Universidad de Oviedo
Universidá d'Uviéu
University of Oviedo

Facultad de Medicina y Ciencias de la Salud

Departamento de Medicina

Programa de Doctorado en Ciencias de la Salud

Doctoral thesis

Environmental risk factors associated to outbreaks of water and vector-borne diseases in urban areas of sub-Saharan Africa

Alexandre Zerbo

Oviedo 2022

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RESUMEN DEL CONTENIDO DE TESIS DOCTORAL

1.- Título de la Tesis	
Español/Otro Idioma: Español/Otro Idioma: **Riesgos medioambientales asociados a brotes de enfermedades hídricas y vectoriales en áreas urbanas del subsahara**.	Inglés: **Environmental risk factors associated to outbreaks of water and vector-borne diseases in urban areas of sub-Saharan Africa.**

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RESUMEN (en español)

Contexto

La región del África subsahariana (SSA) ha experimentado desigualdades socioeconómicas urbanas debido a la urbanización. Estos procesos han dado como resultado la creación de áreas urbanas pobres que carecen de instalaciones básicas de saneamiento, agua e higiene (WASH) y problemas de salud pública subyacentes, como la propagación de enfermedades transmitidas por el agua y por vectores (WBD), (VBD).

Aunque estos riesgos para la salud varían en esta región africana de un país a otro e incluso dentro de las ciudades. Hay muchas similitudes en la dinámica de propagación y los factores de riesgo asociados con WBD y VBD en el entorno urbano.

Comprender los diferentes riesgos ambientales que enfrentan los habitantes urbanos de SSA sigue siendo esencial, ya que podría ayudar a prevenir y controlar la propagación de WBD y VBD.

Métodos

En este sentido, se realizaron revisiones de la literatura para capturar los riesgos ambientales de WBD y VBD. Posteriormente, también se realizó un análisis estadístico y modelos de sistemas con algunos datos sobre la cobertura de WASH y la carga de salud asociada y complejidades dinámicas. Finalmente, se han realizado propuestas de marco conceptual para comprender mejor la exposición a estas enfermedades y también para mejorar las intervenciones públicas en áreas urbanas de SSA.

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Resultados

Este estudio ha revelado una escasez de datos de salud en las áreas urbanas del África subsahariana, particularmente en áreas pobres como los asentamientos informales. Cuando estos datos existen, son pocos o muy agregados.

Además de eso, la urbanización en SSA crea una ecología urbana que conduce a la propagación de VBD's como infecciones virales por *Aedes* que tienen transmisión urbana. Además, este entorno urbano tiene condiciones WASH inadecuadas que favorecen la propagación de WBD's como el cólera.

De hecho, el 7,75 % (CI95% 5,99-9,7 %) de todas las muertes por enfermedades diarréicas en el África subsahariana se atribuyen a WASH inadecuada con una tasa de atribución de factores de riesgo (RFA) del 95,93 % (CI95% ,94-98,24 %).

Además, la complejidad dinámica de los factores de riesgo de VBD's en áreas urbanas del África Subsahariana podría analizarse en términos de sistema en lugar de elemento aislado por herramienta dinámica del sistema, como el ciclo causal y los diagramas de existencias y flujos.

Finalmente, las áreas urbanas podrían dividirse en tres áreas de transmisión de enfermedades: Pública, doméstica e individual. Estas áreas podrían incorporarse en marcos de exposición para WBD y enfermedades fecal-orales (FOD), y también en el marco conceptual DPSEEA (Driving force-pressure-State-Exposure-Effect-Action) para WBD.

Conclusión

Este estudio revela la necesidad de realizar más investigaciones sobre la salud urbana de SSA, ya que esta región es la que se urbaniza más rápidamente en el mundo. Esta escasez de datos de salud urbana esconde una carga de enfermedades que podrían prevenirse.

Dividir el área urbana de transmisión de enfermedades en áreas públicas, domésticas e individuales e incorporar estas áreas en modelos de exposición y marcos conceptuales es útil para comprender mejor las especificidades de la exposición a WBD y FOD.

Estos modelos de exposición y marcos conceptuales podrían mejorar la capacidad de detectar y controlar el riesgo de propagación de WBD y FOD. Además, podría permitir intervenciones de salud pública específica y efectiva en áreas urbanas en SSA.

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RESUMEN (en Inglés)

Background

The sub-Saharan Africa (SSA) region has experienced urban socioeconomic inequalities due to urbanization. These process have resulted in creation of poor urban areas lacking basic sanitation, water and hygiene (WASH) facilities and subjacent public health issues such as the spread of water and vector-borne diseases (WBD's), (VBD's).

Even though these health risks vary across this African region, from country to country, and even within cities, there are many similarities in the spread dynamic and risk factors associated with WBD's and VBD's in the urban environment.

It remains essential to understand the different environmental risks faced by SSA urban dwellers as it might aid in preventing and controlling the spread of WBD's and VBD's.

Methods

In this regard, literature reviews have been conducted to capture environmental risks of WBD's and VBD's. Then a statistical analysis and system modellings have been performed with some data on WASH coverage and associated health burden, and the dynamic complexities. Finally, propositions of conceptual framework have been done to better understand the exposome of these diseases and also to improve public interventions in urban areas of SSA.

Results

This study has revealed a paucity of health data in SSA urban areas, particularly in poor ones such as informal settlements. When these data exist, there are few or so aggregated.

In addition, urbanization in SSA creates an urban ecology that is conducive to the spread of VBD's such as *Aedes*-viral infections which have an urban transmission. Furthermore, this urban environment has inadequate WASH conditions that favor the spread of WBD's such as cholera.

Indeed, 7.75% (CI95%, 5.99-9.7%) of the total deaths due to diarrheal diseases across SSA are attributed to unsafe WASH with a Risk Factor Attribution (RFA) percentage of 95.93% (CI95%, 91.94 – 98.24%).

The dynamic complexity of VBD's risk factors in SSA urban areas could be analysed in term of system rather than isolated element by system dynamic tool such as causal loop and stock and flow diagrams.

Finally, urban areas could be divided into three areas of diseases transmission: Public, domestic and individual. These areas could be incorporated in exposome frameworks for WBD's and faecal-oral diseases (FOD's), and also in DPSEEA (driving force-pressure-state-exposure-effect-action) conceptual framework for WBD's.

Conclusion

This study reveals the need to conduct further research in urban health of SSA, since this region is the fastest urbanizing region in the world. This paucity of urban health data hides a burden of diseases which could be prevented.

The division of urban areas of disease transmission into public, domestic, and individual areas, and the incorporation of these areas into exposome models and conceptual frameworks is helpful to achieve a better understanding of the specificities in exposure of WBD and FOD.

These exposome models and conceptual frameworks could improve the ability to detect and control the risk of WBD and FOD spread. Furthermore, this could enable targeted and effective public health interventions in urban areas of SSA.

SR. PRESIDENTE DE LA COMISIÓN ACADÉMICA DEL PROGRAMA DE DOCTORADO

EN Ciencas de la Salud

Aknowledgments

“Quis enim te discernit quid autem habes quod non accepisti si autem accepisti quid gloriaris quasi non acceperis‘ Propterea gratia ago Domino per quem omnia facta sunt.

À la mémoire de ma très regrettée grand-mère Suzanne et de mon oncle Gaston.

Toutes les lettres ne sauraient trouver les mots qu’il faut, tous les mots ne sauraient exprimer ma gratitude, mon amour, mon respect et ma reconnaissance, aussi c’est tout simplement que…

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À Victoria Gonzaléz, Yaneli Rivera, Marta Sánchez, Ana ordax, Carolina Tuya, Deluzan Tito, Susana Menédez et ma filleule Ornella.

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List of abbreviations

ARK: Africa Risk Knowledge.

CDC: Center for Disease Control.

CLD: Causal Loup Diagram.

DEC: Diethylcarbamazine.

DENV: Dengue Virus.

DHF: Dengue Hemoragic Fever.

DPSEEA: Drinving forces- Pressures-States-Exposure-Effect-Actions.

FAECI: FAEcal Contamination Indicator.

FOD: Faecal-Oral Disease.

GBD: Global Burden of Disease.

HIV: Human Immonodeficiency Virus.

IHME: Institute for Health Metrics and Evaluation.

JMP: Joint Monitoring Programme.

LF: Lymphatic Filariasis.

MDA: Mass Drug Administration.

NCD: Non-Communicables Disease.

PRISMA: Preferred Reporting Items for Systematic Reviews and Meta-analyse

RFA: Risk Factor Attribution.

SFD: Stock and Flow diagram.

SSA: Sub-Saharan Africa.

UNICEF: United Nation International Children's Emergency Fund.

UNISDR: United Nation Internationa Strategy for Disaster Reduction.

VBD: Vector-borne diseases.

WASH: Water, Sanitation and Hygiene.

WBD: Waterborne disease.

WHO: World Health Organization.

1. INTRODUCTION

"*The future of global health is urban health*" Gerry Stimson

1. Introduction

1.1. Sub-Saharan African region and urbanisation

Sub-Saharan Africa (hereinafter referred as SSA) is geographically the part of the African continent located south of the Sahara, it is made up of all African countries and territories that are totally or partially south of this desert [1] [2]. This region includes 46 or 48 countries of the 54 African countries, depending on whether the list of the United Nations or that of the World Bank is consulted [3]. Although the history and geography of these countries are different, there are similarities in the SSA region's urbanization trajectories and co-evolving risk profile [4].

The phenomenon of urbanization is defined as a *"a complex socio-economic process that transforms the built environment, converting formerly rural into urban settlements, while also shifting the spatial distribution of a population from rural to urban areas."* [5]

An approximate 4 billion people, or 55% of the world population, were living in urban areas in 2018, with this proportion predicted to increase to 68% by 2050 [4]. The world is becoming increasingly urbanized and global urban population is increasing by approximately 220,000 people daily, 65 million people each year. This growth in urbanization is occurring mainly in Asia and SSA [6]. The world has witnessed rapid urbanization, as evidenced by the global growth in the proportion of the population in urban areas. The percentage of people residing in urban areas has increased from 43% to 54% between 1990 and 2015 [5].

SSA homes the lowest proportion of urban population with 472 million, approximatively 40% of its total population. However, this region has an annual urban population growth rate of 4.1%, while the global rate is 2% consequently SSA is the world's fastest urbanizing region [7]. In 2015, there were thousands of cities in SSA region: two megacities of 10 million inhabitants, three cities with 5–10 million and 41 cities with 1–5 million [6] . Over the next 30 years African city-inhabitants will outweigh rural area dwellers [7].

Although Africa is the least urbanized continent, the sub-Saharan region has seen rapid urbanization. It has been estimated that the urban population will increase from 40% to

56–62% between 2010 and 2050 [4] [5]. Indeed, in 1950 the percentage of SSA's urban population was 11% of the total population, this percentage grew to 39% in 2015 and it is expected that nearly 60% of the population of the African continent will reside in urban areas by 2050 [7].

Over half of the world's population live in cities, and of this population living in urban areas, nearly 1.2 billion are precarious informal settlement dwellers [8]. Rapid urbanization associated with unplanned urban growth is experienced predominantly in Asia and Africa, resulting in impediments to sustainable development and human health [9]. In fact, in many SSA countries, urbanization does not always go hand in hand with population wealth, thereby generating health inequalities due to socioeconomic disparities [10].

Figure 1 shows the size of the urban population in the capital cities of Sub-Saharan Africa in the year 2020. SSA has the highest proportion of urban population living in informal settlements, 56% in 2015 according to the United Nations Human Settlements Programme (UN-Habitat). The continuing urbanization of this region, mostly due to rural-to-urban migration and natural population growth of cities, leads to increase population density and involves the expansion of informal settlements into areas vulnerable to hazards [11]. However, the growth rate of these poor urban areas exceeds the capacity of government and municipalities to respond to the basic needs of informal settlers. Figure 1 shows the evolution of the urban population, as a percentage of the total population, of SSA from 1960 to 2020.

The flows of people from the countryside and other urban areas to urban informal settlements and vice versa, and the natural growth balance of birth and death, create a dynamic process for increasing or decreasing the population density of informal settlements [12]. In addition to the increasing rate of urban informal settlements, the rapid urbanization brings challenges including inadequate infrastructures and inaqequate basic services, and unplanned urban sprawls which make urban space more vulnerable to disasters [13].

In addition, urbanization in SSA is associated with the production of interconnectivity and accumulation of risks which compromise the living and working conditions of habitants particularly in urban informal settlements. Mainly, poverty is a subjacent reason that forces people to live in dangerous and polluted urban areas: steep-side hills, flood plains, hillside, waste dumps, and close to hazardous industries. They live there without any legal property title and experience the fear of eviction [14]. Informal settlers mostly dwell in areas with limited space, close to where there is work available. The future of global health is urban health [15] and the city is supposed to offer better opportunities in education, employment, services and health, but the available data reveals a different reality [16].

There is uniformly a range of risks associated with health hazards including poor quality housing, overcrowding, air pollution, contaminated drinking water, inadequate sanitation, just to name few ones [17]. Thus, many urban health problems, particularly in Africa, stem from environmental conditions, and it is therefore important to monitor these environmental health risks.

However, urban statistics come more from aggregated data considering a city as a whole and this can mask problems, especially since health status in the city is not evenly distributed. Therefore, disaggregated data, i.e. data on intra-urban environmental health, especially on water-borne (hereinafter referred as WBD) and vector-borne diseases(hereinafter referred as VBD), would be very likely helpful in the understanding of these health problems. Ultimately this effectively would target interventions for a "leave no one behind" health policy in SSA.

Data on health risk outcomes and health determinants are unavailable for most SSA cities, or are too aggregate to be useful when they do exist. This lack of data likely hides a large burden of health, which could be prevented in some cases, and this paucity compromises the efficiency of response intervention in urban areas.

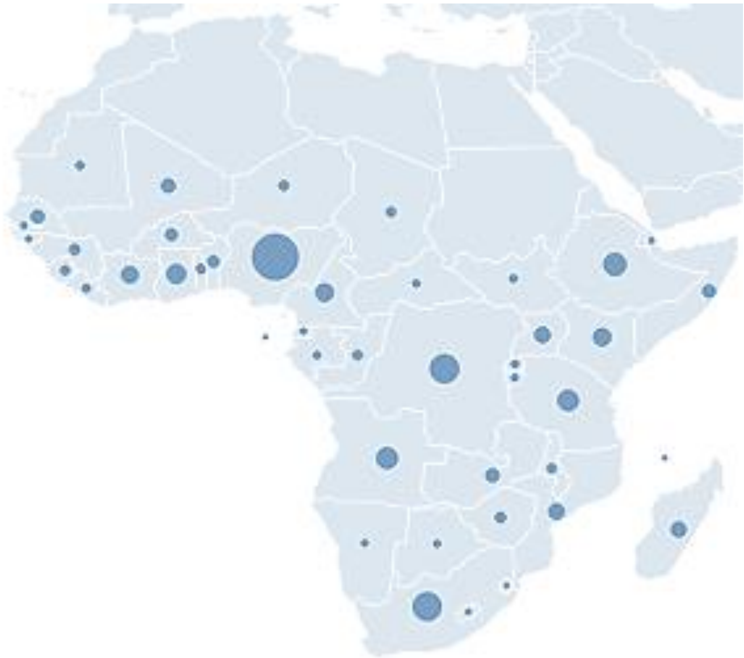


Figure 2: Size of urban population of capital cities of Sub-Saharan Africa in 2020. Source: Grapminder [*https://www.gapminder.org*](https://www.gapminder.org)

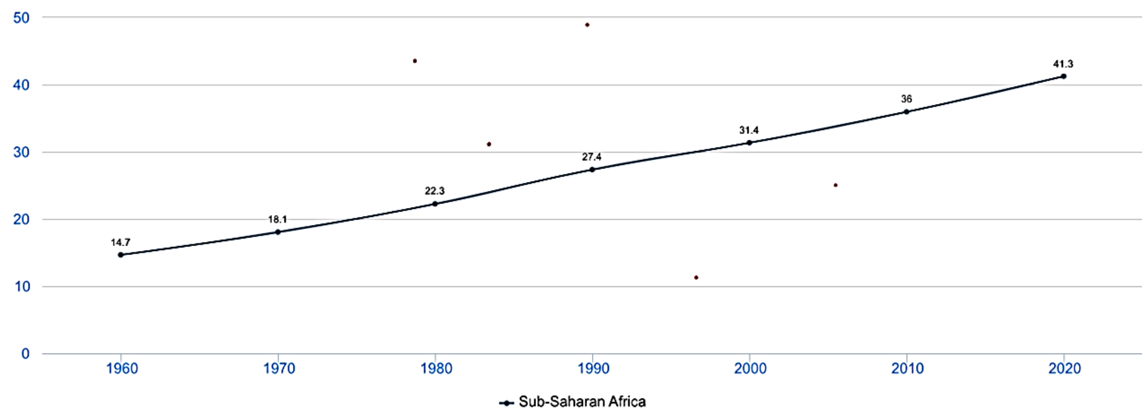


Figure 3: Urban population (percentage of total population) of Sub-Saharan Africa from 1960 to 2020; Source: World Development Indicators, World Bank. [*https://databank.worldbank.org/source/world-development-indicators*](https://databank.worldbank.org/source/world-development-indicators)*.*

1.2. Vulnerability and elements of health risk in sub-Saharan African poor urban areas

SSA has experienced increasing urbanization that has not kept pace with improvements in public health [18]. Public health challenges, which are mainly associated with migration and the creation of poor areas like informal settlements, threaten the development of cities [19]. Indeed, rapid and unplanned urbanization generates poor urban areas where living conditions, such as unsanitary housing, inadequate sanitation and hygiene, and unsafe drinking water, exacerbate the transmission of communicable diseases and pose a threat to public health [20]. The thesis is focus on informal settlement as example for poor urban areas.

