2 = 0.09$ AIC= −56.3 JB [2]: 11.407 (p = 0.003) BP [3]: 5.807 (p = 0.214)			Spatial Error Pseudo $R^2 = 0.059$ AIC= −58.2 JB [2]: 11.859 (p = 0.003) BP [3]: 4.693 (p = 0.320)		
		Coef.	SE	Prob.	Coef.	SE	Prob.	Coef.	SE	Prob.	Coef.	SE	Prob.
% basic water	1.372	0.001	0.063	0.986	0.014	0.062	0.820	0.032	0.061	0.606	0.049	0.064	0.439
% basic sanitation	1.810	**−0.186**	**0.069**	**0.007**	**−0.257**	**0.069**	**0.000**	**−0.181**	**0.067**	**0.007**	**−0.166**	**0.068**	**0.015**
% women lacking access to education	1.674	−0.141	0.075	0.061	**−0.221**	**0.076**	**0.004**	−0.123	0.073	0.092	−0.108	0.074	0.148
Dense, precarious areas [1]	1.074	**0.257**	**0.081**	**0.002**	**0.291**	**0.062**	**0.000**	**0.227**	**0.081**	**0.005**	**0.275**	**0.094**	**0.004**

Bold: significant associations.
[1] Selected landscape metric: proportion of dense, precarious urban areas (total patch area/buffer area).
[2] Jarque-Bera test for normality of errors.
[3] Breusch-Pagan test for heteroskedasticity.

Table 2.4: Regression results of four models for the urban subset ($n = 105$ spatial units), by model type

Included features	Variance Inflation Factor	Unweighted OLS $R^2 = 0.06$ AIC= −50.4 JB [2]: 12.020 (p = 0.003) BP [3]: 4.880 (p = 0.300)			Weighted OLS $R^2 = 0.129$ AIC= 21.75 JB [2]: 10.676 (p = 0.005) BP [3]: 2.881 (p = 0.578)			Spatial Lag Pseudo $R^2 = 0.09$ AIC= −56.3 JB [2]: 11.407 (p = 0.003) BP [3]: 5.807 (p = 0.214)			Spatial Error Pseudo $R^2 = 0.059$ AIC= −58.2 JB [2]: 11.859 (p = 0.003) BP [3]: 4.693 (p = 0.320)		
		Coef.	SE	Prob.	Coef.	SE	Prob.	Coef.	SE	Prob.	Coef.	SE	Prob.
% basic water	1.172	0.082	0.118	0.488	0.112	0.136	0.412	0.081	0.115	0.483	0.089	0.115	0.439
% basic sanitation	1.769	−0.168	0.107	0.119	**−0.252**	**0.107**	**0.021**	−0.167	0.105	0.111	−0.168	0.105	0.110
% women lacking access to education	1.810	−0.013	0.127	0.917	−0.088	0.136	0.520	−0.012	0.124	0.925	−0.012	0.124	0.922
Dense, precarious areas [1]	1.029	**0.315**	**0.090**	**0.001**	**0.316**	**0.079**	**0.000**	**0.318**	**0.093**	**0.001**	**0.318**	**0.090**	**0.000**

Bold: significant associations.
[1] Selected landscape metric: proportion of dense, precarious urban areas (total patch area/buffer area).
[2] Jarque-Bera test for normality of errors.
[3] Breusch-Pagan test for heteroskedasticity.

access to basic water facilities and diarrhea. We observed that neither the directions nor the levels of association between diarrhea and the tested variables changed significantly between the different models. Also, although spatial dependence was detected, the spatial lag model only improved the coefficient of determination when compared to the OLS model, while it was the weighted model using DHS cluster weights that explained most of the variance of diarrhea.

For the urban subset ($n = 105$ spatial units), there was considerably less variation in the models' R^2 and AIC values. In terms of the explained variance of the dependent variable, the models performed better with the urban subset than the full dataset. In this subset, however, the only feature that consistently showed significant coefficients was the proportion of dense, precarious urban areas—having once again the strongest beta coefficients. Except for sanitation, the control variables showed poor coefficients for the urban subset. As in the full dataset analysis, neither the directions nor the levels of association between diarrhea and

the tested variables changed significantly between the different models. Similarly, the model that explained most of the variance of diarrhea was the weighted OLS model (with DHS cluster weights).

2.3.3   Stages of urbanization and landscape patterns

Our stratified regression analyses showed that the proportion of urbanized area within the spatial units affected the coefficients of the selected landscape metric, as well as those of the control variables. Indeed, in the urban subset, the independent variable's coefficients became more important and significant, while the coefficients of the control variables became much less significant than in the analyses with the full dataset.

In addition to the regression coefficients, urbanization also affected the independent variable's rank correlation with the outcome of interest (Figure 2.5). For the full dataset ($n = 267$), the Spearman's correlation coefficient, which was calculated between dense, precarious urban patches and the prevalence of diarrhea, was +0.11 ($p = 0.079$), while for the urban subset ($n = 105$; see orange dots in Figure 5) it increased to +0.24 ($p = 0.013$).
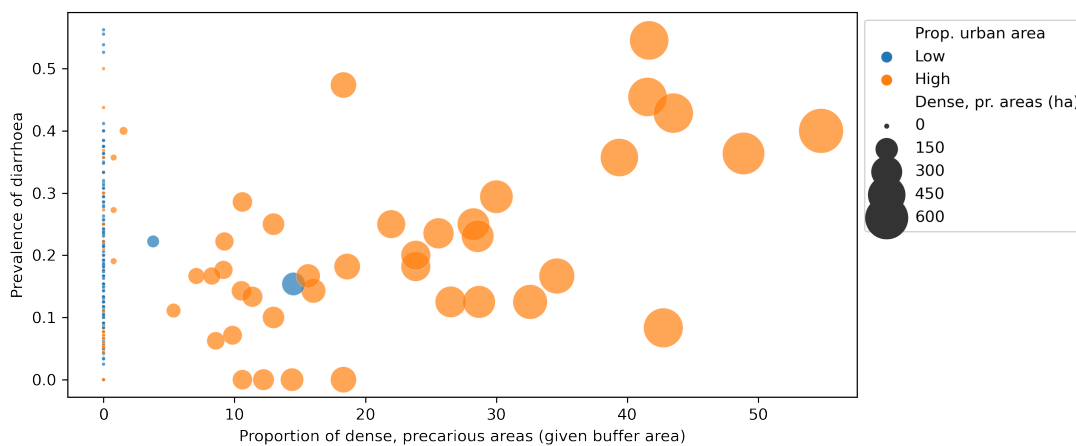
Figure 2.5: Relationship between dense, precarious urban areas (x-axis) and the prevalence of diarrhea (y-axis), by level of urbanization (urban subset shown in orange).

The size of urbanized area (total "urban" pixels counted in each buffer area) was positively correlated with the percentage of urban patches that were characterized as dense and precarious ($\rho = +0.50$, $p < 0.001$). Put differently, as the extent of urbanized areas within the spatial units (buffer areas) increased, the probability of urban areas being classified as "dense and precarious" also increased. Moreover, the cumulated area covered by urban patches was also significantly correlated to the percentage of women without any education ($\rho = -0.35$, $p < 0.001$), access to basic water facilities ($\rho = +0.53$, $p < 0.001$), and to basic sanitation ($\rho = +0.50$, $p < 0.001$).

The correlation between urbanization and access to basic sanitation facilities is less clear than with the other two control variables (Figures 2.6–2.8). Additionally, the correlations changed according to the stage of urbanization: we found higher significance levels (p-values) for Spearman's correlations among spatial units having low proportions of urban areas, as compared to the urban subset. We found $p = 0.002$ for water (against 0.318 for the urban subset); $p \approx 0.000$ for sanitation (against 0.089); $p = 0.002$ for women's education (against 0.939).
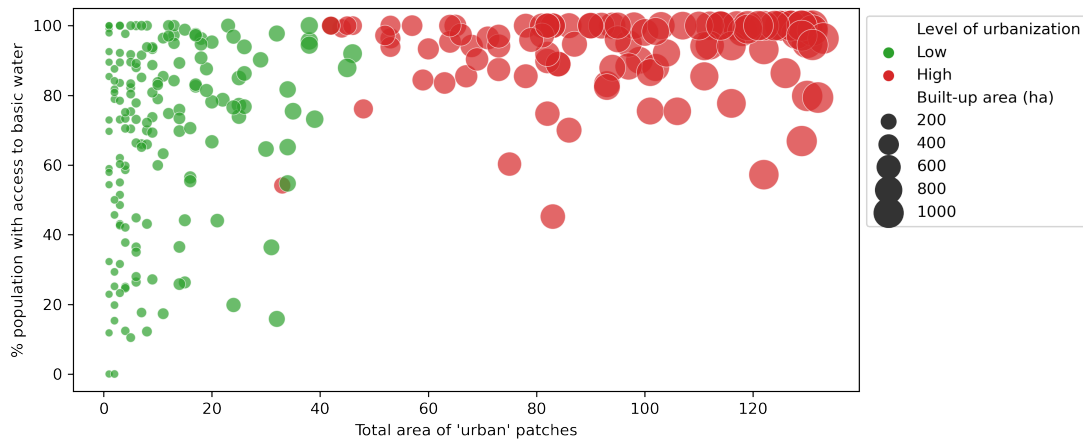
Figure 2.6: Relationship between the size of the urbanized area (x-axis) and access to basic water facilities (y-axis), by level of urbanization (urban subset shown in red).
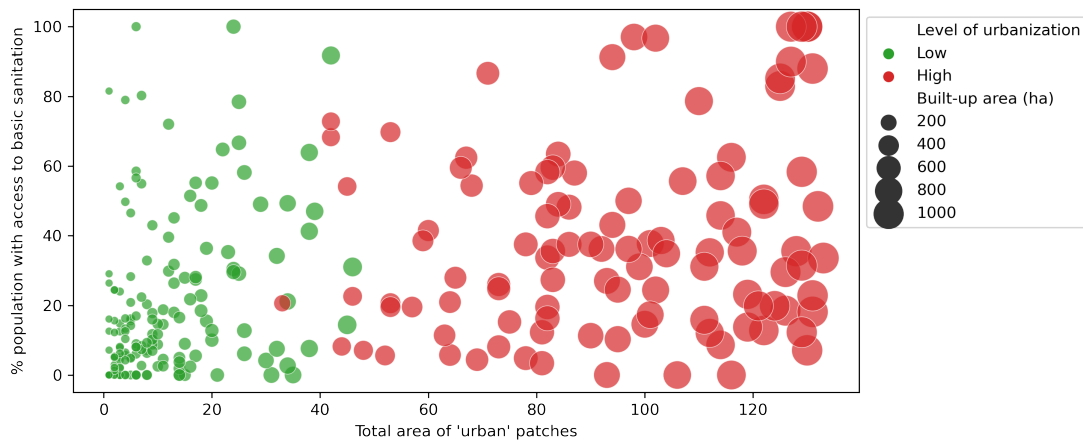
Figure 2.7: Relationship between the size of the urbanized area (x-axis) and access to basic sanitation facilities (y-axis), by level of urbanization (urban subset shown in red).
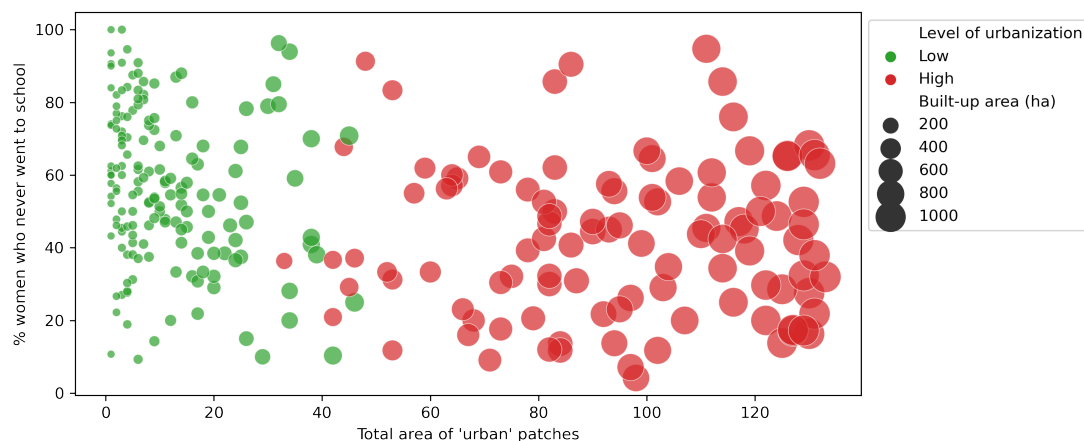
Figure 2.8: Relationship between the size of the urbanized area (x-axis) and the percentage of women lacking access to education (y-axis), by level of urbanization (urban subset shown in red).

2.4 Discussion

2.4.1 Towards spatial predictors of diarrhea in urban areas

Spatial predictors of socio-economic indicators based on the morphology of the built environment have already been studied (Wang et al., 2022; Wurm & Taubenböck, 2018). At the same time, socioeconomic indicators have been assessed as potential risk factors for diarrheal diseases (Mulatya & Ochieng, 2020). However, to our knowledge there are no studies that explore direct associations between the urban landscape and diarrhea. In this sense, our study advanced a selection of landscape metrics as potential predictors of disease. One must note that this research for spatial predictors of diarrhea was facilitated by the availability of open-source software and open-access data on human settlements and populations, which should be encouraged and valorized both by scientists and planning authorities.

We defined "dense, precarious areas" through demographic and night illumination data. Although hypothetical, this initial assumption proved to be useful in identifying potential vulnerabilities in terms of health. The coefficients of both linear regressions and Spearman's rank correlation consistently showed a positive, significant association between "dense, precarious areas" and the prevalence of diarrhea. Among the most urbanized clusters ("urban" subset), the selected landscape metric was a better predictor of the prevalence of diarrhea than the "usual suspects", such as access to basic water and sanitation facilities, or women's educational attainment. In fact, the proportion of dense, precarious urban areas was the only feature to consistently show significant coefficients in all regression models.

These observations call for further investigations on predictors of diarrhea that are more related to global aspects of the urban habitat, and not strictly focused on household-level indicators or facilities. Indeed, in the case of Côte d'Ivoire, we may argue that poor urban

development has led to environmental conditions that limit the potential benefits of basic water and sanitation infrastructures. Without proper urban habitats, the sole presence of these infrastructures may not be sufficient to prevent diarrheal diseases. If this is confirmed, it would have policy implications, as decision-makers should aim to improve the overall urban habitat—instead of punctually improving infrastructures, as it may be the case in "slum upgrading" projects. Further research on this aspect could be useful to shed light on recent controversies regarding the health impacts of WASH interventions, which are not always so clear or significant as expected (Pickering et al., 2019).

Although urbanization in Côte d'Ivoire was correlated to key predictors of diarrhea, such as the access to basic sanitation and the proportion of dense, precarious areas, it was not directly correlated with diarrhea. In fact, neither the size nor the form of urban patches showed significant coefficients. Generally, there was no apparent association between city size and the prevalence of diarrhea, based on aggregated cluster data (Appendix 2.4). Nevertheless, the "quality" of urbanization (indicated here by the extent of "precarious" areas) was a significant feature.

2.4.2   Saturation of urban settlements and health inequities

Urbanization has been associated with better aggregate indicators of social and health outcomes (Galea & Vlahov, 2005; Njoh, 2003; Rydin et al., 2012). In Côte d'Ivoire, our results raised some nuances to this assumption. While access to basic water and sanitation, as well as access to education, were significantly associated with urbanization, the latter alone was not associated in any way with the health outcome of interest—i.e., diarrhea. On the contrary, depending on the urban landscape characteristics (e.g., the proportion of dense, precarious areas), the risk of diarrheal diseases appeared to be significantly higher.

Moreover, our results showed that the size of urban areas was positively associated with the percentage of urban patches that were characterized as dense and precarious. This suggests that infrastructures have failed to keep up with demographic growth, which visibly poses considerable challenges to town planners. The concentration of demographic growth in a few Ivorian cities, and their subsequent saturation, has been discussed previously (Fall & Coulibaly, 2016). As economic limitations hamper investment in infrastructures and access to adequate housing (Nana et al., 2019), the urban habitat becomes a risk factor for disease. If spatial development is not equitable, then urbanization leads to health inequities that inflict a high burden on the most deprived populations—notably those living in "slums" (Ezeh et al., 2017; WHO, 2010).

Our analysis also showed that, at early stages of urbanization, access to basic services significantly increases with urban growth; however, when the extent of urban areas reaches a larger size, this correlation disappears. An explanation could be that it is easier to expand infrastructures in smaller cities than in bigger cities; in the latter, demographic densities would tend to increase without a corresponding increase in infrastructures. In fact, all urban pixels

reclassified as "dense, precarious urban areas" were concentrated in two of Côte d'Ivoire's largest cities, namely Abidjan and San Pédro.

Africa is characterized by the fastest urbanization rate in the world, and most of the future urbanization is expected to occur on this continent (OECD & Sahel and West Africa Club, 2020). Given the important spatial and social transformations that this engenders, specific attention of researchers and urban planners is needed to ensure that the urban environment becomes a catalyst for social development, rather than a health hazard. To this end, early interventions are key to prevent urban areas from becoming saturated and to ensure that basic infrastructures and services keep up with demographic growth. In this sense, focusing on small- and medium-sized cities would be crucial as they approach the "tipping point" (in terms of size of urban area), where it becomes more challenging to expand infrastructures to follow demographic (and spatial) growth.

2.4.3 Study's limitations and need for further research

Our study has several limitations that are offered for consideration and, possibly, point towards paths for future research on spatial predictors of diarrhea. First, the cross-sectional design is susceptible to what is known as the ecological fallacy (Morgenstern, 1995), i.e., limitations to causal inference due to the use of aggregate data. Although precarious spatial development was associated with diarrhea, there are other features in the complex urban system that may impact the prevalence of diarrhea. We addressed these limitations by adding control variables (to mitigate effects of confounders) and by reducing the number of independent variables (which reduced multicollinearity in the statistical models).

Second, study design limitations impacted the prediction power of the regression models, which had R^2 values situated between 0.06 and 0.20. However, we note that low R^2 values are expected in such ecological studies, given the "noise" of environmental variables and the complexity of the studied ecosystems (Møller & Jennions, 2002). In this regard, our model focused on the material aspects of the urban environment, while omitting social dynamics that could be relevant to explain the prevalence of diarrhea. For instance, mobility can be a key variable to model diarrheal diseases, as pathogens may travel long distances with humans (Mari et al., 2012), but this could not addressed here due to the lack of data. Third, although the stepwise feature selection process is a powerful screening tool to identify contender models, it is prone to statistical issues that merit acknowledgment. For instance, searching through a large number of potential features and keeping only the ones that best fit the sample data may lead to "overfitting" the model (Rawlings et al., 1998). In addition, the multiple testing of a large number of contender features makes such selection methods prone to the "false discovery" of features that appear as significant, but in reality are not relevant to estimate the dependent variable (G'Sell et al., 2016). In this sense, the explanatory variable in this study could be further assessed using datasets with a higher spatiotemporal resolution, based on a larger, random populational sample.

Lastly, the study materials were strictly limited to open-access data, and hence, there were limitations in terms of spatial accuracy. While settlement data can be found at a fine spatial resolution, between 100 and 500 m (and potentially up to 0.5 m in the case of very-high resolution satellite imagery), socio-demographic data are only available at low spatial resolutions (in this case, 2 to 5 km). This is certainly due to the ethical considerations regarding privacy. Indeed, researchers must preserve the anonymity of their study participants, and hence, any georeferenced data must be transformed with a geographic blur so that the specific locations of participating households cannot be identified. In our study, this blur made it impossible to determine in which specific type of landscape patch the study subjects lived—which is why we worked with buffer areas and global landscape metrics. Moreover, we note that the socio-demographic data aggregated by clusters came from samples that were not necessarily representative of that same cluster's population.

Further research is needed to verify to which extent the urban landscape effectively impacts the risk of diarrhea. Similar study designs could be implemented, but this time using high-resolution socio-demographic data—the latter would certainly need to be primary data collected through household surveys. More generally, further research addressing WASH interventions and diarrhea from an ecological perspective—i.e., focusing not only on household-level indicators, but also on features observed at community and urban scales—could significantly contribute to fill in the knowledge gaps regarding the health impacts (and efficiency) of different WASH solutions.

2.5   Conclusions

In this exploratory study, we addressed diarrheal diseases from a landscape ecology perspective by considering the physical environment as a key explanatory variable. We presented a framework strictly based on secondary, open-access data to assess whether specific patterns of urban landscapes could be associated with diarrhea. We combined remotely sensed data from different sources to classify urban areas based on demographic density and the intensity of night illumination (used as a proxy for the presence of infrastructures). This allowed us to identify different types of "precarious" urban areas, and to confront them, along with other landscape metrics, with the prevalence of diarrhea among children under the age of five years.

We found that patches of dense, precarious urban areas might be a significant feature to explain the prevalence of diarrhea, given the significance of the associations found. These were stronger in larger urban settlements, where the selected landscape metric was even a better predictor of diarrhea than the control variables (water, sanitation, and education level). Based on these results, we may argue that poor urban development leads to environmental conditions that hamper the potential benefits of basic water and sanitation infrastructures—thus reducing their ability to prevent diarrheal diseases. These observations raise the question of the scope of urban interventions, which should focus on the overall quality of the landscape, and not be limited to punctual infrastructural improvements.

We acknowledge the experimental nature of the framework put forward by this study. There is a need for further research on how the urban environment may be associated with diarrhea, and how it may impact on potential benefits of water and sanitation infrastructures. Urban planners and public health professionals will benefit from a better understanding of how WASH services interact with their spatial and social contexts, which certainly requires design adaptations.

2.6   Supplementary materials

The following supporting information can be downloaded at:

https://drive.switch.ch/index.php/s/G1iQsS9DliJ334v

This is a table showing the Spearman correlation coefficients between all environmental variables ($n = 90$) and the prevalence of diarrhea, with the respective p-value (for each variable, the table also indicates whether it was selected by the stepwise regression).

Data availability

Data available in a publicly accessible repositories are listed below.

- DHS data: restrictions apply to the availability of these data. Data was obtained from the Demographic and Health Surveys Program and are available at:

  https://dhsprogram.com/data/dataset/Cote-d-Ivoire_Standard-DHS_2012.cfm?flag=0

  (accessed on 11 May 2022) with the permission of the Demographic and Health Surveys Program.

- ESA Land Cover CCI data: restrictions apply to the availability of these data. Data was obtained from ESA Land Cover CCI and are available at:

  https://maps.elie.ucl.ac.be/CCI/viewer/download.php

  (accessed on 11 May 2022) with the permission of ESA Land Cover CCI.

- NASA: publicly available datasets were analyzed in this study. This data can be found here:

  https://earthobservatory.nasa.gov/features/NightLights/page3.php

  (accessed on 11 May 2022).

- OpenStreetMap: publicly available datasets were analyzed in this study. This data can be found here:

  https://download.geofabrik.de/africa.html

  (accessed on 11 May 2022).

- Terraclimate: publicly available datasets were analyzed in this study. This data can be found here:

  https://www.climatologylab.org/terraclimate.html

  (accessed on 11 May 2022).

- WorldPop: publicly available datasets were analyzed in this study. This data can be found here:

  https://www.worldpop.org/project/categories?id=3

  (accessed on 11 May 2022).

Computer code

A repository with the code materials used in this study is available at: https://github.com/ceat-epfl/landscape-diarrhea-civ

3 Spatial distributions of diarrhea in relation to housing conditions in informal settlements: a cross-sectional study in Abidjan

Abstract

This study embraced a broad approach to health determinants by looking at housing deprivation characteristics as exposures of interest. We tested the hypothesis whether the risk of diarrhea in informal settlements is associated with inadequate dwelling characteristics, and that their spatial distributions follow similar patterns. This was a cross-sectional study based on georeferenced household surveys in two informal settlements in Abidjan, Côte d'Ivoire. We used local join count statistics to assess the spatial distribution of events and multiple logistic regressions to calculate adjusted odds ratios between diarrhea and the exposures. 567 households were enrolled. We found that non-durable building materials, cooking outdoors, and water service discontinuity were associated with higher risks of diarrhea in the general population. The spatial distribution of diarrheal cases coincided with that of dwelling deprivation characteristics. We observed significant heterogeneity within the study sites regarding the distribution of diarrheal cases and dwelling deprivation. Decision-makers should acknowledge a "spectrum" of deprivation within the heterogeneous universe of informal settlements, adopting a site-specific approach based on high-resolution data.

3.1   Background

Diarrheal diseases remain a global health challenge, as they are among the top five causes of disability-adjusted life years (DALYs) according to the 2019 Global Burden of Disease Study (Vos et al., 2020). This burden disproportionally affects children under the age of five years in sub-Saharan Africa (SSA). In 2016, out of the 446,000 estimated deaths in this age group caused by diarrhea, 290,724 (65%) occurred in SSA (Troeger et al., 2018). The latter is also one of the fastest urbanizing regions of the world (OECD & Sahel and West Africa Club, 2020). This brings along considerable challenges for the provision of water, sanitation, and hygiene (WASH) services and, consequently, the prevention of numerous illnesses, notably diarrhea (Ezeh et al., 2017).

One of the main challenges faced by cities in SSA is the occurrence of "informal" urbanization, characterized by extralegal land occupation, and the dissociation between urban growth and the extension of basic infrastructures. In 2020, more than 230 million urbanites (50.2% of the urban population in SSA) lived in "slum" households (UN-Habitat, 2022). According to the United Nations Human Settlement Programme (UN-Habitat), these households experience one or several of the following deprivations: (i) lack of access to improved water and sanitation facilities; (ii) overcrowded and precarious housing conditions and location; (iii) voicelessness and powerlessness in political systems and governance processes; and (iv) lack of tenure security (UN-Habitat, 2022). Here, we opted to refer to settlements facing any of the deprivations above as "informal settlements," given earlier debates on the pejorative nature of the term "slum" (Gilbert, 2007).

The risk of diarrheal diseases is closely related to access to WASH amenities, which are essential to interrupt contamination pathways, particularly the fecal-oral route (Prüss et al., 2002), but are often lacking in informal settlements (Kim et al., 2022; UN-Habitat, 2022). The international literature has extensively assessed the relationship between diarrhea and WASH services (Prüss et al., 2002; Troeger et al., 2018; Wolf et al., 2014).Additionally, previous studies have focused on factors other than WASH that might govern contamination pathways, notably poor housing conditions and cohabitation with animals (Baker et al., 2022), food handling (Kirk et al., 2017), and exposure to environmental sources of pathogens in public spaces (Medgyesi et al., 2019). These studies reflect a renewed interest in environmental health determinants and raise the need for a broader approach to address variations of morbidity and mortality patterns across populations based on socioeconomic and housing conditions (McKeown, 2009). These studies also draw attention to the complexity of causal pathways for diarrhea by demonstrating how, beyond individual hygiene practices and access to WASH facilities, community-level and dwelling conditions are relevant exposures.

Our study is inscribed within this broader approach, by looking at specific housing deprivation characteristics as environmental exposures of interest, and confronting the latter's spatial distribution to that of diarrheal cases (health outcomes of interest). Although previous studies have already assessed relations between housing deprivation and diarrheal diseases in SSA

(Baker et al., 2022; Penrose et al., 2010), besides a few exceptions (Akullian et al., 2015; Corburn & Hildebrand, 2015) there is a paucity of empirical evidence elaborated on a cartographic basis and at a high spatial resolution (i.e., with precise maps of the built environment, housing characteristics, and cases of diarrhea). This "spatially explicit" approach is critical for urban planners to assess disease risk factors related to the built environment and plan tailored interventions. Such an approach is particularly relevant in informal settlements, where "neighborhood effects" caused by inadequate living conditions exacerbate the risk of numerous illnesses, including diarrhea (Ezeh et al., 2017). Moreover, considering the differences that exist between and within informal settlements (Wamukoya et al., 2020), spatial analyses based on high resolution health data can provide invaluable insights to better understand environmental health determinants in those vulnerable settings.

Building on our recent research (Pessoa Colombo et al., 2022; Pessoa Colombo et al., 2023), and on previous environmental health studies in SSA (Baker et al., 2022; Penrose et al., 2010), this study argues for a holistic approach to the prevention of diarrheal diseases that, beyond WASH services, also addresses the physical environment and the spatial characteristics of poverty (Wurm & Taubenböck, 2018). Our starting point was the assumption that inadequate dwelling conditions hamper potential health benefits expected from WASH interventions, which can be indirectly measured by the risk of diarrhea (Clasen et al., 2014). We tested the hypothesis whether, in addition to access to adequate WASH services, the risk of diarrhea in informal settlements is associated with dwelling deprivation features.

3.2   Materials and methods

3.2.1   Study design and geographic scope

We designed a cross-sectional study. Primary data were collected through household surveys in two informal settlements in Abidjan, Côte d'Ivoire. Given its rapid spatial and demographic growth, and its "urban primacy" (OECD & Sahel and West Africa Club, 2020), Abidjan is a city that illustrates well urbanization processes in SSA. Like other cities in the region, it faces challenges related to access to basic services, notably WASH (Angoua et al., 2018), and a significant share of the population living in informal settlements (Chenal, 2013; Nana et al., 2019).

We purposefully selected two settlements, Azito and Williamsville (Fig. 3.1). This selection was motivated by ensuring sufficient variations in the exposure variables of interest, i.e., housing characteristics. Indeed, the two sites differ in their social and spatial compositions. Azito is an old fishermen's village traditionally occupied by the Ébrié people, located in a peripheral area of Abidjan by the Ébrié Lagoon. Although it is considered an informal settlement for the lack of tenure security and sanitation infrastructures, it is less densely built than most informal settlements, with large open spaces. Its population is relatively wealthy and well-educated. Conversely, Williamsville is very densely built and situated in a central area near to referential

commercial locations. Its population is heterogenous (with diverse geographic origins) and economically vulnerable compared to other sites in Abidjan. In addition to poverty, people in Williamsville face a lack of tenure security, a severe lack of sanitation services (being exposed to open sewerage and garbage disposal), and seasonal flooding events. Accessibility to the sites and acceptance of the study by residents (represented by several "village chiefs") were additional features guiding our selection.
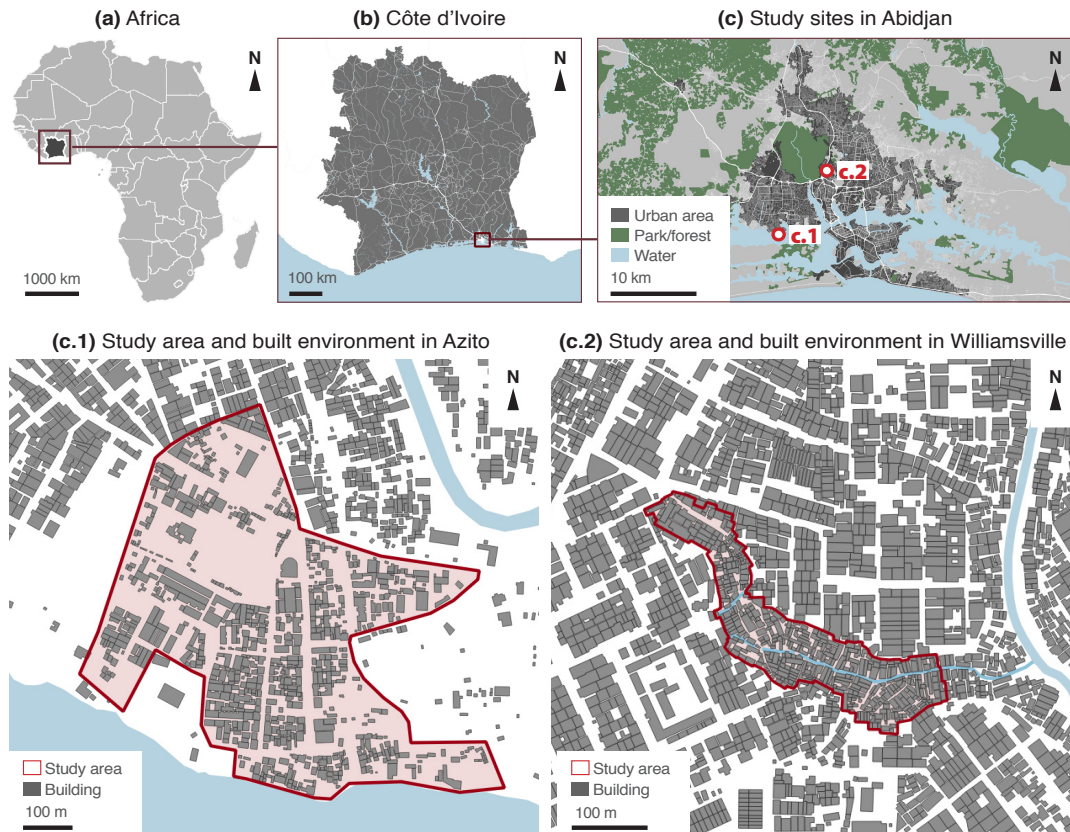
Figure 3.1: Geographic location of the study sites in Abidjan, Côte d'Ivoire. Elaborated from GADM; OpenStreetMap; Ecopia Building Footprints ©2021 Ecopia Tech Corporation, Imagery ©2021 DigitalGlobe, Inc.