The main elements of health risk and vulnerability in poor areas of sub-Saharan Africa are shown in Figure *3.*

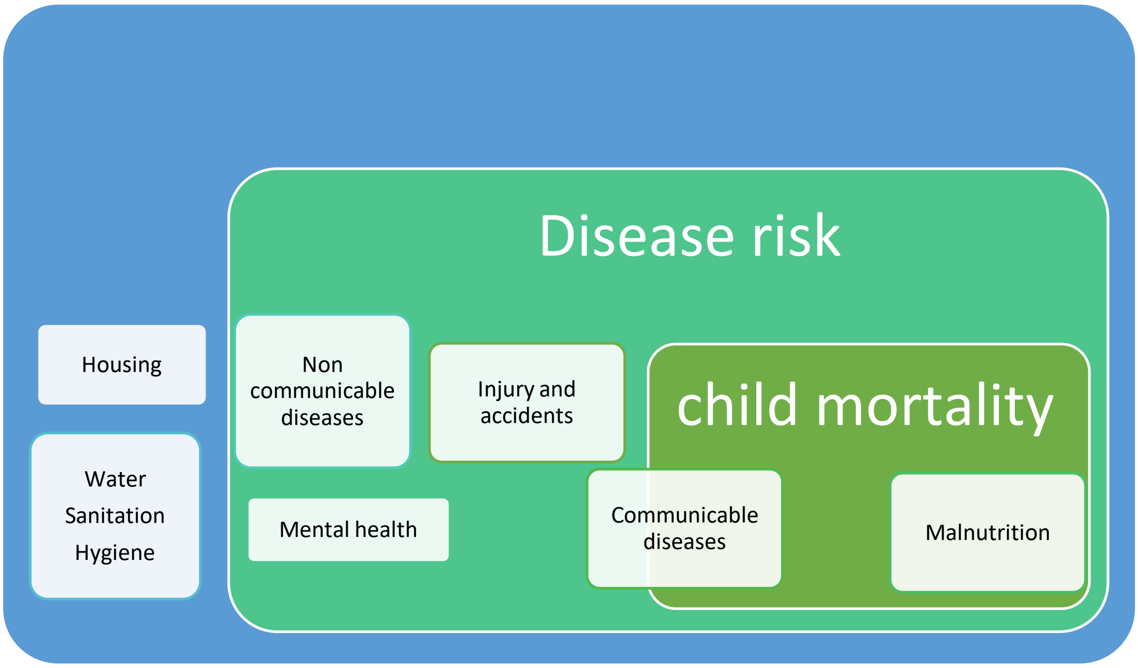


Figure 4: Main elements of health risk and vulnerability in poor areas of sub-Saharan Africa. Source: Own elaboration.

Therefore, disease problems are especially common among socially disadvantaged people and poverty is a major determinant of the global burden of disease. Increasing rates of poverty creates health inequalities which lead to deeper deprivation and generates the vicious circle of the poverty trap [21].

Hazard and vulnerability interplay to create specific risk conditions which are dynamic, geographically and socially specific [22]. Extreme poverty, inadequate social service, insecurity, crime, and high levels of unemployment are characteristics which interact in urban informal settlements [23].

Urban risks can be considered in intensive, extensive and everyday risk categorization. For the UN Office for Disaster Risk Reduction (UNISDR), the everyday risks endanger in aggregate more people than catastrophic events. Because the cumulative everyday hazards induce more victims than large disasters [24], there are some risks which lead to events too small to be considered intensive risks. These risks are those from everyday hazards that cause premature death and injury, or economic loss; and it is these everyday risks that are especially relevant to urban areas.

A wide range of risks from everyday hazards to health risks are faced by poor urban populations due to their living conditions. Indeed, everyday risks are the type of risks that vulnerable people are permanently exposed to; in their workplace, home, and neighborhood, including for disease-causing agent or vectors, chemical pollutants and physical hazards [25]. People living in rural areas are also exposed to the risk of such hazards, but it is the densely populated, overcrowded poor urban area like informal settlements that are particularly at risk and threatened [14].

The neighborhood effects are factors affecting community health regardless of individual household factors, they include pervasive effects existing across the living area of a community [12] [26]. Moreover, informal settlements are spaces where the neighborhood effects related to poor sanitation, overcrowding, poor housing, physical hazard, pollution, and poverty expose the dwellers to everyday health risks and keep them in a “risk trap”. The neighborhood effects occurring in informal settlements intensify health risks and generate specific health determinant.

1.2.1. Housing, water, sanitation and hygiene

Informal settlements are comprised of improvised dwellings made from scrap materials, such as polythene and plywood sheet or corrugated metal sheets. Houses are made with materials that can burn easily, such as wood, thatch and cardboard – all these can generate risks of domestic fires which can spread, especially when homes are packed tightly together [14]. Moreover, houses are crowded with little privacy, there could be air pollution due to toxic smoke and particulate matters from cooking and heating in a poorly-ventilated close space.

Furthermore, informal settlers are not on the urban household list or in official municipality census because they are considered illegal. Added to that, they are constantly exposed to crime and violence and live in constant fear of eviction and insecurity which creates stress [27]. Also, the unsafe water, unsanitary conditions, poor housing, overcrowding, and hazardous location are the living and working conditions of these poor urban areas. This can also create health vulnerabilities particularly among women, elderly, disabled and children [28].

SSA is a region with the highest proportion of urban households lacking water piped to premises and toilet connecting [25]. Informal settlements in the Sub-Saharan urban area mostly do not have lavatories or piped water. The environment is contaminated by pit-latrines and water supplies inclined to contamination.

Additionally, there is no good system of drainage in street and lanes, which are often muddy with the stagnant pool after rains and this environment is favourable to feed disease vectors. Besides, there are not many safe playing spaces for children or relaxing spaces for adults [12].

1.2.2. Disease risks

The inadequate sanitation and lack of potable water creates an environment with risks of infectious diseases like water-borne disease and vector-borne diseases [29]. Moreover, because of the lack of good sanitation, these risks may be higher in urban settlements. Indeed, infectious diseases related to poor sanitation and hygiene practices are the main causes of mortality and morbidity in an urban informal settlement [12].

Diarrhoeal diseases, worm infections, and other infectious diseases spread via contaminated water – confounded by water scarcity – gives families difficulty having basic hygiene around their homes [30]. Indeed, the neighborhood sometime generates conditions propitious for cholera outbreak [31].

Piles of rubbish in urban areas are feeding grounds of parasites and vectors of diseases [32]. *Aedes* mosquito is adapted to informal settlements; and exposes the residents to dengue fever, and emerging infectious disease worldwide [33]. In addition, the overcrowded conditions of informal settlements are favourable for transmission of tuberculosis and spread of Ebola when Ebola outbreak strikes [34].

The informal settlement dwellers are mostly young and mobile and this increases the incidence of HIV [35]. Lack of financial resources leads informal settlers, particularly young women, to adopt risky sexual behaviour and increase their exposure to HIV. For instance, a study on HIV risks in urban poor SSA concludes that HIV prevalence is higher among urban poor areas than urban non-poor areas [36].

The inhabitants of poor urban areas in Africa, particularly children, face a lack of sufficient food and poor nutrition [27]. Indeed, studies on food insecurity reveal a high rate in informal settlements, for example a rate of 85% in households in an informal settlement of Nairobi and 74% for Addis-Ababa [37].

Usually, informal settlement dwellers can only afford pre-cooked food from a street vendor and this type of food covers only 20% of their calorie needs. Consequently, there is malnutrition [38]. Under-nutrition is a leading cause of child mortality in SSA [39]. Besides, unhealthy living conditions have drawbacks on the growth of children, that affect their psychomotor and cognitive abilities and their nutritional status [27]. Meantime, malnutrition leads to stunted growth and is associated with recurrent diarrhoea [37].

Children residing in informal settlements have a high rate of stunting compared to children from other urban areas and rural areas [40]. The breastfeeding rate is low in informal settlement settings [41]. Exclusive breastfeeding up to the sixth month, while partial breastfeeding from the sixth to the 23rd month, has been shown to reduce mortality from diarrhoea and pneumonia in children [12].

The African continent is the one with the highest proportion of children and young people, 41% of the population were under fifteen years old in 2015 [42].

This great proportion of children has implications in exposure to urban risk. Indeed, children have vulnerabilities due to their physiology and psychology. Diarrhoea and pneumonia are the main cause worldwide of under-five child mortality [43]. And children growing up in informal settlements are at high risk [12]. Moreover, children are more vulnerable when they immigrate from rural areas to urban informal settlements, maybe because of lack of immunity for their new environment in this poor urban setting [40].

The epidemiology transition of disease creates a change in the pattern of health and disease in the SSA region. The more people become urbanized the more they change their lifestyle. There is a nutrition transition from a traditional rural diet which is more vegetable-based to fast and processed food and harmful use alcohol and smoking, and also a sedentary lifestyle [44]. Indeed, urbanization and industrialization may be the cause of this transition from infectious disease mortality to non-communicable diseases (hereinafter referred as NCD) like cardiovascular diseases [45].

Despite the fact that NCDs are poorly documented in SSA informal settlements, the lack of access to health care, and the management (treatment and control) of NCDs are a huge problem [46]. The poor purchasing ability of urban informal settlement dwellers limits their access to health care and puts them at high risk for complications from NCDs – it can also set them on the path of downward spiral of ill-health and financial distress leading to a poverty trap [47].

In many low-income country's urban areas, psychosocial health problems are a major cause of morbidity and mortality among adolescent and young adults. It has also been noticed that there are lots of behavioural and emotional problems among children living in informal settlements [12], [48].

As the life and conditions of work are very stressful in informal settlements, the propensity to have stress and then psychological disorders are high [48]. Depression, alcohol abuse, drug abuse, suicide, and interpersonal violence are examples of psychosocial health problems which occur in many cities [49].

The poor quality of housing (overcrowded), living environment (noise, lack of sanitation, garbage collection) and non-environmental factors (inadequate income, insecurity, the constant threat of eviction) create stress which is the underlying cause of many psychosocial disorders [48].

Many accidental injuries are attributed to poor quality and overcrowded housing; accidental fire, burns and scalds occur in overcrowded shelters partly because of the use of flammable materials which increases the risk of accidental fires. There is also a high rate of road traffic accidents [50]. Furthermore, there is a high rate of paediatric burns due to the cooking methods in informal settlements comparatively to non-informal settlements [40]. Besides, more than half of all injury-related deaths are caused by assault [51].

There is an increasing incidence of road traffic accidents due to the increase in number of motorcycles. The users of these vehicles are more injury-prone than car drivers, and motorcycles are much more of a threat to the poor who are more likely to be pedestrians, than to the wealthy who are more likely to be car passengers [30], [45].

1.3. Determinats of vector-borne diseases in sub-Saharan urban areas

VBDs represent more than 17% of all infectious diseases and put over half of the world's population at risk, resulting in more than 1 million annual deaths according to WHO [52] [53]. Furthermore, the poorest countries in tropical and subtropical regions bear the heaviest burden of VBDs [52]. Ill health and disability due to VBDs impact the work and household wealth of the affected people, resulting in adverse consequences on the socio-economic development of these countries [54].

The28wim28ee 4 shows the main conditions that influence the spatial spread of VBDs, such as the determinants related to environment, the vector, the pathogen agent, the epidemiology of the disease and social determinats .

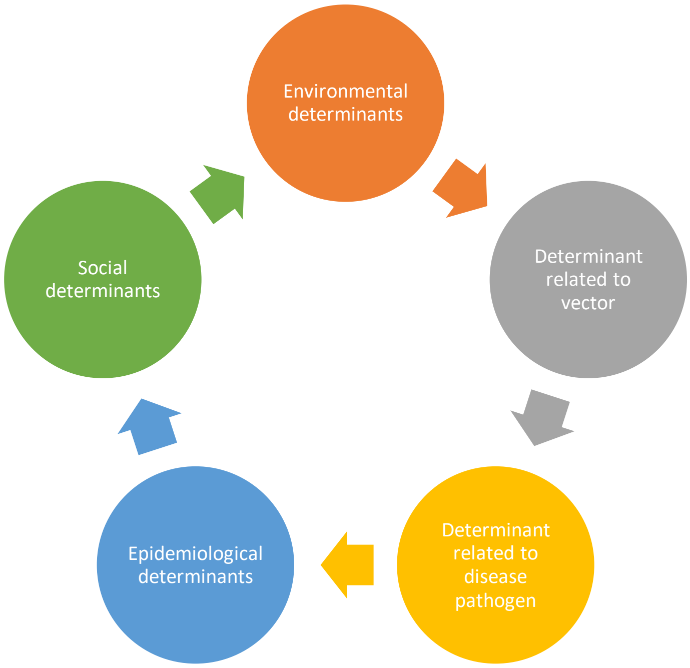


Figure 5:Vector-borne diseases determinant in sub-Saharan Africa urban areas. Source: Own elaboration.

Social determinants and unplanned urbanization intensifies environmental changes and globalization. This, in turn, will modify the epidemiological pattern of VBDs. Besides, the (re)emergence of vector-borne tropical diseases, such as *Aedes*-borne diseases, is favored by not only an environmental change in vector ecosystems, but also explosive demography in urban centers [55], [56].

Figure 5 shows the main factors responsible for the emergence and resurgence of *Aedes*-borne viral infections in the sub-Saharan African urban areas, particularly dengue, *chikungunya*, and *Zika*, have globally emerged and re-emerged during the last decades [57]. Unplanned urbanization can also intensify conditions that favor vector proliferation and dissipation [58]. Investigation of the risk factors and morbidity rates of these arbovirus infections is essential because the world is becoming increasingly globalized and pathogens do not respect geographical limits.

The greatest risk for human health comes from the ability of arboviruses to adopt an urban transmission cycle, resulting in the potential infection of urban vectors by other emerging or unknown viruses [59]. Dengue fever, *chikungunya*, *Zika*, and yellow fever are viral infections transmitted by *Aedes*, which shows an urban transmission cycle and (re)emergence, and, therefore, are a threat to the health of the sub-Saharan urban population.

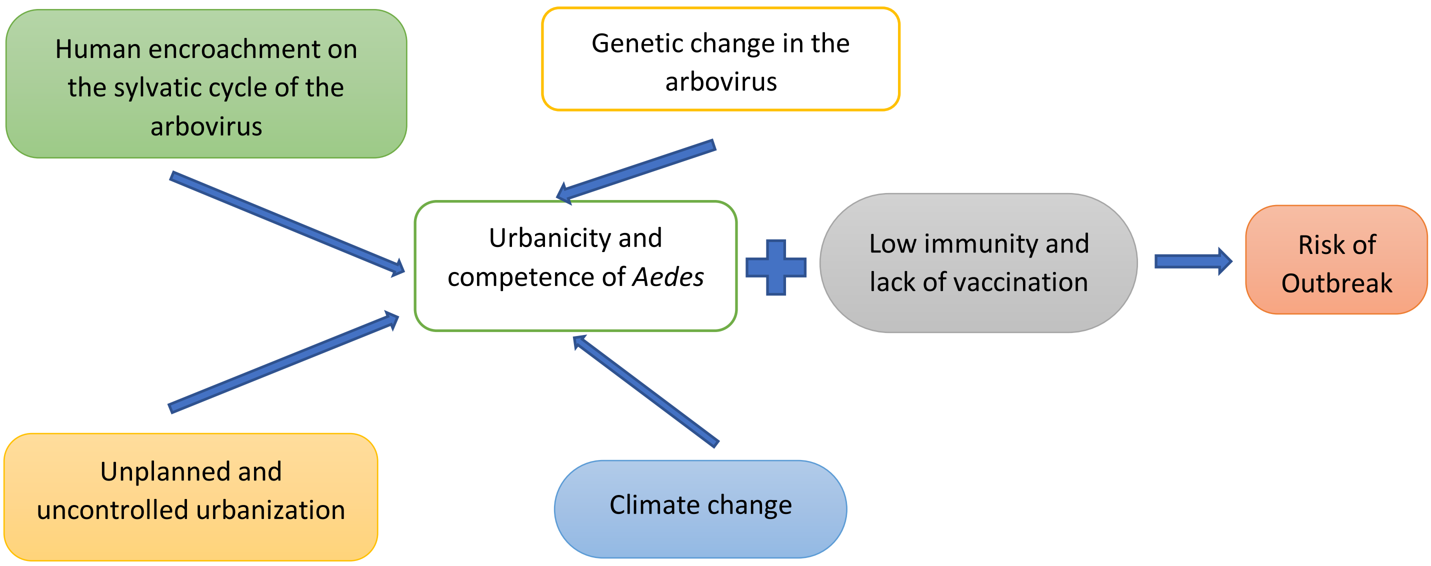


Figure 6:Main factors responsible for the emergence and resurgence of Aedes-borne viral infections in the sub-Saharan African urban areas. Source: Own elaboration.

1.3.1. Social and environmental determinants

In urban areas, vulnerability to disease is a function of the interactions of many social determinants, including socioeconomic status, place of residence, race, ethnicity, gender, and education [60] [61].

There are many health-related heterogeneities in cities, and living conditions are different among different cities and different precincts in the same city [62]. This results in differently distributed exposure to *Aedes*-borne diseases. Consequently, informal settlers and wealthy city residents experience different risk pathways. Indeed, in urban areas, the overcrowding and promiscuity of people increase the risk of disease outbreak [62]. Moreover, urbanization growth can result in the development of informal settlement areas with non-immune populations crowding where the *Aedes* spp. Populate [55].

Poverty is a key social determinant in the propagation of *Aedes*-borne diseases. Indeed, poverty is closely linked to the spread of *Aedes*-borne diseases, particularly through its social expression as poor housing and environmental conditions [63]. Moreover, the burden of these diseases affects economic productivity due to morbidity and maternal-foetal/child health issues [56]. As a corollary of *Aedes*-borne diseases, disabilities, stigmatization, risk of social exclusions, and disruption may exist in local urban endemic communities [64]. Therefore, these may keep urban dwellers in a ‘‘poverty trap.”

Changes in the urban environment may lead to the (re)emergence of some VBDs. Indeed, many rural pathogens have (re)emerged, as they have now adapted to the urban environment [62]. The life cycle of some arbovirus vectors is sensitive to environmental factors, such as water, soil, and air.

Relative humidity, rainfall pattern, and particularly temperature are major parameters of environmental suitability of vectors and potential for *Aedes*-borne disease transmission [65]. As an ectotherm, *Aedes* exhibits a physiology that depends on ambient temperature. Besides, this climatic factor directly affects mosquito survival, vector competence, biting rate, and epidemiology of *Aedes*-borne viral infections [66]. Furthermore, vector competence varies spatially with climatic factors, such as relative humidity and temperature [67].

Due to high population density, the urban environment provides favorable grounds for the spread of epidemics [55]. Poor urban areas are particularly vulnerable to *Aedes*-borne diseases; the reason for this may be environmental degradation, crowding houses, and poor sanitation due to inadequate garbage collection and disposal, thereby creating vector breeding sites [68]. Climate change intervenes by factoring in ‘‘a complex interactive web of an interacting ecosystem that might affect the ecology of the host, parasites, and vectors over both time and space [69].” Climate change affects the burden and spread of infectious diseases, especially arboviral diseases. The population with dengue fever may rise from 1.5 billion in 1990 to 5–6 billion by 2085 in response to climate change [70].

Even at a very local scale, microclimate variation can trigger vector or intermediate host proliferation [69]. However, the (re)emergence of *Aedes*-borne diseases should be attributed to not only climate change, but also the combined factors of poverty and urbanization [71].

1.3.2. Vector, pathogen and disease determinant and burden

Expansion of the population at risk of *Aedes*-borne diseases, including dengue, yellow fever, *Zika*, and *chikungunya*, is associated with the spread of two key vectors, including *Aedes aegypti* and *A. albopictus*. Besides, human movements and the presence of a suitable environment are the main factors of the spread of these vectors [72].

Subtropical and tropical regions, including the SSA countries, show a high degree of suitability for *A. aegypti* and/or *A. albopictus* [67]. *A. aegypti* is native to the African forest, whereas A. albopictus is native to Asia, and their expansion is facilitated by their adaptation to urban areas and a change in their nature from zoophilic to anthropophilic [73]. These vectors spread and re-emerge in the urban areas of tropical, subtropical, and temperate zones [74]. Furthermore, these mosquitoes lay their eggs in manmade water containers [75]. Additionally, oviposition is a key determinant in the urban transmission cycle of arboviruses.

A. aegypti is confined to warm urban environments where it proliferates in manufactured containers around and inside houses. This vector is mainly an indoor settler with short flight dispersion of approximately a few hundred meters[76]. Additionally, it performs anthropophilic daytime bites and is highly competent for the spread of the dengue, *chikungunya*, *Zika*, and yellow fever viruses [74].

A. albopictus, in contrast, prefers the same urban ecology, but can also adapt to rural or suburban settings. It also proliferates in man-made or natural containers. Furthermore, it bites not only humans, but also some other mammals and birds, and shows moderate vector competence for the dengue, *Zika*, *chikungunya*, and yellow fever viruses [74].

A. aegypti shows a greater predilection for urban areas than *A. albopictus*. As they may be sympatric, the competition between *A. aegypti* and *A. albopictus* may lead to competitive displacement or coexistence, which increases the susceptibility to viral pathogens [67] [77]. Furthermore, vector competition modifies the epidemiology of *Aedes*-borne viral infections.

The difference in *Aedes* vector ecophysiology results in the development of different ecological and thermal niches and therefore the varied distribution of transmission risk [74]. *A. albopictus* exhibits a thermal optimum of 26 ºC and can undergo diapause during the cold winter in the temperate region; however, it loses this capability of dormancy in warmer regions. *A. aegypti* exhibits a thermal optimum of 29 ºC and can adapt to the warmer microclimate of urban environments [78].

In response to short-term environmental stress, the *Aedes* mosquito can undergo diapause, a capacity of dormancy affected by temperature and photoperiodicity [69]. Moreover, it is known that gene flow during the vector-virus interaction is higher in the wet season than in the dry season due to transient selection [79]. As a result, the carrying capacity of *Aedes* varies over time and space and plays an important role in the transmission rate of arboviral diseases [80].

Some VBDs have emerged in cities via the adaptation of the vectors to urban settings. *Aedes* spp., the vector for arboviral infections, adapt to urban environmental settings and locate their breeding sites in poor sanitation urban areas [62] [76].

In urban areas, vector proliferation, increased biting rate, and subsequent VBD exposure occur due to poor socioeconomic and sanitation conditions. Moreover, deforestation associated with urbanization can result in closer contact between human populations and wildlife, particularly at the periphery of cities. These meetings disrupt untouched ecosystems and interfere with the zoonotic cycles of the arbovirus vectors [55] [62].

According to the international catalogue of arboviruses, more than 500 viruses have been registered and approximately 25% are known to be human pathogens [81]. Furthermore, these numbers are continuously increasing, resulting in the risk of the emergence of new pathogenic arboviruses in humans in the future [70].

Arboviruses show a high rate of genetic mutation with fast replication capability, since they are RNA viruses that lack the proofreading function. Subsequently, this characteristic gives them the ability to adapt to environmental changes [82]. Moreover, due to the high frequency of genetic mutations, changes at several levels, including virulence, vector capacity, and thus epidemiological pattern, may be involved.

Most *Aedes*-borne disease outbreaks have probably been due to a slight change in viral genetics or the introduction of new strains that increase virulence and viremia in humans [72].

Dengue fever has been reported in 36 African countries, and susceptibility to dengue virus (DENV) infection varies geographically and depends on the vector species [67] [83]. The four serotypes of this flavivirus (*Flaviviridae*) distinctly have the same epidemiology and symptomatology in humans, even though they are antigenically different. However, the cocirculation of several serotypes (hyperendemicity) is associated with the risk of emergence and outbreaks in countries [84].

Viral resurgence may be related to vector competence, viral genetics, changing environmental conditions, urbanization, and human migration. Indeed, human migration creates serotype dispersal and hyperendemicity, and when this is associated with low herd immunity, it increases the risk of outbreaks [84].

Despite some dengue outbreaks in Africa, data on the incidence of dengue remain limited. According to WHO, 20% of the African population is at risk of dengue, but 10,000 dengue hemorrhagic fever (DHF) cases, representing 2.4% of the global DHF cases, were reported on the continent in 2004. Considering the DHF to dengue ratio of 1–5%, 0.2–1.0 million dengue cases were reported in Africa in 2004 [85].

The low prevalence of DENV in Africa may be explained by the reduced susceptibility of vectors to DENV [86]. However, the existence of a sylvatic transmission cycle of DENV poses the risk of emergence of dengue in humans. This risk may be associated with changes in host range, vector competence, and viral serotype selection.

Furthermore, experimentally, all Aedes strains in sub-Saharan Africa show low vector competence with respect to all four DENV serotypes [87]. However, A. albopictus is less competent as an epidemic vector [88].

Susceptibility to and the pathogenesis and clinical expression of DENV infection may exhibit a racial genetic background. Dengue resistance genes may exist among Black people[89]. Furthermore, immunological cross-protection by heterotypic antibodies from other African endemic flaviviruses has been suggested [86] [90].

The lack of epidemic reports on DHF/dengue shock syndrome in sub-Saharan Africa may be due to the prevalence of another endemic febrile illness, such as malaria, in the same region. As a result, this may overshadow the diagnosis of dengue fever and explain the reason behind its low incidence and prevalence in Africa.

Chikungunya, This viral disease has been reported in 26 African countries to date [67]. Additionally, the African population at risk of chikungunya virus transmission was estimated to be more than 240 million in 2015 [91].

The virus was identified for the first time in an African country, Tanzania, in 1953. Additionally, wild primates of the African forest are natural hosts of the *chikungunya* virus and are infected via the bite of forest-dwelling *Aedes*. There are three strains of the virus, and the genetic distinction among them depends on the geographical distribution (West Africa, East and Central Africa, and South Africa) [92].

Very few cases of human infections of this alphavirus (*Togaviridae*) have been reported. This disease is underdiagnosed because it mimics the symptoms of dengue fever, which is also endemic in the same areas [52]. There was a major *chikungunya* infection outbreak with 1700 suspected cases in Kenya in 2004 [93].

For yellow fever**,** the African region that is endemic for yellow fever is a geographical area from 15º north in the southern part of the Sahara Desert to 15º south of the equator in Angola country. This area comprises of 34 countries, of which 27 exhibit a high risk of epidemic outbreaks [94]. The burden of yellow fever is estimated at 84,000–170,000 severe cases with 29,000–60,000 annual deaths in Africa. There were 965 confirmed cases and 400 deaths in Angola and DRC in 2016 [95].

The sylvatic and urban cycles of this flavivirus are important components of the epidemiology of yellow fever; however, in Africa, an intermediate cycle involving different species of *Aedes* is also observed. This specificity increases the force of infection during outbreaks [96].

Furthermore, the urban cycle is the deadliest part of disease transmission. Moreover, major yellow fever outbreaks occur when infected people introduce the virus into densely populated and mosquito-dense areas, where most people are scarcely immunized due to lack of vaccination. During this urban cycle, the virus is transmitted from person to person by *A. aegypti* [93].

Low vaccination coverage is the main driver of high infection rates in endemic regions, and 361.4–360.0 million people in Africa still require vaccination to reach the 80% threshold recommended for epidemic prevention [95]. Furthermore, deforestation and settlement of unvaccinated people around forests are associated with the risk of epidemic outbreaks [59].

Zika disease has been reported in 14 African countries [67]. A study estimated that over 45,258 million people live in African areas that are suitable for Zika virus transmission [96]. *A. aegypti* is the vector for urban transmission of this disease, but this flavivirus can also be transmitted sexually or via blood transfusion or the neonatal route [59].

Sporadic Zika viral infection has been low since 2015, when an outbreak with 7490 cases occurred in Cabo Verde. Many cases were also reported in Guinea Bissau and Angola in 2016 [97] [98].

1.4. Sub-Saharan Africa urban areas and determinants of waterborne diseases

The cities of this African region are also not homogenous with urbanization associated with inequalities among residents [99]. Therefore, health risk factors such as risk for waterborne diseases might vary across the SSA regions, from country to country, and even within cities [100] [101]. However, there are also many similarities in the spread, dynamics, and risk factors associated with WBDs in the urban environment of SSA [102].

WBDs outbreaks generally occur in countries with unsafe drinking water and sanitation conditions [103] [104]. These conditions are associated with socioeconomic settings and environmental challenges, which have been critical in many SSA countries. (Figure 6)The access to improved sanitation facilities is 53% in 2010 – 2015 [105].

Of all WBDs, cholera has had a significant impact in SSA countries since the seventh pandemic of the 1970's [106] [107]. As evident, SSA constitutes a region where cholera has persisted because of sporadic epidemics of high mortality, while geographically, it has been recognized as an endemic region. The majority of cholera outbreaks and deaths have been reported in sub-Saharan Africa. Between 2000 and 2015, the WHO reported that 83% of the total deaths due to cholera were from the SSA region [108] [109].

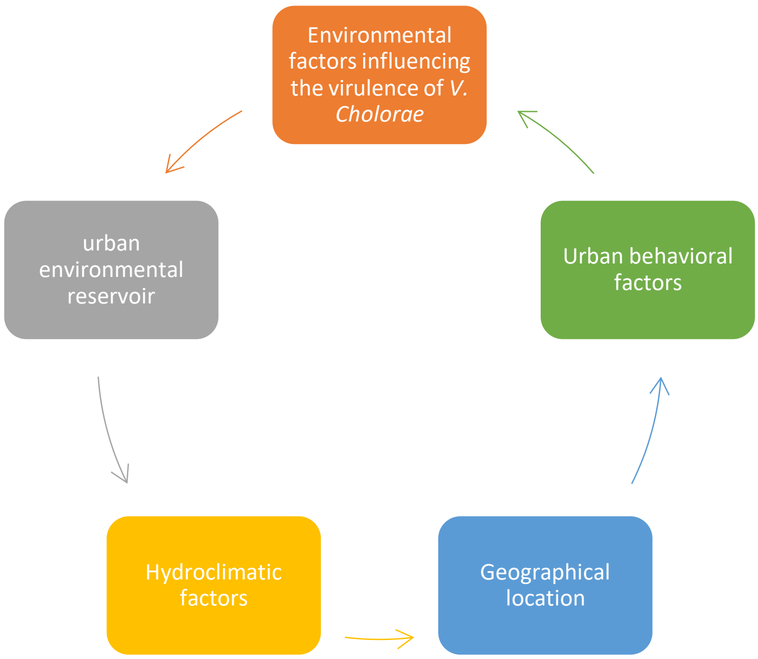


Figure 7:Determination of V. Cholerae in sub-Saharan Africa urban areas. Source: Own elaboration.

Cholera is generally perceived as a waterborne and environmental disease caused by the ingestion of water or food contaminated with faeces. The risk factors associated with the transmission of cholera involved a lack of proper drinking water, poor sanitation, high population density, overcrowding, and low immunity. These environmental factors are often specific to urban areas [110] [111]. Also, in SSA countries, the incidence of cholera appears to be higher in the urbanized areas [112]. Therefore, urbanization has an impact on the epidemiology of cholera.

1.4.1. Environmental determinants

The cholera transmission foci are located along the urban areas in the African coastal urban regions, particularly in estuarine lagoons and ports such as Luanda (Angola), Cape Coast, and Accra in Ghana, and Pointe Noire in Congo. However, within these coastal areas, cholera transmission occurs mainly in overcrowded areas, such as informal settlements, which are characterized by poor sanitation facilities and limited access to safe water [31].

The high risk of the incidence of cholera outbreaks in the urbanized coastal areas could be attributed to the surrounding inlets; high and sometimes brackish water tables, as well as floodplains that are prone to surface water contamination. Unmanaged wellsor shallow boreholes could also be significant risk factors in specific locations [113] [114].

Indeed, the reports of cholera outbreaks in many densely populated urban areas have been associated with lowland areas with hydroecological features. This has been implicated in numerous outbreaks in African cities such as Lomé, Douala, Djibouti, Beira, and Tamatave, where flood-prone urban areas carried the risk of surface water contamination through unprotected wells, or shallow boreholes [31].

In addition, areas neighboring the inlet, backwater, or lagoon were affected by cholera in many coastal cities such as Abidjan, Conakry, and Cotonou [115].

The African Great Lakes Region and the Lake Chad Basin are two inland regions where most of the cases of cholera were reported [116] [117].

The Lake Chad region comprises the Sahelian region of Niger, Nigeria, Cameroon, and Chad, while the African Great Lakes region was constituted by the Albertine rift of Kenya, Uganda, Rwanda, Burundi, DRC, and Tanzania. These regions are dotted with several lakes and rivers, and the proximity of lakes or the fact that a river runs through a city have been reported as a risk factor for cholera [118].

Phytoplankton and zooplankton can be an important reservoir of cholera infection in water sources within the environment, independent of humans influence [119]. Indeed, *Vibrio cholerae*, the bacterium responsible for cholera, has been associated with cyanobacteria, free-living amoebae, crustaceans such as copepods, bivalves, and intestines of certain fishes and aquatic sediments [120] [121].

This presents a risk of infection, especially since some of these organisms are often components of the marine food chain. During interepidemic periods, *V. cholerae* can survive in adverse environmental conditions due to its capacity to enter a viable coccoid state [121].

V cholerae spreads rapidly in overcrowded locations where there are unchecked water sources and where solid and/or liquid wastes and human excreta cannot be safely disposed of [107].

Surface water pollution poses a high risk of cholera spread, especially when a river crosses an overcrowded urban area. The contamination usually arises from human excrement and wastewater [112].

The scarcity of pit latrines, proximity to refusal dumps, poor domestic storage conditions, insufficient drainage network, and lack of efficient treatment of water could be major urban factors that favor the spread of *V. cholerae* [122]–[125].

The growth and proliferation of the pathogen responsible for cholera can also benefit from nutrient-rich brackish and saline water from septic tanks and pit latrines [126]. Additionally, these on-site sanitation systems in poor urban areas are often located near drinking water sources such as boreholes and shallow wells [127]. Moreover, there might be connectivity between on-site sanitation and the groundwater source when the soil is sandy, thereby resulting in contamination of drinking water sources with resident feces [128].

Informal settlements that are closely associated with rapid urbanization in sub-Saharan Africa are often overcrowded, with inadequate sanitation and a lack of basic services. As per the WHO estimates, these factors contribute to a higher risk of communicable diseases, including diarrheal diseases such as cholera [129].

The temporal patterns of cholera outbreaks were influenced by rainfall patterns in many parts of Africa because the seasonal variation in human exposure to *V. cholerae*-contaminated water might be related to a seasonal pattern [110].

The incidence of cholera might increase during the rainy season due to contamination of water supply sources. However, incidences of cholera might also spike up during the drought period because populations would be forced to use unhealthy water supplies in the absence of better alternatives [130]. Moreover, during the dry season, groundwater levels might be low due to excessive water extraction in shallow wells and boreholes. This could expose the groundwater to *V. cholerae* contamination through the establishment of connectivity with the sanitation system [127].

The rainfall patterns are influenced by global climate trends such as ENSO events (El Niño-Southern Oscillation), particularly in East and West Africa. Furthermore, these global climate trends generate hydro-meteorological disasters such as droughts or floods with simultaneous outbreaks of cholera [110]. These natural disasters do not trigger cholera outbreaks, but promote the spread of epidemics, especially in densely populated areas.

1.4.2. Pathogen and disease determinants and burden

As facultative pathogens, many bacteria from the *Vibrionaceae* family do not depend on human hosts for their survival. However, other microbes from the same family such as *V. cholerae* can provoke illness [131].

V. cholerae are generally found in estuarine and brackish natural environments, wherein they are often associated with aquatic organisms, including copepods, crustaceans, waterfowl, cyanobacteria, chironomid eggs, arthropods, shellfishes, and fishes [132]–[137]. Most *V. cholerae* strains in the aquatic environments are non-pathogenic [138] [139].