3.2.2 Outcome of interest and sample size

The outcome used to determine the sample size was diarrhea, i.e., the passage of three or more loose or liquid stools per day (WHO, 2017). Following a previous diarrhea study in Abidjan (Koné et al., 2014), we detected cases of diarrhea occurring in the two weeks preceding the survey. Because the burden of diarrhea is higher among children below the age of five (Troeger et al., 2018), we used the estimated prevalence in this age group as a parameter for sample size calculation. The latter is given by Equation 1.1 (already presented and explained in Chapter 1):

$$n_0 = \frac{Z_{1-\alpha/2}^2 \times P \times (1-P) \times D_{eff}}{e^2}$$

where n_0 is the minimum number of individuals, $Z_{1-\alpha/2}$ is the critical value for the standard normal distribution corresponding to a type I error of α (here, $\alpha = 0.05$; thus $Z_{1-\alpha/2} = 1.96$), P is the expected diarrhea prevalence given by prior studies (Koné et al., 2014) (here, $P = 0.15$), D_{eff} is the "design effect" (here, $D_{eff} = 1.5$), and e is the margin of error at 95% confidence level ($e = 0.05$). Because the survey's unit was the household – not the individual – n_0 was adjusted to correspond to the minimum number of households. It was adjusted by: (i) the proportion of the targeted population (children younger than five years, i.e., 15%); (ii) average household size (4.5 individuals); and (iii) the expected valid response rate (here, 90%), considering potential data entry errors. These calculation parameters resulted in a minimum of 484 households.

3.2.3 Exposures of interest

We selected several housing deprivation features as the exposures of interest. To define these features, we considered the housing components emphasized by UN-Habitat in the definition of "slum" (UN-Habitat, 2022), i.e., construction materials and overcrowding. If the walls, roof, or floor were made of non-durable materials (e.g., rudimentary planks or unfinished surfaces), the dwelling was considered "inadequate"; if the household had more than three individuals per room, it was considered "overcrowded." In addition, as foodborne infections are a main cause of diarrhea (Kirk et al., 2017), we observed whether the household had an indoor cooking space, assuming this may protect food from external contamination sources such as flies or dirt.

We also considered access to WASH services, which were categorized as "at least basic" or "not basic," adhering to definitions put forth by the World Health Organization (WHO) and the United Nations Children's Fund (UNICEF) in their Joint Monitoring Programme for Water, Sanitation, and Hygiene (JMP) (WHO & UNICEF, 2021). As recommended by the JMP (UNICEF & WHO, 2018), we included a question on whether the household had constant access to water in the month preceding the survey. Finally, we considered the educational attainment of the household head and constructed an asset-based wealth index as control variables for socioeconomic status, as they may lead to a recall bias affecting the count of self-reported diarrheal cases (Manesh et al., 2008).

3.2.4 Data collection and inclusion criteria

The household surveys were conducted in February 2022, thus avoiding the rainy season, which could impose accessibility challenges and bias our findings by affecting the incidence of diarrhea. Before the surveys, 10 data collectors followed a four-day training to be familiarized with the household questionnaire and the tools used, i.e., the mobile application KoboCollect 1.30.1 (Kobo; Cambridge, USA) operated in tablets (Galaxy Tab A 8.0 2019, by Samsung; Suwon-si, South Korea).

The investigators and the village chiefs collaboratively defined the study sites' perimeters (Fig. 3.1). Each site was divided into five areas having an equivalent number of built structures (remotely detected from satellite imagery), which served to estimate the number of households in each area. Data collectors were organized into five groups of two, and were instructed to select one out of two addresses, following a random walk trajectory (Johnston, 2011) within their respective areas. All surveys were geo-referenced to the household's location. Only adults having resided for two or more weeks in the study sites' perimeters were eligible to answer the surveys.

3.2.5   Statistical analysis

The analyses were done in Python language (see Supplementary Materials). We used multiple logistic regressions (MLRs) to test associations between diarrhea and exposure variables derived from the dwelling conditions, controlling for access to WASH services and socioeconomic characteristics. Associations with the risk of diarrhea were inferred through the adjusted odd ratio (AOR) obtained from the MLRs and the 95% confidence interval (CI). An association was considered significant if an AOR's 95% CI excluded 1 and the logistic model's overall fit was acceptable – i.e., a likelihood ratio test (LLR) p-value < 0.05. The MLRs were stratified: the first model included all participants (general population), while the second included only children younger than five years.

To build the MLRs (Table 3.1), we first ran a preliminary selection of candidate explanatory variables through bivariate logistic regressions, using diarrhea as the dependent variable. A variable was pre-selected if its beta parameter's p-value was below 0.1. Then, we calculated the pre-selected variables' variance inflation factors (VIFs); those having a VIF score greater than 5 were excluded to avoid multicollinearity. Following this approach, we excluded two variables: access to basic water services (which covered 99% of households) and overcrowding.

We assessed the spatial distribution of diarrheal cases and confronted it with the spatial distribution of deprived dwellings, based on the aforementioned housing variables. To do so, we detected clusters of households affected by diarrhea and each dwelling deprivation feature through local join count (LJC) statistics (Anselin & Li, 2019). The latter consists in counting, for each point-observation where an event happens (e.g., diarrhea), the number of neighboring observations within a pre-defined search radius ("bandwidth") where the same event happens. This count of events occurring in neighbor observations corresponds to the LJC. The definition of the "bandwidth" depends on the spatial density of point observations and the analysis' spatial resolution. As we analyzed small areas, we limited the bandwidth to the closest 16 observations, corresponding to a median distance between points considered as "neighbors" of 36 m in Azito and 17 m in Williamsville. Finally, we ran an algorithm that randomly permutated the points' positions to infer the probability of apparent clusters (i.e., observations with relatively high LJC values) being, in fact, due to chance (spatial randomness).

Table 3.1: Variables included in the multiple logistic regression (MLR) models stratified by age (the models include individual-level observations from the two selected sites in Abidjan).

Dependent variable	Stratification	Selected independent variables
Diarrhea: whether the individual had diarrhea in the 2 weeks preceding the survey (0 = no; 1 = yes)	**MLR 1: General population:** $N_{gen\ pop}$ = 2043 individuals[1] in the general population (two sites combined) **MLR 2: Under-five stratum:** $N_{under\ 5}$ = 235 individuals[1] in the population under 5 years (two sites combined)	• **Exposure 1:** individual lives in a dwelling with an indoor cooking space (0 = no; 1 = yes) • **Exposure 2:** individual lives in a dwelling built with inadequate materials (0 = no; 1 = yes) • **Exposure 3:** individual lives in a dwelling that had constant access to water in the month preceding the survey (0 = no; 1 = yes) • **Control 1:** individual lives in a dwelling with access to basic[2] hygiene amenities (0 = no; 1 = yes) • **Control 2:** individual lives in a dwelling with access to basic[2] sanitation amenities (0 = no; 1 = yes) • **Control 3:** head of household where individual lives has secondary education (0 = no; 1 = yes) • **Control 4:** individual lives in a relatively wealthy household (0 = no; 1 = yes)

[1] *N* corresponds to the number of individuals living in a household with valid answers for all 8 variables.

[2] As defined by the WHO – UNICEF Joint Monitoring Program for water, sanitation, and hygiene (WHO & UNICEF, 2021).

3.3   Results

We collected data from 567 households (266 in Azito and 301 in Williamsville), corresponding to 2498 individuals (1191 in Azito and 1307 in Williamsville). Among those individuals, 53% were female ($n = 1328$), and 11% ($n = 283$) were younger than five years. In Azito, the prevalence of diarrhea in the general population was 15%, and 27% among children under five years old. In Williamsville, these prevalence rates were, respectively, 14% and 22%.

3.3.1   Associations between diarrhea and dwelling deprivation features

The MLRs revealed that, at constant access to basic hygiene and sanitation, and constant socioeconomic levels, the selected dwelling deprivation features were consistently associated with diarrhea (Table 3.2). Overall, the AORs showed consistent trends for all variables, but most of the associations observed were only significant in the general population group (not meeting the significance criteria in the under-five child stratum).

Living in a dwelling built with inadequate materials was consistently associated with higher odds of diarrhea (AORs >1 in both groups), but the AOR only met the significance criteria in the general population group (AOR = 1.79, 95% CI: 1.31–2.44). Still, for children younger than five years, the lower 95% CI value was close to 1, showing a non-negligible, positive association with diarrhea. Cooking indoors was consistently associated with lower odds of diarrhea (AORs <1 in both groups), but the AOR was only significant in the general population (AOR = 0.55, 95% CI: 0.42–0.73). Constant water availability in the month preceding the survey was also consistently associated with lower odds of diarrhea (AORs <1 in both groups) but was only significant in the general population (AOR = 0.68, 95% CI: 0.53–0.89).

Regarding the control variables, most of them showed significant associations with diarrhea, notably access to basic hygiene amenities. Indeed, the latter were strongly associated with lower risks of diarrhea, both in the general population (AOR = 0.60, 95% CI: 0.46–0.79) and in children younger than five years (AOR = 0.37, 95% CI: 0.18–0.73). The household head's education level was also associated with diarrhea, both in the general population (AOR = 1.51, 95% CI: 1.15–1.98) and in children younger than five years (AOR = 2.11, 95% CI: 1.09–4.08). The household's asset-based wealth index was positively associated with diarrhea (AORs > 1), but this was only significant in the general population (AOR = 1.51, 95% CI: 1.15–1.99).

3.3.2   Spatial distribution of diarrheal cases and dwelling deprivation

Although the two study sites occupy relatively small areas, we found significant within-site variations in the prevalence of diarrhea and the physical characteristics of the dwellings. Figures 3.2 and 3.3 depict these variations through LJC statistics characterized by the count number (circle **size**) and likelihood (circle **color**). Circles in darker colors indicate a statistically significant spatial concentration of an event (e.g., diarrhea case), that is, a cluster.

Table 3.2: Adjusted odds ratios (AORs) for cases of diarrhea reported in the two selected sites in Abidjan (February 2022), stratified by age group.

Exposure	General population (n = 2043[1])				Age < 5 years old (n = 235[1])			
	aOR	Lower CI (95%)	Upper CI (95%)	Significance	aOR	Lower CI (95%)	Upper CI (95%)	Significance
Indoors cooking space	**0.55**	**0.42**	**0.73**	****[2]	0.70	0.35	1.42	Not significant
Inadequate dwelling materials	**1.79**	**1.31**	**2.44**	****[2]	2.06	0.98	4.33	*[2]
Water availability	**0.68**	**0.53**	**0.89**	***[2]	0.63	0.33	1.23	Not significant
Access to basic hygiene	**0.60**	**0.46**	**0.79**	****[2]	**0.37**	**0.18**	**0.73**	***[2]
Access to basic sanitation	1.20	0.89	1.62	Not significant	1.48	0.73	3.00	Not significant
Household head with secondary education	**1.51**	**1.15**	**1.98**	***[2]	**2.11**	**1.09**	**4.08**	**[2]
Relatively wealthy household	**1.51**	**1.15**	**1.99**	***[2]	1.25	0.63	2.51	Not significant

Bold: statistically significant variables.

[1] Corresponds to the number of individuals in the two sites living in a household with valid answers to all 8 variables (1 dependent variable and 7 control variables) included in the model.

[2] The number of * indicates the significance of each *beta* coefficient resulting from the multiple logistic regression (MLR), which corresponds to the probability of the aOR being equal to 1: *P value < 0.1, **P value < 0.05, ***P value < 0.01, ****P value < 0.001.
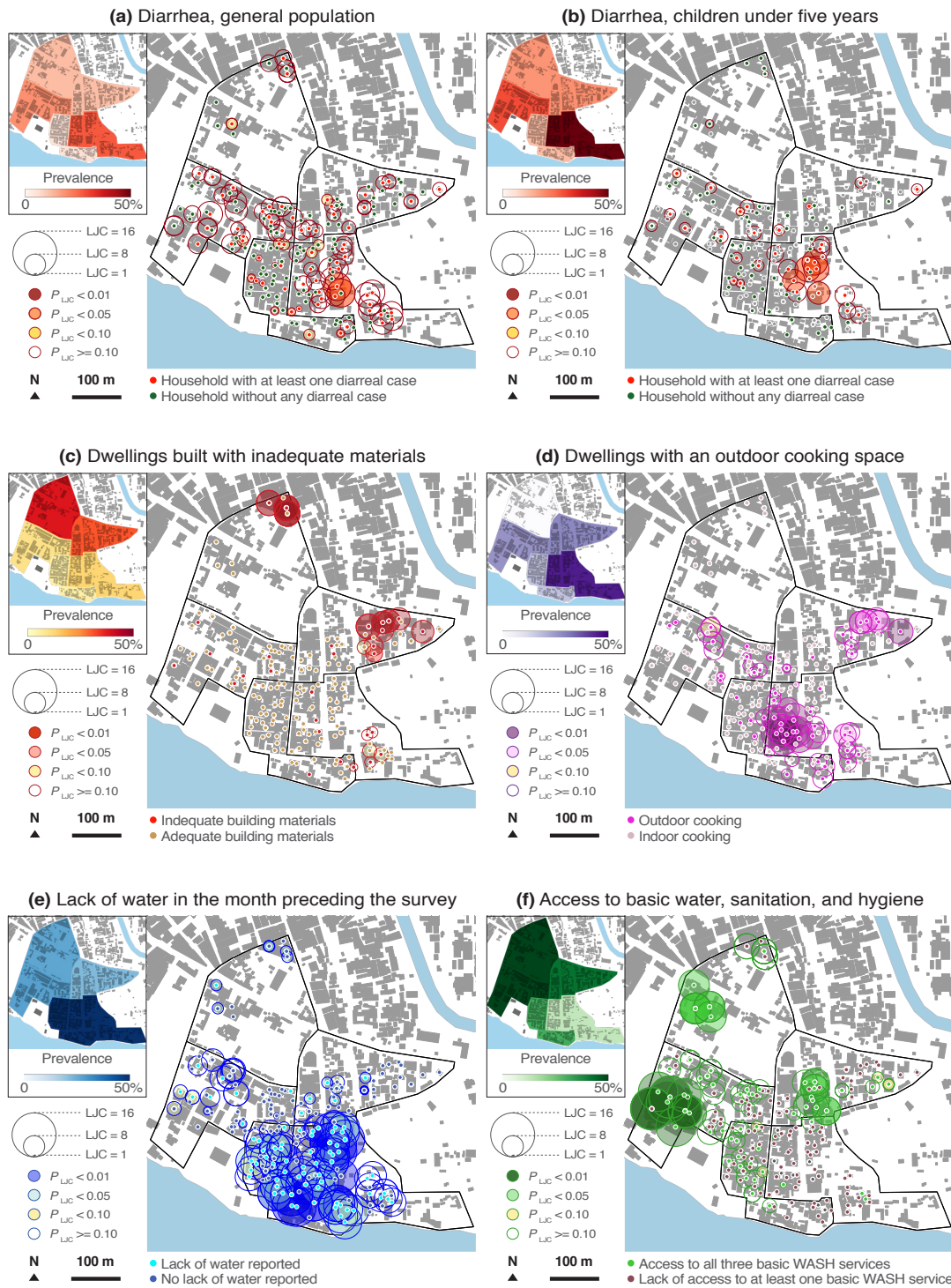
Figure 3.2: Spatial analysis in Azito (distribution of cases and dwelling deprivation features in February 2022). Elaborated from Ecopia Building Footprints ©2021 Ecopia Tech Corporation, Imagery ©2021 DigitalGlobe, Inc.
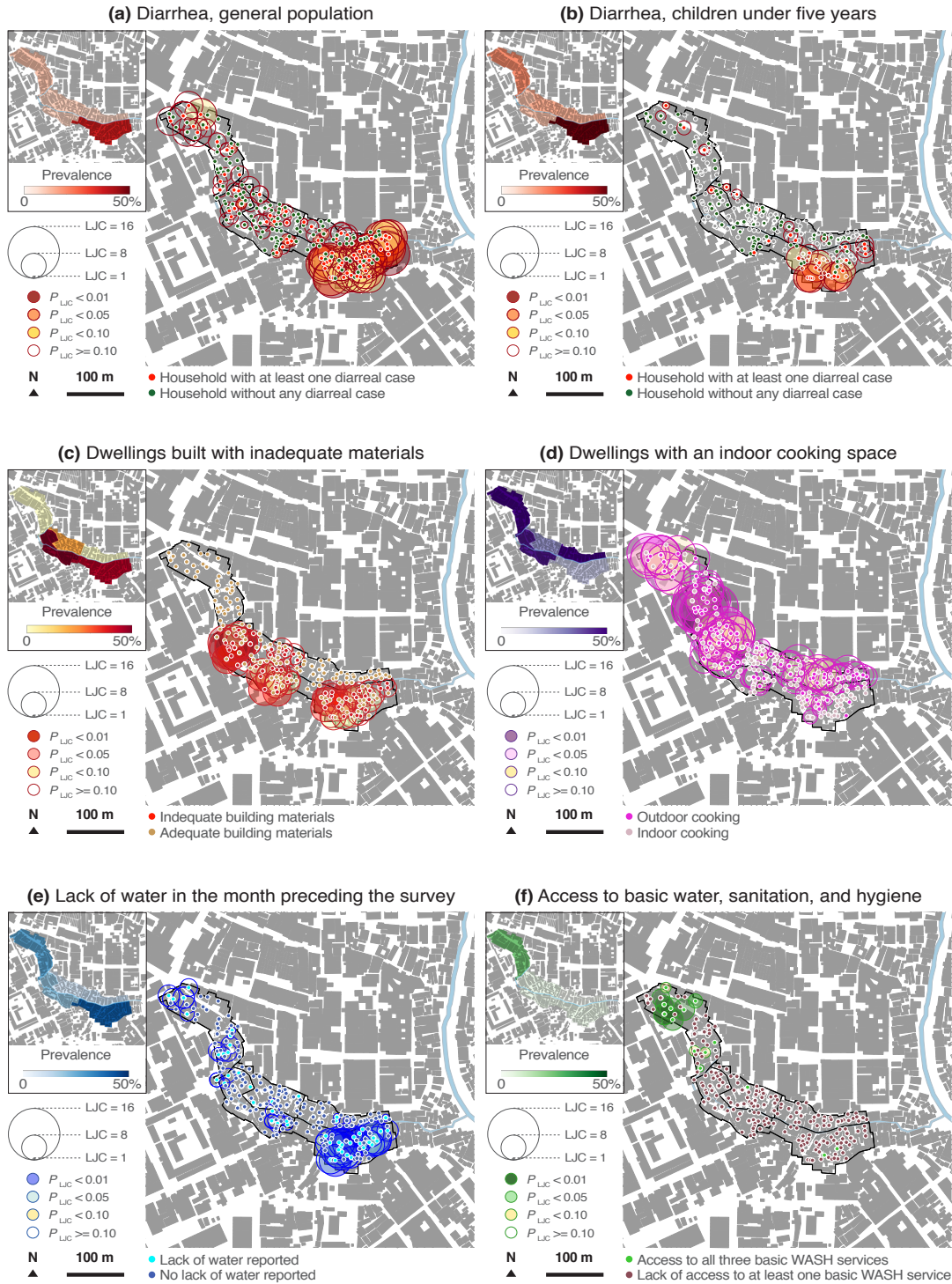
Figure 3.3: Spatial analysis in Williamsville (distribution of cases and dwelling deprivation features in February 2022). Elaborated from Ecopia Building Footprints ©2021 Ecopia Tech Corporation, Imagery ©2021 DigitalGlobe, Inc.

Overall, the spatial analysis corroborated the AORs. Sectors with more households affected by the lack of water, the lack of at least one basic WASH service, and the lack of an indoor cooking space corresponded to those more affected by diarrhea (both in the general population and in children younger than five years). Regarding the dwelling materials, the trends differed. In Williamsville, the location of inadequately built dwellings corresponded approximatively to that of diarrheal cases, while in Azito their spatial distributions did not match.

In each site, we identified a sector that was more affected than others by dwelling deprivation and diarrhea. In Williamsville, the sector located in the South-East corner of the study site had significant clusters of diarrheal cases (both in the general population and children under five years), as well as significant clusters of households lacking access to basic WASH, constant water service, an indoor cooking space, and adequate building materials. In Azito also, the sector located in the South-East corner had significant clusters of diarrheal cases (both groups) and significant clusters of households lacking access to basic WASH, constant water service, and indoor cooking space.

3.4 Discussion

3.4.1 Dwelling conditions and diarrhea

Construction materials and spatial disposition of cooking spaces were consistently associated with higher risks of diarrhea, even accounting for access to basic sanitation and hygiene amenities, continuity of water services, and socioeconomic status. These results corroborate previous findings regarding spatial predictors of diarrhea in Côte d'Ivoire (Pessoa Colombo et al., 2022), suggesting that housing conditions may play an important role in mediating contamination pathways that cause diarrhea.

For instance, living in a dwelling built with inadequate materials may exacerbate exposure to environmental reservoirs of diarrheal pathogens, as indoor spaces are not effectively protected from external elements like wastewater or dirt (Julian, 2016; Prüss et al., 2002). This observation is especially salient in contexts where basic sanitation coverage is limited, and environmental exposure to pathogens relatively high. Of relevance, although the association between diarrhea and inadequate dwelling materials showed consistent trends in the AORs, these events' spatial distributions did not always coincide: they did in Williamsville, but not in Azito. This observation might be explained by the different baseline levels of access to WASH services, which were much lower in Williamsville compared to Azito, making protection from environmental contamination sources more relevant in the former than in the latter.

Similarly to inadequate building materials, indoor cooking spaces might offer better protection from environmental contaminants by physically protecting food handling from external elements like flies or dirt. In fact, if food is exposed to such contamination sources, the household members are exposed to higher risks of diarrhea independently of having access to basic hygiene facilities (Kirk et al., 2017). Moreover, protecting indoors spaces is critical when

cohabitating with animals, as they pollute the environment with their feces, which in turn attract flies (Baker et al., 2022). We observed this was a common situation in Williamsville, notably in the areas having significant clusters of diarrheal cases. However, we note that indoor cooking with firewood or charcoal (very common in informal settlements) is negatively associated with respiratory health, especially in poorly ventilated spaces (Kansiime et al., 2022). Therefore, the general health benefits of indoor cooking also depend on the type of fuel used, as well on their ventilation.

As for the continuity of water services (proxied by the constant availability of water during the month preceding the survey), it is a requirement to implement basic hygiene practices (WHO & UNICEF, 2021). In fact, access to "basic" hygiene amenities (which include the presence of water and soap/detergent at the time of the survey) was consistently and significantly associated with lower risks of diarrhea across age groups. Having such amenities within premises surely facilitates handwashing, thus breaking contamination pathways at key moments (e.g., before eating and after defecation).

Surprisingly, access to basic sanitation had no significant association with diarrhea. This may be related to limitations in the data collected, which did not assess how excreta were managed. Another unexpected result was the significant association between heads of households with secondary education and higher risks of diarrhea. This may be due to a recall bias given by socioeconomic status, which has been detected elsewhere (Manesh et al., 2008). The same recall bias might explain the association we observed between asset-based wealth and diarrhea.

3.4.2   Spatial distributions of housing deprivation and diarrhea

We located specific areas in each site that were disproportionately affected by diarrhea and dwelling deprivation. Such high-resolution information is crucial to guide cost-effective interventions to improve housing, infrastructures, and address intra-urban health inequities (Elsey et al., 2016). Moreover, we found that diarrheal cases followed spatial patterns very similar to those of dwelling deprivation features in the two study sites. This trend is visible in the prevalence and LJC maps (Figures 3.2 and 3.3). The spatial coincidence observed between diarrhea and dwelling deprivation suggests that, even within small areas, differences in housing and habitat conditions might generate health inequities.

Given that a same settlement may have significant disparities within its boundaries regarding housing conditions and risk of diarrhea, it is essential to conceive of a spectrum of deprivation in the universe of informal settlements. Indeed, as previous studies besides this one have shown (Jankowska et al., 2011; Wamukoya et al., 2020), these communities are not homogenous and, hence, have different needs. These observations highlight the importance of having structures such as "urban health observatories" (Caiaffa et al., 2014), for instance, the Nairobi Urban Health and Demographic Surveillance System (NUHDSS) in Kenya. These observatories collect high resolution health data and, hence, are able to provide relevant intelligence to

support efficient interventions.

3.4.3 WASH services are essential, but not enough: policy implications and further research

In informal settlements, the sole availability of "basic" WASH services might be insufficient to prevent diarrheal diseases. Our findings suggest that, although access to those services is essential, their potential health benefits may be hampered if housing conditions remain inadequate. Indoor spaces must be protected from external reservoirs of pathogens, especially in areas where people cohabitate with animals, and with limited coverage of safely managed water and sanitation – i.e., safe management of excreta and constant delivery of potable water (WHO & UNICEF, 2021). Against this background, "slum upgrading" projects should improve dwelling conditions in addition to upgrading urban infrastructures and services. As contamination pathways are multiple and vary across sites and populations (Julian, 2016; McKeown, 2009), only a combination of interventions may effectively prevent diarrheal diseases.

Furthermore, our results suggest that access to a "basic" water source does not guarantee a continuous water service (i.e., available whenever needed). Although 99% of the participating households had access to a "basic" water source, only 66% effectively had constant access to water during the month preceding the survey. This confirms the necessity of indicators simultaneously addressing the safety and availability of water in household questionnaires, as advised by the JMP (UNICEF & WHO, 2018), and as determined by Sustainable Development Goal 6, indicator 6.1.1. Of relevance, we found that continuous access to water was consistently associated with lower risks of diarrhea in the two study sites. Given its public health implications, new research is needed to improve water distribution systems in the context of informal settlements.

3.4.4 Study limitations

Given our study's cross-sectional design, and the lack of a quantitative microbial risk assessment, our results cannot prove any causal relation between the selected housing deprivation variables and diarrhea. From an inferential standpoint, we acknowledge that the maps only show "circumstantial" associations between diarrhea and dwelling characteristics (events occurring in the same place simultaneously). Moreover, from an epidemiological standpoint, we did not address the specific etiology of diarrheal cases, and could not confirm them as they were self-reported. Although we did not have the resources to address the epidemiological limitations, the inferential shortcomings were mitigated by combining the spatial analyses with the MLRs, which tested associations based on individual-level observations. This procedure did neither allow inferring causal associations, nor confirming whether housing conditions mediate contamination pathways of diarrhea. However, our exploratory approach was helpful to identify potential risk factors for diarrhea that have not been sufficiently examined from a spatial (cartographic) perspective.

3.5   Conclusions

Our findings suggest that non-durable building materials, discontinuity of water service, and cooking outdoors constitute potential risk factors for diarrheal diseases in informal settlements. Although the construction and extension of safe WASH amenities are crucial to prevent diarrheal diseases, their health gains are limited if communities do not access dignified housing conditions. Planners should account for possible relations between contamination pathways causing diarrhea and the urban habitat by adopting an integrated approach that combines the upgrading of both WASH services and housing conditions.

We observed significant heterogeneity within and between the two study sites in Abidjan. Marked differences in housing characteristics coincided with different risk levels of diarrhea. These findings corroborate previous evidence pointing to the necessity of conceiving of spatial determinants of the risk of diarrhea and, especially, of a "spectrum" of deprivation within the heterogeneous universe of informal settlements. The latter are, indeed, extremely diverse and require a setting-specific understanding to tailor interventions and maximize public health gains.

3.6   Supplementary materials

Anonymized input data and Python notebooks are available at:

https://github.com/ceat-epfl/housing-deprivation-diarrhea

4 Environmental determinants of access to shared toilets in informal settlements: a cross-sectional study in Abidjan and Nairobi

Abstract

Efforts are underway to improve access to sanitation in informal settlements, often through shared facilities. However, access to these facilities and their potential health gains – notably, the prevention of diarrheal diseases – may be hampered by contextual aspects related to the built environment. This study explored interrelations between the built environment, perceived safety to access toilets, and diarrhea. A cross-sectional study was carried out including 1,714 households in informal settlements in Abidjan (Côte d'Ivoire) and in Nairobi (Kenya). We employed adjusted odds ratios (AORs) obtained from multiple logistic regressions (MLRs) to test association between toilet location, the surrounding built environment, and perceived safety. We also tested associations between the latter and diarrhea. In both cities, toilet location and the built environment were associated with the perceived security. The latter was associated with diarrhea in the general population (but not in children below the age of 5 years). The sole availability of facilities may be insufficient to prevent diarrheal infections. Further investigation is needed on how the built environment affects perceived safety.

Reference

Pessoa Colombo, V., Chenal, J., Orina, F., Meme, H., Koffi, J. D. A. A., Koné, B., & Utzinger, J. (2023). Environmental determinants of access to shared sanitation in informal settlements: a cross-sectional study in Abidjan and Nairobi. Infectious Diseases of Poverty, 12(1), 1-19. https://doi.org/10.1186/s40249-023-01078-z

4.1   Background

Sub-Saharan Africa is one of the fastest-urbanizing regions of the world (OECD & Sahel and West Africa Club, 2020). This rapid urban growth brings about considerable challenges, such as the provision of services and infrastructures that are essential to public health. In 2020, more than 230 million people (50.2% of the urban population in this region) lived in "slum" households (UN-Habitat, 2022), i.e., households that lack one or more of the following: access to adequate sanitation facilities, eventually shared by a "reasonable" number of households; easy and affordable access to clean water; durable housing structure; sufficient living space; and security of tenure (UN-Habitat, 2022). Considering previous debates on the term "slum" (Gilbert, 2007), which can be perceived as demeaning, we will henceforth refer to such areas as "informal settlements."

Urban poverty and the ubiquity of improvised, informal settlements constitute a major challenge for global health and the pursuit of several of the United Nations' Sustainable Development Goals (SDGs), particularly SDG 1 (no poverty), SDG 3 (good health and well-being), SDG 6 (clean water and sanitation), and SDG 11 (sustainable cities and communities). Beyond poverty, people living in informal settlements are exposed to specific "neighborhood effects" that exacerbate the risk of infectious and non-communicable diseases (Ezeh et al., 2017). In this regard, the recent COVID-19 pandemic highlighted urban health inequities, recalling the need to improve access to essential services in informal settlements – notably, safe sanitation amenities – while addressing their specific social and economic vulnerabilities (Corburn et al., 2020; UN-Habitat, 2022). In 2020, one out of five people in sub-Saharan African cities lacked access to improved sanitation (WHO & UNICEF, 2021), even though the latter is essential to prevent threatening diarrheal infections that represent the main contributor to the disease burden from water, sanitation, and hygiene (WASH) (WHO, 2019b; Wolf et al., 2022).

To monitor progress toward SDG 6, the World Health Organization (WHO)/United Nations Children's Fund (UNICEF) Joint Monitoring Program for Water and Sanitation (JMP) provides a "sanitation ladder" to estimate access to sanitation services. This ladder classifies facilities into "unimproved", "limited" (shared, improved facility), "basic" (private, improved facility), or "safely managed" (private, improved facility with adequate evacuation and/or treatment of excreta). Sanitation facilities are classified as "improved" when they hygienically separate excreta from human contact (WHO & UNICEF, 2021). In addition to these technical aspects, a critical notion to consider is the accessibility to improved facilities. The JMP suggests the following definition of accessibility: "facilities that are close to home that can be easily reached and used when needed" (Thomas et al., 2018).

In informal settlements, where shared facilities are common, access to sanitation can be undermined by security concerns, leading to unsafe defecation practices (Winter et al., 2018). This accessibility issue disproportionately affects women due to exposure to sexual violence (Corburn & Hildebrand, 2015; Simiyu, 2016), raising controversies around shared sanitation solutions and the criteria used in the JMP's sanitation ladder. For instance, the fact that

both the "safely managed" and even "basic" sanitation categories exclude, indistinctively, any amenity used by more than one family has been challenged (Buckley & Kallergis, 2019). The JMP's definition contrasts with the more extensive definition given by the United Nations Human Settlement Program (UN-Habitat), applied when characterizing "slum" households, that is, "access to adequate sanitation in the form of a private or public toilet shared by a reasonable number of people" (UN-Habitat, 2017). Clearly, there is no one-size-fits-all solution. Experts in the field argue that different settlement "types" (defined by physical, socioeconomic, and cultural aspects) require different technical solutions (Parkinson et al., 2014; Reymond et al., 2016), and hence, the solutions implemented should be as varied as the settlement "types" addressed.