It is in its natural environment that the emergence of the virulence trait of *V. cholerae* occurs under biotic and abiotic pressures. Indeed, changes in pH, temperature and salinity, nutrient limitation, protozoan grazing, and phage predation are abiotic and biotic stressors to which *V. cholerae* is usually confronted, which threatens its survival [140]–[142].

The acquisition of virulence capacity through environmental pressures gives *V. cholerae* survival advantage in its aquatic environment. Therefore, this adaptive bacterial capacity increases the ability to infect and colonize the human organism via the mechanism of colonization factor of N-acetyl glucosamine binding protein A or by the expression of the cholerae toxin gene (ToxR). By selecting and amplifying the virulence clone and its traits, the human host enables the emergence and evolution of pathogenic *V. cholerae* [131].

V. cholera can live in different environments and infect the human gut. Within the gut, some of the genes of the pathogen accelerate their activities and make the bacterium 700 times more infectious [143].

There are also reports that indicated the lateral transfer of genetic material in the bacterium. Indeed, genes that confer virulence are disseminated in the environment by different *V. cholerae* serogroups, thereby creating an environmental reservoir of virulent gene [144].

The combined condition of temperature and salinity (optimum 2–14 g/L) might raise the probability of the presence of *V. cholerae* with an accuracy of 75.5% to 88.5% in some environments. Moreover, these physicochemical parameters have been shown to display seasonal patterns. In addition, there is a significant correlation between the elevated sea surface temperature, the El Niño event, and the cholera incidence [145].

The spread of cholera might benefit from certain anthropogenic factors, including human migration, trade, poor sanitation, and crude hygiene practices [127].

The lack of the practice of handwashing before eating and after using the toilet as well as the consumption of leftovers without heating are unhealthy practices associated with many cholera outbreaks. Moreover, some African foods such as millet gruel and peanut sauce might be adequate for the growth of *V. cholerae* [110]. Also, the consumption of contaminated aquatic foods such as fish might pose a risk of infection [126].

The spread of cholera has also been associated with drinking 41wiming in contaminated rivers and lakes. In addition, commercial areas such as the African market might contribute to the spread of cholera in urban areas. Furthermore, cholera can also spread by land and sea from the coastal cities to create a transboundary epidemic [110].

Through their characterization of the geographical distribution of the risk of cholera in sub-Saharan Africa, Lessler et al. revealed that more than 200 million people live in areas with at least some instances of cholera incidence. Moreover, 87.2 million live in a district with high incidence and 21.7 million in areas with high cholera incidence [146].

As per the reports from the African nations to the WHO, there were 4 million cholera cases in the five past decades [147].

In 2017, DRC, Ethiopia, Nigeria, Somalia, South Sudan, Sudan, and Zambia have witnessed cholera outbreaks [148]. In the same year in Africa, there were 179,835 cases and 3220 deaths, with case fatality rates ranging from 0 to 6.8%. Notably, in Zambia, the case fatality rate was 3.8%, while in Angola and Chad, it was 5.2% and 6.8% respectively [102].

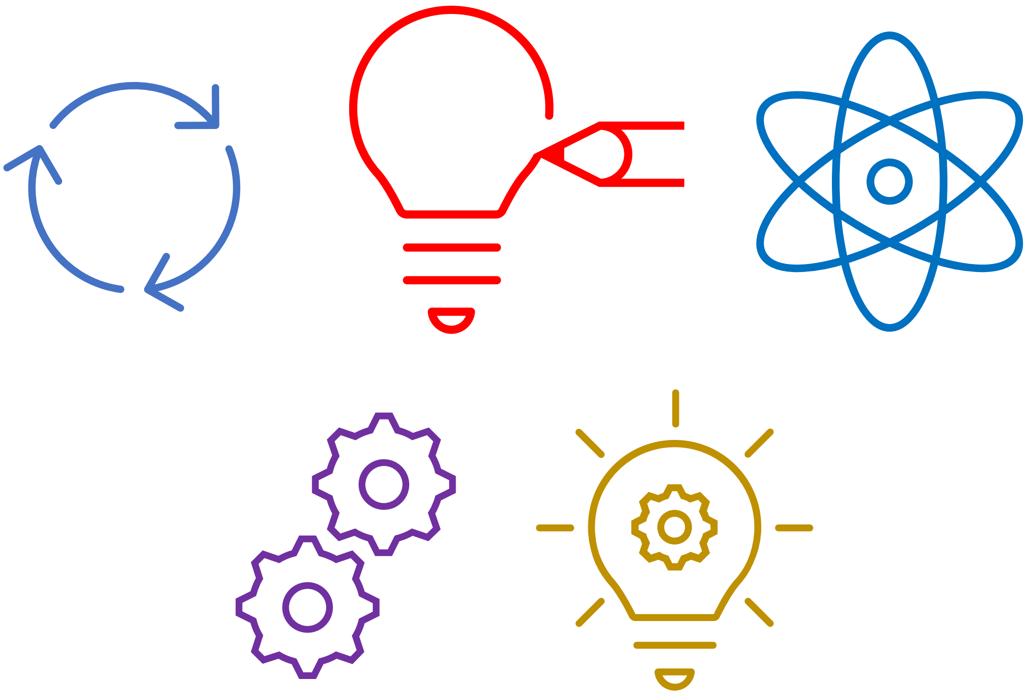
However, the number of cholera cases is often underreported and could be much higher than the official records of WHO. Indeed, in 1970, 16 African countries reported data for cholera cases, 45 in 2006, and 17 in 2017 [147]. Furthermore, there is no permanent data for cholera. This might be due to inadequate surveillance systems.

A large part of the cholera burden occurs in urban areas, particularly in dense urban settings. This is evident from the attack rates and the cases per 1000 people in different demographic settings. Notably, it was reported that cases per 1000 people ranged from 1.2 in low-density residential suburbs to 90.3 in overcrowded suburbs [110] [147] [148].

2. HYPOTHESIS AND OBJECTIVES

"*Truth in science can be defined as the working hypothesis best suited to open the way to the next better one*"

Konrad Lorenz



2. Hypothesis and Objectives

Hypothesis

There are specific environmental risk factors in urban areas of SSA that can increase the prevalence of outbreaks of water and vector-borne diseases and those factors can be conceptualized and modelled according their interrelationships.

Objectives

The general objective of this thesis is to elucidate the specific environmental risk factors in urban areas of SSA that increases the prevalence of outbreaks of water and vector-borne diseases in a way that facilitate their modellization.

Specific objectives are:

1. To establish the typology of the environmental risk to water and vector-borne diseases in SSA urban areas.

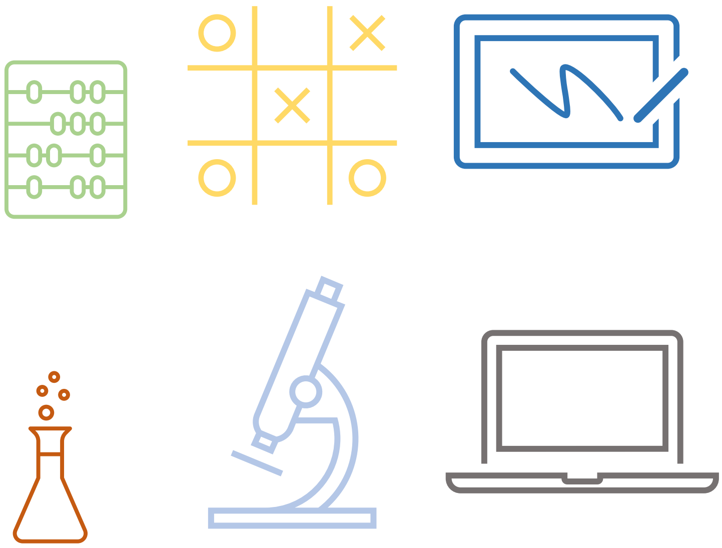
2. To determine how the urban environment factors trigger water and vector-borne disease outbreaks.

3. To determine the specificities and contributions of urban environment in the exposure to water and vector-borne diseases.

4. To propose a conceptualization of urban environment to face the water and vector-borne diseases risks.

3. MATERIALS AND METHODS

"Methodology is intuition reconstructed in tranquility" Paul Lazarsfeld



3. Materials and Methods

3.1. Design of study and literature review

This is an retrospective observational study. Due to the fact that the specific objectives refer to different topics, three specific bibliographic searches have also been carried out. A first search has been done focusing on the health risks of urban informal settlement environments, mainly in the search engine and databases of MEDLINE, WHO Library and Information Networks for Knowledge (WHO library) and Urban Africa Risk Knowledge (Urban ARK). The first two databases were chosen based of their particularity to capture more health science publications, and the and the third (Urban ARK) because it is dedicated to urban African research and have substantial publications on African cities. With MEDLINE, this sentence was used with the Boolean operator AND "health risks AND Sub-Saharan AND urban slum"; with WHO library the term "slum" and with Urban ARK website, the term "urban health".

A critical read has been performed for each selected publication in order to get a different aspect of vulnerabilities and health risk. The structure of this review is articulated around the analysis and discussion of the most common item of this literature search.

The second literature search was a comprehensive review of the published documents in PubMed, Scopus, and Web of Science using PRISMA methodology and key terms, including ''*Aedes*-borne AND diseases AND Africa," ''dengue AND African AND urban areas," ''yellow fever AND African AND urban areas," ''*chikungunya* AND African AND urban areas," and ''*Zika* AND African AND urban areas." Additionally, websites from the UN agencies, World Bank, and CDC were consulted to obtain relevant information for this study, and the references of each selected paper were checked for relevance. English and French were chosen as the languages for the search from January 2000 to July 2019. Information on epidemiology, urbanicity, (re)emergence risks, and entomological data of *Aedes* in sub-Saharan Africa was extracted.

A third review of literature was undertaken to assess the presence of cholera risk factors in the urban environment of SSA. Relevant databases such as MEDLINE, SCOPUS, and Web of Science were utilized to identify publications between January 2000 and October 2019. A PRISMA framework was conducted, and a search combining keywords associated with cholera outbreak risk and SSA were employed to identify relevant publications.

Available reports in English and French language, scientific articles, United Nations reports, government reports, and NGO reports were included in the review. Additional articles were identified manually by searching the reference list from relevant reports. The scientific articles were further screened for relevance by title or by reading the abstract or full text when the title was not sufficiently relevant for the review.

3.2. Statistical data analyse and system modelling

Household data from the WHO/UNICEF Joint Monitoring Programme on Water supply, Sanitation and Hygiene (JMP) [149] for the year 2017 were used to perform an analysis of WASH coverage in urban areas of SSA. Raw data from the JMP website were used to create graphs (radar charts) of WASH coverage (total, urban, and rural) of all SSA subregions (western, eastern, central, and southern). Microsoft Excel was used for data visualization and analysis.

The analysis combined data on attributable mortality from both sexes and all age groups with percentages of risk factor attribution (RFA) for WASH coverage. These data were extracted using interactive and visualization tools from the Institute for Health Metrics and Evaluation (IHME) of the University of Washington [150] and are presented in tables for all SSA subregions

A ynamic complexity of vector-borne diseases in sub-Saharan Africa were analyzed and by SD modelling approach (Forrester, 1961) [151]. A causal loop diagrams (CLD) and stock-and-flow diagrams (SFD) were constructed using the Vensim PLE software [152].

Graphics illustrating how the elements of a system are related were created through the construction of CLDs. The CLDs were created by capturing the different risk factors of

VBD's and LF across African urban areas. From these diagrams, an analysis of the risks and possible interventions and policies was conducted.

A quantitative model, an SFD diagram, which conceptualizes a system of ''stocks" (rectangles) representing stocks or accumulations, connected by arrows and valves representing rates, was utilized. From the CLD of the LF transmission, an SFD was created to quantify the risk in stock with flows with other variables.

The SFD was parameterized by defining the different stocks, rates, and initial values. Then, the model was run with Vensim PLE software to simulate the effects over time. An SFD and simulation were designed based on the pathogenesis of the LF parasite (*Wuchereria bancrofti*).

The values of auxiliary variables, stock variables, and flow variables were determined based on parasitological data of LF:

- Within the mosquito, the duration of development from the microfilara stage to the infectious larva stage l_3 takes 11 to 21 days (on average 15 days), and the microfilara lives for approximately 6 months [153].

- The number of infectious mosquito bites is 15,500, with an adult worm producing microfilariae [154].

- Among the infectious larvae present in human blood, only 1 in 700 become adults, and it takes 1 year for an infective larva to become an adult worm, with an average lifespan of 10 years (7– 12 years).

- The adult worm has an optimal microfilariae production period during the first 3 years. An adult worm can produce 10,000 microfilariae per day or 360,000 per year [155].

With 15,500 infectious mosquito bites, a proportion of 1 in 700 larvae become an adult worm, and there is a production of 10,000 microfilariae per day per adult worm; a model was built and simulated for 3 years.

3.3. Proposition of conceptual frameworks

To propose a new framework for waterborne diseases exposome for SSA urban areas the follow steps have been done: (a) Reasoning for a new approach to urban exposomes; (b) Adapting exposomes for urban areas of exposome to waterborne diseases in sub-Saharan Africa, (c) Selection of a conceptual framework for waterborne diseases in sub-Saharan Africa; and (d) Adapting urban areas to address the dynamics of waterborne diseases in the DPSEEA conceptual frameworks.

For the faecal-oral diseases exposome dynamic diagram, the following step to conceptualize have been done: (a) Urban areas of faecal-oral diseases transmission; (b) Urban exposomes for faecal-oral diseases; (c) Conception of diagram for faecal-oral infections transmission in urban areas; and (d) Potential application of the diagram.

4. RESULTS

"Without data, you're just another person with an opinion."

W. Edwards Deming

4. Results

4.1. Literature review bibliometric analysis and characteristic of selected articles

After a removal of duplicates, 86 articles were found, the titles and the abstracts were examined for their relevance according to the eligibility criteria. Total of 23 articles were obtained after skimming the title and the abstracts. In case of doubt about the relevance of the articles, the complete manuscripts were read according to the same eligibility criteria; this is how 8 articles were excluded from the 23 articles. Finally, 15 articles were included in the analysis. The process of literature searching was shown in Fig. 7 as below.

Studies covering urban informal settlements have been identified for four SSA countries with cross-sectional studies as a methodology. Seven studies were carried out in Kenya, two in Nigeria, one in Uganda and one in Serra Leone.

Four review articles were identified with a focus on informal urban settlements in Sub-Saharan Africa as a whole. The majority of articles focused on communicable diseases in informal urban settlements in Sub-Saharan Africa.

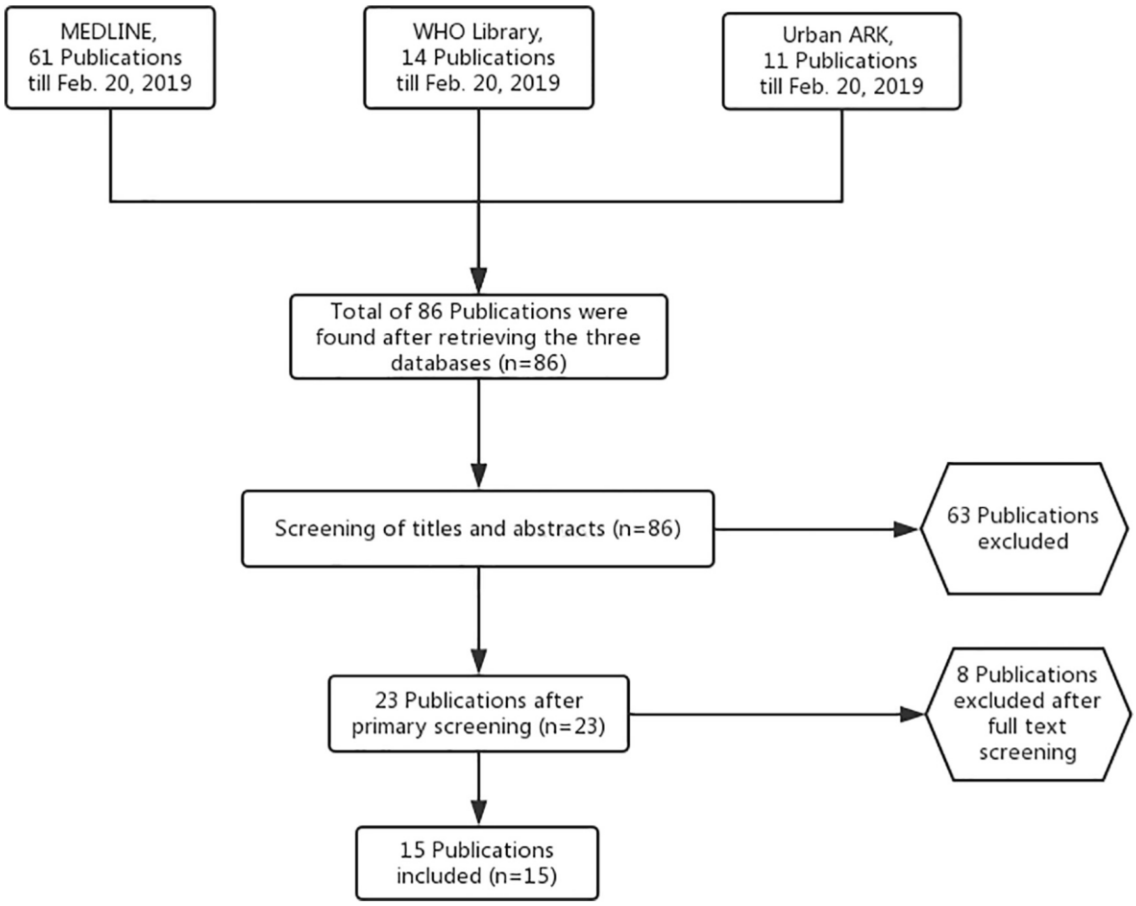


Figure 8:Flowchart of the selection of publication. Source: Own elaboration.

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Of the selected 300 articles, 24 were retained based on the relevance of the information on urban issues in SSA (Figure 8).

Of these 24 articles, 20 were literature reviews, two were case studies, one was a systematic review, and one was a meta-analysis.

Based on the themes, four articles were related to dengue, five to yellow fever, three to *chikungunya*, and two to *Zika*. Additionally, five papers dealt with the environmental suitability of *Aedes* in Africa, three with climate change and arboviruses, and two with arboviruses in African cities (Figure 8).

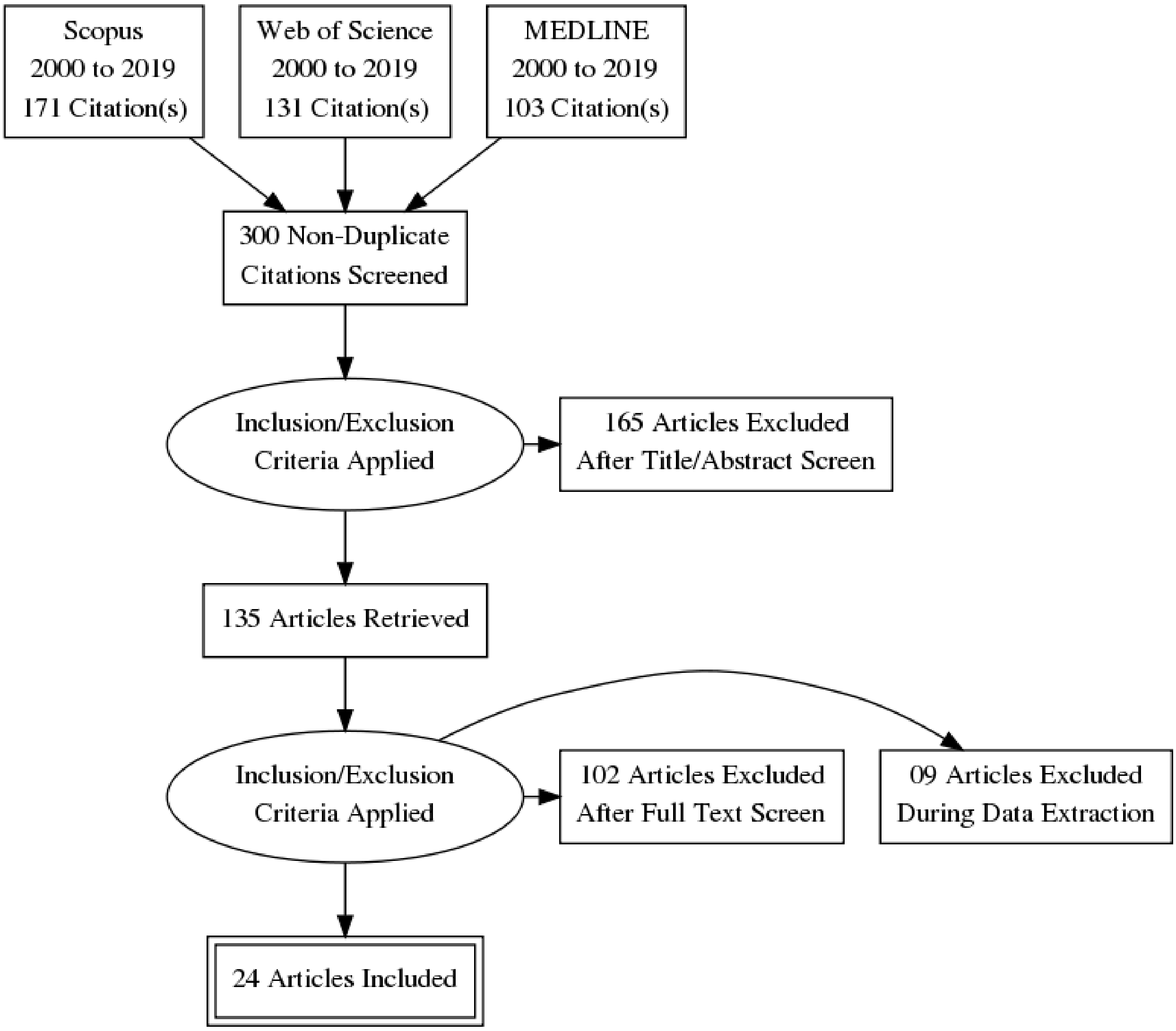


Figure 9:Flowchart showing the steps of article selection. Source: Own elaboration.

The search yielded 144 publications, and 18 were included in the analysis. Table 1 Figure 9 shows the PRISMA flow chart of the review process.

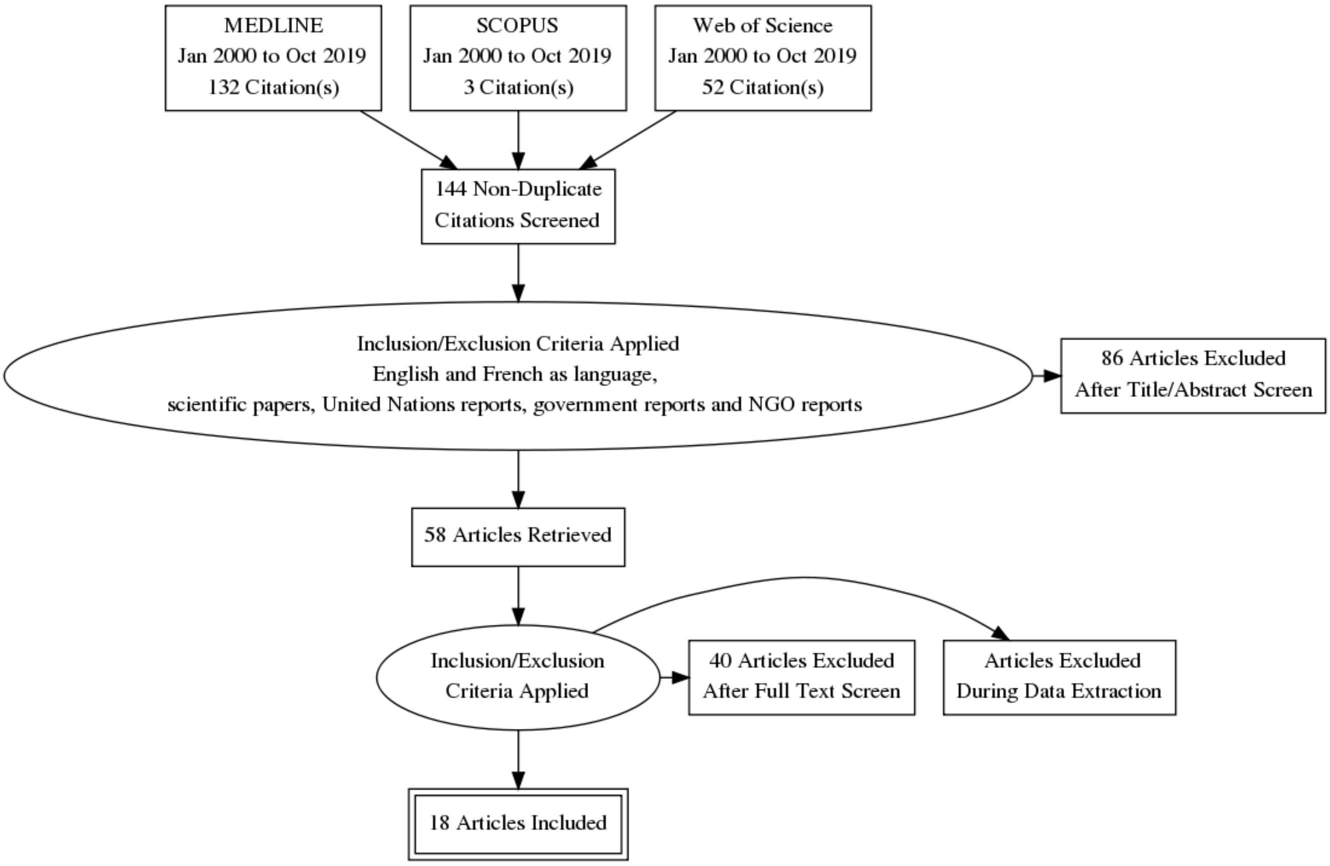


Figure 10:PRISMA flow chart illustrating the methodology adopted to screen relevant scientific literature. Source: Own elaboration.

Table 1:Summary of risk factors associated with cholera outbreaks. Source: Own elaboration.

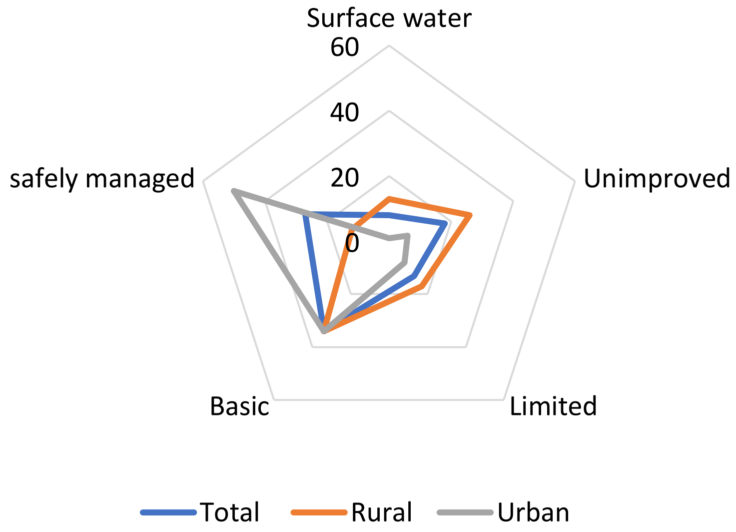
Table 1
Summary of the risk factors associated with cholera outbreaks with citations.

Risk factor	Reference	Number of references mentioning each risk factor and %	Year	Type of document
Geographical location of urban areas	Rebaudet *et al.*	4	2013	Review
	Nkoko *et al.*		2011	WHO report
	Lessler *et al.*	22%	2018	Mapping study
	Rebaudet *et al.*		2013	Review
Hydroclimatology	Rebaudet *et al.*	4	2013	Review
	Lessler *et al.*		2018	Mapping study
	Gwenzi *et al.*	22%	2019	Review
	Rebaudet *et al.*		2013	Review
Urban Environment-sanitation	Penrose *et al.*	10	2010	Cohort study
	Legros *et al.*		2000	Cross-sectional
	Azman *et al.*		2012	Case-control study
	Osei *et al.*		2008	Mapping study
	Sasaki *et al.*		2008	Mapping study
	Sasaki *et al.*	55%	2009	Mapping study
	Okello *et al.*		2019	Case-control study
	Gwenzi *et al.*		2019	Review
	Boyce *et al.*		2019	Review
	Pande *et al.*		2018	Case-control study
Urban behavior	Gwenzi *et al.*	2	2019	Review
	Rebaudet *et al.*	11%	2013	Review

4.2. Attributable mortality and morbidity and WASH coverage in Sub-Saharan Africa

<u>Drinking water coverage</u>

Figure 10 shows the situation of drinking water coverage for the whole SSA area (Figure 10-A) and for 3 subregions (Figure 10 B,C and D). In general, drinking water coverage is better in urban areas than rural areas across the SSA. Southern SSA has the best urban coverage in drinking water, followed by urban areas in western and middle SSA.



Figue 10-A: Percentage of coverage of drinking water in the total SSA region and in rural and urban areas in 2017.

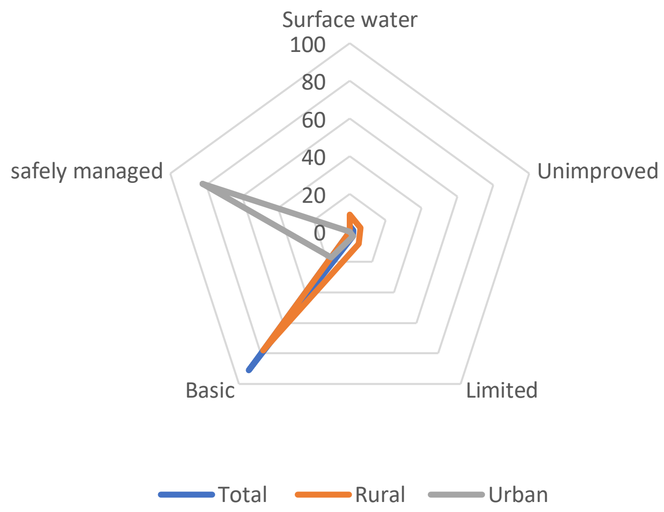


Figura 10-B: Drinking water coverage comparison of rural, urban areas and whole southern subregion of sub-Saharan Africa region in 2017.

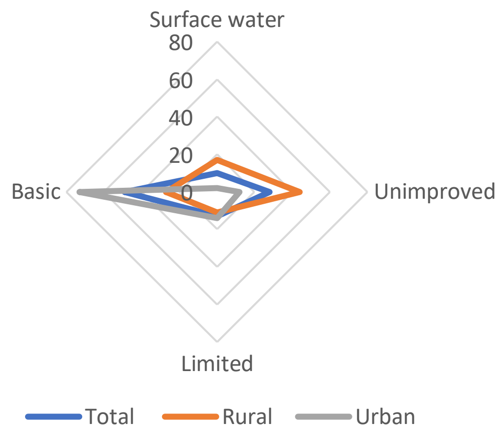


Figure 10-C: Drinking water coverage comparison of rural, urban areas and whole middle subregion of sub-Saharan Africa region in 2017.

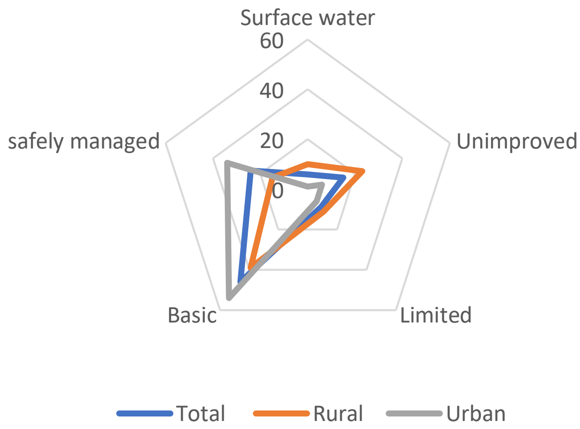


Figure 10-D: Drinking water coverage comparison of rural, urban areas and whole western subregion of sub-Saharan Africa region in 2017.

Figure 11:. Drinking water coverage in sub-Saharan Africa, A: sub-Saharan whole region, B: southern subregion, C: middle subregion, D: western subregion. Source: Own elaboration from data obtained with permission of WHO/UNICEF Joint Monitoring Programme for Water Supply, Sanitation and Hygiene.

Sanitation coverage

The coverage of access to sanitation facilities is better in urban areas compared to rural areas across SSA. Southern SSA has the best urban coverage, followed by urban areas in western and middle SSA. Figure 11.

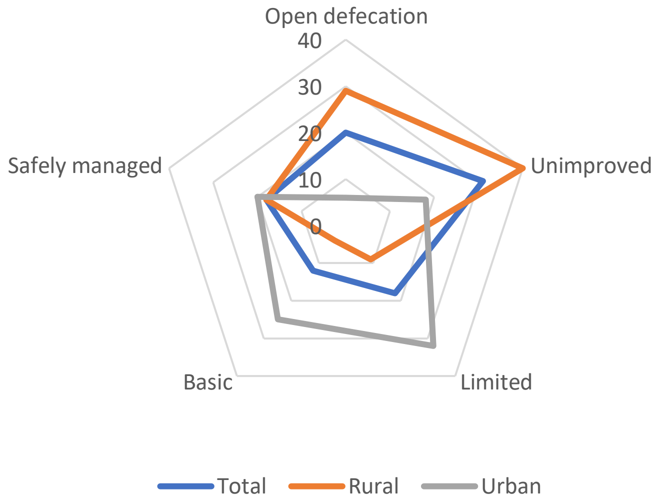


Figure 11-A: Sanitation coverage comparison of rural, urban areas and sub-Saharan Africa region in 2017.

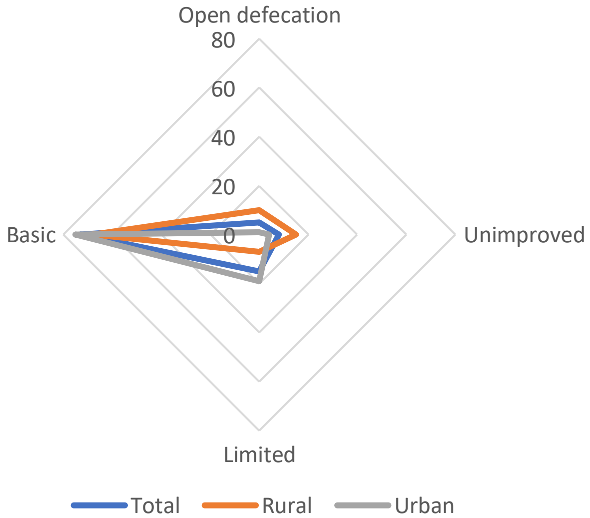


Figure 11-B: Sanitation coverage comparison of rural, urban areas and whole southern subregion of sub-Saharan Africa region in 2017.

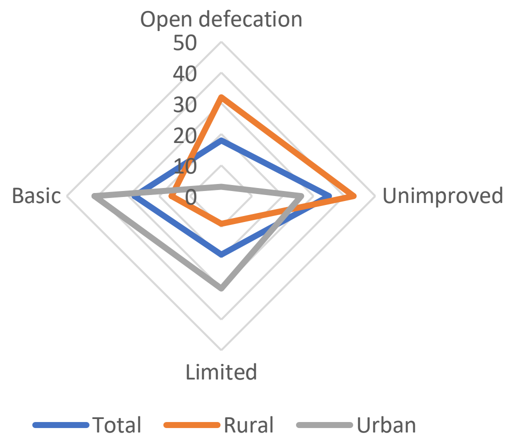


Figure 11- C: Sanitation coverage comparison of rural, urban areas and whole middle subregion of sub-Saharan Africa region in 2017.