In the short-term, transitional and affordable sanitation solutions are urgently needed, especially in impoverished settings. These probably include on-site solutions that may or may not be shared by more than a single household. In sub-Saharan cities, on-site sanitation solutions – latrines or toilets connected to septic tanks – are already more prevalent and on the rise, being utilized by 62% of the urban population in 2020 (WHO & UNICEF, 2021). Between 2000 and 2020, while the coverage of safely managed sanitation increased and open defecation decreased, the part of "limited" sanitation services – i.e., improved facilities that are shared by more than one household – has remained stable, covering 32% of the population (WHO & UNICEF, 2023). This raises short-term challenges to expanding access to private (non-shared) sanitation in this region, which, by the time the SDGs were launched, required a substantial increase in investments in the WASH sector hardly achievable by low- and middle-income countries (Hutton & Varughese, 2016).

Against this background, it is crucial to investigate what specific conditions favor safe access to sanitation in situations where private facilities are not attainable in the short- or medium-term. This is particularly relevant in cities like Nairobi (in Kenya), where innovative, shared sanitation solutions are rising (Auerbach, 2016). Numerous studies focused on the health impacts of different sanitation interventions based on the JMP categories (Bohnert et al., 2016; Fuller et al., 2014; Pickering et al., 2019). However, they often did not address other relevant aspects, for instance, how the location of toilets and the built environment impact access to these facilities, thus hampering their potential health benefits.

There is a lack of empirical studies assessing environmental determinants of access to shared sanitation facilities from an explicitly spatial perspective, notably in informal settlements. Our study addressed this gap by investigating how the location of toilets and the built environment relate to the perceived safety of users, and to the risk of diarrheal infections in two African cities. By nuancing our understanding of shared facilities, this research contributes to improving sanitation policies and monitoring tools. Our research might also inform future interventions aiming to improve access to sanitation in low-income settings. The purpose of this study was to determine whether the configuration of the built environment and the specific location of toilets is associated with the perceived safety to access these facilities, and whether the latter is associated with the occurrence of diarrheal infections.

4.2   Materials and methods

4.2.1   Geographic scope

The study focused on informal settlements located in Abidjan, Côte d'Ivoire, and Nairobi, Kenya. We choose these cities because they are illustrative of recent urbanization trends in sub-Saharan Africa, which has concentrated demographic growth in a limited number of locations, at the same time the lack of affordable housing in the formal sector has pushed most of the population to live in informal settlements (Parnell & Pieterse, 2014). Indeed, in 2020, over half of the Ivorian and Kenyan urbanites lived in informal settlements (UN-Habitat, 2022), making them the predominant type of urban habitat, notably in Abidjan and Nairobi (Mwau et al., 2020; Nana et al., 2019). This poses sizeable challenges to planners in both countries regarding access to essential services such as adequate sanitation. Moreover, including study sites from distinct African regions accounts for differences in how people use sanitation facilities, as the health benefits of shared toilets can vary geographically (Fuller et al., 2014). Most importantly, the two cities included are characterized by a variety of urban forms (Chenal, 2013; Rahbaran et al., 2014), which are the key exposure variables in this study. We sought sites with different spatial dispositions of the dwellings' structures and of shared sanitation facilities, following two main typologies (Fig. 4.1): (i) a "courtyard" typology, i.e., dwellings placed around a semi-private courtyard, with one or more shared facilities located in the courtyard; and (ii) a "detached" housing typology, i.e., dwellings accessible directly from the street, with shared toilets located in the public space.

Figure 4.2 shows the locations of the selected study sites. In Abidjan, Azito (Fig. 4.2, a.1) is a fishers' village located by the lagoon, in a peripheral area; Williamsville (Fig. 4.2, a.2) is situated near to one of the main roads leading to Abidjan's central business district (CBD). In Nairobi, Mabatini (Fig. 4.2, b.1) is located in a former quarry along Mathare River, 5 km away from the CBD; and Vietnam (Fig. 4.2, b.2) is located next to Nairobi's main industrial area, in the southern periphery of the city. The four sites and their respective perimeters were determined in collaboration with the research partners from Kenya Medical Research Institute (KEMRI; Nairobi) and the Centre Suisse de Recherches Scientifiques en Côte d'Ivoire (CSRS; Abidjan), and community leaders (village chiefs and community health volunteers).

4.2.2   Data and procedures

We used two types of data layers: sociodemographic, and settlement morphology. The former consisted of primary data collected through structured household questionnaires using the mobile application KoboCollect 1.30.1 (Kobo, Cambridge, USA). The latter consisted of maps of the buildings' footprints of the respective sites, extracted from very high-resolution satellite imagery (± 50 cm/pixel) obtained from Ecopia Tech Corporation (2021). To ensure accuracy, these maps were manually corrected following on-site verifications, using the geographic information software QGIS 3.10.4 (Free Software Foundation, Boston, USA).

(a) " Courtyard " typology

Toilets
accessible
from
courtyard

Dwellings organized around
a semi-private courtyard

(b) " Detached " typology

Toilets
accessible
from the
street

Dwellings not following any
specific spatial arrangement
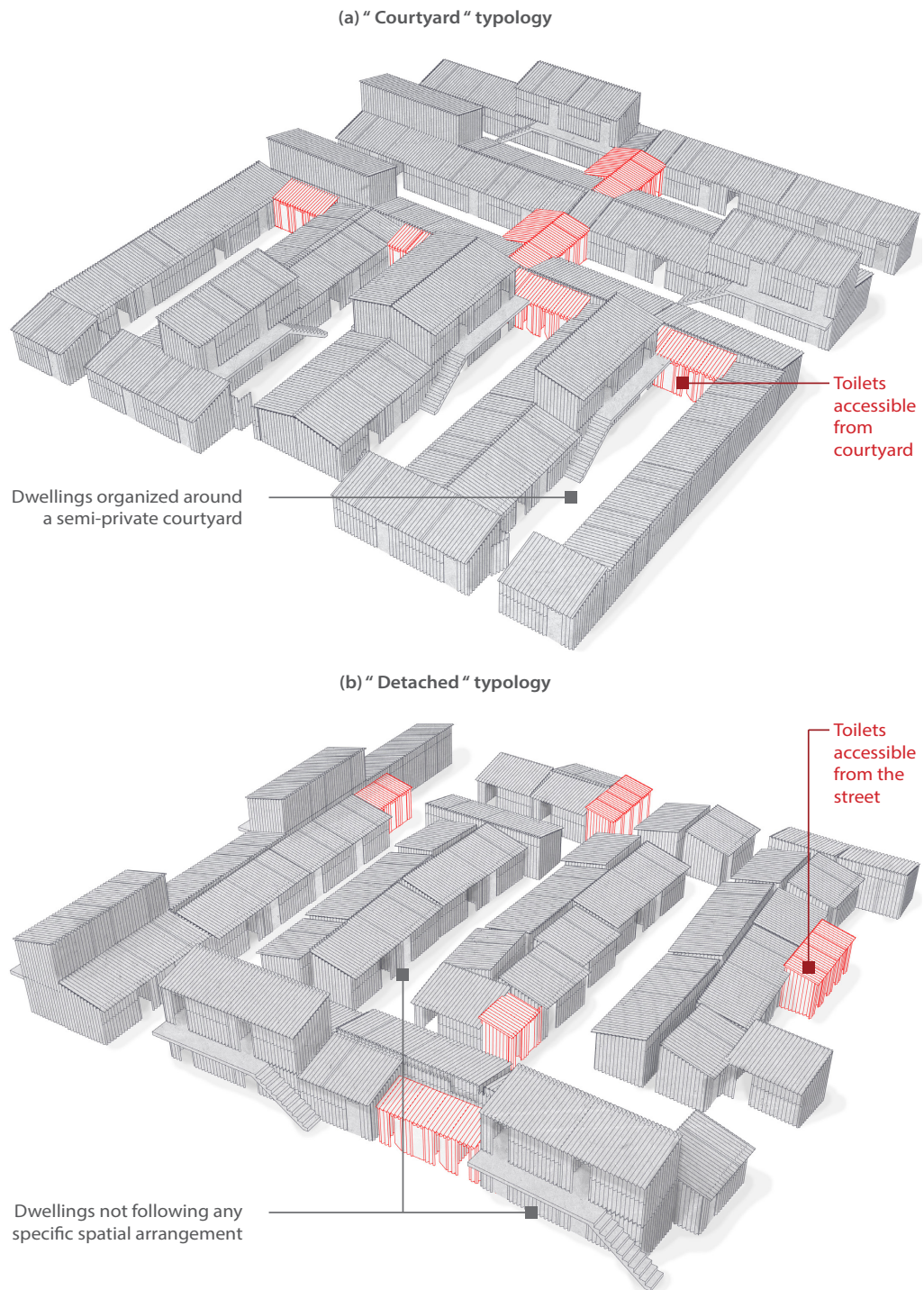
Figure 4.1: Main typologies of the spatial disposition of dwellings and toilet facilities observed
in the selected informal settlements.
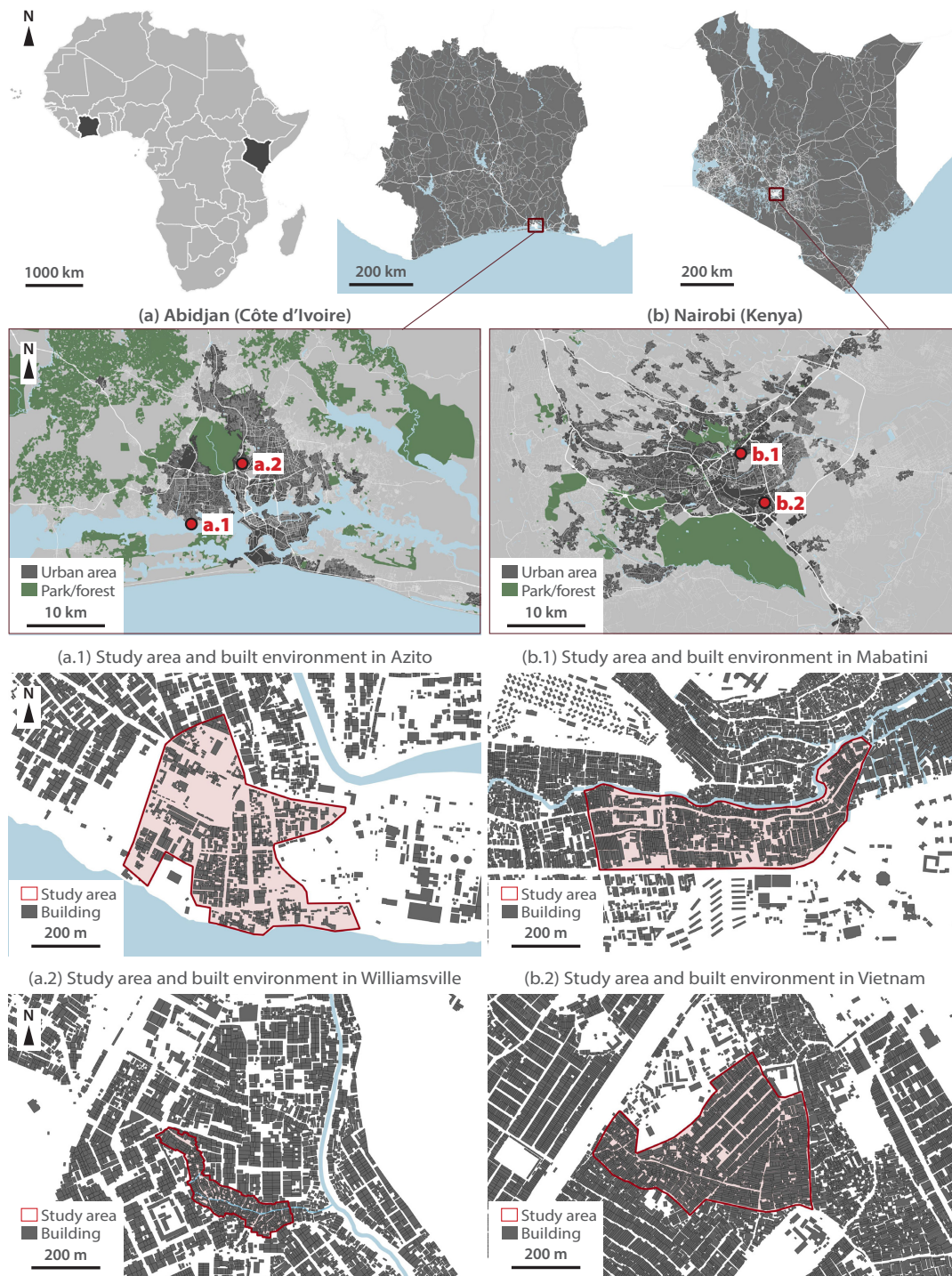
Figure 4.2: Geographic location of selected study sites in Abidjan and Nairobi. Elaborated from GADM; OpenStreetMap; Ecopia Building Footprints ©2021 Ecopia Tech Corporation, Imagery ©2021 DigitalGlobe, Inc.

Household data collection in Nairobi took place between July and August 2021, and in Abidjan in February 2022. In both cities, we aimed to avoid the rainy season – which, besides posing accessibility challenges, could affect the incidence of diarrhea (Carlton et al., 2014) and thus bias our findings. The household questionnaires were conducted by a team of field enumerators who received a 4-day training to be familiarized with the questionnaire and the mobile applications used. Each enumerator was equipped with a tablet Galaxy Tab A 8.0 2019 (Samsung, Suwon-si, South Korea), which they used to administer the questionnaire, with the KoboCollect app. The investigators supervised all the fieldwork on-site. In total, 1,147 valid surveys were obtained in Nairobi, and 567 in Abidjan; hence, meeting the quantitative requirements determined by the sample size calculation. The field enumerators were instructed to conduct the questionnaire with the head of the household, or their companion (adults only).

To ensure a homogenous spatial distribution of the household surveys, each study site was divided into several areas based on the number of residential buildings (Fig. 4.3). Each area received the same number of surveys. Between two and three enumerators worked in each area, and each group was accompanied by a local resident during the fieldwork, either a community health volunteer or a community leader. The enumerators used their tablets as a navigation tool: an interactive map of each site showing all buildings' footprints and survey areas was available on the navigation app OsmAnd 3.9 (OsmAND B.V., Amstelveen, Netherlands), which displayed their live position through the tablet's global positioning system (GPS). To randomize the sample, the field enumerators were instructed to do a random walk, selecting one out of two addresses. Every household survey was geo-tagged, using the tablet's GPS.

The location of toilets and the user's perceived safety to access them were essential information to this study. Hence, the questionnaire included questions regarding these two aspects, following the algorithm shown in Figure 4.4. The precise locations of toilets situated outside premises (i.e., outside the dwelling or the compound's walls) were recorded with the tablet's GPS, when applicable. For households having a toilet inside the dwelling, or inside the compound walls, the location attributed to the toilet was the same as the household's location, in which case we applied a theoretical distance of 0 m.

4.2.3   Health outcome of interest

Diarrhea is the principal contributor to the disease burden from WASH (WHO, 2019b) and is an indicator commonly used to measure the health impact of water and sanitation services (Clasen et al., 2014). Building on previous cross-sectional studies in Nairobi (African Population and Health Research Center, 2014) and Abidjan (Koné et al., 2014), we identified cases of diarrhea occurring in the 2 weeks preceding the survey. We used the WHO definition for diarrhea, i.e., the passage of three or more loose or liquid stools per day (WHO, 2017).
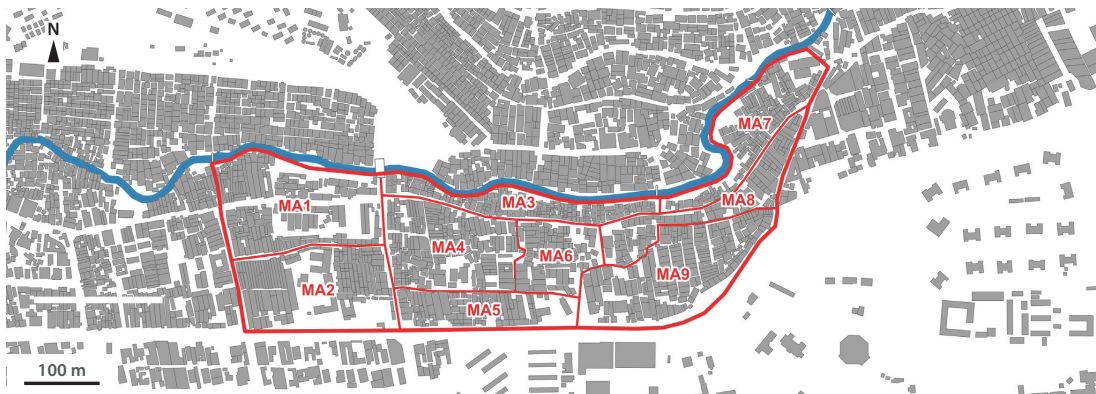
Figure 4.3: Map of Mabatini (Nairobi), with the perimeters of its nine survey areas ("MA1" to "MA9") marked in red. Elaborated from GADM; OpenStreetMap; Ecopia Building Footprints ©2021 Ecopia Tech Corporation, Imagery ©2021 DigitalGlobe, Inc.
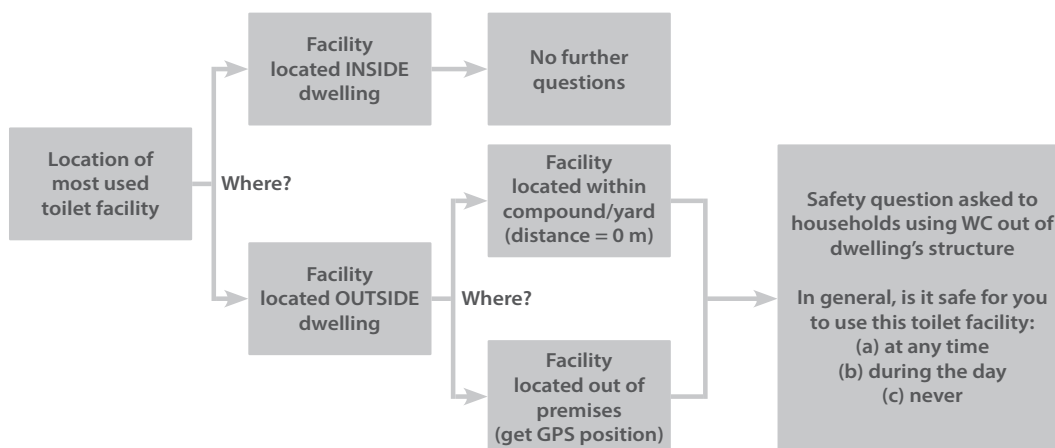
Figure 4.4: Algorithm for questions regarding toilet location and perceived safety to access a toilet.

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Table 4.1: Estimation of minimum sample sizes in Nairobi and Abidjan.

Parameter	Nairobi	Abidjan
$Z_{1-\alpha/2}$ (95% level of confidence)	1.96	1.96
Expected prevalence rate (P)	0.20	0.15
Design effect (D_{eff})	1.50	1.50
Margin of error (e)	0.05	0.05
Unadjusted sample size (minimum number of individuals)	**369**	**294**
Proportion of children under the age of 5 years	0.12[1]	0.15[2]
Number of people needed given the proportion of children under 5 years	3073	1959
Average household size (number of individuals)	3.0[1]	4.5[2]
Expected valid response rate	0.9	0.9
Adjusted sample size (minimum number of households)	**1138**	**484**

[1] Parameter obtained from the 2019 Kenya Population and Housing Census

[2] Parameter obtained from the 2014 Population and Housing Census of Côte d'Ivoire

4.2.4 Sample size

The sample size was determined by the expected prevalence of the health outcome of interest, i.e., diarrhea. Because the prevalence is usually higher amongst children under the age of 5 years than their older counterparts, we used the expected prevalence amongst children in this age group as a parameter. Moreover, diarrheal diseases represent one of the leading causes of death in under-5-year-old children (Troeger et al., 2018) which justifies accounting for this specific age group. The sample size formula was given by the guidelines of Lwanga and Lemeshow (1991) for prevalence studies. The parameters used were based on previous studies on diarrhea in vulnerable communities in Nairobi (African Population and Health Research Center, 2014) and Abidjan (Koné et al., 2014). The sample size (number of individuals) was given by Equation 1.1 (already presented and explained in Chapter 1):

$$n_0 = \frac{Z_{1-\alpha/2}^2 \times P \times (1-P) \times D_{eff}}{e^2}$$

Where n_0 is the total number of people theoretically required for the survey. As explained previously, to obtain a minimum number of households, we rectified the unadjusted sample (n_0) by a composite factor given by: (i) the proportion of the targeted population; (ii) average household size; and (iii) the expected valid response rate (proportion of questionnaires effectively completed, and without data entry errors). Table 4.1 shows the adjusted sample sizes.

4.2.5 Settlement morphology

The field of urban morphology focuses on the form of the built environment, which can be decomposed and assessed quantitatively through specific indicators (Dibble, 2016). These

indicators can be derived from buildings' shape, size, and orientation at different geographic scales, from the single object level to the block or city level (Fleischmann et al., 2020; Schirmer & Axhausen, 2015). Based on previous studies that focused on the morphology of informal settlements across the globe (Kohli et al., 2012; Taubenböck et al., 2018), we selected a series of indicators related to the density and entropy of the built environment. Given the detailed geographic scale of our analysis, these indicators were calculated at the object (single building) and block level, as described in Table 4.2.

The indicators in Table 4.2 were calculated in Python language from the buildings' footprints maps, using the package Momepy (version 0.5.0) (Fleischmann, 2019). We used the maps of the buildings' footprints of the respective sites to calculate the morphological indicators. In these maps, each building footprint was represented by a single polygon. Figure 4.5 illustrates the morphological indicators described in Table 4.2 through thematic maps, showing the example of the study site in Mabatini, Nairobi. As can be seen, Mabatini is a densely occupied area – at least in terms of the number of buildings and the covered area ratio (CAR). Also, the building orientation map shows a high variation (depicted by the colors ranging from red to blue), which means the level of entropy of the built environment is relatively high. This is certainly due to the topographic complexity of the site, which used to be a quarry and has an important variation in terms of altitude between Juja road (southern perimeter of the study site) and the Mathare River (northern perimeter of the study site).

4.2.6   Statistical analysis

All statistical analyses were conducted in Python language, using the packages Geopandas 0.9.0 (Jordahl et al., 2021), SciPy 1.7.1 (Virtanen et al., 2020), and Statsmodels 0.13.2 (Seabold & Perktold, 2010). We used adjusted odds ratios (AORs) to test associations between the location of the most frequently used toilet and the perceived safety to use this facility, and between perceived safety and diarrhea. Indeed, given the presence of several relevant variables for the two outcomes of interest (perceived lack of safety and diarrhea), we used two multiple logistic regression models (MLR) to obtain AORs (Sperandei, 2014) – i.e., one MLR for each outcome, as shown in Table 4.3. All independent variables included in the MLRs had a variance inflation factor inferior to 5, thus reasonably averting issues due to multicollinearity. The AORs' significance was given by two parameters: the 95% confidence interval (CI) had to exclude 1, and the logistic model's overall fit needed to be acceptable, i.e., a likelihood ratio test's (LLR) p-value <0.05.

Perceived safety was defined based on a structured question (Fig. 4.4): if the respondent declared to feel safe to use the facility at *any time* (including at night), we considered the facility in question to be perceived as "safe". The MLR used to calculate AORs for the perceived lack of safety included four variables: toilet's location (inside or outside premises), whether it is shared with one or more household(s), respondent's sex, and education level (potential confounders). Then, we tested associations between the perceived lack of safety and the se-

Table 4.2: List of morphological indicators, distinguished by object and block level.

Variable	Level	Description / calculation
Building orientation (entropy)	Object (building)	*if Azim $_{MBR}^1$ < 45°:* O_{Bi} = Azim $_{MBR}$ *if Azim $_{MBR}^1$ ≥ 45°:* O_{Bi} = Azim $_{MBR}$ − 2x(Azim $_{MBR}$ − 45)
Mean deviation with first four neighbors (entropy)	Object (building)	$$\frac{|O_{B0} - O_{B1}| + |O_{B0} - O_{B2}| + |O_{B0} - O_{B3}| + |O_{B0} - O_{B4}|}{4}$$
Zonal, mean deviation from neighbors (entropy)	Block (100 m radius)	Iterative calculation: for each building, get the mean deviation values of all neighbors within 100 m
Voronoi tessellation (density)	Object (building)	Voronoi tessellation cells obtained from the buildings' footprints, generating a plot-like structure (Fleischmann et al., 2020)
Covered area ratio (density)	Object (building)	$$\frac{Area_{building\ footprint}}{Area_{tessellation\ cell}}$$
Zonal, mean covered area ratio (density)	Block (100 m radius)	Iterative calculation: for each building, get the mean covered area ratio of all neighbors within 100 m
Circular compactness (density)	Object (building)	$$\frac{Area_{building\ footprint}}{Area_{enclosing\ circle}}$$
Zonal, mean circular compactness (density)	Block (100 m radius)	Iterative calculation: for each building, get the mean circular compactness of all neighbors within 100 m
Number of neighboring structures (density)	Block (100 m radius)	Iterative calculation: for each building, count the number of structures (building footprints) within 100 m
Altitude standardized by site (topography)	Object (building)	$$\frac{Alt_{household} - Alt_{site\ min.}}{Alt_{site\ max.} - Alt_{site\ min.}}$$

[1] Azimuth of minimum bounding rectangle (MBR): orientation of axis between 1st and 3rd quadrant of the MBR.
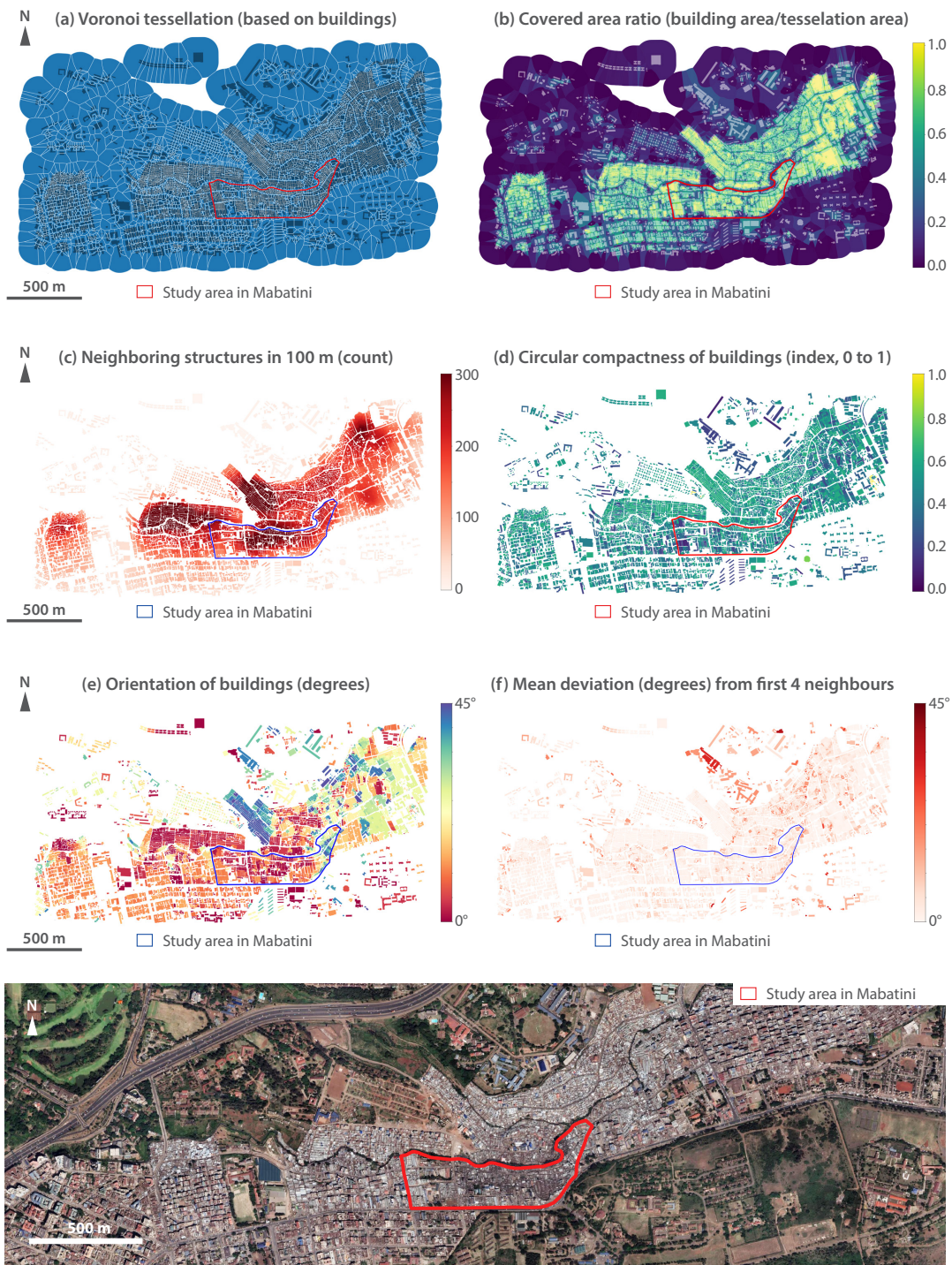
Figure 4.5: Morphological indicators used in the analysis: example of the study site in Mabatini, Nairobi. Elaborated from Google Earth (Google, n.d.); and Ecopia Building Footprints ©2021 Ecopia Tech Corporation, Imagery ©2021 DigitalGlobe, Inc.

Table 4.3: Variables included in the multiple logistic regression models used to calculate adjusted odds ratios.

Dependent variable	Stratification	Independent variables
Perceived lack of safety to access the most used toilet [MLR model 1]: whether the respondent representing the household considers it unsafe to access the toilet at any time	Stratum in Abidjan: N_1 = 245 households (with valid answers for all 5 variables) Stratum in Nairobi: N_1 = 948 households (with valid answers for all 5 variables)	• Toilet most frequently used by the household is located out of premises (exposure) • Toilet most frequently used by the household is shared with other household(s) (control) • Head of the household attained at least secondary education (control) • Respondent was female (control)
Diarrhea [MLR model 2]: whether the individual had diarrhea in the 2 weeks preceding the survey	Strata in Abidjan: $N_{2\ gen\ pop}$ = 942 individuals in the general population (living in a household with valid answers for all 7 variables)[2] $N_{2\ under\ 5}$ = 106 individuals in the population under 5 years (living in a household with valid answers for all 7 variables)[2] Strata in Nairobi: $N_{2\ gen\ pop}$ = 1,899 individuals in the general population (living in a household with valid answers for all 7 variables)[2] $N_{2\ under\ 5}$ = 250 individuals in the population under 5 years (living in a household with valid answers for all 7 variables)[2]	• Individual lives in a household where access to the most frequently used toilet is considered unsafe (exposure) • Individual lives in a household where the most frequently used toilet is considered 'improved'[1] (control) • Individual lives in a household where the most frequently used toilet is considered 'dirty' or 'very dirty' by most users (control) • Individual lives in a household with access to basic[1] hygiene amenities (control) • Individual lives in a household where consumption of street food is frequent (control) • Head of the household where the individual lives attained at least secondary education (control)

[1] As defined by the WHO – UNICEF Joint Monitoring Program for water, sanitation and hygiene (WHO & UNICEF, 2021)

[2] For MLR model 2, the analysis was done at individual level because the cases of diarrhea were reported at individual level. MLR: Multiple logistic regression.

lected morphological indicators (Table 4.2) through descriptive statistics and bivariate logistic regressions. We included the distance to the most frequently used toilet in both the descriptive analysis and the logistic regressions. In the former, we summarized the characteristics of the built environment around the household of: (i) those feeling *unsafe*; and (ii) those feeling *safe* to use the toilet at any time, obtaining their mean values for these two groups. To compare the two groups, the values were standardized to a common scale (0–100) and displayed in polar graphs (Fig. 4.7). To test the significance of the associations between each morphological indicator and safety, we ran bivariate logistic regressions, stratified by city and site within each city.

For diarrhea, the logistic regressions were stratified by city and age groups: general population in Abidjan and Nairobi, and children under the age of 5 years in Abidjan and Nairobi. In addition to the exposure of interest (lack of safety), the MLR included toilet characteristics that may affect the risk of diarrhea: whether it was considered "improved", and its hygiene conditions. The latter was reported by a single respondent representing the household, and was based on smell, presence of personal hygiene items and/or traces of excreta. We used a 4-scale categorization ("very dirty", "dirty", "clean", and "very clean") that was recoded into a binary variable: toilets considered "very dirty" or "dirty" by 50% or more users were categorized as "dirty". To account for reporting bias related to socio-demographic factors (Manesh et al., 2008), the MLR included the education level and sex of the respondent (head of the household). To account for diarrhea risk factors that are not related to the household's environment, we included the frequency of street food consumption (twice or more per week was considered 'frequent').

4.3   Results

4.3.1   Toilet location and its association with perceived safety and diarrhea

The question about safety was applicable to households using a toilet anywhere out of their dwelling, including in their compound's yard, or a neighbor's house. In Nairobi, 1,075 households out of the 1,147 interviewed used a toilet out of their dwelling, and in Abidjan, 281 households out of 567. We found a significant association between the use of toilets outside premises (outside the walls of the compound where the dwelling is located), and lack of safety (Table 4.4). This trend was consistently found in both cities, but the odds were much higher in Nairobi (AOR = 57.97) than in Abidjan (AOR = 3.14). Females tended to be more affected by the lack of safety than males when using a toilet facility outside premises, both in Abidjan (AOR = 1.62) and Nairobi (AOR = 1.25) – but the AORs did not meet the significance criteria, as the respective 95% CIs included 1. Of relevance, sharing a toilet with one or more households was not significantly associated with the perceived safety – again, the respective 95% CIs included 1 and, in Nairobi, this exposure certainly did not have a sufficient variation for the statistical test to be reliable (only 15 out of 948 respondents used a private toilet).

Table 4.4: Adjusted odds ratios (AORs) for perceived lack of safety to access toilets (MLR model 1), by city.

Exposure	Respondents in Abidjan ($n = 245^1$)				Respondents in Nairobi ($n = 948^1$)			
	AOR	Lower *CI* (95%)	Upper *CI* (95%)	Significance	AOR	Lower *CI* (95%)	Upper *CI* (95%)	Significance
Toilet shared by more than one household	1.58	0.61	4.13	Not significant	$5.06e^7$	0.00	*inf*	Not significant
Household's head with secondary education	0.54	0.27	1.09	*[2]	0.81	0.52	1.27	Not significant
Female respondent	1.62	0.88	3.16	Not significant	1.25	0.80	1.96	Not significant
Toilet located out of premises	**3.14**	**1.13**	**8.70**	****[2]**	**57.97**	**35.93**	**93.53**	******[2]**

Bold: statistically significant variables.

[1] Corresponds to the number of household surveys having valid answers to all five variables included in the model.

[2] The number of * indicates the significance of each *beta* coefficient resulting from the multiple logistic regression (MLR) which corresponds to the probability of the AOR being equal to 1: *P value < 0.1, **P value < 0.05, ***P value < 0.01, ****P value < 0.001.

Lack of safety to use a toilet facility at any time was associated with higher odds of diarrheal infection in the general population (Table 4.5), even adjusting by relevant variables like the toilet's hygiene conditions and presence of basic hygiene amenities at home (i.e., water, soap, and a hand-washing structure). This trend was consistently found in Abidjan and Nairobi (respectively, OR = 1.90 with 95% CI:1.29–2.79, and OR = 1.69 with 95% CI: 1.22–2.34). Toilets considered "dirty" were also significantly associated with higher risks of diarrhea in both cities. In Abidjan, having basic hygiene amenities at home was significantly associated with lower risks of diarrhea.

When analyzing the odds of diarrheal infection in children under the age of 5 years (Table 4.6), we found no significant association. For this age group, the only variable that showed a significant association with diarrhea was the presence of basic hygiene amenities at home, in Abidjan. Children under the age of 5 years living in a household using a toilet considered "dirty" were more likely to have diarrhea in both cities, but the AORs were not statistically significant. Of relevance, in Nairobi the MLR model was not reliable for this age group, as it had a likelihood ratio test resulting in a *p*-value greater than 0.05.

Table 4.5: Adjusted odds ratios (AORs) for cases of diarrhea in the general population (MLR model 2), by city.

Exposure	Respondents in Abidjan (*n* = 942[1])				Respondents in Nairobi (*n* = 1,899[1])			
	AOR	Lower *CI* (95%)	Upper *CI* (95%)	Significance	AOR	Lower *CI* (95%)	Upper *CI* (95%)	Significance
Access to basic hygiene amenities	0.58	0.39	0.84	***[2]	0.76	0.41	1.42	Not significant
Access to improved sanitation facility	1.27	0.88	1.85	Not significant	0.92	0.67	1.25	Not significant
Household's head with secondary education	1.36	0.93	2.00	Not significant	1.08	0.80	1.45	Not significant
Frequent consumption of street food	1.45	0.96	2.20	*[2]	1.24	0.90	1.71	Not significant
Toilet considered dirty	**1.84**	**1.28**	**2.64**	******[2]**	**1.57**	**1.11**	**2.22**	****[2]**
Lack of safety to use toilet	**1.90**	**1.29**	**2.79**	*****[2]**	**1.69**	**1.22**	**2.34**	*****[2]**

Bold: statistically significant variables.

[1] Corresponds to the number of individuals living in a household with valid answers to all seven variables included in the model.

[2] The number of * indicates the significance of each *beta* coefficient resulting from the multiple logistic regression (MLR), which corresponds to the probability of the AOR being equal to 1: *P value < 0.1, **P value < 0.05, ***P value < 0.01, ****P value < 0.001.

4.3.2 Morphological characteristics of safe and unsafe settings

We found different levels of perceived safety to use toilets in the four study sites (Table 4.7), which, in turn, had different settlement morphologies. The polar graphs in Figures 4.6 and 4.7 show descriptive statistics for the morphological indicators in different contexts. Figure 4.6 shows the standardized indicators calculated from all buildings in each site, giving an overview of their general morphology. Figure 4.7 shows the standardized indicators of the buildings where the participants lived, disaggregated by city and distinguished by "safe" and "unsafe" situations. Globally, households located in larger buildings and in higher locations in terms of topographic elevation were associated with safe access to toilets. On the other hand, households located in areas more congested – with numerous neighboring structures – and more entropic – with higher deviations in orientation between neighbors – were associated with lack of safety to access toilets. Some indicators differed between cities; namely, building compactness was associated with lack of safety in Nairobi, but not in Abidjan, while the covered-area ratio was associated with lack of safety in Abidjan, but not in Nairobi.

Mabatini (Nairobi) and Williamsville (Abidjan) presented similar morphological features (Figure 4.6), such as a complex topography, with important variations in elevation, and a relatively entropic built environment, and numerous small buildings close to one another. These two sites had a relatively high proportion of respondents feeling unsafe to use a toilet (Table 4.7): 47% in Mabatini and 29% in Williamsville, against 3% in Vietnam and 13% in Azito.

Table 4.6: Adjusted odds ratios (AORs) for diarrhea among children under the age of 5 years (MLR model 2), by city.

Exposure	Respondents in Abidjan ($n = 106^1$)				Respondents in Nairobi ($n = 250^1$)			
	AOR	Lower *CI* (95%)	Upper *CI* (95%)	Significance	AOR	Lower *CI* (95%)	Upper *CI* (95%)	Significance
Access to basic hygiene amenities	**0.31**	**0.11**	**0.88**	****²**	2.90	0.68	12.45	Model's LLR³ *P* value >0.05
Access to improved sanitation facility	2.48	0.94	6.54	*²	1.03	0.56	1.89	Model's LLR³ *P* value >0.05
Household's head with secondary education	0.98	0.34	2.78	Not significant	0.87	0.49	1.52	Model's LLR³ *P* value >0.05
Frequent consumption of street food	1.49	0.51	4.32	Not significant	1.72	0.93	3.18	Model's LLR³ *P* value >0.05
Toilet considered dirty	2.49	0.93	6.67	*²	1.72	0.87	3.38	Model's LLR³ *P* value >0.05
Lack of safety to use toilet	0.77	0.24	2.46	Not significant	0.88	0.44	1.75	Model's LLR³ *P* value >0.05

Bold: statistically significant variables.

[1] Corresponds to the number of individuals living in a household with valid answers to all seven variables included in the model.

[2] The number of * indicates the significance of each *beta* coefficient resulting from the multiple logistic regression (MLR), which corresponds to the probability of the AOR being equal to 1: *P value <0.1, **P value <0.05, ***P value <0.01, ****P value <0.001.

[1] LLR: likelihood ratio test.
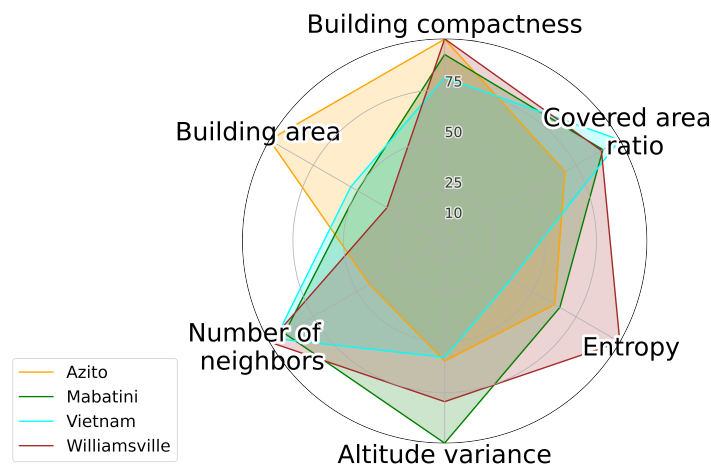
Figure 4.6: Standardized morphological indicators.

Table 4.7: Perceived safety in the study sites

Site	Respondents feeling unsafe (%)
Azito (Abidjan)	12.5
Williamsville (Abidjan)	28.6
Mabatini (Nairobi)	46.7
Vietnam (Nairobi)	2.7
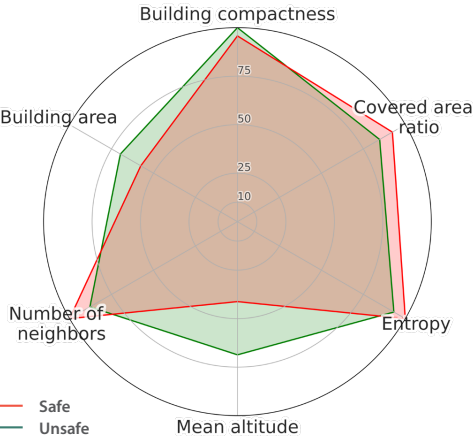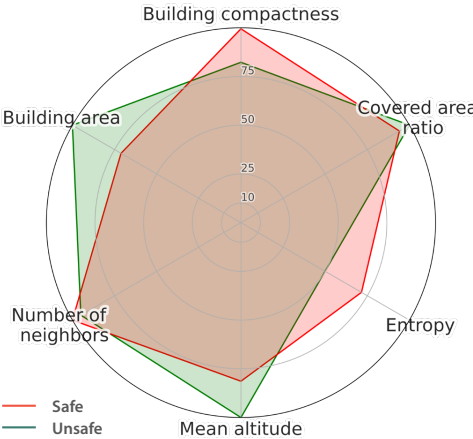
Figure 4.7: Aggregated, morphological indicators by group ("safe" and "unsafe" situations) and city.

Table 4.8: Model parameters of the bivariate logistic regressions, by variable and city.

Variable	City	*P* value	LLR *P* value	Pseudo R^2
Building area (footprint)	Abidjan	0.201	0.153	0.01
	Nairobi	< 0.001	< 0.001	0.04
Number of neighboring structures within 100 m	Abidjan	0.001	< 0.001	0.04
	Nairobi	< 0.001	< 0.001	0.01
Zonal, mean building circular compactness	Abidjan	< 0.001	< 0.001	0.06
	Nairobi	< 0.001	< 0.001	0.26
Zonal, mean covered area ratio	Abidjan	0.008	0.002	0,03
	Nairobi	< 0.001	< 0.001	0.11
Zonal, mean deviation from neighbors	Abidjan	0.006	0.003	0.03
	Nairobi	< 0.001	< 0.001	0.09
Altitude (standardized elevation)	Abidjan	< 0.001	< 0.001	0.09
	Nairobi	< 0.001	< 0.001	0.03
Euclidean distance to toilet facility	Abidjan	0.009	0.008	0.02
	Nairobi	< 0.001	< 0.001	0.37

Figure 4.8 shows the scatterplots of the bivariate regressions, stratified by site (on the left) and by city (on the right), and Table 4.8 shows the individual model parameters for each regression. Each observation corresponds to a single surveyed household, and the morphological indicators correspond to those of the building where the household is located. Three morphological indicators – circular compactness, covered area ratio, and deviation – consisted of a zonal statistic, i.e., for each building, we calculated the mean values of all neighbors within 100 m.

Overall, the logistic regressions corroborate the findings shown in the polar graphs for both cities. The most significant result can be seen graphically in Figure 4.8(a): the distance to the toilet facility was patently associated with safety in Nairobi ($P < 0.001$, pseudo $R_2 = 0.37$). Indeed, beyond ±30 m between the household and the facility, people were very likely to feel unsafe to use the facility. The same effect was observed in Abidjan, which was also statistically significant ($P = 0.009$), but much less important in terms of explaining variance in the outcome (pseudo $R_2 = 0.02$). Another variable that had an important association with safety was the circular compactness of the buildings (Fig. 4.8(b)). In Nairobi, it was significantly associated with the lack of safety ($P < 0.001$, pseudo $R_2 = 0.26$), while in Abidjan, on the contrary, it was associated with a feeling safety ($P < 0.001$, pseudo $R_2=0.06$). All the other variables, except for building area in Abidjan, also had a statistically significant association with safety ($P < 0.05$) but did not attain a pseudo-R_2 value beyond 0.11 – and thus explained very little of the variance in the outcome of interest. In general, the morphological indicators performed better in Nairobi than in Abidjan.
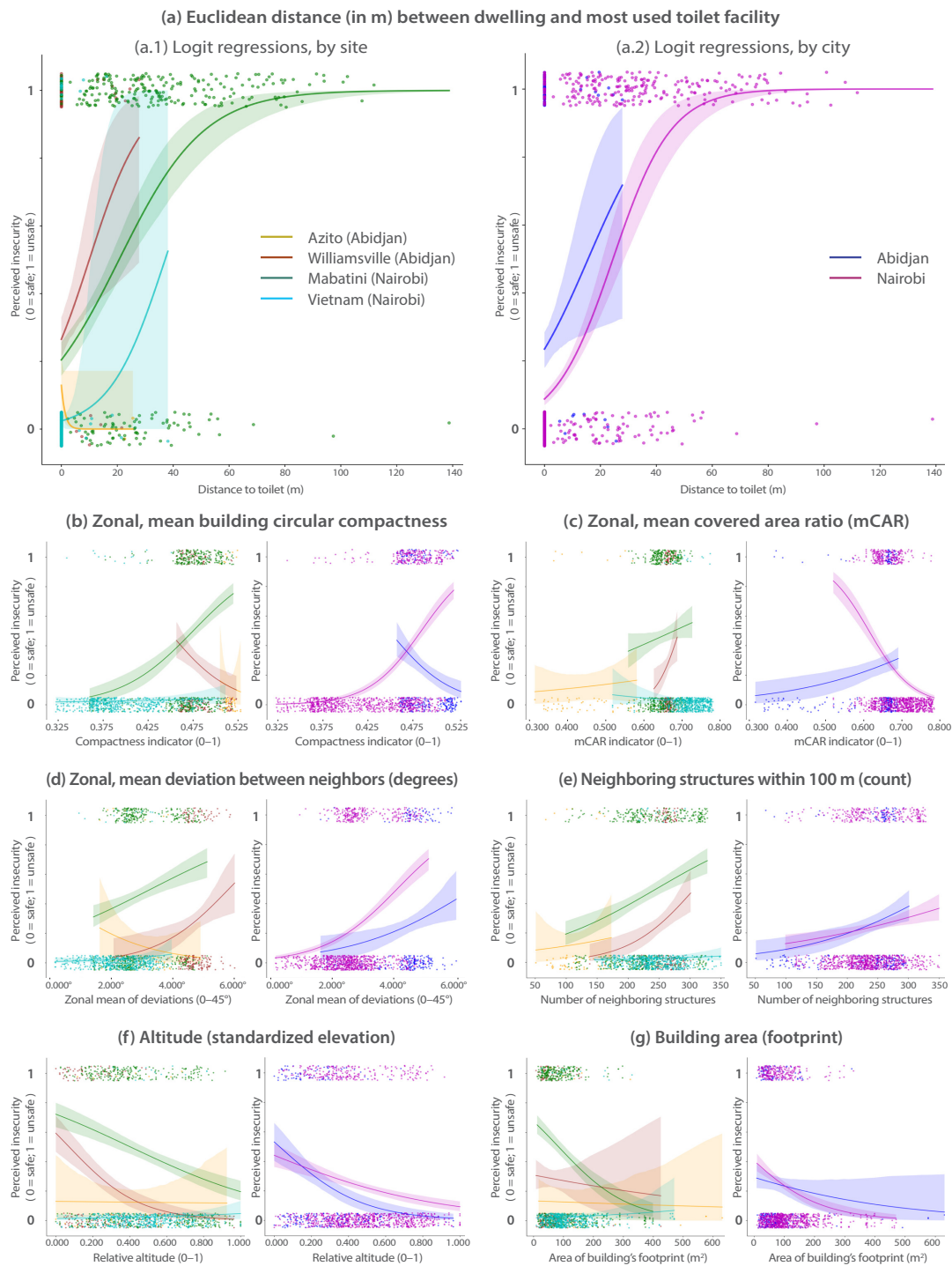
Figure 4.8: Scatterplots of bivariate logistic regressions between perceived safety to access toilets and selected morphological indicators.

4.4   Discussion

4.4.1   Toward criteria to define safe settings for shared sanitation

Shared, on-site sanitation is among the most used types of infrastructure in sub-Saharan cities (WHO & UNICEF, 2021). However, there are concerns regarding their actual health benefits, notably the prevention of diarrheal infections, due to issues related to the management of excreta (Buckley & Kallergis, 2019) and exposure to violence (Winter et al., 2018). The WHO Guidelines on Sanitation and Health (WHO, 2018) acknowledge that shared sanitation solutions should be considered when private facilities are not feasible, either for financial limitations or for lack of physical space, notably in crowded informal settlements. In such situations, though, WHO emphasizes the importance of identifying a safe location and access route to the facility, if applicable. In fact, in line with previous investigations (Corburn & Hildebrand, 2015; Simiyu, 2016; Winter et al., 2018), our results suggest that lack of safety is a major obstacle to accessing shared sanitation, especially among women.

Although normative guidelines on sanitation facilities such as those put forward by WHO provide detailed technical recommendations, they often lack clear recommendations regarding the criteria to define a "safe location" for shared facilities, notably in the context of informal settlements. Current guidelines generally focus on toilet design and technical aspects related to the safe contention and treatment of excreta (Tilley et al., 2014; WHO, 2018, 2022), and only marginally address issues related to the perceived safety when accessing toilets. There are some exceptions (UNICEF and WaterAid and WSUP, 2018), but there is still a lack of evidence based on empirical, spatially explicit analyses. This study addressed this knowledge gap by putting forward specific risk factors related to the toilet location – whether inside or outside the compound's walls – and the spatial configurations of the built environment (i.e., morphological aspects).

4.4.2   The physical morphology of safe settings: empirical observations

Several aspects related to the built environment's configuration were associated with the perceived safety to access sanitation facilities. The most significant was the toilet's location – whether inside or outside a compound's walls. Indeed, privacy plays a key role in the quality and safety of sanitation facilities (Simiyu et al., 2017), thus locating such facilities in a private or semi-private location – e.g., compound's yard, inside walls – is an efficient way to ensure safety and, naturally, users' convenience. On the contrary, people relying on toilets situated in public locations were more likely to feel unsafe to use them in both cities, even adjusting by potential confounders such as the respondent's sex (Table 4.4). Moreover, our results suggest that location is a more significant determinant of safety than sharing a toilet with other households, per se – which raises questions regarding the JMP's current definition of "basic" sanitation. The risk of feeling unsafe significantly increased with the distance travelled: beyond approximately 30 m, it was very likely that the person felt unsafe to access the toilet.

According to informal discussions with residents of the study sites, the main reason for such perceived lack of security was the fear of being harassed or mugged on their way to the facility, or even inside the facility, especially at night. This corroborates findings of previous studies in similar contexts, where social vulnerability and violence significantly affect access to sanitation, notably among women (Winter et al., 2018). In Nairobi, most crimes committed in informal settlements happen in the evening or at early night, consisting mostly of robbery and mugging, but also sexual violence (Musoi et al., 2014; Wa Teresia, 2022), which could explain the fear to go to a toilet at night in our study sites. In Abidjan, chronic poverty and social exclusion has led to the rise of brutal assaults by youngsters (known as "microbes"), which has raised a generalized concern in the population (Crizoa, 2019).

Regarding the spatial disposition and form of buildings, several indicators were associated with the lack of safety in Nairobi and in Abidjan: the mean deviation with neighboring structures within a 100 m radius, the number of neighbors within a 100 m radius, and the relative altitude in each site. The fact that common trends were observed in sites of distinct African regions corroborates the idea that settlement morphology is a key determinant of the perceived safety to access shared facilities. Indeed, the two sites with the highest rate of perceived lack of safety, namely, Mabatini and Williamsville, had common characteristics: amongst the four selected sites, these two had the most entropic built environment, with a high concentration of buildings within a 100 m radius, and smaller footprints (Figure 4.6). Moreover, these two sites were in areas with high variations in elevation, and the relative altitude played a significant role in increasing safety: respondents living in higher locations felt safer than those living in lower locations. The higher locations were closer to the main streets and well-illuminated areas, which certainly played a role – night-time illumination is critical to enhance safety (UNICEF and WaterAid and WSUP, 2018).

In the logistic regressions, the morphological indicators generally performed better in Nairobi than in Abidjan. This may be explained by statistical effects given by the considerably lower number of outcomes (respondents feeling unsafe) in Abidjan. The fact that housing units in Abidjan are often organized in a "courtyard" typology (Chenal, 2013), with shared toilets often placed in semi-private areas or even inside the dwelling, certainly affected the perceived safety. In this sense, the spatial typology of informal settlements in Abidjan may foster safer access to sanitation. Otherwise, almost all indicators were statistically significant in both sites, with p values below 0.05, but explained very little of the variation in safety, with pseudo-R_2 seldom higher than 0.1. This is not unusual in such study designs, given the "noise" of environmental variables and the complexity of the studied ecosystems (Møller & Jennions, 2002).

The physical morphology of informal settlements could be an indirect predictor – not necessarily a causal factor – of diarrhea and, more broadly, general health and well-being. As other authors argued, there are specific features of the built environment that can be proxy indicators of social and economic vulnerability (Kohli et al., 2012; Kraff et al., 2022; Wurm & Taubenböck, 2018). With our study, we emphasize the need for further research on the physical form of impoverished settlements and its potential implications for public health.

4.4.3   Perceived safety to access sanitation facilities and risk of diarrheal infections

The AORs showed a consistent association between the lack of safety to access toilets and the risk of diarrheal diseases in the general population, both in Nairobi and in Abidjan (Table 4.5). We hypothesize that settlement morphology indirectly affects the risk of diarrhea, by facilitating – or hindering – access to sanitation facilities. Should people feel unsafe to access proper toilets, notably women, they may recur to alternatives such as buckets of plastic bags, which are much less safe in terms of the containment of excreta (Winter et al., 2018), hence entailing the threat of diarrheal infections. Indeed, in such situations there is an increased exposure to potential fecal-oral infection pathways (Prüss et al., 2002), which might explain the higher risk of diarrhea in the general population, amongst those feeling unsafe to access a toilet. Among children under the age of 5 years, however, this association between lack of safety and diarrhea was not observed. We may question whether such a relation is even relevant for this age group, given that young children are not necessarily users of the toilets analyzed, and certainly recur more often to home-based solutions (diapers or bucket). If not handled properly, the latter constitute potential sources of contamination, regardless of the safety and quality of toilets commonly used by the household members. Toilet hygiene, however, was consistently associated with higher risks of diarrhea across cities and age groups (although not always significant), which might be explained by pathogens spread from "dirty" toilets to the household.

As in Chapters 2 and 3, our results suggest that the health benefits of sanitation infrastructures in informal settlements rely on aspects beyond the facilities themselves. Besides the toilets' availability and hygiene conditions, their specific location seems just as important to prevent diarrheal infections. In our case studies, the spatial context was more significantly associated with diarrhea than whether the facility type was "improved", thus reminding an old debate on the reliability of such categories purely based on technical (design) aspects of the toilet (Clasen, 2016). There are aspects related to the specific settlement's morphology that are associated with the perceived safety in accessing those facilities, and this may have significant health implications. These findings resonate with Chapters 2 and 3, which showed that some features of the built environments in informal settlements were substantially associated with diarrhea, sometimes even more so than sanitation facilities. In fact, although the availability of sanitation services represents a theoretical improvement, in practice, the health benefits of these improved services may be null if the targeted populations do not feel safe to use them.

There have been debates on the actual health impacts of WASH interventions in low-income settings, which are not always clearly detected (Pickering et al., 2019; WHO, 2019a). This led to discussions on the ways to measure access to WASH and exposure to environmental contamination, including the coverage at communal level, in addition to household-level observations (Wolf et al., 2019). These discussions could be further enriched by adding an explicit spatial dimension. Indeed, more research is needed to better understand how expected health benefits of sanitation interventions relate with local spatial conditions. Such investigations can be useful to inform future interventions and policies.

4.4.4 Policy implications: revisiting normative definitions and monitoring indicators

There is no consensus on the exact definition of "basic" sanitation, and there are growing concerns on the current pace of advancement toward SDG 6 (WHO & UNICEF, 2021). For instance, attaining SDG 6 can be particularly challenging in settings marked by rapid urban and demographic growth, with a high prevalence of poverty. In the short-term, such contexts require a variety of solutions that are suitable and affordable to the different social and spatial contexts. In these cases, innovation and adaptation of sanitation solutions are not an option, and there are interesting examples, notably in Nairobi, of how on-site sanitation systems could work. However, these adaptations often clash with normative definitions, notably those of the JMP. From an urban health perspective, there is still little evidence regarding the trade-off between affordable, short-term solutions that would be classified as "limited" sanitation (for they are shared), and more desirable, but also more expensive, long-term solutions that would be classified as "basic" or "safely managed". With 49% of the population in sub-Saharan Africa still relying on unimproved facilities or open defecation (WHO & UNICEF, 2021), this question is certainly relevant if we want to expand access to improved sanitation at a faster pace.

The discussion on the definition of "basic" infrastructures is essential, as it determines the key indicators used to monitor advancements in social development and infrastructural projects, notably the SDGs. In fact, the targets and indicators of SDG 6 are based on the JMP service ladder, which does not account for the location of sanitation facilities. However, the JMP acknowledges that "using a facility located on premises may be more important for health and well-being than whether the facility is shared with other households", and recommends including a question about the location of sanitation facilities (UNICEF & WHO, 2018). Given the evidence put forward by this study, policymakers should consider toilet location as a parameter to define "basic" sanitation, and include this information in monitoring frameworks. Important survey programs, such as the Demographic and Health Surveys (DHS) have already included a specific question about the toilet's location. However, this is not the case for some national censuses, notably in Kenya. Indeed, the 2019 Population and Housing Census (Government of Kenya, 2022) did not include any question regarding toilet location.

4.4.5 Study limitations

The perception of safety is subjective, varying between individuals, and these differences can be further accentuated when analyzing distinct regions. To account for eventual regional differences, we stratified the statistical analyses by city. Regarding the individual dimension of perceived safety, the goal was not to estimate a precise measure of lack of safety in each site and city, but rather to identify global trends and associations with the built environment – which was possible thanks to the sufficiently large sample sizes in both cities.

Regarding the risk of diarrhea, like in other studies based on self-reporting, the quantification of cases in this study was prone to reporting bias (Arnold et al., 2013). We used a recall period

of 2 weeks, in line with the DHS (n.d.) and the Nairobi Cross-Sectional Slums Surveys (African Population and Health Research Center, 2014). Although a 2-week recall period is relatively long when compared to other cross-sectional studies on diarrhea, reducing this period would have substantially decreased the study's power, considering that the occurrence of diarrhea was measured only once.

Finally, the specific etiology of the observed diarrheal infections by bacteria or viruses was not addressed, as this was not the primary goal of the study. We acknowledge that, among the cases detected, some infections might have occurred outside the community's boundaries; hence, were not related to the built environment in the study area. Moreover, the cross-sectional study design employed here cannot establish any causal relations – while highly relevant for identifying potential risk factors, including the perceived safety to access sanitation facilities and their hygiene conditions. Although this relation may be intuitive, and previous studies have reported that the lack of safety leads to hazardous defecation practices in other contexts, we could not demonstrate any causal relation in our study.

4.5   Conclusions

Until "safely managed" sanitation – as defined by the JMP – is universally accessible (and affordable), shared sanitation solutions should be considered in some circumstances, notably, where the available space is scarce and financial resources are limited. In such situations, it is imperative to understand in what conditions shared sanitation can be safe. Our findings suggest that there are environmental determinants of the perceived safety to access toilets in the context of informal settlements. Toilets located outside the premises were often perceived as less safe than those located within the premises, while certain aspects of the built environment exacerbated the perceived lack of safety, notably the entropy of buildings, the density of structures, and the relative elevation.

Taken together, the built environment's configuration and the specific location of sanitation facilities may indirectly affect their health benefits, by facilitating or hampering access to these facilities. In fact, our findings showed a significant association between the perceived lack of safety to access toilets and the odds of diarrhea in the general population. Hence, it is crucial to ensure the privacy and security of sanitation facilities by placing them in adequate locations. Existing normative definitions "basic" and "safely managed" sanitation rightly emphasize the importance of the facility's design ("improved" or "unimproved") and maintenance (proper management of excreta and overall hygiene conditions) to prevent threatening diarrheal infections. However, such normative definitions should address more explicitly the facility's location (which may be more relevant to determine safety than sharing a facility per se). Similarly, existing sanitation guidelines should include explicit recommendations regarding the choice of location of sanitation facilities to ensure safety of access.

4.6   Supplementary materials

Geo-referenced household data: the "raw", geo-referenced household datasets analyzed during the current study are not publicly available due to concerns of privacy and protection of anonymity but are available from the corresponding author on reasonable request, given that ethical concerns are properly addressed. An anonymized version of the data allowing to replicate the analysis, can be found here:

https://github.com/ceat-epfl/sanitation-informal-settlements

Building footprint data: the data that support the findings of this study are available from Ecopia but restrictions apply to the availability of these data, which were used under license for the current study, and so are not publicly available. Data are, however, available from the authors upon reasonable request and with permission of Ecopia.

5 Associations between different water systems, service continuity and diarrhea in informal settlements: a cross-sectional study in Nairobi

Abstract

Transitional water distribution systems are needed in fast growing cities in low- and middle-income countries, as networked systems have failed to keep pace with the expansion of human settlements. In Nairobi, Kenya, alternative systems have emerged. This study investigated on the efficacy of such systems, aiming to inform future policies to expand access to safe drinking water in informal settlements. We conducted a cross-sectional survey including 1,147 households in two informal settlements of Nairobi. Water distribution systems served as exposures of interest. They were categorized into four types: (i) piped to premises; (ii) piped to a neighboring dwelling; (iii) public tap/dispenser; and (iv) street vendor. Efficacy was determined by two outcomes: water availability (indicator of service continuity and accessibility) and diarrhea (indicator of quality). To test associations between these outcomes and the exposures, while accounting for confounding variables, adjusted odds ratios were calculated using multiple logistic regressions. Obtaining water from public taps/dispensers or street vendors was associated with service continuity. Conversely, piped sources were consistently associated with the lack of water, especially when obtained from a neighboring dwelling. Regarding quality, public taps/dispensers were associated with lower odds of diarrhea in children younger than 5 years, while water from street vendors was associated with higher odds in the general population. There is a balance to be found in distribution systems, considering both availability and safety. Public taps and dispensers seem to offer such a balance, and hold promise as a transitional water distribution system in informal settlements.

5.1   Background

Universal access to safe drinking water whenever needed is a human right inscribed in two of the United Nations' Sustainable Development Goals (SDGs) – namely, SDG 6 (water and sanitation, target 6.1) and in SDG 11 (sustainable cities and communities, target 11.1). However, attending to this fundamental right by 2030, as aspired by the SDGs, remains a global challenge, especially in low- and middle-income countries (LMICs). According to the World Health Organization (WHO) and United Nations Children's Fund (UNICEF) Joint Monitoring Program for Water Supply, Sanitation and Hygiene (JMP), in 2020, an estimated 2 billion people lacked access to "safely managed" water services, including about 800 million people that did not have access even to a "basic" drinking water source (WHO & UNICEF, 2021). The JMP defines "safely managed" water services as facilities that provide "drinking water from an improved source that is accessible on premises, available when needed and free from fecal and priority chemical contamination" (*ibid.*, p.28). As for "basic" drinking water services, the JMP defines them as facilities that provide "drinking water from an improved source, provided collection time is not more than 30 minutes for a round trip, including queuing" (*ibid.*, p.28). Given these definitions, the JMP alerts that global progress rates observed between 2015 and 2020 need to increase by a factor of 4 to achieve SDG target 6.1 (universal access to "safely managed" water services).