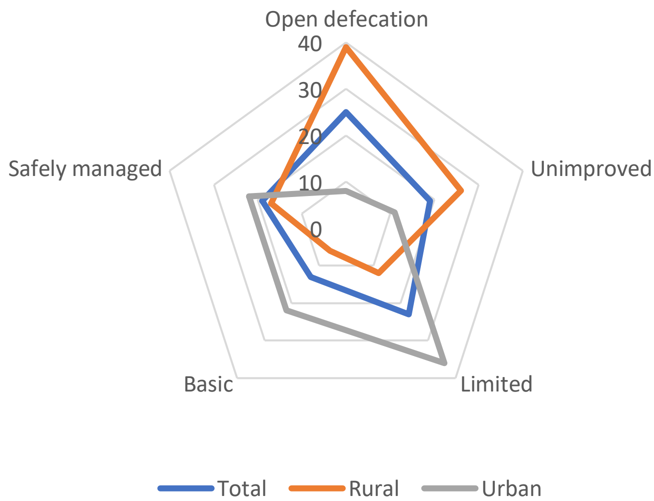


Figure 11-D: Sanitation coverage comparison of rural, urban areas and whole southern subregion of sub-Saharan Africa region in 2017.

Figure 12: Sanitation coverage in sub-Saharan Africa, A: sub-Saharan whole region, B: southern subregion, C: middle subregion, D: western subregion. Source: Own elaboration from data obtained with permission of WHO/UNICEF Joint Monitoring Programme for Water Supply, Sanitation and Hygiene.

<u>Hygiene coverage</u>

The coverage of access to handwashing facilities is better in urban areas relative to rural areas across SSA. Southern SSA has the best urban coverage, followed by urban areas in western and middle SSA. Figure 12.

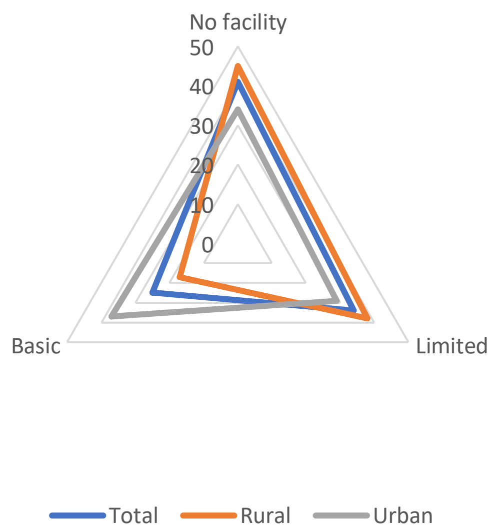


Figure 12-A: Hygiene coverage comparison of rural, urban areas and whole of sub-Saharan Africa region in 2017.

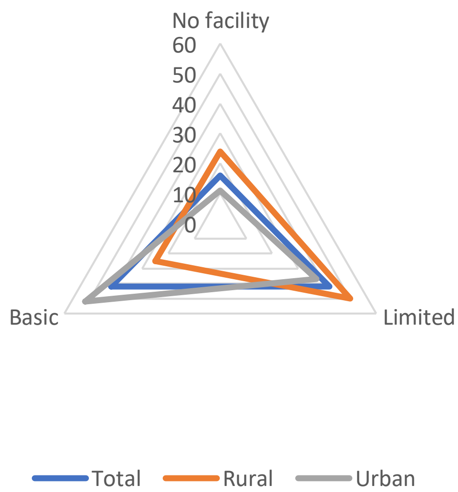


Figure 12-B: Hygiene coverage comparison of rural, urban areas and whole southern subregion of sub-Saharan Africa region in 2017.

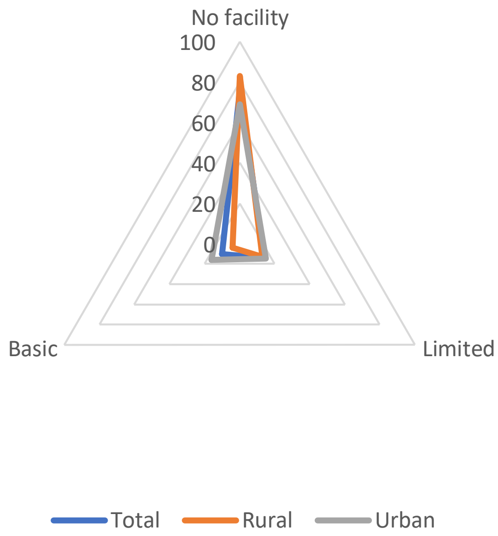


Figure 12-C: Hygiene coverage comparison of rural, urban areas and middle southern subregion of sub-Saharan Africa region in 2017.

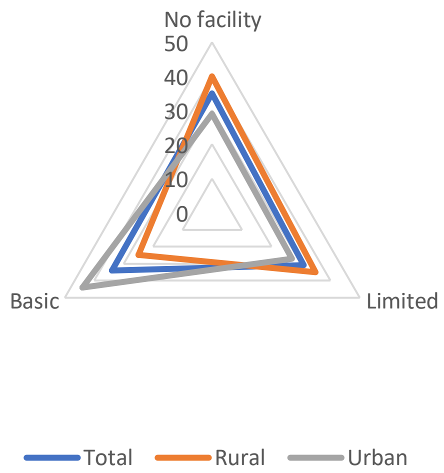


Figure 12-D: Hygiene coverage comparison of rural, urban areas and whole southern subregion of sub-Saharan Africa region in 2017.

Figure 13:: Hygiene coverage in sub-Saharan Africa, A: sub-Saharan whole region, B: southern subregion, C: middle subregion, D: western subregion. Source: Own elaboration from data obtained with permission of WHO/UNICEF Joint Monitoring Programme for Water Supply, Sanitation and Hygiene.

Trends in types of urban WASH facilities

There is an increase in the urban coverage rate of sewers and septic tanks, along with a decrease in urban coverage of running water and latrines. Figure 13.

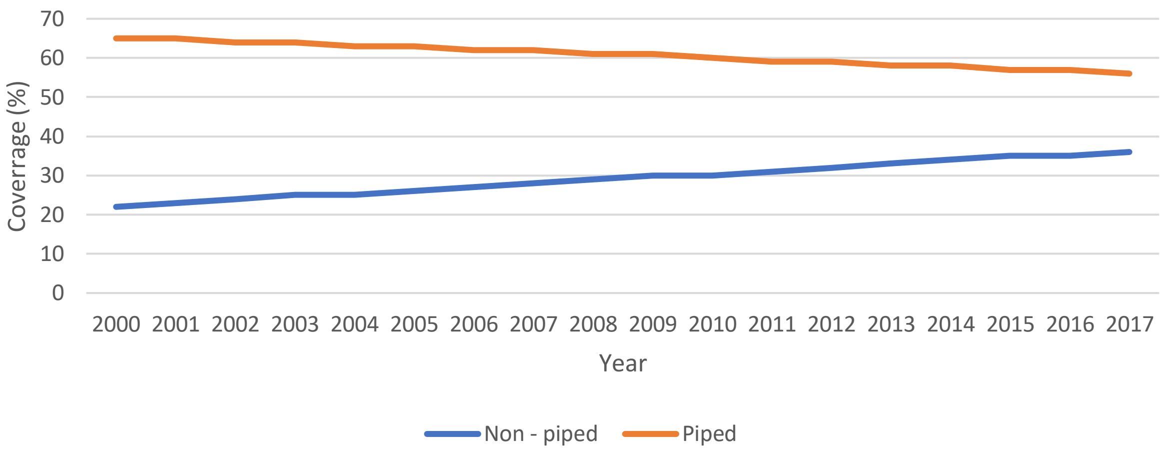


Figure 13-A: Trends in percentage of coverage of drinking water facility from 2000 to 2017 in sub-Saharan Africa.

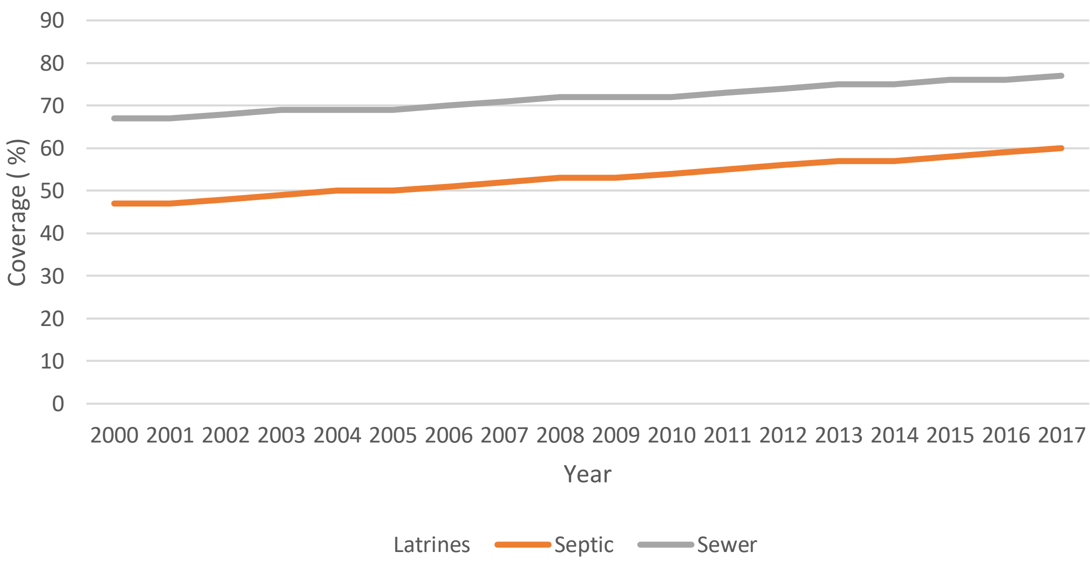


Figure 13-B: Trends in percentage of coverage of sanitation facilities from 2000 to 2017 in sub-Saharan Africa.

Figure 14:Trends in drinking water(A), sanitation(B) coverage in sub-Saharan Africa in the period from 2000 to 2017. Source: Own elaboration from data obtained with permission of WHO/UNICEF Joint Monitoring Programme for Water Supply, Sanitation and Hygiene.

Estimated number of SSA countries with basic WASH coverage by 2030

Twelve SSA countries are estimated to have made negative progress in coverage of basic WASH services by 2030, while 23 countries are expected to make slow progress, and only 8 will be on track. In addition, 9 countries will have made negative progress in coverage of basic sanitation service, 33 will be making slow progress, and only 2 will be on track. Figure 14.

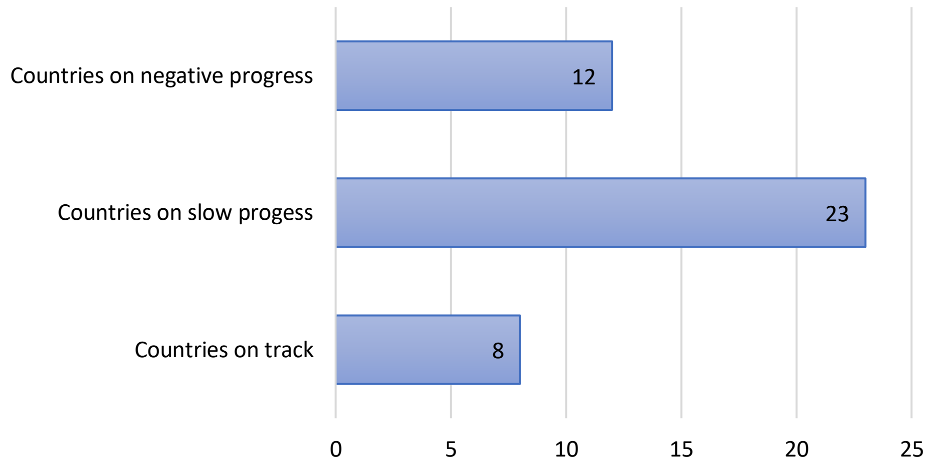


Figure 14-A: universable basic water service in sub-Saharan Africa by 2030

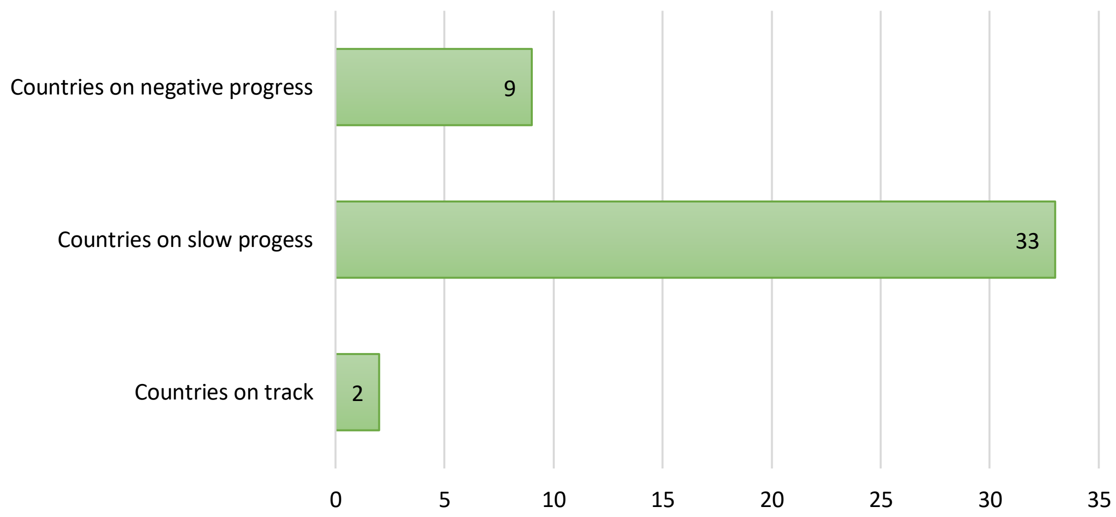


Figure 14-B: universal basic sanitation in sub-Saharan Africa by 2030

Figure 15: Estimated water, sanitation, and hygiene (WASH) coverage in sub-Saharan Africa countries by 2030(A: basic water service, B: basic sanitation). Source: Own elaboration from data obtained with permission of WHO/UNICEF Joint Monitoring Programme for Water Supply, Sanitation and Hygiene.

Mortality attributable to unsafe WASH

Regarding mortality associated with diarrheal diseases for both sex and all age groups related to WASH coverage in 2019, Table 2 shows that an estimated 7.75% (CI95% 5.99–9.7%) of total deaths from diarrheal diseases across SSA is attributable to unsafe WASH practices with a risk factor attribution (RFA) of 95.93% (CI95% 91.94–98.24%). Western SSA has the highest percentage of deaths attributable to WASH at 9.67% (CI95% 7.54–11.99%) with a RFA of 96.19% (CI95% 92.3– 98.39%), while southern SSA has the lowest at 2.9% (CI95% 1.99–4.48%) with a RFA of 88.4% (CI95% 79.96–94.09%).

Table 2:Burden of diarrheal diseases attributable to unsafe water, sanitation, and hygiene (WASH) practices in sub-Saharan Africa (SSA) in 2019. Source: Institute for Health Metrics and Evaluation (IHME).

	Sub-Saharan Africa	Central SSA	Eastern SSA	Southern SSA	Western SSA
Deaths (%) (CI95%)	7.75 (5.99 - 9.7)	6.61 (4.18-9.71)	6.94 (5.05- 8.98)	2.9 (1.99 - 4.48)	9.67 (7.54 - 11.99)
RFA (%) (CI95%)	95.93 (91.94 98.24)	96.15 (92.3- 98.36)	96.29 (92.61 - 98.42)	88.4 (79.96 - 94.09)	96.19 (92.3 - 98.39)

Considering the predicted mortality associated with diarrheal diseases for both sexes and all age groups related to WASH by 2030 and as shown in Table 3, SSA is projected to have 6.77% (CI95% 2.39–15%) deaths attributable to unsafe WASH with a RFA of 93.15% (CI95% 82.8–98.13%) by 2030. The highest percentage is projected to be in eastern SSA at 8.49% (CI95% 2.63–18.82%) and a RFA of 93.97% (CI95% 84.4–98.41%), and the lowest percentage of deaths will be in southern SSA at 3.24% (CI)%% 0.98–8.47%) and a RFA of 87.21% (CI95% 73.16–95.91%).

Table 3:Burden of diarrheal diseases attributable to unsafe water, sanitation, and hygiene (WASH) practices in sub-Saharan Africa (SSA) by 2030. Source: Institute for Health Metrics and Evaluation (IHME).

	Sub-Saharan Africa	Central SSA	Eastern SSA	Southern SSA	Western SSA
Deaths (%) (CI95%)	6.77% (2.39% – 15%)	6.63% (2.11%–15.48%)	8.49% (2.63%–18.82%)	3.24% (0.98% – 8.47%)	6.29% (2.43% – 14.4%)
RFA (%) (CI95%)	93.15% (82.8 %– 98.13%)	94.11% (84.86% – 98.49%)	93.97% (84.4% – 98.41%)	87.21% (73.16% – 95.91%)	92.68% (81.44% – 98.04%)

4.3. Causal loop and stock and flow diagrams of risk factor dynamic of vector-borne infections in sub-Saharan Africa urban areas

Climate change has an impact on weather patterns which in turn can influence climate-related disasters and, therefore, the amount of stagnant water in urban areas [156]. The combined effects of migration, socio-economic status, and climate change can generate urbanization, which could create certain sanitation conditions leading to stagnant water [53]. (A) Figure 15 shows the causal loop diagram of risk factors dynamic of vector-borne infections in SSA. As a result of sanitation conditions, urbanization can generate vector habitats and breeding sites, resulting in an abundance of vectors. (B) Moreover, the interaction between vector abundance and vector infection influences vectorial capacity, which together with the vulnerability of city dwellers, based on their immunity, can expose them to the risk of vector-borne diseases [157].(C)

Causal loop diagram of risk transmission dynamic of urban filariasis

From infectious mosquito bites, humans receive infectious larvae that grow into adult worms, mate, and produce microfilariae [153].