From a financial perspective, there are considerable challenges to attain the SDG's water target 6.1. The latter is evaluated by the proportion of people accessing "safely managed" water services. By the time the SDGs were launched, Hutton and Varughese (2016) pointed out that, if global investments on water, sanitation, and hygiene (WASH) remained the same than in the period between 2000 and 2015, this target would not be achieved. The authors emphasized that universal access to safely managed water services required tripling the annual investments that had been done in that period. Additionally, the authors stressed that developing regions faced an even greater financial challenge, even to attain universal coverage of lower service levels, i.e., "basic" water services.

From an engineering perspective, although neither the definition of "safely managed" or that of "basic" water services explicitly impose a specific facility type or distribution system, historically, much focus has been given to capital-intensive systems like city-wide piped water or sewerage networks. Since the urban reforms of 19th century Europe, "modern" urban planning ideals have promoted networked infrastructures to address public health concerns, while making cities a single, cohesive spatial entity (Graham & Marvin, 2001). This constituted a "technological paradigm" directly associated with the idea of development, being exported from Europe to the rest of the world. Notably, it was transposed to the colonies in southern regions where it has been implemented to date (Lawhon et al., 2018; Nilsson, 2011).

The types of infrastructure promoted by the "modern" paradigm are relatively costly in their construction and maintenance (World Bank, 2017). In the short- and medium terms, this consists in a barrier to their implementation in LMICs. Indeed, for decades, critical urban

scholars have challenged the indiscriminate transposition of urban infrastructure models and the predominance of the "networked city" (Graham & Marvin, 2001; Guma & Wiig, 2022; Lawhon et al., 2018). One of the main critiques is that this model has fostered intra-urban disparities in LMICs. For instance, during the colonial period, while in Europe the design and implementation of urban infrastructures aimed to cover the entire city, in the colonies they were often concentrated in the areas where the ruling class (Europeans) lived, deliberately under-serving or bypassing areas allocated to the "Natives" (Njoh, 2016). These disparities in spatial development continued even after the independence movements – only this time, the socio-spatial segregation was not given by ethnicity, but by economic means. Transposed "modern" urban planning models were maintained, "sweeping the poor away" (Watson, 2009) through inflexible building regulations that made the formal housing markets unaffordable to low-income populations (Buckley et al., 2016).

Against this background, many cities in LMICs have had their growth marked by an inequitable spatial development of infrastructures and services. Marginalized populations have been pushed to live in so-called "informal settlements", which the United Nations Human Settlements Program (UN-Habitat) defines as "residential areas where inhabitants are deemed by the authorities to have no legal claim to the land they occupy and the system of occupation ranges from squatting to informal rental housing" (UN-Habitat, 2017). This broad definition includes areas often referred to as "slums", which constitute the most deprived settlements in terms of access to essential services and housing conditions. The social and spatial disparities affecting cities across the world have translated into urban health inequities. Indeed, as residents of informal settlements are less likely to access essential services, they are, hence, more vulnerable to numerous infectious and non-communicable diseases (Ezeh et al., 2017; Kim et al., 2022).

Given the current challenges to provide universal access to adequate water services in the short-term, governments should consider transitional solutions to mitigate current deficiencies in water services. In this regard, recent experiences with "non-conventional" water distribution systems in Nairobi, Kenya's capital, could be particularly informative to elaborate policies in low-income settings with constrained resources. The adaptation of these systems to the local socio-economic and cultural contexts, and their ability to provide constant service, have been discussed and even contested by several urban scholars (Guma & Wiig, 2022; Sarkar, 2019b, 2020). However, there is a paucity of observational, quantitative studies comparing the ability of the different systems to provide continuous access to water and protect from threatening diarrheal infections.

We addressed this gap by assessing the how different water distribution systems performed in two informal settlements in Nairobi, based on their associations with two outcomes: water availability (indicator of service continuity and accessibility) and diarrhea (proxy indicator of quality). In this way, this study aimed to provide empirical evidence to enhance the efficacy of current policies to deliver drinking water in impoverished urban settings that require immediate – even if transitional – solutions.
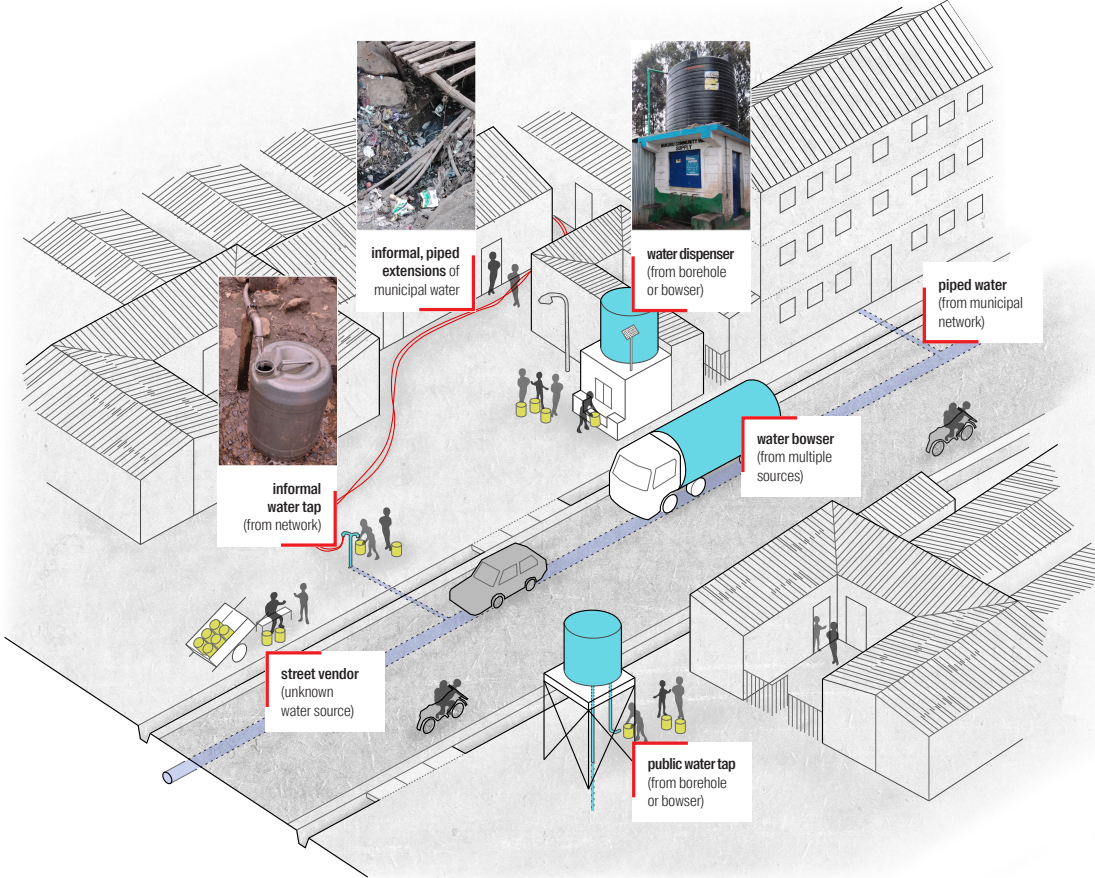
Figure 5.1: Types of water distribution systems in informal settlements in Nairobi

5.2   Materials and methods

5.2.1   Study design and definitions

We designed a cross-sectional survey and collected primary data from quasi-randomly selected households in a transdisciplinary collaboration with the Kenya Medical Research Institute (KEMRI) and the Nairobi City County. Water distribution systems were categorized into four types: (i) piped to premises; (ii) piped to a neighboring dwelling; (iii) public tap or dispenser (non-networked systems, including water "ATMs"); and (iv) street vendor. We distinguished water piped to the household's premises (first type) from water piped to a neighboring dwelling (second type) because the latter is often part of informal water reselling schemes (Sarkar, 2019b, 2020). The second type of water distribution system is more similar to street vendors (fourth type) than water piped to premises. The four types correspond to the JMP category of "improved" water sources. Of relevance, this category focuses on the means used to deliver water to the consumer, without addressing its chemical properties and quality (e.g., presence of bacteria or other pathogens), which was not assessed in this study.

5.2.2   Geographic scope

From an urban planning perspective, Nairobi is a relevant study site given the diversity of technologies used to deliver water to low-income areas, ranging from piped networks to independent water vendors and shared standpipes. Since the creation of the Informal Settlements Department in 2009, the Nairobi City Water and Sewerage Company (NCWSC) has elaborated innovative strategies to expand "formal" services to low-income areas through a variety ("menu") of service deliveries systems (Drabble et al., 2018). In this context, decentralized systems have emerged, from independent water vendors to the so-called water "ATMs" provided since 2015 by the NCWSC.

Moreover, the coverage of at least "basic" water sources in Kenyan cities has stagnated at 87%, while access to "safely managed" water services slightly decreased from 61% in 2000 to 58% in 2020 (WHO & UNICEF, 2023). Understanding the potential health benefits of alternative, low-cost water distribution systems might be a critical contribution to address the urgent need to expand this service in Nairobi, and in other settings facing similar challenges. From a public health perspective, diarrheal diseases continue to inflict a major burden in East Africa (Troeger et al., 2018). Although non-communicable diseases are on the rise in urban areas in this region, informal settlements remain highly susceptible to infectious diarrheal diseases, notably in Nairobi (Mberu et al., 2016).

In 2019, 70% of the population in Nairobi was estimated to live in informal settlements (Mwau et al., 2020). This study focused on such settlements because they illustrate the contemporary challenges in extending access to adequate WASH services to low-income populations, as these services are often insufficient in those areas (Kim et al., 2022). Most importantly, the variety of water distribution systems present in informal settlements in Nairobi (including
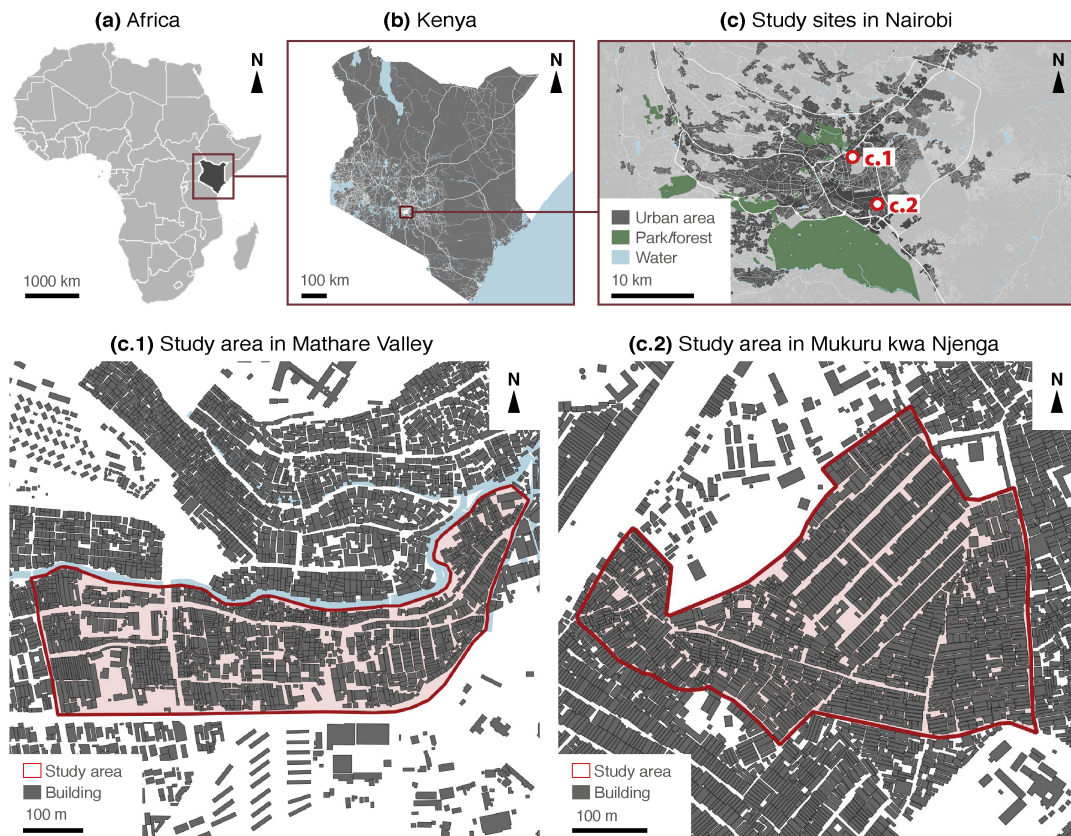
Figure 5.2: Location of selected study sites in Nairobi, Kenya. Elaborated from GADM; Open-StreetMap; Ecopia Building Footprints ©2021 Ecopia Tech Corporation, Imagery ©2021 DigitalGlobe, Inc.

both "formal" and "informal" services) render these areas particularly relevant. Hence, we selected two study sites located in large informal settlements in different parts of Nairobi; namely (i) Mabatini, located in the Mathare Valley, and (ii) Vietnam, located in Mukuru kwa Njenga (Fig. 5.1). The former is situated in the north-eastern part of the city, along the Mathare River, while the latter is in the southern part of the city, in close proximity to a large industrial area. The selection was governed by the presence of all four types of water distribution systems introduced before.

5.2.3 Outcomes of interest

The first outcome of interest was diarrhea, defined as the passage of three or more loose or liquid stools within 24 hours (WHO, 2017). Diarrhea was chosen as the health outcome because it has been used by multiple studies as a reference outcome to estimate the quality of WASH services in general (Clasen et al., 2014; Wolf et al., 2014). Moreover, even though they are preventable and treatable, diarrheal diseases remain among the main causes of death worldwide, with an estimated total of more than 1.6 million deaths in 2016), of which

approximately half were directly attributed to the use of unsafe WASH services (WHO, 2019b). Notably, this burden disproportionally affects sub-Saharan Africa, where the mortality rate attributed to diarrhea was 61.8 per 10,000 in 2016, the highest among all regions (Troeger et al., 2018).

The second outcome of interest was the availability of drinking water over a 30-day period. This was based on the JMP's 2018 update on core questions on WASH for household surveys, that recommends addressing the continuity of access to water by asking whether there had been "any time when the household did not have sufficient quantities of drinking water when needed in the month preceding the survey" (WHO & UNICEF, 2021).

5.2.4 Sample size

The sample size was determined based on the expected prevalence of diarrhea (health outcome of interest). It was calculated with the Equation 1.1 explained in Chapter 1:

$$n_0 = \frac{Z^2_{1-\alpha/2} \times P \times (1-P) \times D_{eff}}{e^2}$$

Where n_0 is the total number of people theoretically required for the survey. As explained previously, to obtain a minimum number of households, we rectified the unadjusted sample (n_0) by a composite factor given by: (i) the proportion of the targeted population; (ii) average household size; and (iii) the expected valid response rate (proportion of questionnaires effectively completed, and without data entry errors). On this basis, the initial sample (n_0) was adjusted by a composite factor given by: (i) the proportion of the targeted population (% of children younger than 5 years in the general population, estimated at 12%); (ii) the average household size (number of people, estimated at 3 individuals); and (iii) the expected valid response rate (here, 90%). The proportion of children under the age of 5 years and the average household size were obtained from the 2019 Kenya Population and Housing Census (Government of Kenya, 2019b). Following these parameters, the minimum sample size was 1,138 households.

5.2.5 Data collection and inclusion criteria

We collected primary data between July and August 2021 through structured household questionnaires conducted by a team of 18 enumerators. We chose this period to avoid the rainy season, which could impose logistical issues to enter in the selected sites. Enumerators followed a 4-day training prior to the survey, to become familiarized with the household questionnaire and with the mobile data collection tools used, that is, the application KoboCollect 1.30.1 (Kobo; Cambridge, USA) operated in tablets (Galaxy Tab A 8.0 2019, by Samsung; Suwon-si, South Korea).

Each study site was subdivided into survey areas with an equivalent count of buildings (detected from aerial images). The same number of household surveys was conducted in each survey area to ensure a homogenous spatial distribution of data collection. The enumerators were instructed to apply the "random walk" method (Johnston, 2011) to select households in their respective survey area. In this method, one household is selected every "X" households in a predetermined itinerary. For example, for an area having 500 households where 100 surveys would be required, the enumerator would select every 5th household. Adults (aged >18 years) were targeted by the questionnaire, and preference was given to heads of households.

5.2.6   Statistical analysis

To test associations between diarrhea and water distribution systems, we used adjusted odds ratios (AORs) obtained from multiple logistic regressions (MLRs), stratified by age (general population and children under the age of 5 years). Diarrhea was the dependent variable, and the four types of water distribution systems were the exposure variables (see Table 5.1). Using MLRs allowed to calculate AORs that accounted for several control variables (Sperandei, 2014) derived from access to WASH services and socio-economic characteristics, which have been reported to be associated with diarrhea (Manesh et al., 2008; Wolf et al., 2022). Because we had four mutually exclusive exposure variables (drinking water distribution systems), we ran four separate MLRs (i.e., one for each distribution system). This analysis used individual-level data, as diarrhea cases were reported individually for each household member.

To assess the ability of each system to ensure constant access to water, we used both unadjusted odds ratios (ORs) in bivariate analyses and AORs obtained from MLRs to account for variables that might affect the household's ability to purchase water in sufficient quantities. This time, while the exposure variables in the MLRs remained the same (types of water distribution system), the dependent variable was the availability of water in the month preceding the survey, and the control variables were asset-based wealth, education attainment of the head of the household, and overcrowding (Table 5.2). For the latter, we used the criterion given by SDG 11 to determine a sufficient living space (UN, 2023), that is, a maximum of 3 household members per habitable room. Differently from the previous analysis, the MLRs were based on household-level data, as water availability was reported collectively (i.e., for the entire household).

In the two analyses, an association was considered statistically significant if it met the two following conditions: (i) the AOR's 95% confidence interval (CI) excluded 1 and (ii) the logistic model's overall fit was acceptable, i.e., a likelihood ratio test's (LLR) p-value smaller than 0.05. We checked for multicollinearity between the variables included in the MLRs by calculating their variance inflation factors (VIFs). To be included in the model, a variable needed to have a VIF smaller or equal to 5. Further details are given in the Supplementary materials section.

Table 5.1: Variables included in the multiple logistic regressions (MLRs) to test associations between diarrhea and water distribution systems in two informal settlements in Nairobi in July and August 2021.

Dependent variable	Stratification	Selected independent variables
Diarrhea: whether the individual had diarrhea in the 2 weeks preceding the survey (0 = no; 1 = yes)	**General population:** $N_{gen\ pop}$ = 2,332 individuals[1] in the general population (two sites combined) **Under-five stratum:** $N_{under\ 5}$ = 305 individuals[1] in the population under 5 years (two sites combined)	• **Exposure:** type of distribution system delivering water to the individual's household, with 1 MLR run separately for each of the 4 types (0 = given type is *not* used; 1 = given type is used) • **Control 1:** individual lives in a household with access to improved[2] sanitation amenities (0 = no; 1 = yes) • **Control 2:** individual lives in a household with access to basic[2] hygiene amenities (0 = no; 1 = yes) • **Control 3:** the individual's household had access to sufficient water in the month preceding the survey, whenever needed (0 = no; 1 = yes) • **Control 4:** individual lives in a relatively wealthy household (0 = no; 1 = yes) • **Control 5:** individual lives in a household where consumption of street food is frequent (0 = no; 1 = yes)

[1] *N* corresponds to the number of individuals living in a household with valid answers for all 7 variables used in the MLRs.

[2] As defined by the WHO & UNICEF (2021) Joint Monitoring Program (JMP) for water, sanitation and hygiene.

Table 5.2: Variables included in the multiple logistic regressions (MLRs) to test associations between water availability and distribution systems in two informal settlements of Nairobi in July and August 2021.

Dependent variable	Selected independent variables
Water availability: whether the household had sufficient quantities of drinking water when needed, throughout the month preceding the survey (0 = no; 1 = yes)	• **Exposure:** type of distribution system delivering water to the individual's household, with 1 MLR run separately for each of the 4 types (0 = given type is *not* used; 1 = given type is used) • **Control 1:** individual lives in a household considered overcrowded[1] (0 = no; 1 = yes) • **Control 2:** the head of the household where the individual lives accomplished secondary education (0 = no; 1 = yes) • **Control 3:** individual lives in a relatively wealthy household (0 = no; 1 = yes)

[1] As defined by the Sustainable Development Goal (SDG) 11 (UN, 2023).

5.3   Results

Overall, we obtained 1,147 valid household surveys (576 in Mabatini and 571 in Vietnam), corresponding to a total of 3,786 individuals (1,935 in Mabatini and 1,851 in Vietnam). Among these, 2,011 participants were female (53%), and 491 (13%) were children under the age of 5 years. Nearly all households (99%) had access to at least "basic" water services. Among these, 75% obtained drinking water mainly from a public tap or dispenser, 8% had water piped to their premises, 12% obtained water from a piped source at a neighboring dwelling, and 3% mainly obtained water from street vendors.

Children below the age of 5 years living in households where the main source of drinking water was a public tap or dispenser had significantly lower odds of having diarrhea than those obtaining water from other distribution systems (AOR = 0.56, 95% CI: 0.32–0.99) (Table 5.3). Conversely, obtaining water mainly from a piped source located at a neighbor's dwelling (or yard) was positively associated with diarrhea, but the association lacked statistical significance (AOR = 1.88, 95% CI: 0.97–3.61, with a *p*-value for AOR=1 between 0.05 and 0.1). The other distribution systems did not show any significant association or trend for diarrhea in under 5-year-old children. In the general population, obtaining drinking water mainly from street vendors was significantly associated with higher odds of diarrhea (AOR = 2.73, 95% CI: 1.14–6.57). The other distribution systems did not show any significant association or trend for diarrhea in the general population.

Table 5.3: Adjusted odds ratios (AORs) for diarrhea in two informal settlements of Nairobi (observed in July and August 2021), obtained from the multiple logistic regressions (MLRs) ran separately for each type of water distribution system.

Distribution system	General population (*n* = 2,332[1])				Children < 5 years (*n* = 305[1])			
	AOR	Lower CI (95%)	Upper CI (95%)	Significance	AOR	Lower CI (95%)	Upper CI (95%)	Significance
Water piped to premises	0.92	0.56	1.52	Not significant	1.03	0.35	2.99	Not significant (LLR *P* value >0.05)
Water piped to a neighboring dwelling	0.88	0.61	1.26	Not significant	1.88	0.97	3.61	*[2]
Public tap or dispenser	1.00	0.75	1.33	Not significant	**0.56**	**0.32**	**0.99**	**[2]
Street vendor	**2.73**	**1.14**	**6.57**	**[2]	1.78	0.31	10.01	Not significant (LLR *P* value >0.05)

Bold: statistically significant results.

[1] Corresponds to the number of individuals living in a household with valid answers for all 7 variables (dependent, exposure and control variables) used in the MLRs.

[2] The number of * indicates the significance of each *beta* coefficient resulting from the MLR, which corresponds to the probability of the AOR being equal to 1: *P* value <0.1, **P* value <0.05, ***P* value <0.01, ****P* value <0.001.

When assessing water availability (Table 5.4), street vendors and public taps/dispensers showed a consistent, positive association with service continuity, while piped water systems were consistently associated with service disruption, i.e., one or more episodes of lack of water in the month preceding the survey. Obtaining water from street vendors was the mode of distribution most clearly associated with water availability. Both the unadjusted and adjusted ORs showed a very strong, positive association (OR = 12.94, 95% CI: 4.51–37.16; AOR = 11.16, 95% CI: 2.45–50.82). Regarding public taps/dispensers, the unadjusted OR was not statistically significant, but the AOR showed a significant association with water availability (AOR = 1.45, 95% CI: 1.06–1.99). As for water obtained mainly from a piped source in a neighboring dwelling or yard, in contrast to street vendors and public taps/dispensers, it was consistently and significantly associated with service disruption (OR = 0.42, 95% CI: 0.27–0.66; AOR = 0.45, 95% CI: 0.28–0.70).

Table 5.4: Unadjusted odds ratios (ORs) and adjusted odds ratios (AORs) for the availability of water by distribution system in two informal settlements of Nairobi (observed in July and August 2021), obtained from bivariate analyses and multiple logistic regressions (MLRs).

Distribution system	Unadjusted ORs (n = 1,143[1])				Adjusted ORs (n = 1,027[2])			
	OR	Lower CI (95%)	Upper CI (95%)	Significance	AOR	Lower CI (95%)	Upper CI (95%)	Significance
Water piped to premises	0.94	0.60	1.46	Not significant (LLR P value > 0.05)	0.96	0.60	1.55	Not significant (LLR P value > 0.05)
Water piped to a neighboring dwelling	**0.42**	**0.27**	**0.66**	****[3]	**0.45**	**0.28**	**0.70**	****[3]
Public tap or dispenser	1.22	0.92	1.63	Not significant (LLR P value > 0.05)	**1.45**	**1.06**	**1.99**	**[3]
Street vendor	**12.94**	**4.51**	**37.16**	****[3]	**11.16**	**2.45**	**50.82**	***[3]

Bold: statistically significant results.

[1] Corresponds to the number of households with valid answers for the 2 variables (dependent and exposure variables).

[2] Corresponds to the number of households with valid answers for all 5 variables (dependent, exposure and control variables) used in the MLRs.

[3] The number of * indicates the significance of each *beta* coefficient resulting from the MLR, which corresponds to the probability of the AOR being equal to 1: *P value <0.1, **P value <0.05, ***P value <0.01, ****P value <0.001.

5.4   Discussion

5.4.1   Public taps and dispensers are the most common distribution system

Public taps and dispensers were the most frequently used drinking water distribution systems in the two study sites in Nairobi. Indeed, approximately three-quarters of the households reported public taps and dispensers as main source of drinking water. This is in line with the 2019 Kenya Population and Housing Census (Government of Kenya, 2022), that presented public water taps and standpipes as the main drinking water sources in urban informal settlements. Our findings also corroborate previous observations on the limitations to provide, in the short- and medium-term, drinking water through capital-intensive piped systems (Graham & Marvin, 2001; Guma & Wiig, 2022; Nilsson, 2016). On this basis, decentralized systems such as public taps and dispensers are certainly the most feasible solution to scale-up access to drinking water services in rapidly growing cities of LMICs.

In our study, the fact that the NCWSC first implemented water "ATMs" in Mathare Valley (6 years before the current household survey) might have influenced residents' preference for this specific type of distribution system. It should also be noted that the implementation of water taps and dispensers aimed at regulating water prices in informal settlements renders

them more affordable through direct provision of water by the NCWSC. This is not the case, for instance, of independent reselling schemes (e.g., street vendors or domestic water reselling). However, as Sarkar showed in recent studies (Sarkar, 2019a, 2019b), this economic advantage depends on the group of people managing each water point. The author explains that, although distributers are usually accredited by the public utility, in some cases water from public dispensers and taps may be resold extralegally by independent vendors who charge higher prices than those practiced by the public utility.

5.4.2   Water availability and risk of diarrhea

In terms of water availability, street vendors and public taps/dispensers were at higher odds of providing constant access to water than piped systems. This finding might be explained by a higher flexibility and capillarity of such distribution systems, which can be mobile (in the case of independent vendors) and provide water on demand in customized quantities. Of note, Nairobi is chronically affected by water shortages that result in disruptions in water delivery through piped networks and disproportionally affect the poorest areas (Mutono et al., 2022). In this context, the ability to store water is crucial to ensure the continuity of water services (Kasper & Schramm, 2023). It is precisely this resilience against water shortages that may explain why we observed higher odds of water availability in water taps/dispensers and independent water vendors, than in piped networks.

In terms of quality, the AORs for diarrhea in children below the age of 5 years suggested that obtaining water mainly from a public tap or dispenser was safer than obtaining water from street vendors, or from a piped source located in a neighboring dwelling. These differences might be related with the use of unsafe containers (i.e., that fail to prevent the introduction of external objects and, hence, contamination) when carrying or storing water, which is a major risk factor for diarrheal diseases (Wolf et al., 2014). In Nairobi, previous studies have reported the use of unsafe water containers by informal water vendors (Sarkar, 2020). Also, the lack of a governance framework adapted to the decentralized water provision currently implemented in Nairobi might negatively impact the quality of water sold by independent vendors. While sectoral reforms brought by the 2002 Water Act expanded access to water by including independent vendors as service providers, these reforms have failed to provide performance indicators of "pro-poor" interventions and, particularly, to enforce quality standards in the distribution of water by independent providers (Sarkar, 2019b, 2020).

From a general perspective, the findings suggest an interrelation between the continuity of water services and the odds of diarrhea in young children. The higher odds of diarrhea observed when obtaining water from a piped source at a neighboring dwelling might be explained by the chronic lack of water (needed to adopt hygiene practices) associated with this distribution mode. Conversely, the lower odds of diarrhea observed in water obtained from public taps or dispensers might be related to their ability in ensuring the continuity of water services.

5.4.3   Policy recommendations and research needs

When assessing transitional solutions to expand water services through low-cost interventions, there is a balance to be found between safety and availability of water. Our findings suggest that the continuity of water services was more likely to be guaranteed through a decentralized distribution system based on street vendors. At the same time, this distribution mode was significantly associated with higher odds of diarrhea in the general population. Public water taps and dispensers, on the other hand, performed well both in terms of service continuity and water quality.

From an infrastructure design perspective, systems relying on safe water storage are more resilient, particularly in contexts where water shortages are common. Moreover, with an adequate governance framework regulating water tariffs, public water taps and dispensers could increase the affordability of this essential service. Indeed, they have the potential to ensure the safety and continuity of water services where piped networks are not available or affordable. Surely, there is no one-fits-all solution. Lawhon and colleagues advanced the notion of "heterogenous infrastructure configurations" (Lawhon et al., 2018), arguing for a wider perspective on infrastructures that moves beyond a purely technological approach, and includes the social relations around them. In this sense, to effectively provide water services, cities with stark differences in socio-economic and spatial configurations such as Nairobi should recur to a variety of infrastructures that match these intra-urban differences. This includes transitional solutions that are implementable in the short-term, until "safely managed" services can be universally introduced.

From a monitoring perspective, our results suggest that "basic" water sources are not necessarily reliable in terms of service continuity or microbiological safety. This confirms the necessity of including indicators of both safety and availability of water in the JMP water service ladder, as it is the case in the "safely managed" category, and as recommended by the JMP in their 2018 update on core questions on WASH for household surveys (UNICEF & WHO, 2018). Of relevance, in our study we did not observe any association between "conventional" infrastructures (piped water) and service continuity. In fact, households using water from public taps, dispensers or street vendors were more likely to have constant access to water than those obtaining water from a piped source.

Finally, access to water in sufficient quantities and when needed implies a balance between the number of people (demand), the water available (offer) and the households' capacity to procure this essential service. In this regard, based on an additional analysis, we found that overcrowding (households having more than 3 members per room) were significantly associated with the lack of water (AOR = 0.69; 95% CI: 0.52 –0.91). We verified this observation by running an additional MLR testing the association between the availability of water (dependent variable) and overcrowding (exposure), controlling for levels of wealth and education (variables susceptible to impact purchasing power). New research is needed to better understand how living conditions in general, at household and community scale, might affect water

availability and the risk of diseases related to the lack of hygiene, especially in the context of vulnerable, impoverished urban settlements.

5.4.4   Study limitations

The cross-sectional nature of this study is a limitation. Although this design was useful to explore associations between different water distribution systems and a selection of outcomes, no causal association could be established. In the case of diarrhea, no etiological inference could be made, but this was beyond the scope of the study. It should also be noted that data collection took place during a period when the Kenyan government implemented preventive measures against COVID-19, generally increasing access to water services. These measures included the increase of water "boozers", which might have impacted the availability of water in public taps and dispensers, as they rely on water boozers.

5.5   Conclusions

We assessed the efficacy of different water distribution systems in two large informal settlements of Nairobi, based on their ability to ensure service continuity and their association with diarrheal diseases (as a proxy indicator of quality). Our findings suggest that public taps and water dispensers are the most effective distribution systems in the context of low-income urban areas that are often affected by water shortages. They were associated with better indicators of service continuity and quality than piped systems. Their ability to store large quantities of renders water taps and dispensers more resilient, while their tariffs can be more affordable, as water is provided directly by the public utility. For these reasons, public taps and water dispensers hold promise as transitional solution to expand access to safe water in LMICs in the short-term.

5.6   Supplementary materials

The materials and data processing steps used in the statistical analyses can be found here:

https://github.com/ceat-epfl/water-informal-settlements

6 Synthesis and outlook

6.1 Summary of main contributions

This thesis addressed risk factors of diarrheal diseases, a main cause of death and disability in sub-Saharan Africa, from a spatial perspective. The underlying question was to better understand how the urban form and the design of WASH technologies are associated with the risk of these diseases in the context of socio-economically vulnerable populations in African cities. This study joined, hence, recent efforts to reconnect urban planning and public health, using methods from the two disciplines to explore how the built environment can be, directly or indirectly, a risk factor for diarrhea.

One aspect highlighting the scientific significance of this research is the epistemological fusion of the two disciplinary fields through the combination of spatial analyses with epidemiological investigations. Surely, the cross-sectional study design and statistical models employed are relatively simple and do not allow to establish any causal relations between the exposures derived from the built environment and diarrhea. Nonetheless, the methods and tools used here still allowed us to advance a new, spatially explicit perspective on risk factors of diarrheal diseases in low-income urban settings. Indeed, the emphasis on the built environment allowed us to explore a new dimension of risk factors of diarrhea that might be invaluable to address recent debates on the health impacts of WASH facilities in low-income settings (Cumming et al., 2019; Pickering et al., 2019).

Indeed, this study provided empirical results suggesting that the accessibility and health benefits of WASH facilities in informal settlements are interrelated with the form and composition of the built environment at different scales, from the single housing conditions to the community level. Chapter 2 demonstrated how, at the urban scale, the prevalence of built-up areas characterized as "precarious" was significantly associated with the prevalence of diarrhea in Côte d'Ivoire, even controlling for access to "basic" WASH. In fact, the landscape metrics characterizing the built environment in this ecological analysis were more significant predictors of diarrhea than "basic" WASH services in all four multivariate regression models used. These associations were further analyzed at a higher level of detail in Chapter 3, which focused on the

relations between specific housing conditions and diarrhea in informal settlements of Abidjan, the largest Ivorian city. This more detailed analysis corroborated the findings of Chapter 2, showing once again that, at constant access to WASH, material deprivations affecting the built environment (inadequate building materials and the lack of protected cooking spaces) were significantly associated with diarrhea.

While Chapters 2 and 3 highlighted the possibility of direct relations between diarrheal diseases and the built environment (advancing the hypothesis that precarious housing conditions exacerbate exposure to pathogens), Chapter 4 emphasized indirect relations between the urban form and these diseases. The fourth Chapter demonstrated that, in Abidjan and Nairobi, the urban form and spatial disposition of sanitation facilities were associated with the perceived safety to access these facilities – and, hence, were indirectly related to the risk of diarrhea. Because the interrelations between shared sanitation, the built environment, and diarrhea might vary between places (as explained in the Introduction), this study included analyses in two countries of different African regions. In this regard, although Abidjan and Nairobi are very different from a historical, cultural, and social perspective, it was compelling to find similar associations between the spatial disposition of shared sanitation facilities and their accessibility in the two cities. This increases the findings' significance, suggesting that the identified associations might, in fact, be transposable to different geographic contexts.

Another important aspect of this research is that it sought to learn from urban experiences in Africa by focusing on "non-conventional" WASH services that have been implemented as affordable alternatives for low-income populations. As discussed before, the main motivations for choosing study sites located in Africa were *not* the continent's evident challenges related to rapid and spatially concentrated urbanization or the relatively high burden of diarrhea. Rather, the choice of African sites was motivated by the presence of a variety of water distribution systems and sanitation solutions that showed the potential to attend to the specific needs of vulnerable populations living in informal settlements.

Of relevance, our results suggest that some of the WASH solutions observed in both cities were able to meet both public health expectations (being associated with reduced risks of diarrhea) and service reliability (providing water and sanitation services that were constantly available). Indeed, Chapter 4 argued that shared sanitation can be safely accessed in informal settlements if well-maintained and located in semi-private areas. Then, Chapter 5 demonstrated that in contexts where water shortages are common, non-networked, shared water points proved to be more resilient than more "conventional" systems such as piped water. Further analyses are needed to verify this but, based on the research findings, these "non-conventional" services might constitute solutions that could be transposed to other places facing similar challenges to expand access to WASH. In this regard, while the extended geographic scope of this research did not aim to provide a comparative study, it raised potential synergies between the selected sites, which could mutually benefit from their own experiences. For instance, non-networked water services currently used in Nairobi could be implemented in Abidjan, as the current dependence on piped water seems to expose low-income populations to chronic

water shortages. Conversely, the "courtyard" housing typology typical of Abidjan seems to be an adapted spatial disposition to increase the safety of accessing shared sanitation facilities in informal settlements while maintaining their low-rise/high-density typology.

From a more global perspective, the lessons learned from the study sites analyzed here provide invaluable insights into current WASH policies and might effectively consist in African contributions to address global health challenges related to the rapid expansion of cities in low- and middle-income countries. On this basis, we advance several recommendations regarding the implementation of WASH services in informal settlements in sub-Saharan Africa.

6.2 Recommendations based on the key findings

6.2.1 Design implications: spatial determinants of diarrhea and access to WASH

Our findings suggest that, beyond the availability of adequate WASH facilities, there are contextual aspects related to the built environment in informal settlements that must be considered to ensure the accessibility and service continuity of these facilities and thus prevent diarrhea. In other words, with constant access to the same WASH services, the risk of diarrheal infection may vary depending on the specific configuration of the built environment. These variations were consistently observed at different scales (Chapters 2 and 3), which suggests that the built environment and, more globally, the "urban context" (Ompad et al., 2017), may be key exposures to explain the risk of diarrheal diseases. This is in line with previous studies that argued for the need to address the specific spatial characteristics of vulnerable, low-income urban areas as key health determinants that can exacerbate the risk of numerous diseases through "neighborhood effects" (Ezeh et al., 2017).

To address these spatial determinants of the risk of diarrhea in informal settlements and acknowledge the complex nature of urban health, a more integrated approach toward "slum upgrading" projects is needed. WASH facilities, housing, and the urban form should not be addressed independently; they are deeply interrelated and, consequently, their impact on human health is a result of the overall urban context they provide – not just one or the other. Concretely, several recommendations can be put forward for future interventions in informal settlements, notably:

- Shared sanitation solutions can be a transitional solution in congested, low-income areas, given that their location is carefully defined. Considering that the urban form is associated with the perceived safety to access shared facilities, the latter should be located, ideally, in semi-private spaces such as inner courtyards. This must be negotiated with those managing the land (which includes "informal" landlords). For instance, one could envisage a minimum ratio of shared sanitation facilities per dwelling rented. In November 2022, this very idea was being discussed by urban planning officials in the Nairobi City Government.

- In areas affected by water shortages or where there is an important gap between built-up areas and water networks, non-piped systems should be envisaged. A key design feature of these decentralized water systems is that they must have an important, in-situ storage capacity, allowing to go through several days of water shortage and still provide constant services. These water points do not need to be located within premises and can take the form of public dispensers. In the latter case, water can be provided directly by the relevant public utility, which, with appropriate governance and regulations, may guarantee constant access to affordable water in low-income settings.

- Although it is justifiable that common infrastructures such as shared WASH facilities have priority, interventions are also needed to improve the quality of housing units when they are not built with minimally adequate materials. Housing units should have indoor spaces effectively protected from external sources of pollution, which depends on the adequacy of building materials. The quality of housing could be progressively improved through incremental construction methods (replicating a logic that is already predominant in informal settlements), while adequate materials could be more affordable through public subsidies or economies of scale supported by the government.

- Cooking areas should be addressed as critical spaces to prevent diarrheal infections and be located away from animals, waste, and any other environmental reservoir of pathogens. Certainly, this is not merely a spatial problem but also a behavioral one; hence, sensitizing communities on environmental risk factors and hygiene practices when cooking may also be needed. Moreover, informal settlements are often congested and there may not be sufficient space for individual, indoor cooking areas - or it may even be dangerous given the lack of ventilation. In these cases, shared and well-designed kitchens could be envisaged to effectively ensure hygiene and protect food from external sources of contamination, while avoiding hazards related to indoors air pollution.

6.2.2   Policy implications: a more realistic approach to SDG 6

Globally, universal access to networked infrastructures like water piped to premises and individual toilets connected to centralized sewerage is not affordable in the short- or medium-term, and even ensuring access to "basic" WASH services by 2030 is challenging (Hutton & Varughese, 2016; World Bank, 2017). In addition, the findings in Chapters 4 and 5 suggest that non-networked, shared sanitation and water services that are not considered "safely managed" or even "basic" services by the WHO-UNICEF JMP ladder can, in fact, be safe and provide continuous services – surely, under specific circumstances.

Against this background, this study joins recent scholarship in a critical appraisal of universalizing standards, initially imposed by the "modern" urban planning paradigm (Graham & Marvin, 2001; Nilsson, 2016), and now induced by key multilateral agencies and the universalizing approach of the SDGs (Bohnert et al., 2016; Buckley & Kallergis, 2019; Meili et al., 2022). Particularly, the SDG targets 6.1 and 6.2 seem too ambitious and inflexible, as they are

measured by the proportion of the population with access to "safely managed" WASH, which requires quadrupling the global investments in WASH done between 2015 and 2020 (WHO & UNICEF, 2021).

Of note, the critical assessment advanced here does not question the importance of the SDGs as drivers for positive global changes. Also, it does not question the idea that universal access to "safely managed" WASH services should be the final goal. Rather, the position defended here challenges the feasibility of targets 6.1 and 6.2 within the given "deadline" (2030) while raising the need for transitional, affordable, and functional solutions – instead of ideal solutions that are not immediately implementable. Therefore, what is argued here is a more progressive (and realistic) approach to the WASH targets currently put forward by SDG 6 (and not their elimination), as well as to their monitoring methods. This focus on the SDGs is motivated by their global influence on national policies, as well as monitoring efforts such as national censuses (Clasen, 2016). On this basis, the following policy recommendations are put forward:

- From a strategic perspective, until universal access to "safely managed" services is financially feasible, short-term, transitional solutions should be implemented. While upgrading service levels is more expensive than directly building "safely managed" facilities, this is only true if the means are immediately available (Hutton & Varughese, 2016). In fact, the health (and eventually economic) gains are greater by ensuring immediate access to a shared facility than waiting for years or decades without any service. If the design recommendations previously mentioned are followed, shared WASH facilities certainly constitute a promising alternative to rapidly expand access to minimally adequate services. Most importantly, urban planners must ponder that, in practice, networked systems may be less efficient than simpler, non-networked ones, depending on the context. In Nairobi, our findings suggest that shared water services (public taps and dispensers), which are only considered a type of "basic" service, were more efficient than piped water to ensure service continuity and microbiological safety in informal settlements.

- From a monitoring perspective, the JMP service ladder and the monitoring indicators derived from it should be further refined to measure access to adequate WASH services. Surely, the fact that the new JMP ladder disaggregated the "improved"/"unimproved" WASH categories used in the Millennium Development Goals is a considerable advancement. But further adaptations could be made to acknowledge the need for a more progressive advancement toward targets 6.1 and 6.2, notably regarding sanitation. Indeed, the definitions in the JMP service ladder should envisage considering shared sanitation facilities located in a semi-private area and shared by a limited number of households as "basic" sanitation (instead of "limited"). In this regard, although the core questions on WASH for household surveys advanced by the JMP (UNICEF & WHO, 2018) already include the location of sanitation facilities, this is not always implemented in national censuses. For instance, neither the Kenyan (2019) nor the Ivorian (2014) censuses included any question about the location of the sanitation facility.

6.3   Methodological aspects and outlook for future research

6.3.1   Study limitations

Given the cross-sectional design of this research, it was not possible to establish any causal relations between the outcome and the exposures of interest. Nevertheless, this study was highly relevant for identifying potential risk factors for diarrhea not previously explored, such as the specific features of the built environment assessed here. Moreover, the multi-scale approach allowed us to critically test associations at different geographic scales and contexts. Even if the results were obtained through cross-sectional observations, the consistency and convergence of findings in different scales and contexts added significance to them.

Regarding the specific etiology of the observed diarrheal infections, determining whether bacteria or viruses caused them was not addressed, as this was not within the scope of the study. In addition, we acknowledge that some of the cases detected might have been caused by an infection occurring outside the community's boundaries – hence, unrelated to the built environment in the study area. This limitation is also known as the Uncertain Geographic Context Problem (Kwan, 2012), i.e., when the exposure is determined based on a fixed location (in this case, the place of residence), while other relevant exposures that occur outside the predetermined area are not addressed. To mitigate this problem, we included the frequency of consumption of street food in the detailed analyses at the individual level (Chapters 3-5), thus accounting for enteric infections related to external factors. Still regarding the estimation of exposures, because they were based on the residence location, all individuals living in the same household were considered to be exposed to the same built environment characteristics. This simplification does not account for eventual gendered divisions of labor and occupations inside and outside the house. We note that, although these considerations may be relevant to adults, they are certainly less relevant for children under five, who will tend to stay close to their homes and, hence, to whom environmental exposures are certainly more determined by the place of residence than elsewhere.

Finally, regarding the sampling method, although we obtained more than the minimum number of household surveys to observe the prevalence of diarrhea, the selection of participating households was not randomized. At the moment of the study design, we did not have an accurate number and spatial distribution of households in the selected sites, and we lacked the means of doing an extensive count and mapping of every household. Rather, we recurred to an alternative quantification method (mapping and counting building footprints) to estimate the number and location of households. It was based on this estimated number (not the real one) that we implemented the "random walk" selection method explained in section 1.4.2.4 – which is a systematized sampling method but, because of the lack of an accurate baseline population data, here it cannot be considered a randomized method. To mitigate this limitation, we ensured that the spatial distribution of surveys followed the density of housing structures, covering in an equitable way the study areas.

6.3.2   Ways forward: urban health data challenges and future research

From a general point of view, significant data challenges must be addressed to improve urban health research. There is a need for more reliable, high-resolution data, especially in low- and middle-income countries. Indeed, data resolution is key to identifying environmental health determinants and intra-urban health inequities, but current open data sources are either too coarse or have insufficient samples for intra-urban analyses and may be biased by the underrepresentation of low-income populations in peri-urban areas (Elsey et al., 2016; Friesen et al., 2020). Moreover, urban policies in many countries currently do not have measurable targets (Lowe et al., 2022), which constitutes a major problem as their progress are hardly quantifiable. Quoting urban scholar Giles-Corti et al. (2022), "what gets measured gets done", hence the importance of obtaining updated, high-resolution data to assess the quality of urban environments and locate where interventions are needed.

Regarding the built environment, important advancements took place in the past decades, notably with the rise of open-access geographic data, very-high resolution satellite imagery, and drones. However, methods based on this type of data still need improvement and do not suffice to grasp the multiple "layers" of information on human settlements needed for urban health studies. For instance, Earth observation and remote sensing offer a great potential to extract precise information on the physical environment, notably in cities marked by informal urbanization (Kohli et al., 2012; Kraff et al., 2020; Wang et al., 2022). Nonetheless, there is still a need to validate such "top-down" observations with "bottom-up" methods that give a more accurate perspective from the field and, most importantly, provide key health and socioeconomic indicators that are not detectable from aerial imagery (Lilford et al., 2019). As for the use of open data, a large group of urban scholars recently proposed a globally implementable computational framework to obtain relevant indicators of the urban environment at a high spatial resolution (Boeing et al., 2022), but the success of such an approach depends on the adoption of open data policies by local governments. From a citizen science perspective, recent research has shown the potential of crowdsourcing and collaborative mapping to collect data in informal settlements (Santos et al., 2023), but the scalability of these methods is limited by material and human resources.

Against this background, "urban health observatories" (WHO, 2014) appear as a promising way to provide the much needed longitudinal, socio-demographic, and health data at spatial and temporal resolutions that allow a more reliable assessment of the relations between the urban environment and health outcomes. In the past decades, they have already proven to be invaluable data sources to better understand urban health determinants in informal settlements in low- and middle-income countries (Caiaffa & de Lima Friche, 2019; Ezeh & Mberu, 2019). Also, by combining technical expertise with deeply-rooted local knowledge, these observatories offer an interesting framework to produce empirical evidence useful to address the specific health issues of different areas in a city. They could be envisaged as a way to implement action research, potentially bridging the still significant gap between urban health research and decision-making in urban planning (Lowe et al., 2022), by connecting

scientists, non-expert citizens, and government authorities. Most importantly, urban health observatories are needed to address the significant data gap that hampers urban health research, especially in settings where "official" data sources are unreliable or simply inexistent at a scale sufficiently disaggregated for intra-urban analyses.

From a more specific perspective, regarding the environmental risk factors of diarrheal diseases advanced in Chapters 2, 3, and 4, there is a need to verify the associations observed through longitudinal, randomized studies. This is also applicable to the health impacts of different types of WASH facilities analyzed in Chapters 4 and 5, which remain a subject of controversy. In this sense, one possible research path could be to obtain georeferenced, longitudinal health data from existing urban health observatories to test the associations advanced by the present study in a more robust manner. In addition, quantitative microbial risk assessments (QMRAs) would be useful to better understand the relations between housing conditions and the different pathogens causing diarrheal diseases. For instance, a QMRA could be implemented to verify how the material and spatial characteristics of the dwelling analyzed here (e.g., construction materials, disposition of critical amenities such as cooking spaces, and overcrowding) might impact on hygiene and, hence, exposure to pathogens.

Finally, as the risk food-borne and water-borne diseases will most certainly rise with climate change (Cissé, 2019), ensuring safe housing conditions (that protect from environmental hazards and their negative health impacts) becomes all the more relevant. Indeed, as cities are more susceptible to floods, droughts, and other extreme climatic phenomena, developing resilient urban living conditions - which includes appropriate housing and WASH services - is a most pressing global health challenge.

Overall, the research gaps addressed by this thesis (which consisted of a series of exploratory studies) deserve further scientific attention. Our findings suggest that the form and composition of the built environment are relevant topics to understand the risk of diarrheal infections in informal settlements, and to elaborate more pragmatic WASH policies that can address the social and spatial needs of low-income urban settings. Although they were consistent, those findings still need to be verified through longitudinal and randomized studies.

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Appendices

Appendix 1.1: Household questionnaires

The household questionnaires were conducted in digital format using the mobile application KoboCollect. Therefore, they are more easily visualized online, through the following below.

Abidjan: https://kf.kobotoolbox.org/#/forms/aF68WT3jZxgrrM7u6QofCK

Nairobi: https://kf.kobotoolbox.org/#/forms/a8VrndSe6CN4eBuXPvGdQ7

The source code for the two questionnaires is openly available here:

https://github.com/ceat-epfl/household-surveys-thesis-vpc

A print version of the questionnaires (extracted from the KoboToolbox platform) is available in the body of this thesis (see following pages). However, it is highly recommended to consult their digital versions.

Abidjan

Nom de l'enqueteur
Ecrivez votre nom complet

_____

Code de la zone
Indiquez le code de la zone dans laquelle se trouve le menage

_____

[INTRODUISEZ-VOUS] Bonjour. Mon nom est . Je travaille avec le Centre Suisse de Recherches Scientifiques en Côte d'Ivoire et l'université suisse EPFL. Nous menons une enquête sur les impacts d'équipements d'eau, toilettes et hygiène sur la diarrhée. Les informations collectées vont contribuer à mieux planifier ces équipements dans des communautés comme celle-ci. Votre ménage a été selectionné par tirage au sort pour participer à l'enquête. Si vous êtes d'accord de participer, j'aimerais vous poser des questions concernant la situation de votre ménage en ce qui concerne l'accès à l'eau et aux toilettes, et aussi des possibles cas de diarrhée. Cela prendra entre 20 et 30 minutes au maximum, et vous recevrez une compensation pour votre temps. Toutes les informations données resteront confidentielles. C'est à vous de décider si vous participez ou non, mais nous espérons que si, car votre participation est très importante pour l'étude. Vous n'êtes pas obligé de répondre à toutes les questions, et vous pouvez interrompre le questionnaire à tout moment.
Voici un document avec des informations plus précises sur l'étude [DONNEZ FEUILLE D'INFORMATION].
Donnez la feuille d'information à la personne interviewée et vérifiez si elle donne son consentement. Répondez à des éventuelles questions.

○ Je (l'enquêteur) confirme avoir presenté l'objectif de l'enquête et avoir remis la fiche d'information au/à la participant(e). J'ai répondu à toutes les questions de manière satisfaisante.

○ Le/la participant(e) n'a PAS reçu la fiche d'information ou a encore des questions sur l'enquête.

La personne intérogée a donné son consentement pour participer?
Si le consentement a été donné, vérifiez que le/la participant(e) a bien signé le formulaire de consentement.

○ OUI, le/la participant(e) a donné son consentement éclairé pour participer. (POURSUIVEZ l'enquête)

○ NON, le/la participant(e) N'A PAS a donné son consentement pour participer. (TERMINEZ l'enquête)

MEMBRES DU MENAGE

[NOTE] Par la suite, vous devrez saisir le prénom d'un ou de plusieurs résidents. En glissant vers la droite, il vous sera demandé si vous voulez ou non ajouter un nouveau résident. Pour ajouter un nouveau résident, cliquez sur "AJOUTER". Sinon, choisissez l'autre option ("NE PAS AJOUTER") pour passer à la question suivante.

» PRENOM

1

Veuillez me donner les PRÉNOMS de toutes les personnes qui vivent habituellement dans votre ménage, en commençant par le/la chef/fe de ménage.

Juste pour m'assurer que j'ai une liste complète : il y a un total de personnes qui vivent ici, ce nombre est-il correct ?

Si ce n'est pas correct, revenez en arrière et saisissez les prénoms manquants, ou corrigez la liste (bouton avec FLECHE en haut à gauche).

○ OUI

○ NON

» DETAILS PERSONNELS

EAU ET HYGIENE

OÙ obtenez-vous habituellement l'EAU POTABLE pour ce ménage ?

Considérez la situation AU MOMENT DE L'ENQUÊTE. Choisissez l'option qui correspond le mieux à l'équipement du ménage.

○ Source PRIVEE/SEMI-PRIVEE, située dans logement ou cour appartenant à vous ou à un voisin

○ Source PUBLIQUE/COMMERCIALE, située dans un lieu public

○ EAU de SURFACE (rivière/canal/lac/étang)

○ Ne sait pas / ne veut pas répondre

Plus précisément, quel TYPE de SYSTEME fournit habituellement l'EAU POTABLE à ce ménage ?

Considérez la situation AU MOMENT DE L'ENQUÊTE. Choisissez l'option qui correspond le mieux à l'équipement du ménage.

○ CANALISATION : arrivée d'eau à l'INTERIEUR du LOGEMENT

○ CANALISATION : arrivée d'eau dans COUR où se trouve le ménage

○ CANALISATION : arrivée d'eau chez un VOISIN

○ SOUTERRAIN : eau pompée localement par FORAGE (sous pression)

○ PUITS : AVEC protection (fermé), eau prelevée manuellement

○ PUITS : SANS protection (ouvert), eau prelevée manuellement

○ EAU de PLUIE

○ AUTRE

○ Ne sait pas / ne veut pas répondre

Veuillez préciser la principale source d'eau potable.

Si inconnu ou pas de réponse, saisissez "NA".

Plus précisément, dans quel TYPE d'établissement ou de commerce obtenez-vous habituellement de l'EAU POTABLE pour ce ménage ?
Considérez la situation AU MOMENT DE L'ENQUÊTE.

○ BORNE-FONTAINE

○ COMMERÇANT : camion d'eau ou vendeur de rue

○ SOUTERRAIN : eau pompée localement par FORAGE (sous pression)

○ PUITS : AVEC protection (fermé), eau prelevée manuellement

○ PUITS : SANS protection (ouvert), eau prelevée manuellement

○ AUTRE

○ Ne sait pas / ne veut pas répondre

Veuillez préciser la principale source d'eau potable.
Si inconnu ou pas de réponse, saisissez "NA".

De quelle forme obtenez-vous habituellement de l'eau potable ?
Considérez la situation AU MOMENT DE L'ENQUÊTE.

○ CAMION d'eau

○ BARRIL

○ Eau en BOUTEILLE

○ Eau en SACHET

○ AUTRE

○ Ne sait pas / ne veut pas répondre

Veuillez préciser la principale source d'eau potable.
Si inconnu ou pas de réponse, saisissez "NA".

Est-ce que cette borne-fontaine/robinet d'eau est géré par un distributeur AUTORISÉ (comme la SODECI) ?
Choisissez une des options ci-dessous.

○ OUI

○ NON

○ Ne sait pas / ne veut pas répondre

Si elle n'est pas située dans le logement ni dans la cour, veuillez indiquer l'emplacement de la source d'eau.
Si possible, prenez note de l'emplacement sur la carte imprimée.

○ Localisation de la source d'eau a été indiquée

○ Ne sait pas / ne veut pas répondre

Pouvez-vous indiquer le nom d'un POINT DE REFERENCE (site religieux, marché ou place) proche de cette source d'eau ?
Si inconnu ou pas de réponse, saisissez "NA".

Combien de temps (en MINUTES) faut-il pour aller là-bas, chercher de l'eau et revenir ?

Comptez le temps en MINUTES (sans tenir compte des files d'attente). Si inconnu ou pas de réponse, saisissez "9999".

_____

Quel type de RECIPIENT utilisez-vous d'habitude pour stocker votre eau potable ?

Si plus d'un, indiquez le plus utilisé. Si le conteneur n'a PAS de couvercle approprié : indiquez "OUVERT". Choisissez l'une des options ci-dessous.

- ◯ PLASTIQUE : récipient OUVERT
- ◯ PLASTIQUE : récipient FERMÉ
- ◯ MÉTALLIQUE : récipient OUVERT
- ◯ MÉTALLIQUE : récipient FERMÉ
- ◯ AUTRE : récipient OUVERT
- ◯ AUTRE : récipient FERMÉ
- ◯ Ne sait pas / ne veut pas répondre

Si plus d'un récipient, énumérez TOUS les types ici.

Si le conteneur n'a PAS de couvercle approprié : indiquez "OUVERT". Choisissez l'une des options ci-dessous.

- ☐ PAS D'AUTRE RÉCIPIENT
- ☐ PLASTIQUE : récipient OUVERT
- ☐ PLASTIQUE : récipient FERMÉ
- ☐ MÉTALLIQUE : récipient OUVERT
- ☐ MÉTALLIQUE : récipient FERMÉ
- ☐ AUTRE : récipient OUVERT
- ☐ AUTRE : récipient FERMÉ
- ☐ Ne sait pas / ne veut pas répondre

Au cours du mois dernier, est-il arrivé que votre ménage ne dispose pas d'une quantité suffisante d'eau potable pour répondre à ses besoins ?

Choisissez une des options ci-dessous.

- ◯ OUI
- ◯ NON
- ◯ Ne sait pas / ne veut pas répondre

Est-ce que vous traitez l'eau avant de la boire, pour la rendre plus propre ?

Choisissez une des options ci-dessous.

- ◯ OUI
- ◯ NON
- ◯ Ne sait pas / ne veut pas répondre

Que faites-vous habituellement pour rendre l'eau plus sûre à boire ?
Sélectionnez toutes les options mentionnées.

- [ ] Faire BOUILLIR
- [ ] Addition de CHLORE
- [ ] Usage de FILTRE en CÉRAMIQUE
- [ ] Filtrage avec un TISSU
- [ ] Désifection SOLAIRE
- [ ] DÉCANTATION
- [ ] AUTRE
- [ ] Ne sait pas / ne veut pas répondre

Veuillez préciser quel autre type de traitement est utilisé.
Si inconnu ou pas de réponse, saisissez "NA".

Hier (ou dans les dernières 24 heures), à quelles occasions vous êtes-vous lavé les mains ?
Sélectionnez toutes les options mentionnées.

- [ ] Avant de CUISINER ?
- [ ] Avant de MANGER ?
- [ ] Après changer les COUCHES ?
- [ ] Après être allé aux TOILETTES ?
- [ ] Ne sait pas / ne veut pas répondre

Hier (ou dans les dernières 24 heures), à quelles occasions vous êtes-vous lavé les mains ?
Sélectionnez toutes les options mentionnées.

- [ ] Avant de CUISINER ?
- [ ] Avant de MANGER ?
- [ ] Après être allé aux TOILETTES ?
- [ ] Ne sait pas / ne veut pas répondre

Est-ce que vous payez pour votre eau potable (par ex. facture SODECI) ?
Choisissez une des options ci-dessous.

- ( ) OUI
- ( ) NON
- ( ) Ne sait pas / ne veut pas répondre

Est-ce que vous avez bénéficié d'un branchement SOCIAL de la SODECI (prix du compteur moins cher) ?
Choisissez une des options ci-dessous.

- ( ) OUI
- ( ) NON
- ( ) Ne sait pas / ne veut pas répondre

Approximativement, combien coûterait un fût (barril) de 25 litres d'eau si on l'achetait dans le quartier ?

Indiquez le prix en francs CFA. Si inconnu ou pas de réponse, saisissez "9999".

_____

Nous aimerions connaître les endroits que les ménages utilisent pour se laver les mains. Pouvez-vous s'il vous plaît me montrer où les membres de votre ménage se lavent le plus souvent les mains ?

Choisissez une des options ci-dessous.

- ◯ OUI
- ◯ NON : pas de permission pour voir
- ◯ NON : pas situé dans logement ni cour
- ◯ NON : Autre raison

» INFRASTRUCTURE LAVAGE MAINS

[OBSERVEZ] Verifiez le TYPE d'équipement.

Documentez l'observation (choisissez une des options ci-dessous).

- ◯ Structure fixe
- ◯ Équipement mobile

[OBSERVEZ] Verifiez la présence (disponibilité) d'eau pour se laver les mains.

Documentez l'observation (choisissez une des options ci-dessous).

- ◯ OUI, il y a de l'eau pour se laver les mains
- ◯ NON, il N'Y a PAS d'eau pour se laver les mains

[OBSERVEZ] Verifiez la présence (disponibilité) de savon, détergent, ou autre agent nettoyant pour les mains.

Si pas visible, demandez si du savon est disponible. Documentez l'observation (choisissez l'une des options ci-dessous).

- ◯ SAVON et/ou DETERGENT disponible
- ◯ CENDRES ou BOUE disponible
- ◯ AUCUN agent nettoyant disponible

En moyenne, à quelle fréquence les membres de votre ménage mangent dehors ?

Choisissez une des options ci-dessous.

- ◯ 0 à 1 fois par semaine
- ◯ 2 à 4 fois par semaine
- ◯ 5 fois par semaine ou plus
- ◯ Ne sait pas / ne veut pas répondre

ASSAINISSEMENT

OÙ se trouvent les toilettes que les membres de votre ménage utilisent habituellement ?

Considérez la situation AU MOMENT DE L'ENQUÊTE. Choisissez une des options ci-dessous.

- ⚪ Dans le LOGEMENT même
- ⚪ Dans la COUR où se trouve le logement
- ⚪ Chez un VOISIN, dans son logement
- ⚪ Chez un VOISIN, dans sa cour
- ⚪ Toilettes PUBLIQUES (situées en lieu public)
- ⚪ PAS de toilettes : défécation à l'air libre
- ⚪ Ne sait pas / ne veut pas répondre

Quel TYPE de toilettes les membres de votre ménage utilisent habituellement ?

Considérez la situation au moment de l'enquête. DEMANDEZ LA PERMISSION D'OBSERVER L'ÉTABLISSEMENT.

- ⚪ Structure fixe, avec CHASSE d'EAU
- ⚪ Structure fixe, toilettes SÈCHES ou COMPOST
- ⚪ Structure fixe, sur PILOTIS
- ⚪ MOBILE : toilettes CHIMIQUES
- ⚪ MOBILE : toilettes à SEAU
- ⚪ AUTRE
- ⚪ Ne sait pas / ne veut pas répondre

Veuillez préciser le type de toilettes.

Si inconnu ou pas de réponse, saisissez "NA".

Plus précisément, à quel type de SYSTÈME ces toiletts sont reliées ?

Choisissez une des options ci-dessous.

- ⚪ Au RÉSEAU d'ÉGOUTS
- ⚪ À une FOSSE SEPTIQUE
- ⚪ À une FOSSE simple, COUVERTE
- ⚪ À une FOSSE simple, PAS COUVERTE
- ⚪ Vers la NATURE / espace ouvert
- ⚪ AUTRE
- ⚪ Ne sait pas / ne veut pas répondre

Veuillez préciser le type de toilettes.

Si inconnu ou pas de réponse, saisissez "NA".

Plus précisément, quel est le TYPE de toilettes ?
DEMANDEZ LA PERMISSION D'OBSERVER L'ÉTABLISSEMENT.

- ○ Latrine améliorée, VENTILÉE
- ○ Latrine améliorée, SANS VENTILATION
- ○ Latrine SANS DALLE (support au sol)
- ○ Toilettes à COMPOST
- ○ Ne sait pas / ne veut pas répondre

Veuillez préciser le type de toilettes.
Si inconnu ou pas de réponse, saisissez "NA".

Si pas située dans le logement ni dans la cour, veuillez indiquer l'emplacement des toilettes.
Si possible, prenez note de l'emplacement sur la carte imprimée.

- ○ Localisation des toilettes a été indiquée
- ○ Ne sait pas / ne veut pas répondre

Pouvez-vous indiquer le nom d'un POINT DE REFERENCE (site religieux, marché ou place) proche de ces toilettes ?
Si inconnu ou pas de réponse, saisissez "NA".