(D) Immunity acquired from the worm load may reduce the survival of infectious larvae and the fecundity of worms [158].

The quality of housing, personal protection, proximity to the mosquito breeding site, and periodicity of microfilariae are some of the factors that can put humans and mosquitoes in contact [159].

The density of microfilariae within mosquitoes depends on their survival and the proportion of microfilariae developing in infectious larvae [153]. A phenomenon called density dependence, referring to the parasite's development and uptake of the microfilariae by the mosquito, occurs in this part of the CLD. (E and F)

Indeed, a negative density dependence (limitation) occurs with *Culex quinquefasciatus*; in this case, the proportion of microfilariae developing in infectious larvae declines with an injection of microfilariae by the mosquito. In addition, a positive density dependence, facilitation, occurs with the *Anopheles Spp.* The proportion of microfilariae developing in infective larvae increases with an increase in the injection of microfilariae by the mosquito [153] [159].

Causal loop diagram of control/elimination of urban filariasis

Public health interventions: Screening of the population at risk, especially in poor urban areas with poor sanitary conditions where there is rural–urban migration and rural migrants from rural areas endemic with LF7 .Figure 17

Reduction/elimination of microfilaremia and adult worms by the mass drug administration (MDA) program using ivermectin and diethylcarbamazine (DEC) [160].

Vector control: Reduction in the number of mosquito bites through personal protection, protective clothing, mosquito nets, and repellents. The change in exposure time to mosquito bites because the infectious larvae (l_3) have a periodicity.

Larviciding reduces the density of mosquito larvae, which consequently reduces the density of mosquitoes. This includes larvicides, environmental and biological control, and genetic engineering.

Reduction in the lifespan of mosquitoes by use of insecticides. Within the mosquito, microfilariae take an average of 12 days to become infectious larvae (l_3), reducing the mosquito lifespan, interruption of larval development, and transmission.

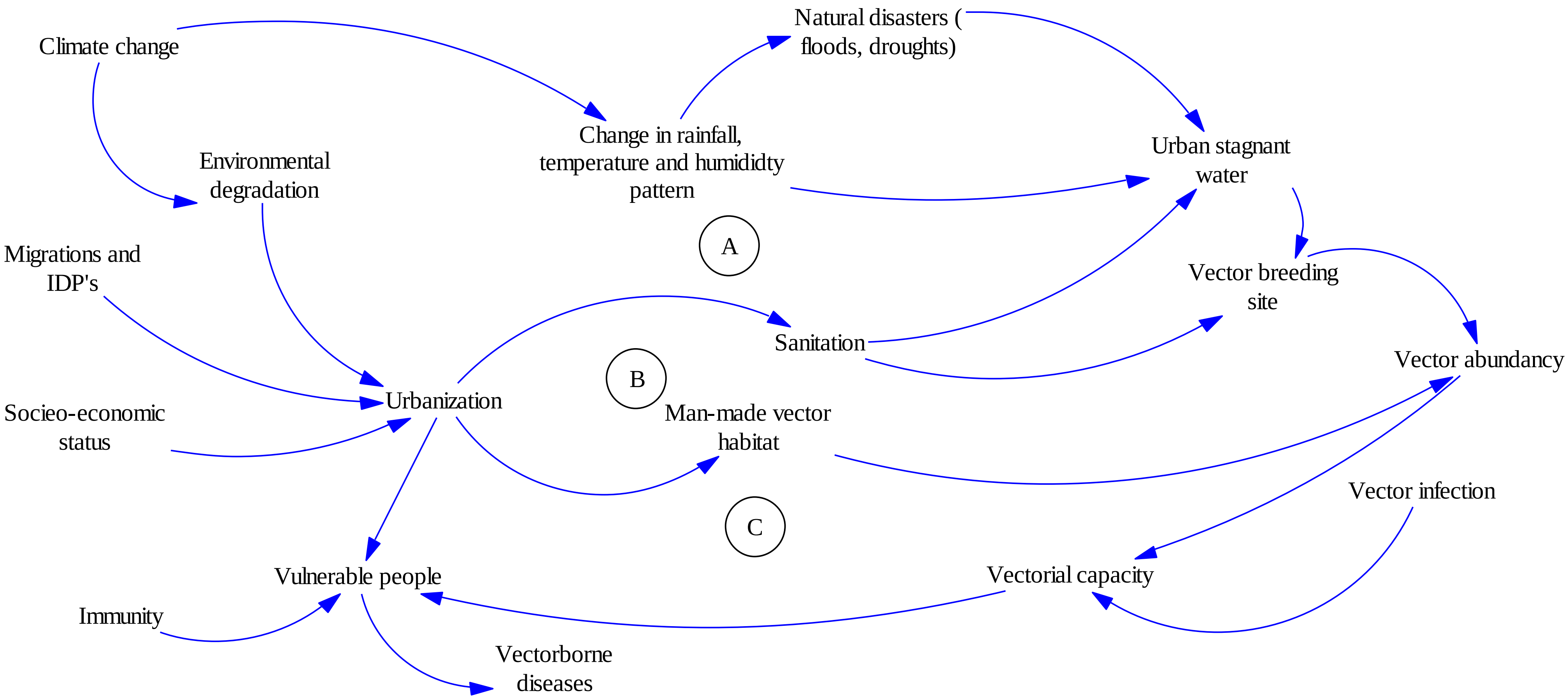


Figure 16:Causal loop diagram of risk factors dynamic of vector-borne infections in sub-Saharan Africa urban areas. Source: Own elaboration.

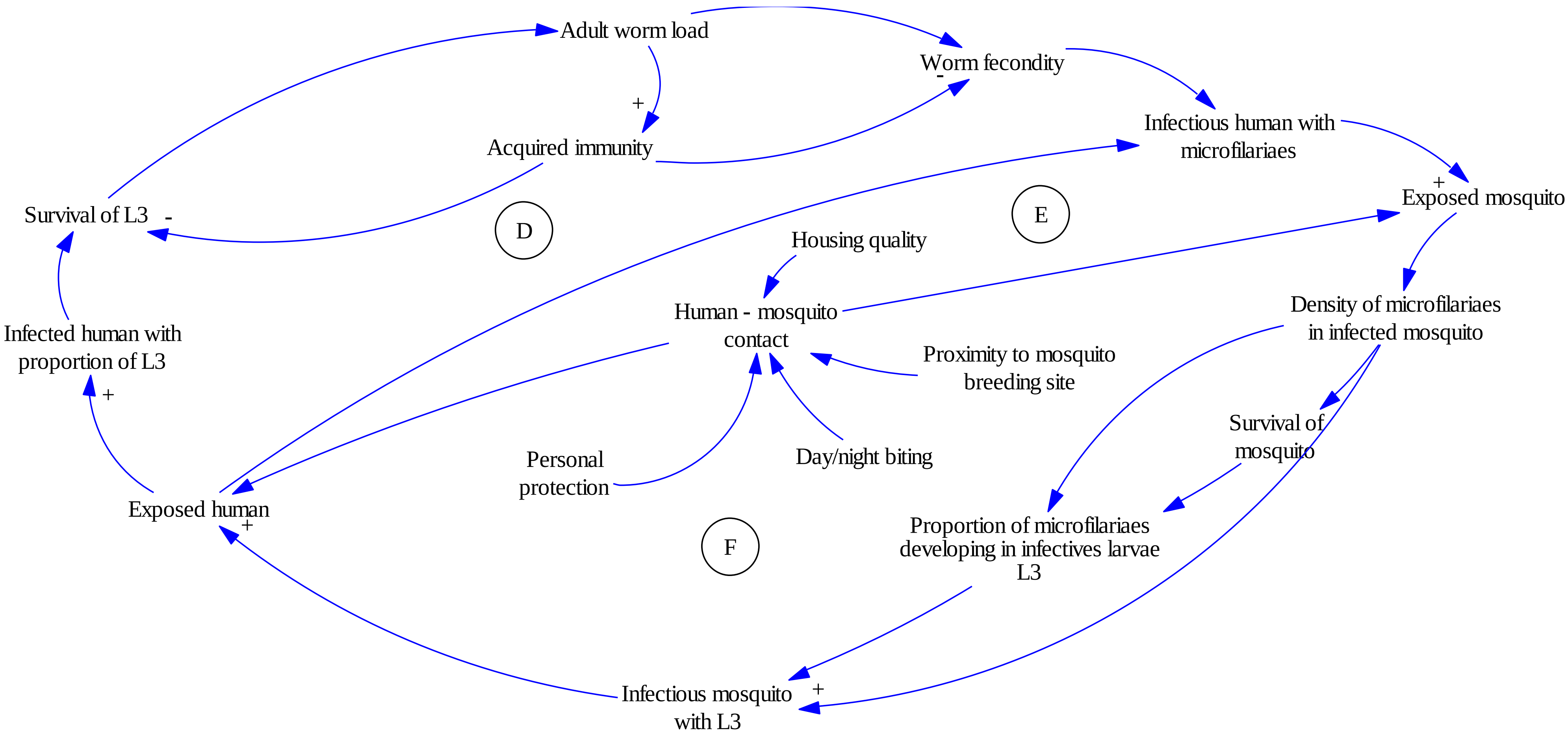


Figure 17:Causal loop diagram of risk transmission dynamic of urban lymphatic filariasis. Source: Own elaboration.

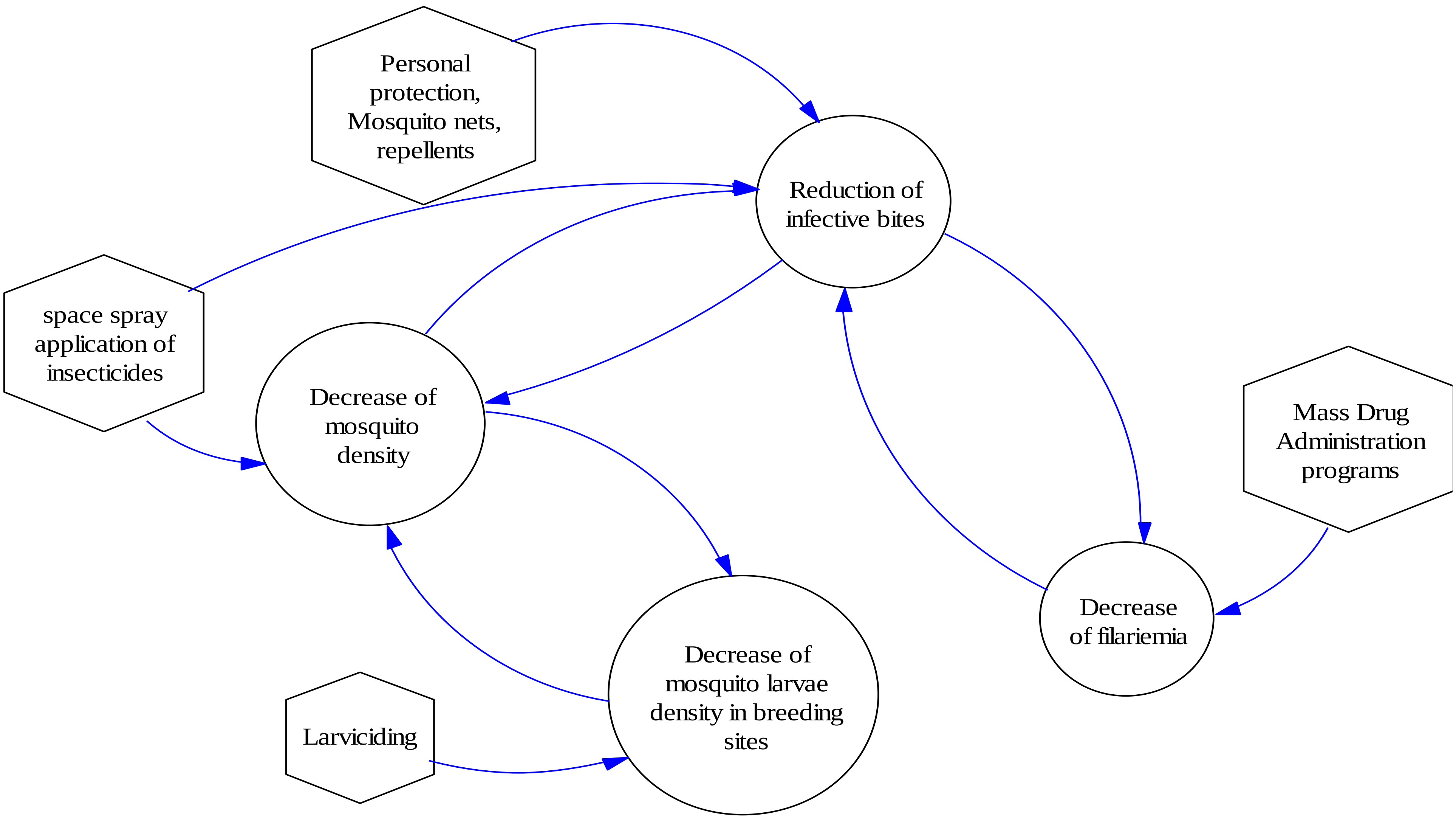


Figure 18:Causal loop diagram of intervention for control/ elimination of lymphatic filariasis in urban areas. Source: Own elaboration.

Stock and flow diagrams

The simulation of the SFD diagram shows a constant supply of infectious mosquito bites to contract human infection (Figures 18 and 19). The number of infectious larvae in human blood increases to a certain point and remains constant. The growth curve of adult worms showed the same pattern as the growth curve of microfilaria production.

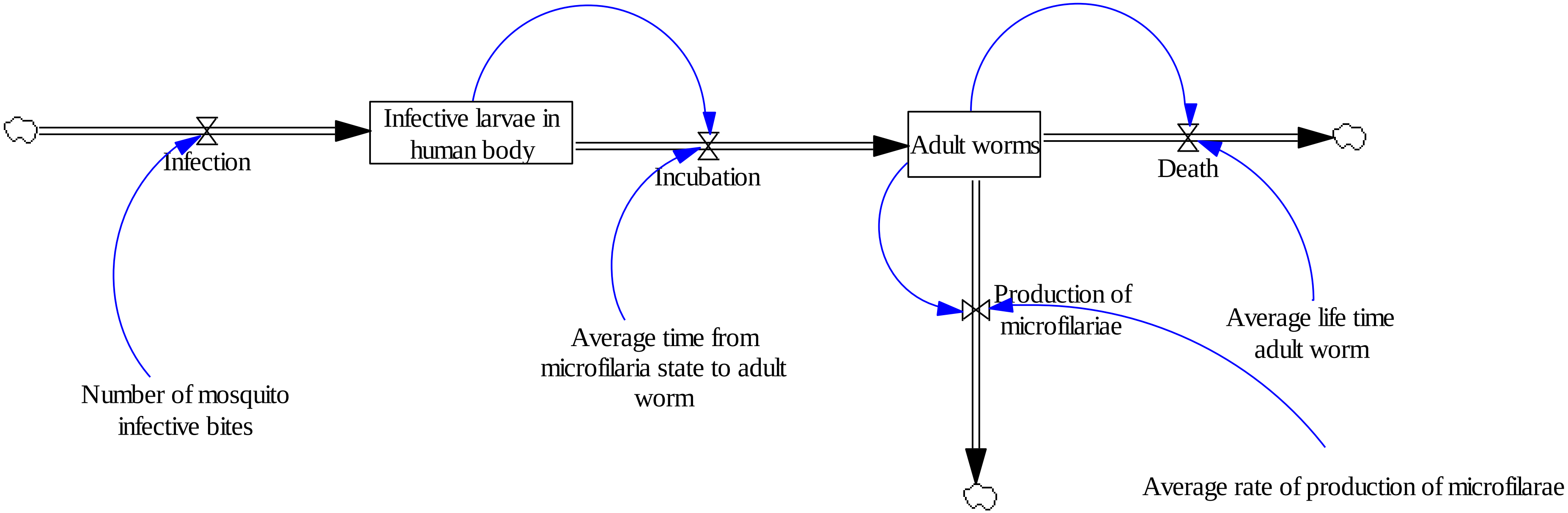
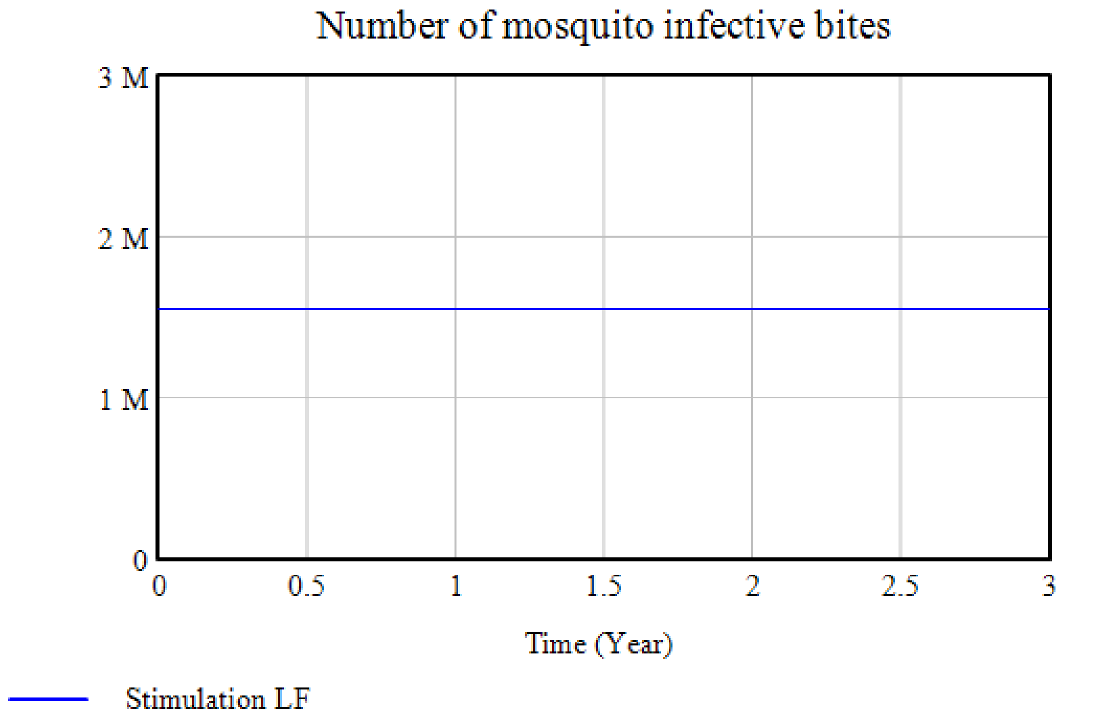
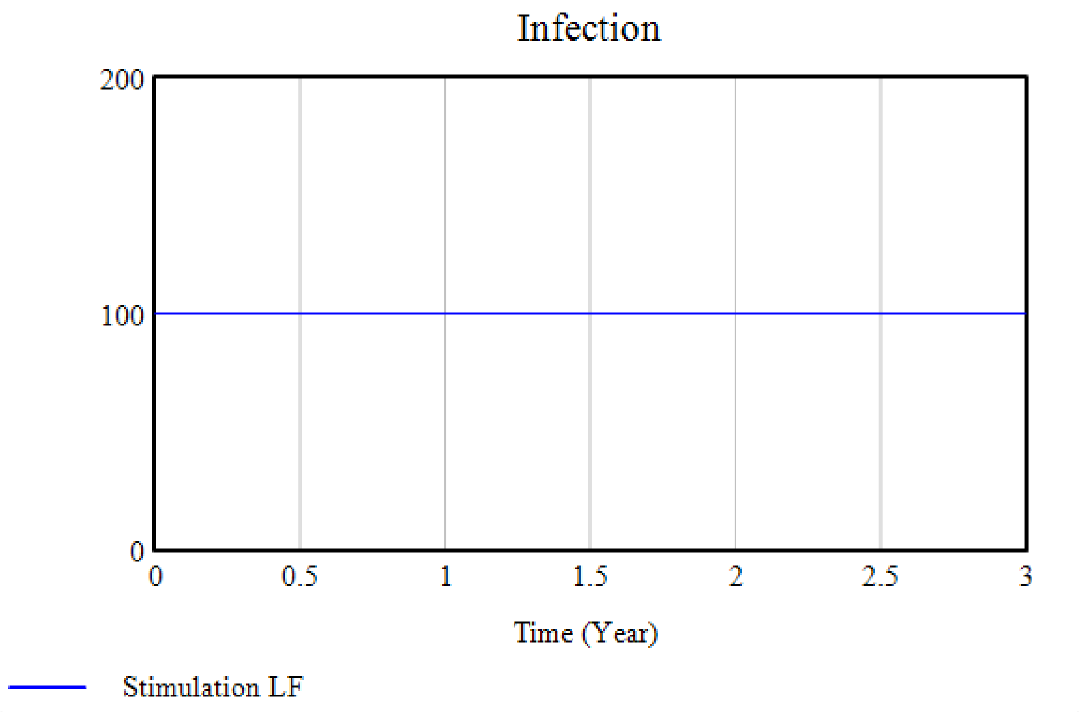