Veuillez indiquer OÙ vous faites vos besoins habituellement.
Si possible, prenez note de l'emplacement sur la carte imprimée. ECRIVEZ "DAL" sur la localisation notée.

- ○ Une localisation a été donnée
- ○ Ne sait pas / ne veut pas répondre

Combien de temps (en MINUTES) faut-il pour aller à ces toilettes ?
Comptez le temps en MINUTES. Si inconnu ou pas de réponse, saisissez "9999".

Est-ce qu'il y a un TOIT couvrant les toilettes ?
Choisissez une des options ci-dessous.

- ○ OUI
- ○ NON
- ○ Ne sait pas / ne veut pas répondre

Est-ce que le contenu de ces toilettes est vidé de temps en temps ?
Choisissez une des options ci-dessous.

- ○ OUI
- ○ NON
- ○ Ne sait pas / ne veut pas répondre

OÙ sont vidés les contenus de ces toilettes ?

Choisissez une des options ci-dessous.

○ Station d'épuration

○ Enterrés dans une fosse couverte

○ Jettés dans terrain ouvert

○ Jettés dans l'eau (rivière/canal/lagune)

○ Autre

○ Ne sait pas / ne veut pas répondre

Veuillez indiquer où sont vidés les contenus des toilettes.

Si inconnu ou pas de réponse, saisissez "NA".

Est-ce que vous partagez ces toilettes avec d'autres ménages?

Choisissez une des options ci-dessous.

○ OUI

○ NON

○ Ne sait pas / ne veut pas répondre

Incluant votre propre ménage, combien de ménages (en tout) partagent ces toilettes ?

Si 20 ou plus, saisissez "222". Si inconnu ou pas de réponse, saisissez "9999".

Qui a construit ces toilettes ?

Choisissez une des options ci-dessous.

○ Auto-construites (par l'habitant)

○ Service professionnel (par entreprise)

○ Association de quartier

○ ONG

○ Autre

○ Ne sait pas / ne veut pas répondre

Veuillez indiquer qui a construit ces toilettes.

Si inconnu ou pas de réponse, saisissez "NA".

Est-ce que vous payez pour utiliser ces toilettes ?

Choisissez une des options ci-dessous.

○ OUI

○ NON

○ Ne sait pas / ne veut pas répondre

Quel est le niveau de propreté des toilettes que vous utilisez d'habitude?

Choisissez une des options ci-dessous. Tenez compte de l'odeur, la présence d'articles d'hygiène personnelle sur le sol et/ou les traces d'excréments.

○ TRÈS PROPRES

○ PROPRES

○ SALES

○ TRÈS SALES

○ Ne sait pas / ne veut pas répondre

En général, vous sentez-vous en sécurité pour aller jusqu'à ces toilettes à tout moment, ou cela dépend de l'heure ?

Choisissez une des options ci-dessous.

○ À TOUS moments, jour et nuit

○ SEULEMENT de JOUR

○ Ne se sent JAMAIS en sécurité

○ Ne sait pas / ne veut pas répondre

CONDITIONS SOCIO-ECONOMIQUES

Est-ce que votre ménage possède :

Choisissez une des options ci-dessous.

☐ Électricité ?

☐ Radio ?

☐ Télévision ?

☐ Téléphone portable type smartphone ?

☐ Ordinateur ?

☐ Frigo ?

☐ Four ?

☐ Connexion Internet (y compris via le portable) ?

☐ Aucun des items listés ci-dessus

☐ Ne sait pas / ne veut pas répondre

Ce ménage possède-t-il et garde-t-il des animaux dans ses locaux ?

Choisissez une des options ci-dessous.

○ OUI

○ NON

○ Ne sait pas / ne veut pas répondre

Combien de pièces (espaces fermés) ce ménage a-t-il ?

Si 10 ou plus, entrez "111". Si inconnu ou pas de réponse, saisissez "999".

_____

La cuisine se fait-elle habituellement dans la maison, dans un bâtiment séparé ou à l'extérieur ?

Choisissez une des options ci-dessous.

○ Dans le logement même

○ Autre bâtiment

○ Dehors (y compris dans cour)

○ Autre

Indiquez où se fait la cusine habituellement.

Si inconnu ou pas de réponse, saisissez "NA".

Combien de "portes" (ménages) il y a dans ce même BATIMENT (structure sous le même toit) ?

Si inconnu ou pas de réponse, saisissez "999".

Nous aimerions en savoir plus sur les matériaux de construction des ménages. Puis-je observer les matériaux de construction de votre ménage ?

Choisissez une des options ci-dessous.

○ OUI

○ NON

» MATERIELS DE CONSTRUCTION

[OBSERVEZ] Vérifiez le matériau principal du PLANCHER. Documentez l'observation.

Choisissez une des options ci-dessous.

○ Plancher NATUREL : Terre / sable

○ Plancher RUDIMENTAIRE : Planches en bois rustique

○ Plancher RUDIMENTAIRE : Bambou

○ Plancher AVEC FINITIONS : Ciment

○ Plancher AVEC FINITIONS : Céramique

○ Plancher AVEC FINITIONS : Parquet / bois poncé

○ Plancher AVEC FINITIONS : moquette

○ AUTRE

Indiquez le matériau principal du plancher.

Si inconnu ou pas de réponse, saisissez "NA".

[OBSERVEZ] Vérifiez le matériau principal du TOIT. Documentez l'observation.
Choisissez une des options ci-dessous.

○ Toit NATUREL : Chaume / feuilles de palmier

○ Toit RUDIMENTAIRE : Panneaux métalliques

○ Toit RUDIMENTAIRE : Tôles en fibrociment

○ Toit RUDIMENTAIRE : Bois rustique ou bamboo

○ Toit RUDIMENTAIRE : Plastique

○ Toit AVEC FINITIONS : Tuiles en céramique

○ Toit AVEC FINITIONS : Revêtement métallique

○ Toit AVEC FINITIONS : Dalle en béton

○ Toit AVEC FINITIONS : Tôles en fibrociment

○ Toit AVEC FINITIONS : Bambou ou bois

○ AUTRE

Indiquez le matériau principal du toit.
Si inconnu ou pas de réponse, saisissez "NA".

[OBSERVEZ] Vérifiez le matériau principal des MURS EXTERNES. Documentez l'observation.
Choisissez une des options ci-dessous.

○ Murs NATURELS : Troncs d'arbre

○ Murs NATURELS : Terre / argile

○ Murs RUDIMENTAIRES : Bois rustique

○ Murs RUDIMENTAIRES : Tôle métallique rustique

○ Murs RUDIMENTAIRES : Brique ou pierre rustique

○ Murs FINIS : Maçonnerie rêvetue (crépi)

○ Murs FINIS : Lattes en bois

○ Murs FINIS : Béton / pierre appareillée

○ AUTRE

○ PAS de murs

Indiquez le matériau principal des murs externes.
Si inconnu ou pas de réponse, saisissez "NA".

[OBSERVEZ] Combien d'ETAGES ce bâtiment a-t-il, y compris le rez-de-chaussée ?
Comptez le nombre de niveaux (étages), en incluant le rez-de-chaussée.

OBSERVATIONS ENQUETEUR

[REMERCIEZ LE PARTICIPANT] Nous sommes arrivés à la fin du questionnaire, merci beaucoup pour votre temps. Si vous avez des questions ou des préoccupations concernant les informations que vous avez partagées aujourd'hui, n'hésitez pas à contacter les personnes en charge de cette étude (voir les coordonnées dans le formulaire de consentement).

[VOS NOTES] Commentaires de l'enquêteur (optionnel) :

Si vous avez des commentaires sur une question spécifique ou sur le déroulement global de l'enquête, écrivez-les ici.

[NOTE] Contactez votre GUIDE de zone pour enregistrer les emplacements avec le GPS.

LOCALISATION MENAGE

[POUR ENQUETEUR] Indiquez le numéro du ménage interviewé, tel qu'indiqué sur la carte.

Consultez votre position sur l'app OsmAnd. Trouvez le numéro de ménage sur la carte qui est le plus proche de votre position (point bleu).

[POUR ENQUETEUR] Enregistrez la position GPS du ménage.

SORTEZ et placez-vous DEVANT LA MAISON/BÂTIMENT. Cliquez sur le bouton "Start GeoPoint" pour détecter votre position actuelle.

latitude (x.y °)

longitude (x.y °)

altitude (m)

accuracy (m)
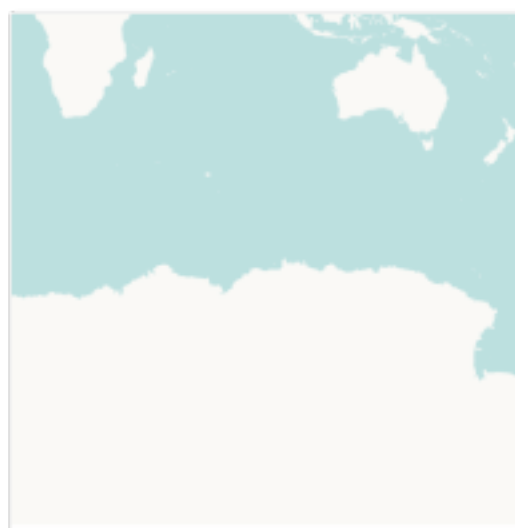
LOCALISATION EAU / TOILETTES

[POUR ENQUETEUR] Déplacez-vous jusqu'aux TOILETTES utilisées par le ménage. Une fois là-bas, enregistrez la localisation GPS des toilettes.

Placez-vous DEVANT la structure des toilettes, et cliquez le bouton "Start GeoPoint" pour détecter votre position GPS.

latitude (x.y °)

longitude (x.y °)

altitude (m)

accuracy (m)
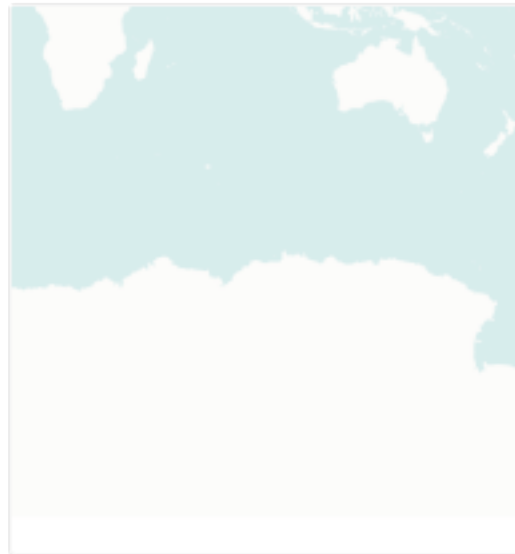
[POUR ENQUETEUR] Déplacez-vous jusqu'au POINT d'EAU utilisé par le ménage. Une fois là-bas, enregistrez la localisation GPS du point d'eau.

Placez-vous DEVANT la borne-fontaine/point de vente, et cliquez le bouton "Start GeoPoint" pour détecter votre position GPS.

latitude (x.y °)

longitude (x.y °)

altitude (m)

accuracy (m)
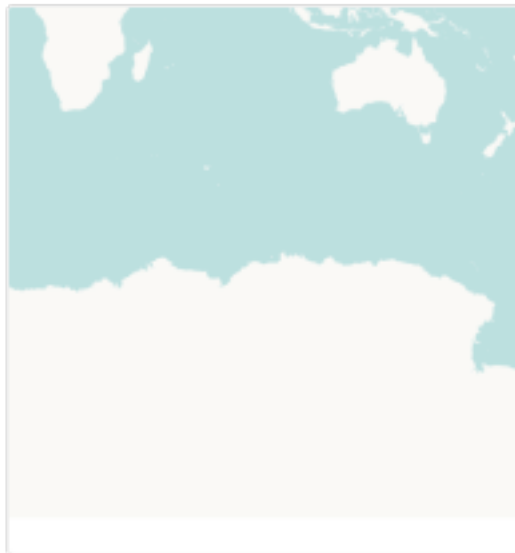
[NOTE] FIN de l'enquête : SAUVEGARDEZ le formulaire et appelez votre GUIDE. Allez au ménage suivant (RESTEZ DANS VOTRE ZONE D'ATTRIBUTION).

[NOTE] FIN de l'enquête : Appelez votre GUIDE et allez au ménage suivant (RESTEZ DANS VOTRE ZONE D'ATTRIBUTION).

Nairobi

Enumerator's name

Enter your full name

_____

Area code

Enter the code of the area where the household is located

_____

[INTRODUCE YOURSELF] Hello. My name is . I am working with the Kenya Medical Research Institute and the Swiss university EPFL. We are conducting a survey about the impacts of water, sanitation and hygiene on diarrhoea. The information we collect shall help the government and communities to plan better water and sanitation services. Your household was randomly selected for the survey. I would like to ask you some questions about your household and the people living with you. It usually takes about 45 minutes to answer to all the questions. All of the answers you give will be confidential and will not be shared with anyone other than members of our study team. It is up to you to decide if you would like to participate to the survey or not, but we hope you will agree to answer the questions since your views are very important to the study. If I ask you any question you don't want to answer, just let me know and I will go on to the next question. Also, you can stop the interview at any time. Here is an information sheet with more details on the study we are conducting [GIVE INFORMATION SHEET].
If you would like, you can also contact the person leading the survey [SHOW CONTACT DETAILS ON SHEET].

Give information sheet to interviewee and verify if he/she gives their informed consent to participate. Answer to eventual questions.

○ I (enumerator) informed the respondent about the purpose of the survey, and gave him/her the information sheet. All questions were answered satisfactorily.

○ Respondent did NOT receive the information sheet or still has questions about the survey.

Did the participant give his/her consent to participate to the survey?

If the informed consent was given, please collect the participant's signature (sign informed consent form)

○ The participant gave his/her informed consent to participate. (Proceed survey)

○ The participant did NOT give his/her informed consent to participate. (End survey)

HOUSEHOLD MEMBERS

[NOTE] Next you will have to enter the name of one or more residents. As you swipe to the right (next question), you will be asked whether or not you want to add a new name. To add a new resident, choose 'ADD'. Otherwise, choose the other option and move on to the next question.

» NAME

1

Please give me the FIRST NAMES of all the persons who usually live in your household, starting with the head of the household.

Just to make sure that I have a complete listing: there is a total of people living here, is this number correct?

If not, please go back and enter the names missing.

- ◯ Yes
- ◯ No

» PERSONAL DETAILS

WATER AND HYGIENE

WHERE do you usually obtain DRINKING water for this household?

Consider situation AT THE TIME OF THE SURVEY. Choose the option that best corresponds to the household's facility.

- ◯ PRIVATE/SEMI-PRIVATE source in dwelling or yard belonging to you or a neighbour
- ◯ PUBLIC/COMMERCIAL source located in a public space
- ◯ SURFACE water (river/lake/pond/canal)
- ◯ Prefers not to answer

More precisely, what TYPE of system usually provides DRINKING water for this household?

Consider situation AT THE TIME OF THE SURVEY. Choose the option that best corresponds to the household's facility.

- ◯ PIPED: into dwelling
- ◯ PIPED: to own yard or plot
- ◯ PIPED: to neighbour's dwelling or yard
- ◯ GROUND: tube well or borehole
- ◯ GROUND: protected well
- ◯ GROUND: unprotected well
- ◯ RAINWATER
- ◯ OTHER
- ◯ Does not know / prefers not to answer

Please specify the main drinking water source.

If unknown, or unwilling to answer, enter "NA".

More precisely, in what TYPE of facility or commerce do you usually get DRINKNG water for this household?

Consider situation AT THE TIME OF THE SURVEY. Choose the option that best corresponds to the household's facility.

- ○ TAP
- ○ DISPENSER or 'ATM'
- ○ VENDOR: water boozer or street vendor
- ○ GROUND: tube well or borehole
- ○ GROUND: protected well
- ○ GROUND: unprotected well
- ○ OTHER
- ○ Does not know / prefers not to answer

Please specify the main drinking water source.

If unknown, or unwilling to answer, enter "NA".

From what kind of commerce do you usually get DRINKING water?

Consider situation AT THE TIME OF THE SURVEY. Choose the option that best corresponds to the household's facility.

- ○ Water BOOZER
- ○ CART
- ○ BOTTLED water
- ○ SACHET water
- ○ OTHER
- ○ Does not know / prefers not to answer

Please specify the main drinking water source.

If unknown, or unwilling to answer, enter "NA".

Is this water dispenser/tap run by an AUTHORISED distributor (like the Nairobi City Water and Sewerage Company)?

Choose the option that best corresponds to the household's facility.

- ○ Yes
- ○ No
- ○ Does not know / prefers not to answer

If not located in own dwelling or yard/plot, please indicate the location of the water source.

Mark location on the printed map.

- ○ Drinking water source has been indicated on map
- ○ Does not know / prefers not to answer

Could you indicate the name of a REFERENCE POINT (religious site, market or square) close to this water source?

If unknown, or unwilling to answer, enter "NA".

How long (in MINUTES) does it take to go there, get water, and come back?
Count time in MINUTES (disconsider queuing). If unknown, or unwilling to answer, enter "999".

_____

What type of recipient do you USUALLY use to STORE your drinking water?
If more than one, indicate the MOST USED. If container has NO PROPER LID: mark "OPEN". Choose one of the options below.

○ PLASTIC: OPEN container

○ PLASTIC: CLOSED container

○ METALLIC: OPEN container

○ METALLIC: CLOSED container

○ OTHER material: OPEN container

○ OTHER material: CLOSED container

○ Does not know / prefers not to answer

If more than one recipient, please list ALL types of recipients
If container has NO PROPER LID: mark "OPEN". Choose one of the options below.

☐ NO OTHER CONTAINER

☐ PLASTIC: OPEN container

☐ PLASTIC: CLOSED container

☐ METALLIC: OPEN container

☐ METALLIC: CLOSED container

☐ OTHER material: OPEN container

☐ OTHER material: CLOSED container

☐ Does not know / prefers not to answer

In the last month, has there been any time when your household did not have sufficient quantities of DRINKING water when needed?
Choose one of the options below.

○ Yes

○ No

○ Does not know / prefers not to answer

Do you do anything to the water to make it safer to drink?
Choose one of the options below.

○ Yes

○ No

○ Does not know / prefers not to answer

What do you usually do to make the water safer to drink?
Select all mentioned.

- ☐ Boil
- ☐ Add bleach / chlorine
- ☐ Strain through a cloth
- ☐ Use water filter (ceramic / sand / composite)
- ☐ Solar desinfection
- ☐ Let it stand and settle
- ☐ Other
- ☐ Does not know / prefers not to answer

Please specify what other water treatment is used
If unknown, or unwilling to answer, enter "NA".

Yesterday (within last 24 hours) at what instances did you wash your hands?
Choose one or more options below.

- ☐ BEFORE preparing food?
- ☐ BEFORE eating?
- ☐ AFTER changing diapers?
- ☐ AFTER going to the toilet?
- ☐ Does not know / prefers not to answer

Yesterday (within last 24 hours) at what instances did you wash your hands?
Choose one or more options below.

- ☐ BEFORE preparing food?
- ☐ BEFORE eating?
- ☐ AFTER going to the toilet?
- ☐ Does not know / prefers not to answer

Do you pay for your drinking water?
Choose one of the options below.

- ○ Yes
- ○ No
- ○ Does not know / prefers not to answer

How much do you pay (approximately) for a 20-liters jerrican?
Indicate the price in KES. If unknown, or unwilling to answer, enter "9999".

We would like to learn about the places that households use to wash their hands. Can you please show me where members of your household most often wash their hands?

Choose one of the options below.

◯ Yes

◯ NO : No permission to see

◯ NO : Not in dwelling / yard

◯ NO : Other reason

» HAND WASH PLACE

[OBSERVE] Verify type of amenity.

Choose one of the options below.

◯ Fixed place

◯ Mobile amenity / hygiene utensils

[OBSERVE] Verify presence of water at the place for handwashing.

Record observation (choose one of the options below).

◯ Water is available

◯ Water is NOT available

[OBSERVE] Verify presence of soap, detergent, or another cleansing agent at the place for handwashing.

If not visible, ask if soap is available. Record observation (choose one of the options below).

◯ Soap or detergent (bar, liquid, powder or paste)

◯ Ash, mud or sand

◯ None

In average, how often do the members of your household eat street food?

Choose one of the options below.

◯ 0-1 time per week

◯ 2-4 times per week

◯ 5 or more times per week

◯ Does not know / prefers not to answer

SANITATION

WHERE is the location of the toilet facility that members of your household usually use?

Consider situation AT THE TIME OF THE SURVEY. Choose one of the options below.

- ◯ In own dwelling
- ◯ In own yard or plot
- ◯ In a neighbour's dwelling
- ◯ In a neighbour's yard or plot
- ◯ Public toilet (located in public space)
- ◯ No facility: Bush, river or 'flying toilet'
- ◯ Does not know / prefers not to answer

What TYPE of toilet facility is it, that the members of your household usually use?

Consider situation AT THE TIME OF THE SURVEY. IF NOT POSSIBLE TO DETERMINE, ASK PERMISSION TO OBSERVE THE FACILITY.

- ◯ FIXED, FLUSH/POUR FLUSH toilet
- ◯ FIXED, DRY or COMPOSTING toilet
- ◯ FIXED, HANGING toilet (over river or any open ground)
- ◯ MOBILE toilet: CHEMICAL toilet
- ◯ MOBILE toilet: FRESH FIT
- ◯ BUCKET toilet
- ◯ Other
- ◯ Does not know / prefers not to answer

Please specify the type of toilet facility.

If unknown, or unwilling to answer, enter "NA".

More precisely, to what type of SYSTEM is this toilet facility connected to?

Choose one of the options below.

- ◯ To PIPED SEWER system
- ◯ To SEPTIC TANK
- ◯ To COVERED pit
- ◯ To UNCOVERED pit
- ◯ To RIVER / OPEN GROUND
- ◯ To somewhere else
- ◯ Does not know / prefers not to answer

Please specify the type of toilet facility.

If unknown, or unwilling to answer, enter "NA".

More precisely, what is the TYPE of this toilet facility?

IF NOT POSSIBLE TO DETERMINE, ASK PERMISSION TO OBSERVE THE FACILITY.

- ◯ FRESH LIFE toilet
- ◯ VENTILATED improved pit LATRINE
- ◯ Pit LATRINE with slab, BUT without ventilation
- ◯ Pit LATRINE without slab/open pit
- ◯ COMPOSTING toilet
- ◯ Does not know / prefers not to answer

Please specify the type of toilet facility.

If unknown, or unwilling to answer, enter "NA".

If not located in own dwelling or yard/plot, please indicate the location of the facility

Mark location on the printed map.

- ◯ Toilet facility has been indicated on map
- ◯ Does not know / prefers not to answer

Could you indicate the name of a REFERENCE POINT (religious site, market or square) close to this toilet facilty?

If unknown, or unwilling to answer, enter "NA".

Please indicate where you usually go to defecate.

Mark location on the printed map: WRITE "OD" on point location.

- ◯ Place has been indicated on map
- ◯ Does not know / prefers not to answer

Please indicate how long it takes (IN MINUTES) to go to the toilet facility.

Count time in MINUTES. If unknown, or unwilling to answer, enter "999".

Has this toilet facility ever been emptied?

Choose one of the options below.

- ◯ Yes
- ◯ No
- ◯ Does not know / prefers not to answer

Where are the contents emptied to?
Choose one of the options below.

○ Treatment plant

○ Buried in a covered pit

○ Uncovered pit/bush/field/open ground

○ Surface water (river/dam/lake/pind/stream/canal/irrigation channel)

○ Other

○ Does not know / prefers not to answer

Please specify where the contents are emptied.
If unknown, or unwilling to answer, enter "NA".

Do you share this toilet facility with other households?
Choose one of the options below.

○ Yes

○ No

○ Does not know / prefers not to answer

Including your own household, how many households use this toilet facility?
If 20 or more, enter "222". If unknown, or unwilling to answer, enter "999".

By whom was this toilet facility constructed?
Choose one of the options below.

○ Self-built

○ Professional company or contract worker

○ Landlord

○ Youth group / Community-based Org.

○ Faith-based organisation

○ Other

○ Does not know / prefers not to answer

Please specify who constructed this toilet facility.
If unknown, or unwilling to answer, enter "NA".

Do you pay to use this toilet facility?
Choose one of the options below.

○ Yes

○ No

○ Does not know / prefers not to answer

In general, how clean is the toilet facility you usually use?

Choose one of the options below. Observe smell, presence of personal hygiene items on the floor and traces of excreta.

- ◯ VERY CLEAN
- ◯ CLEAN
- ◯ DIRTY
- ◯ VERY DIRTY
- ◯ Does not know / prefers not to answer

In general, is it safe for you to use this toilet facility at any time?

Choose one of the options below.

- ◯ Safe to use at any time
- ◯ Safe to use only during the day
- ◯ Unsafe to use the facility
- ◯ Does not know / prefers not to answer

SOCIO-ECONOMIC HOUSING CONDITIONS

Does your household have:

Choose one or more options below.

- ☐ Electricity?
- ☐ A radio device?
- ☐ A television?
- ☐ A smartphone?
- ☐ A computer?
- ☐ A refrigerator?
- ☐ An oven?
- ☐ A microwave?
- ☐ Internet connection of any type (incl. via smartphone)?
- ☐ None of the above
- ☐ Does not know / prefers not to answer

Does this household own and keep any livestock/animals in its premises?

Choose one of the options below.

- ◯ Yes
- ◯ No
- ◯ Does not know / prefers not to answer

How many rooms does this household have?

If 10 or more, enter "111". If unknown, or unwilling to answer, enter "999".

_____

Is the cooking usually done in the house, in a separate building, or outdoors?
Choose one of the options below.

◯ In the house

◯ In a separate building

◯ Outdoors

◯ Other

Please specify where the cooking usually is done.
If unknown, or unwilling to answer, enter "NA".

What do you use in cooking?
Choose one of the options below.

◯ Electric cooker

◯ Solar cooker

◯ Gas cooker

◯ Kerosene cooker/stove

◯ Solid fuel cooker

◯ Three stone stove/open fire

◯ Other

◯ Does not know / prefers not to answer

Please specify what you use in cooking.
If unknown, or unwilling to answer, enter "NA".

How many households are located in this same BUILDING (structure containing all rooms)?
If unknown, or unwilling to answer, enter "999".

We would like to learn about the construction materials of the households. May I observe the construction materials of your household?
Choose one of the options below.

◯ Yes

◯ No

» CONSTRUCTION MATERIALS

[OBSERVE] Verify main material of the floor of the dwelling. Record observation.
Choose one of the options below.

- ○ NATURAL FLOOR: Earth/Sand
- ○ NATURAL FLOOR: Dung
- ○ RUDIMENTARY FLOOR: Wood planks
- ○ RUDIMENTARY FLOOR: Palm/Bamboo
- ○ FINISHED FLOOR: Parquet or polished wood
- ○ FINISHED FLOOR: Ceramic tiles
- ○ FINISHED FLOOR: Cement
- ○ FINISHED FLOOR: Carpet
- ○ OTHER

Please specify main material of the floor of the dwelling.
If unknown, or unwilling to answer, enter "NA".

[OBSERVE] Verify main material of the roof of the dwelling. Record observation.
Choose one of the options below.

- ○ NATURAL ROOFING: Thatch/Palm leaf
- ○ RUDIMENTARY ROOFING: Rustic mat
- ○ RUDIMENTARY ROOFING: Cardboard
- ○ RUDIMENTARY ROOFING: Rustic wood or bamboo planks
- ○ RUDIMENTARY ROOFING: Rustic metal sheets
- ○ FINISHED ROOFING: Bamboo or wood
- ○ FINISHED ROOFING: Metallic cladding
- ○ FINISHED ROOFING: Cement fiber
- ○ FINISHED ROOFING: Ceramic tiles
- ○ FINISHED ROOFING: Concrete slab
- ○ OTHER
- ○ NO ROOF

Please specify main material of the roof of the dwelling.
If unknown, or unwilling to answer, enter "NA".

[OBSERVE] Verify main material of the exterior walls of the dwelling. Record observation.
Choose one of the options below.

- ○ NATURAL WALLS: Cane/Palm/Trunks
- ○ NATURAL WALLS: Dirt/Uncovered adobe
- ○ RUDIMENTARY WALLS: Cardboard
- ○ RUDIMENTARY WALLS: Rustic wood/plywood or bamboo
- ○ RUDIMENTARY WALLS: Rustic metal sheets
- ○ RUDIMENTARY WALLS: Stone with mud
- ○ FINISHED WALLS: Covered adobe
- ○ FINISHED WALLS: Wood planks/Shingles
- ○ FINISHED WALLS: Bricks (made of earth)
- ○ FINISHED WALLS: Cement / stone
- ○ OTHER
- ○ NO WALLS

Please specify main material of the exterior walls of the dwelling.
If unknown, or unwilling to answer, enter "NA".

_____

[OBSERVE] How many floors does the BUILDING (structure containing all rooms) have?
Count the number of floors

_____

INTERVIEWER OBSERVATIONS

[THANK PARTICIPANT] We have reached the end of the questionnaire, thank you very much for your time. If you have any questions or concerns regarding the information you shared today, do not hesitate to contact the people in charge of this study (see contact details in consent form).

_____

[FOR SURVEYOR ONLY] Comments :
If you have any specific questions, please write them here

_____

[NOTE] Please CONTACT YOUR AREA SUPERVISOR to record GPS locations

_____

LOCATE HOUSEHOLD

[FOR SURVEYOR ONLY] Enter household number indicated on the map
Enter the number attributed to the household (indicated on map)

_____

[FOR SURVEYOR ONLY] Record current GPS location: HOUSEHOLD

GO OUTSIDE AND STAND IN FRONT of THE HOUSE/BUILDING, or go next to a window. Click on 'Start GeoPoint' button to detect your current location.

latitude (x.y °)

_____

longitude (x.y °)

_____

altitude (m)

_____

accuracy (m)

_____
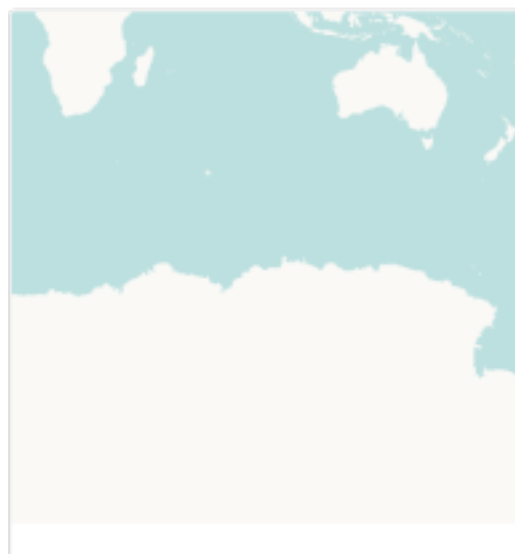
LOCATE WASH FACILITIES

[FOR SURVEYOR ONLY] Go to the location of the TOILET facility and record GPS location

Once you are in front of the facility, click on 'Start GeoPoint' button to detect your GPS location

latitude (x.y °)

_____

longitude (x.y °)

_____

altitude (m)

_____

accuracy (m)

_____
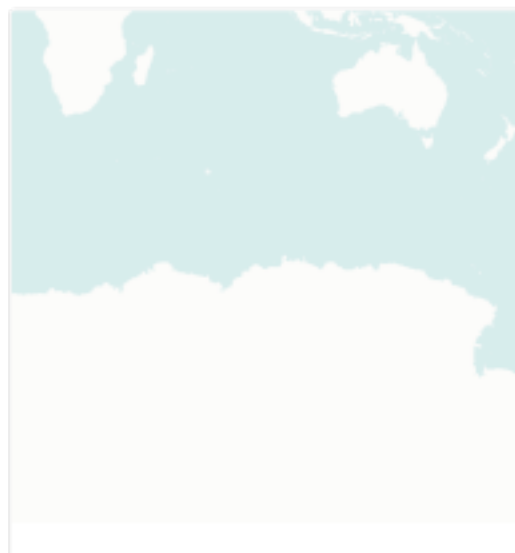
[FOR SURVEYOR ONLY] Go to the location of the drinking WATER source and record GPS location

Once you are in front of the facility, click on 'Start GeoPoint' button to detect your GPS location

latitude (x.y °)

longitude (x.y °)

altitude (m)

accuracy (m)

[NOTE] END of survey: SAVE form and move to next household (FOLLOW THE WALKING PATH INDICATED ON MAP)

[NOTE] END of survey: Call you area supervisor and move to next household (FOLLOW THE WALKING PATH INDICATED ON MAP)

Appendix 1.2: Informed consent forms

In the following pages, you will find copies of the informed consent forms used in Abidjan and in Nairobi.

FORMULAIRE DE CONSENTEMENT ÉCLAIRÉ

Titre de l'étude de recherche : Santé urbaine à Nairobi et Abidjan : prédicteurs spatiaux de maladies diarrhéiques et bénéfices des infrastructures d'eau, d'assainissement et d'hygiène

Organisations impliquées : Centre Suisse de Recherche Scientifique (CSRS, Côte d'Ivoire), École Polytechnique Fédérale de Lausanne (EPFL, Suisse) et Institut Suisse de Santé Publique et Tropicale (SwissTPH, Suisse)

Chercheurs principaux : Dr. Brama KONÉ (CSRS), Jérôme CHENAL (EPFL) et Jürg UTZINGER (SwissTPH)

Co-enquêteurs : Vitor PESSOA COLOMBO (EPFL), Akuto AKPEDZE KONOU (EPFL), Dr. Rémi JALIGOT (EPFL).

Lieu de l'étude : Abidjan (Azito et Williamsville).

Vous êtes invité à participer à une étude de recherche. L'encadré ci-dessous vous indique les éléments importants auxquels vous devez réfléchir avant de décider de participer à l'étude. Nous vous fournirons des informations plus détaillées dans les prochaines pages. Vous pouvez poser des questions sur l'une ou l'autre des informations avant de décider de participer à l'étude. Vous pouvez également parler de cette étude à d'autres personnes (par exemple, votre famille ou vos amis) avant d'accepter d'y participer.

Informations clés à prendre en compte (voir page suivante pour plus de détails)
Consentement volontaire. Vous êtes invité à participer à une étude de recherche. C'est à vous de décider si vous voulez y participer ou non. Il n'y a pas de pénalités et vous ne perdrez rien si vous décidez de ne pas participer ou si, plus tard, vous décidez d'arrêter et de vous retirer de l'étude.
Objectif. Nous voulons apprendre plus sur l'impact d'infrastructures d'eau et d'assainissement (toilettes) sur la santé. Nous pensons que ces connaissances pourraient nous aider à apprendre comment les différents types d'équipements sont utilisés. Nous voulons savoir comment ils peuvent être améliorés, adaptés ou mieux distribués en fonction des besoins locaux.
Durée. Votre partie de l'étude durera environ 30 minutes.
Procédures et activités. Nous vous demanderons de répondre à un questionnaire.
Risques. La participation à cette étude ne comporte aucun risque pour la santé.
Avantages. Votre participation peut avoir un impact positif sur votre communauté à long terme, en fournissant des informations importantes aux professionnels de la planification.
Alternatives. La participation est volontaire et l'alternative est de ne pas participer.

1. Objectif de la recherche

En Côte d'Ivoire, de nombreuses personnes souffrent de la diarrhée, en particulier les enfants. Nous voulons trouver des moyens d'empêcher que cela ne se produise. Nous pensons que vous pouvez nous aider en nous parlant des pratiques d'hygiène en général, et des services d'eau, d'assainissement et de santé qui sont à votre disposition. Nous voulons connaître les différentes façons dont les gens accèdent aux services d'eau et aux toilettes, et comment les gens réagissent aux épisodes de diarrhée. Le principal objectif de l'étude est de comprendre comment des villes et des communautés comme la vôtre peuvent être construites de manière à protéger les gens contre les maladies causant la diarrhée.

2. Description de la recherche

Cette recherche porte sur différentes communautés d'Abidjan et de Nairobi (au Kenya, où nous menons aussi cette étude). Votre communauté a été sélectionnée pour cette étude parce qu'il existe ici des types très différents d'équipements d'eau, d'assainissement et d'hygiène que nous aimerions étudier. Votre ménage a été sélectionné par tirage au sort pour participer à cette recherche. Nous pensons que votre expérience en tant que résident de cette communauté peut contribuer grandement à notre compréhension de l'impact d'équipements d'eau et toilettes sur le risque de diarrhée.

Si vous acceptez de participer à cette recherche, vous serez invité à répondre à un questionnaire. Il faut environ 30 minutes pour répondre à toutes les questions. Si vous ne souhaitez pas répondre à une des questions de l'enquête, vous pouvez la sauter et passer à la question suivante. Nous appliquons ce même questionnaire dans différents ménages situés dans cette zone. Le questionnaire vous sera lu, et vous pourrez répondre à haute voix. Ce sont des questions sur différents aspects des équipements d'eau et de toilettes que vous utilisez, ainsi que sur votre état de santé et vos habitudes d'hygiène. Il y aura aussi des questions sur l'état de santé récent de vos enfants et sur leur fréquentation scolaire. La localisation de votre ménage sera enregistrée, parce que cette information est très importante pour l'étude. Les informations individuelles qui seront collectées resteront confidentielles.

Les résultats de cette étude seront partagés et discutés avec d'autres professionnels intéressés par l'évaluation des services d'eau, d'assainissement et d'hygiène, et leurs impacts sur la diarrhée, comme les urbanistes ou les fonctionnaires publics. Nous ne partagerons aucune information personnelle lors de ces discussions.

3. Dommages potentiels, blessures, inconforts ou désagréments, risques

Il n'y a aucun risque pour votre santé si vous acceptez de participer. Le seul inconvénient peut être le partage d'informations personnelles. Toute information que vous nous communiquez sera protégée et accessible uniquement à l'équipe de recherche (personnes listées à la page 1).

4. Avantages potentiels

À long terme, votre participation peut avoir un impact positif sur votre communauté : par exemple, les informations obtenues avec cette étude peuvent contribuer à la planification d'infrastructures à Abidjan, y compris votre quartier.

5. Confidentialité

Nous ne communiquerons pas les informations vous concernant à des personnes extérieures à l'équipe de recherche (personnes listées à la page 1). Toute information vous concernant et concernant votre ménage portera un numéro, au lieu de votre nom. Seule l'équipe de recherche connaîtra votre numéro et nous garantissons la protection de ces informations. Toutes les informations personnelles que nous collecterons seront gardées privées, protégées conformément aux lois de la Côte d'Ivoire et de la Suisse. Aune personne externe à l'équipe de recherche ne pourra identifier les participants.

6. Participation

Votre participation à cette recherche est entièrement volontaire. C'est à vous de décider si vous voulez y participer ou non. Vous pouvez aussi changer d'avis plus tard et cesser de participer même si vous avez accepté plus tôt. Le questionnaire contient des questions sur vos enfants, si vous en avez. La réponse à ces questions dépend du consentement des parents/tuteurs des enfants. Tous les participants à l'étude recevront une copie du présent formulaire de consentement (à conserver).

7. Financement

Cette étude est financée par le Fonds National Suisse (FNS) pour la recherche scientifique.

8. Contact

Pour toute question ou préoccupation concernant cette étude, vous pouvez contacter le coordinateur de l'étude :

Centre Suisse de Recherches Scientifiques en Côte d'Ivoire (CSRS)
01 BP 1303 Abidjan 01
Adiopodoumé – Km 17, Route de Dabou

Téléphone :
(+225) 07 78 26 81 21

E-mail :
secretariat@csrs.ci

9. Options de consentement et de signature

_____ **J'accepte** que mes informations soient utilisées et partagées sans mon consentement supplémentaire, avec ou sans identifiants, par les enquêteurs du projet intitulé "*Santé urbaine à Nairobi et Abidjan : prédicteurs spatiaux de maladies diarrhéiques et bénéfices des infrastructures d'eau, d'assainissement et d'hygiène*".

_____ **Je n'accepte pas** que mes informations soient utilisées et partagées sans mon consentement supplémentaire, avec ou sans identifiants, par les enquêteurs du projet intitulé "*Santé urbaine à Nairobi et Abidjan : prédicteurs spatiaux de maladies diarrhéiques et bénéfices des infrastructures d'eau, d'assainissement et d'hygiène*".

(*Pour un usage futur*) Insérez vos initiales sur les phrases de votre choix, puis signez ci-dessous :

_____J'autorise le stockage des informations recueillies dans le cadre de cette étude pour les utiliser dans de futures études de recherche.

_____Je n'autorise pas le stockage des informations recueillies dans le cadre de cette étude en vue de leur utilisation dans de futures études de recherche.

SIGNATURE DU PARTICIPANT / DE LA PARTICIPANTE

_____
Nom complet (en caractères d'imprimerie)

_____   _____
Signature   Date

_____ _____
Adresse permanente

(UNIQUEMENT SI ANALPHABÈTE) SIGNATURE DU TÉMOIN DE LA PROCÉDURE DE CONSENTEMENT
(Peut être un parent du participant ou participante, mais ne peut pas être une personne impliquée dans l'étude).
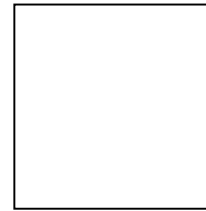
J'ai été témoin de la lecture précise du formulaire de consentement au participant / à la participante potentiel-le, et le/la participant-e a eu l'occasion de poser des questions. Je confirme que le/la participant-e a donné son consentement librement.

Nom du témoin   _____

Signature du témoin   _____

Date   _____
                         Jour/mois/année

Empreinte (pouce) participant-e

SIGNATURE DE LA PERSONNE QUI ADMINISTRE LE CONSENTEMENT
(Doit être signé uniquement par un enquêteur ou un membre du personnel autorisé à administrer le consentement)

J'ai lu avec précision la fiche d'information au/à la participant-e potentiel-le, et je me suis assuré au mieux de mes capacités de lui expliquer les trois points suivants :

1. Un questionnaire sera appliqué, avec des questions sur différents aspects des services d'eau et d'assainissement utilisés par le ménage du participant, et sur l'état de santé et les habitudes d'hygiène du répondant et, le cas échéant, de ses enfants.
2. Toutes les informations recueillies dans le cadre de cette enquête resteront confidentielles et ne seront accessibles qu'à l'équipe de recherche ; le participant peut trouver ou supprimer ses informations personnelles à tout moment.
3. Les résultats de cette recherche seront partagés et discutés dans un format anonyme avec les professionnels des domaines de l'urbanisme et la santé publique.

Je confirme que le/la participant-e a eu la possibilité de poser des questions sur l'étude, et que toutes les questions posées ont reçu une réponse correcte. Je confirme que la personne n'a pas été contrainte de donner son consentement et que celui-ci a été donné librement et volontairement. Une copie du présent FCE a été fournie au/à la participant-e.

_____
Nom de la personne administrant le FCE

_____   _____
Signature de la personne administrant le FCE   Date

INFORMED CONSENT FORM

Title of the Research Study: Urban health in Nairobi and Abidjan: Spatial predictors of diarrhoeal diseases and benefits of water, sanitation & hygiene infrastructures

Involved Organisations: Kenya Medical Institute of Research (KEMRI, Kenya) and École Polytechnique Fédérale de Lausanne (EPFL, Switzerland)

Principal investigator: Dr. Hellen MEME (KEMRI)

Lead investigator Jérôme CHENAL (EPFL)

Co-investigators: Vitor PESSOA COLOMBO (EPFL), Dr. Rémi JALIGOT (EPFL), Dr. Evans AMUKOYE (KEMRI), Fred Orina (KEMRI), Michael OTIENO (Nairobi City Government).

Study location: Nairobi (Mukuru kwa Njenga and Mathare).

You are being asked to take part in a research study. The box below tells you important things you should think about before deciding to join the study. We will provide more detailed information below the box. Please ask questions about any of the information before you decide whether to participate. You may also wish to talk to others (for example, your family, friends, or your doctor) about this study, before agreeing to join.

Key Information for You to Consider (see next page for more details)

Voluntary Consent. You are being asked to participate to a research study. It is up to you whether you choose to participate or not. There are no penalties and you will not lose anything if you decide not to joint or if after you join, you decide to quit.

Purpose. We want to know more about hygiene practices in general, and about water, sanitation and healthcare services that are available to you. We believe this knowledge might help us to learn how different types of water, sanitation and healthcare services are used, and how they can be improved, adapted or better distributed according to local needs.

Duration. Your part of the study will last about 45 minutes.

Procedures and Activities. We will ask you to answer to a questionnaire.

Risks. There are no health risks in participating to this study.

Benefits. There will be no direct benefit to the participants. However, your participation is very important to help us find out more about how to prevent different diseases related to water, sanitation and hygiene in your community and also other locations.

Alternatives. Participation is voluntary and the only alternative is to not participate.

---

1. Purpose of the Research:

In Kenya, many people suffer from diarrhoea, especially children. We want to find ways to stop this from happening. We believe that you can help us by telling us about hygiene practices in general, and about water, sanitation and healthcare services that are available to you. We want to learn about the different ways that people access water and sanitation services in the community, and how people react to episodes of diarrhoea. We want to know more about local practices because this knowledge might help us to learn how different types of water, sanitation and healthcare services are used, and how they can be improved, adapted or better distributed according to local needs. The main goal of the study is to understand how cities and communities like yours can be built in a way that protects people from diarrhoeal diseases like cholera or dysentery.

2. Description of the Research:

This research comprises different communities in Nairobi and Abidjan (Côte d'Ivoire, where we are also carrying this study). Your community was selected for this study because there are very different types of water, sanitation and hygiene facilities that are available here, that we would like to study. Your household has been selected by chance to take part in this research. We feel that your experience as a resident of this community can contribute much to our understanding and knowledge of local concerns related to water and sanitation, and to the causes of diarrhoea.

If you accept to take part in this research, you will be asked to answer to a questionnaire. It takes about 45 minutes to answer to all the questions. If you do not wish to answer any of the questions included in the survey, you may skip them and move on to the next question. We are applying this same questionnaire in different households located in this area, to understand how this community deals with water and sanitation issues, and to which extent diarrhoea affects you. The questionnaire will be read to you and you can say out loud the answer you want me to write down. For most of the questions, we will ask you to choose one answer among several possibilities (multiple choice questionnaire), and only a few will be open questions. These questions will be about different aspects of water and sanitation services that you use, and about your recent health status and hygiene habits. There will also be questions about your children's recent health status and their school attendance. The location of your household will also be recorded, because this information is very important to the study. All this information will give us a chance to understand more about the causes of diarrhoea. The information recorded is confidential.

In each participating community we applied the questionnaires, we will come back to present the first (preliminary) results of the study. During this occasion, we will provide food and beverages to the participants. The results of this study will also be shared and discussed with other professionals interested in evaluating water, sanitation and hygiene services, and their impacts on diarrhoea, like urban planners or public officials. We will not share any personal information in any of these discussions.

3. Potential Harm, Injuries, Discomforts or Inconvenience, Risks:

There is no health risk to you if you agree to participate. The only inconvenient may be sharing personal information. Any information that you share with us will be protected and accessible only to the research team (investigators listed in page 1).

4. Potential Benefits:

There will be no direct benefit to the participants. However, your participation is very important to help us find out more about how to prevent different diseases related to water, sanitation and hygiene in your community and also other locations.

5. Confidentiality:

We will not be sharing information about you to anyone outside of the research team (investigators listed in page 1). Any information about you and your household will have a number on it, instead of your name. Only the research team will know what your number is and we will lock that information up with a lock and key. This means that any information that you give us will be stored in a secured facility in KEMRI's offices in Nairobi, and in EPFL's offices in Lausanne. All personal information that we will collect will be kept private, protected according to the laws of Kenya and Switzerland. Any publication resulting from this study will contain only anonymised information, so that nobody can identify you or your household.

6. Reimbursement:

You will not be provided any financial compensation to take part in the research.

7. Participation:

Your participation in this research is entirely voluntary. It is your choice whether to participate or not. Also, you may change your mind later and stop participating even if you agreed earlier. The questionnaire includes questions about your children, if you have any. Answering to these questions depend on the consent of the children's parents/guardians. All study participants will be given a copy of the present consent form (signed and dated) to keep.

8. Funding:

This study is sponsored by the Swiss National Science Foundation (Switzerland).

9. Authorisations:

This research has been approved by the competent scientific and governmental authorities of Kenya.

10. Contact / complaints:

Until your data is made anonymous, you can ask us what personal data we hold about you, you can ask us to change or delete your personal data. If you are unhappy with the way in which we have handled your personal data, you have the right to file a complaint.
For any questions pertaining to rights as a research participant, the contact person is: The Committee Chairperson, KEMRI Scientific and Ethics Review Unit, P. O. Box 54840-00200, Nairobi; Telephone numbers: 020-2722541, 0717719477; Email address: seru@kemri.org

11. Consent and signature options:

…………… **<u>I agree</u>** for my information to be used and shared without my additional consent, with or without identifiers, by the investigators of the project entitled "*Urban health in Nairobi and Abidjan: Spatial predictors of diarrhoeal diseases and benefits of water, sanitation & hygiene infrastructures*".

…………… **<u>I do not agree</u>** for my information to be used and shared without my additional consent, with or without identifiers, by the investigators of the project entitled "*Urban health in Nairobi and Abidjan: Spatial predictors of diarrhoeal diseases and benefits of water, sanitation & hygiene infrastructures*".

(*For future use*) Please initial the sentences that reflect your choices, and then sign below:

_____ I authorize the storage of data collected as a part of this study for use in future research studies.

_____ I do not authorize the storage of data collected as a part of this study for use in future research studies.

With regard to future research studies done on stored data that has a link to my personal identity:

_____ I do not wish to be notified by investigators in the event of research findings of possible importance to my family members or myself.

_____ I wish to be notified by investigators in the event of research findings of possible importance to my family members or myself. I agree that my current principal investigator may use any appropriate identifier (name or current address) to locate me in the future.

SIGNATURE OF PARTICIPANT

_____
Printed Name of Participant

_____   _____
Signature of Participant   Date

_____
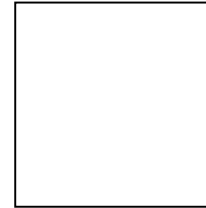**Permanent Address of Participant**

I have witnessed the accurate reading of the consent form to the potential participant, and the individual has had the opportunity to ask questions. I confirm that the individual has given consent freely.

Print name of witness   _____

Signature of witness   _____

Date   _____

          Day/month/year   *Thumb print of participant*

SIGNATURE OF INDIVIDUAL ADMINISTERING CONSENT
(Can only be signed by an investigator or staff approved to administer consent)

I have accurately read out the information sheet to the potential participant, and to the best of my ability made sure that the participant understands that the following will be done:

1. A questionnaire will be applied, with questions about different aspects of water and sanitation services used by the participant's household, and about recent health status and hygiene habits of the respondent and, if applicable, of their children.
2. All information collected in this survey will be kept confidential and will be accessible only by the research team; the participant can find or delete their personal information at any time.
3. The results of this research will be shared and discussed in an anonymised format with the participating communities, the scientific community and the local public officers.

I confirm that the participant was given an opportunity to ask questions about the study, and all the questions asked by the participant have been answered correctly and to the best of my ability. I confirm that the individual has not been coerced into giving consent, and the consent has been given freely and voluntarily. A copy of this ICF has been provided to the participant.

_____
Printed Name of Administering Individual

_____   _____
Signature of Administering Individual   Date

Appendix 2.1: Reclassification of urban pixels

Figure A illustrates the rationale behind the reclassification of urban pixels (300 × 300 m), based on the levels of demographic density and night illumination. Three thresholds were established for these two statistical series, corresponding to: (i) first decile; (ii) median; (iii) last decile. These thresholds allowed to classify each pixel into 4 classes of demographic density and night illumination (1 to 4, with "4" corresponding to the highest values, i.e., within the last decile of the series). Urban pixels with a density class higher than its illumination class were considered "precarious".
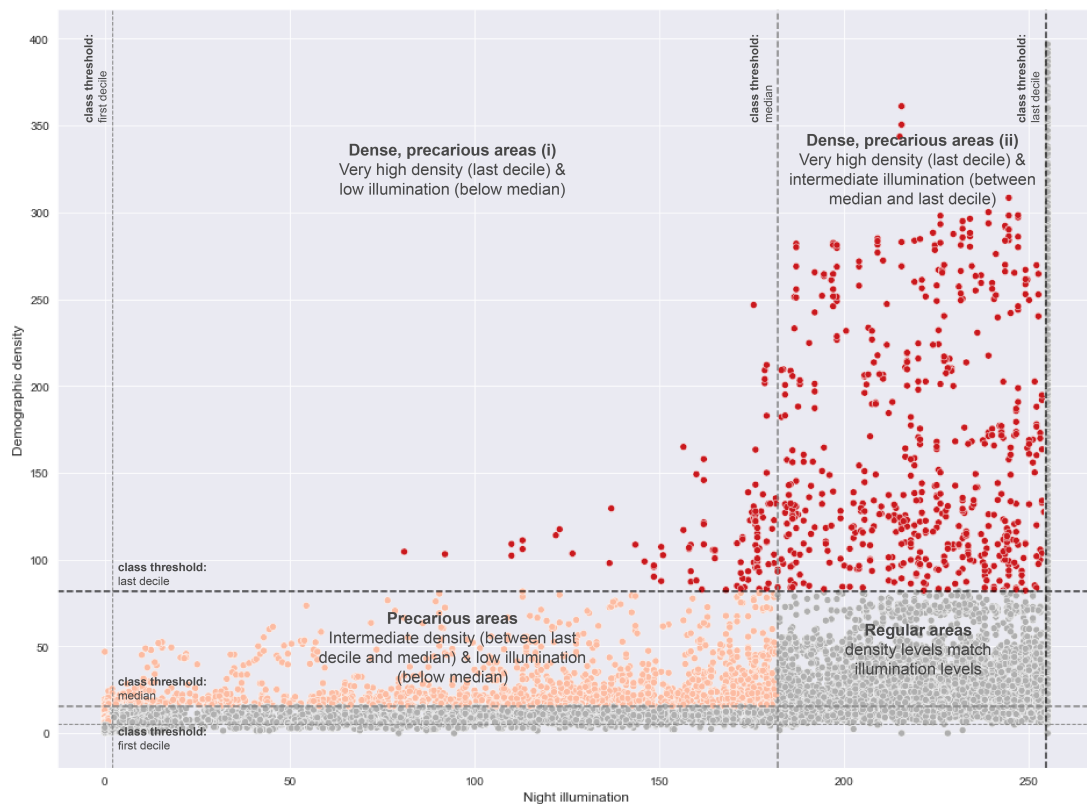

Figure A

Appendix 2.2: Results of the weighted OLS regression done with a pre-selection of control variables

Table A shows the results of the weighted OLS regression done with a pre-selection of control variables. The regression used the cluster weights provided by the DHS and was run with the 267 spatial units included in the study. The pre-selection of control variables was done based on the literature, including features that have been associated with diarrheal diseases (as explained in Section 2.2). Considering the extremely poor performance of variables related to climatic conditions and hygiene facilities, we opted to exclude them from the analysis. Only the variables related to water, sanitation and women's education were retained as control variables.

Table A

Pre-Selected Control Variables	Variance Inflation Factor	Weighted OLS (DHS Cluster Weights) $R^2 = 0.059$/AIC = 46.45 Jarque-Bera Test for Normality of Errors: 31.090 ($p < 0.001$) Breusch-Pagan Test for Heteroskedasticity: 4.152 ($p = 0.656$)		
		Coef.	Std. error	Prob.
Constant	-	0.448	0.079	0.000
% of the population with access to basic water facilities [1]	1.468	0.074	0.067	0.270
% of the population with access to basic sanitation facilities [1]	1.970	−0.254	0.076	0.001
% of the population with access to safe hygiene facilities [1]	1.363	−0.034	0.054	0.535
% of the female population who never went to school	1.744	−0.261	0.079	0.001
Mean accumulated precipitation (monthly values) in 2012	1.260	0.049	0.063	0.436
Mean maximal temperature (monthly values) in 2012	1.165	0.0008	0.091	0.993

[1] Definitions of "basic" and "safe" WASH facilities based on the WHO & UNICEF Joint Monitoring Programme.

Appendix 2.3: Characteristics of the excluded and retained spatial units

Table B shows the general characteristics of the excluded and retained spatial units, based on the variables provided by the DHS surveys. The reader must note that it was not in the scope of this study to analyse these differences. In fact, our analysis focused on human settlements, which requires the presence of urban land cover "patches"—which is why we only included spatial units containing at least 1 pixel (300 × 300 m) classified as "urban". Globally, the 84 units that did not meet the inclusion criteria (explained in Section 2.5) showed similar prevalence rates of diarrhea, as well as access to basic water facilities, to the 267 units retained for the analysis. As for the levels of access to basic sanitation and women's education, the values were significantly different.

Table B

Statistic	Prevalence of diarrhea (%)		Access to basic [1] water (%)		Access to basic [1] sanitation (%)		Women who never went to school (%)	
	Excluded	Retained	Excluded	Retained	Excluded	Retained	Excluded	Retained
	obs. (n = 84)	obs. (n = 267)	obs. (n = 84)	obs. (n = 267)	obs. (n = 84)	obs. (n = 267)	obs. (n = 84)	obs. (n = 267)
Median value	16.7	16.7	67.1	87.4	3.7	18.5	83.0	50.0
Mean value	17.8	18.2	61.0	78.1	6.2	27.0	80.1	51.0
Standard deviation	10.9	12.6	27.7	24.9	7.9	26.1	15.4	22.2
Minimum value	0.0	0.0	0.0	0.0	0.0	0.0	34.8	4.2
Maximum value	42.9	56.3	100.0	100.0	33.3	100.0	100.0	100.0

[1] Definitions of "basic" and "safe" WASH facilities based on the WHO & UNICEF Joint Monitoring Programme.

Appendix 2.4: Observed prevalence of diarrhoea among children under-under five in a selection of Ivoirian cities (2012)

Table C shows the prevalence of diarrhea among children under the age of five years in 2012, in a selection of cities across Côte d'Ivoire. These cities were selected based on their population sizes and, also, based on their role as "connectors" within the urban system of Côte d'Ivoire (Fall & Coulibaly, 2016). The data was aggregated spatially: the mean cluster-level prevalence of diarrhea was calculated by selecting the specific clusters that were located in each city. There was no apparent association between city size (suggested here by the number of clusters comprised in each city) and the mean prevalence of diarrhea; although Abidjan showed the highest maximum value (54.5%), small- and medium-sized towns such as Daloa and Douékoué showed much higher, mean prevalence rates of diarrhea (26.0 and 43.8%, respectively).

Table C

Location	Size and category [1]	N° Clusters	Mean Prevalence of Diarrhoea [2]	Standard Deviation of Sample	Range (Min. and Max. Values)
Abidjan	Large ("global connector")	48	21.4	13.8	0.0/54.5
Yamoussoukro	Medium ("global connector")	5	14.5	11.0	0.0/29.4
San Pédro	Medium ("global connector")	4	14.5	13.2	0.0/28.6
Bouaké	Medium-large ("regional connector")	16	12.1	9.4	0.0/33.3
Korhogo	Medium ("regional connector")	6	12.5	11.5	0.0/29.4
Daloa	Medium ("regional connector")	4	26.0	7.5	20.0/36.8
Katiola	Small ("local connector")	2	5.9	8.3	0.0/11.8
Douékoué	Small ("local connector")	1	43.8	-	-
Divo	Small ("local connector")	1	15.4	-	-

[1] "Connector" categories based on the work by Fall and Coulibaly (2016).
[2] Mean values resulting from aggregated DHS data.

Curriculum Vitae

CV Vitor PESSOA COLOMBO

Informations personnelles

Naissance / Lieu	07.11.1987 / São Paulo, Brésil
Nationalités	Brésil + Suisse
E-mail	vitor.pessoacolombo@epfl.ch
Adresse	Rue du Valentin 45, 1004 Lausanne, CH

Expertise

Domaines	Urbanisme; quartiers informels; santé en ville; Afrique; Amérique Latine
Compétences	Systèmes d'information géographique (SIG); relevés de terrain; analyses spatiales

Position actuelle

Depuis 03.2019

École Polytechnique Fédérale de Lausanne (Lausanne, Suisse)
Chercheur, chargé de cours

- **Enseignement SIG :** chargé du cours 'Planification urbaine dans le Sud', visant à introduire la prise de décision basée sur l'évidence donnée par l'usage des SIG

- **Recherche en urbanisme :** thèse de doctorat sur les déterminants spatiaux du risque de maladies diarrhéiques dans les quartiers informels de villes Africaines, basée sur des analyses spatiales empiriques (géo-données collectées dans différents sites)

- **Enquêtes ménage :** collecte de données géo-référencées de 1'714 ménages habitant différents quartiers informels situés à Abidjan (Côte d'Ivoire) et Nairobi (Kenya) - travail fait avec la collaboration de 28 enquêteurs formés et supervisés par moi

- **Cartographie :** relevé de terrain détaillé et géo-référencé de l'environnement bâti de quatre quartiers informels à Abidjan (Côte d'Ivoire) et Nairobi (Kenya)

Expérience professionnelle

07.2020 - 12.2020

Consultant indépendant
Spécialiste SIG

- **Restructuration urbaine à Djibouti :** élaboration de différents scénarios de restructuration d'un quartier précaire à Djibouti, et analyse de leur impact social sur la base de données géo-référencées des ménages habitant la zone

02.2018 - 01.2019
03.2016 - 09.2017

Università della Svizzera Italiana (Mendrisio, Suisse)
Architecte, collaborateur scientifique

- **Planification urbaine :** élaboration de bases de données géo-référencées et anaylses spatiales pour guider les stratégies de développement urbain du Canton du Tessin

- **Recherche en SIG :** adaptation de différents instruments de cartographie pour le relevé de géo-données dans les quartiers précaires de villes du Sud

- **Enseignement géographie urbaine :** assistant d'enseignement pour le cours Master «Géographie Urbaine», en contribuant avec l'analyse de case d'étude au Brésil

02.2014 - 02.2016

Agile Atelier d'Architecture (Lutry, Suisse)
Architecte

- **Principaux projets :** conception et exécution d'une crèche à Renens; étude de faisabilité pour la transformation d'une friche industrielle en zone résidentielle à Bulle

Volontariat

02.2016 - 06.2020

ONG Teto (São Paulo, Brésil)
Spécialiste SIG, coordinateur technique

- **Cartographie de quartiers précaires :** élaboration d'une méthode de collecte de géo-données sur l'environnement bâti de quartiers précaires à São Paulo; supervision technique d'une équipe de 10 volontaires (collecteurs de données)

Éducation

03.2019 - 09.2023* *estimé*	**École Polytechnique Fédérale de Lausanne (Suisse)** *Doctorat en Architecture et Sciences de la Ville* - Sous la direction de Jérôme Chenal & Jürg Utzinger - 2 publications d'articles de recherche - 4 présentations orales dans des conférences internationales - 2 workshops transdisciplinaires (Nairobi et Cotonou, avec autorités locales)
08.2011 - 07.2013	**Accademia di Architettura di Mendrisio (Suisse)** *Master of Science in Architecture* - Diplôme avec M. Burkhalter & C. Sumi: *Paral·lel – Urban Acupuncture in Barcelona* - École d'été WISH (Workshop on International Social Housing), avec Harvard GSD
09.2006 - 07.2009	**École Polytechnique Fédérale de Lausanne (Suisse)** *Bachelor of Science in Architecture*

Compétences linguistiques

Portugais	Langue maternelle
Français	Bilingue
Anglais	Niveau avancé
Italien	Niveau avancé
Espagnol	Niveau basique

Compétences informatiques

QuantumGIS	Niveau avancé
ArcGIS	Niveau avancé
Python	Niveau avancé
AutoCAD	Niveau avancé
R	Niveau basique

Sélection de publications

04.2023 Article de recherche	**Pessoa Colombo, V.**, Chenal, J., Orina, F., Meme, H., Koffi, J.A.A., Koné, B., Utzinger, J. Environmental determinants of access to shared sanitation in informal settlements: a cross-sectional study in Abidjan and Nairobi. Infectious Diseases of Poverty. DOI: 10.1186/s40249-023-01078-z
03.2023 Chapitre de livre	Pereira Santos, A., **Pessoa Colombo, V.**, Heider, K. & Rodriguez Lopez, M. *A VGI comparison framework based on citizen participation: comparing volunteered data acquisition methods on informal settlements for two large cities in Latin America.* In: López, S. (eds) Socio-Environmental Research in Latin America. The Latin American Studies Book Series. Springer, Cham. DOI: 10.1007/978-3-031-22680-9_12
06.2022 Article de recherche	**Pessoa Colombo, V.**, Chenal, J., Koné, B., Bosch, M., Utzinger, J. *Using open-access data to explore relations between urban landscapes and diarrhoeal diseases in Côte d'Ivoire.* International Journal of Environmental Research and Public Health, DOI: 10.3390/ijerph19137677
11.2018 - 10.2019 Recontre scientifique et édition d'un livre de résumés	**Pessoa Colombo, V.**, Bassani, J., Torricelli, G. P. & Alves de Araújo, S., eds. (2019). *Participatory Mapping: Technology and Citizenship. Conference Proceedings of the International Meeting «Mapping Techniques and Citizenship» (São Paulo, 2018).* 1st edition. Editora da Faculdade de Arquitetura e Urbanismo da Universidade de São Paulo, São Paulo. ISBN: 978-85-8089-174-4
06.2018 Présentation orale	**Pessoa Colombo, V.** (2018). *Citizen Mapping: Using Common Geospatial Technologies to Map Informal Settlements in São Paulo, Brazil.* In: 2018 International Tech4Dev Conference : Voices of the Global South, 27-29 June 2018, Lausanne, Switzerland