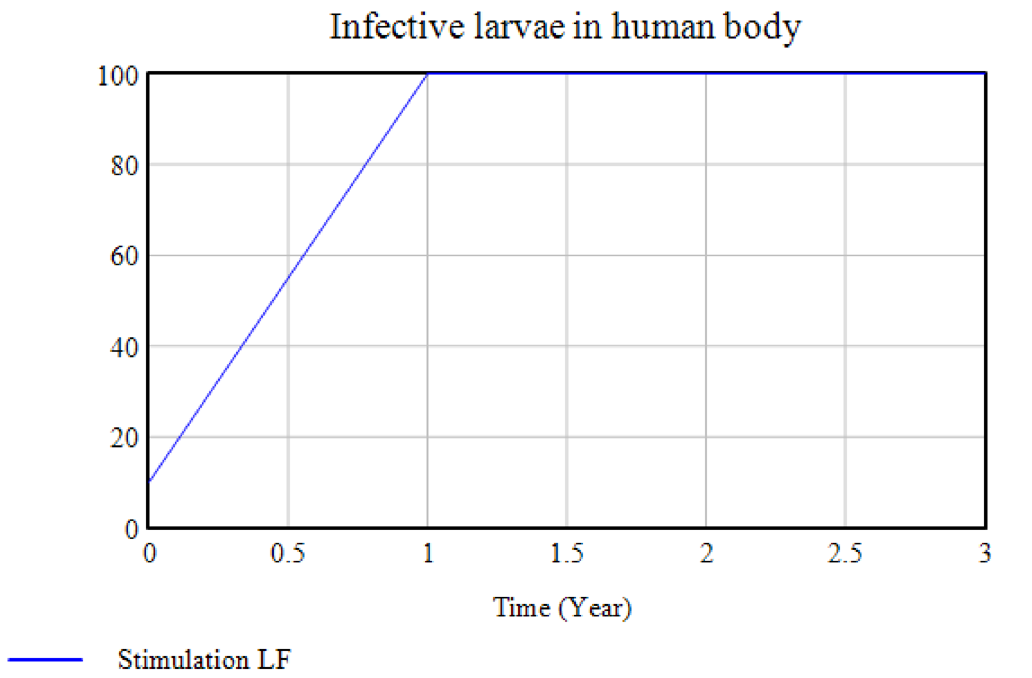
Figure 19:Stock and flow diagram of lymphatic filariasis. Source: Own elaboration.



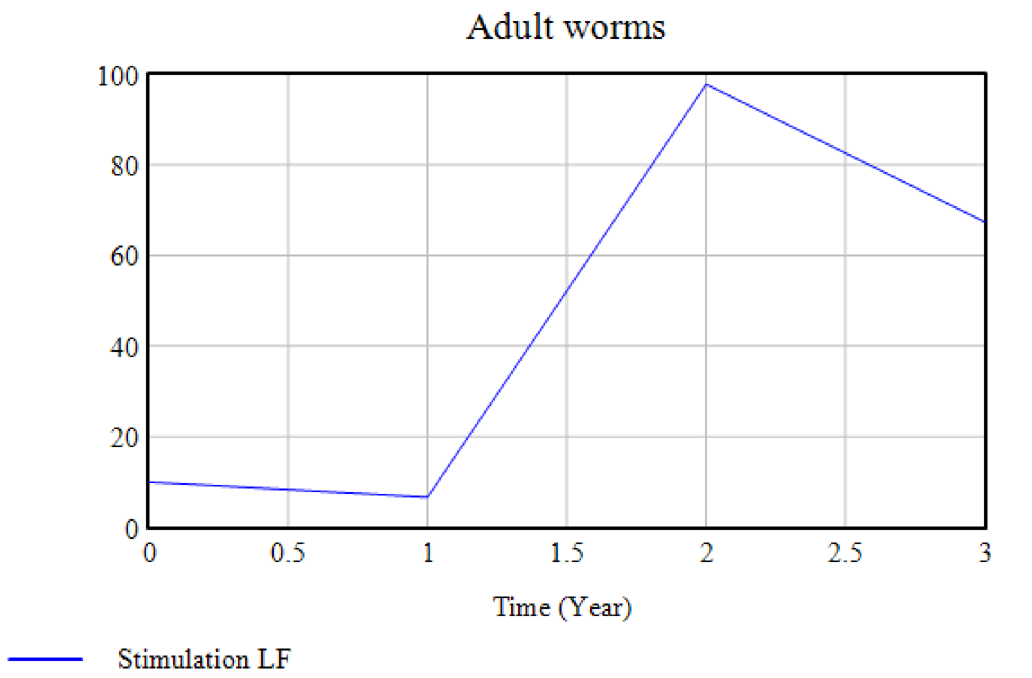
A: Stimunaltion with a number of mosquitos infectives bite during the 3 years. Source Own elaboration.



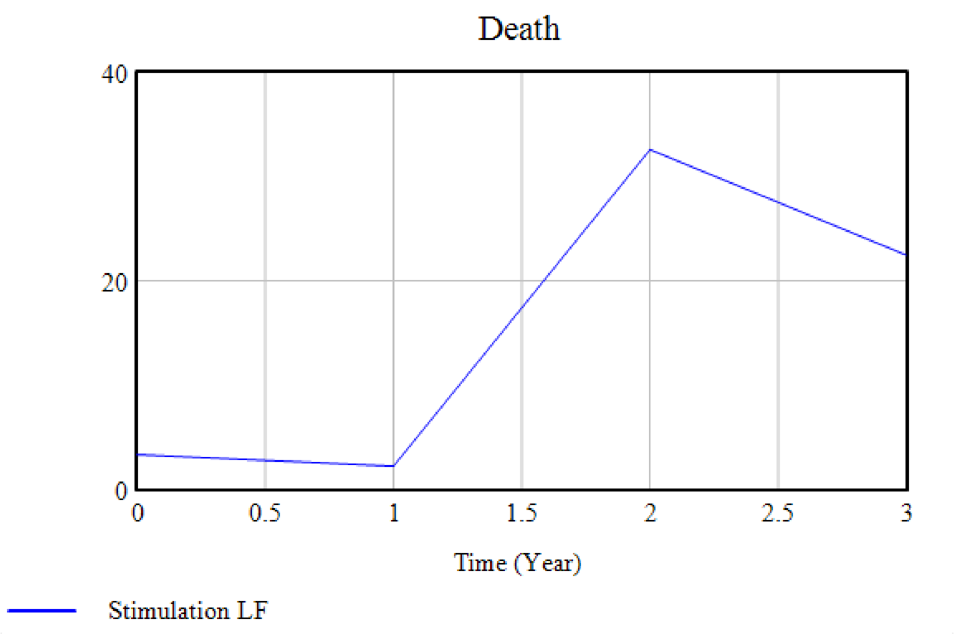
B: Stimualation of a constant infection number during 3 years. Source: own elaboration.



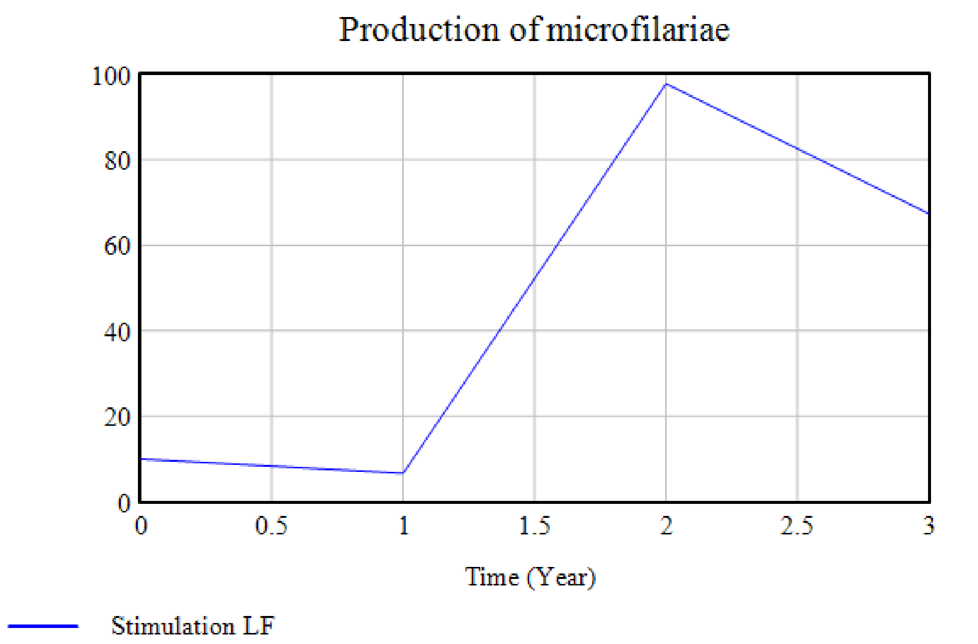
C: stimulation for the number of infective larvae in human body during 3 years. Source: own elabaoration.



D: stimulation for the number of adult worms during the 3 years. Source: own elaboration.



E: stimulation for the number of adult worm death during the 3 first years. Source own elaboration.



F: stimulation for the production of microfilariae during the first 3 years.Source: own elaboration.

Figure 20:Stimulation of the stock and flow diagram. Source: Own elaboration.

4.4. Proposition of conceptualization and urban exposomes for waterborne diseases in sub-Saharan Africa

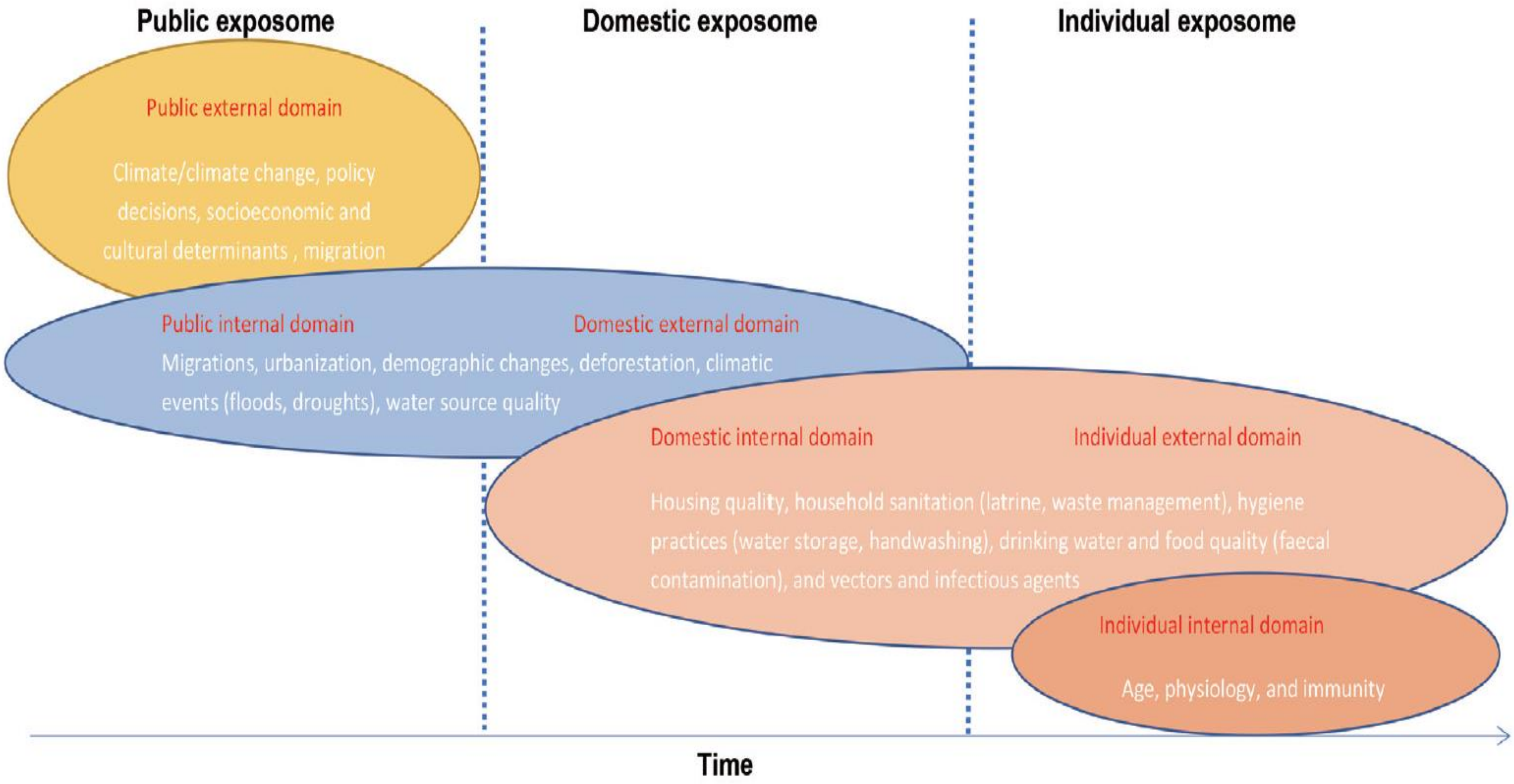


Figure 21:Urban exposomes for waterborne diseases in sub-Saharan Africa. Source: Own elaboration.

Public exposome

External public domain (general and specific)

Wider parameters with an impact on the dynamics of the natural and built-environment such as climate/climate change, policy decision, socioeconomic and cultural determinants, and migration.

Internal public domain

Parameters with a direct impact on the organization of the urban setting such as migrations, urbanization, demographic changes, deforestation, disaster events (floods, droughts), and water source quality.

Domestic exposome

External domestic domain (general and specific)

Parameters with a direct impact on the organization of the urban setting such as migrations, urbanization, demographic changes, deforestation, disaster events (floods, droughts), and water source quality.

Internal domestic domain

Parameters with an impact on the vulnerability and exposure to water-related diseases such as housing quality, household sanitation (latrine, waste management), hygiene practices (water storage, handwashing), drinking water and food quality (faecal contamination), and vectors and infectious agents.

Individual exposome

External individual domain (general and specific)

Parameters with an impact on the vulnerability and exposure to water-related disease such as housing quality, household sanitation (latrine, waste management), hygiene practices (water storage, handwashing), drinking water and food quality (faecal contamination), and vectors and infectious agents.

Internal individual domain

Non-genetic parameters internal to the human body that affect susceptibility to water-related diseases such as age, physiology, and immunity.

Each parameter, as a component of the various exposomes of waterborne diseases in urban areas, evolves dynamically over time. For example, the climate as a component of the public exposome may change over time, just as age as a component of the individual exposome may also vary over time. This continuum of urban exposomes is in constant flux.

4.5 Conceptual framework DPSEEA for urban waterborne diseases

Exposures in the urban environment and the resulting health effects can be represented in the DPSEEA framework. In addition, the DPSEEA framework captures the lifestyle and behavioural parameters that influence exposures. We therefore consider a combination of the DPSEEA framework and the 3 above-defined urban domains for waterborne diseases as shown in Figure 21.

Driving forces, such as climatic and socioeconomic factors and associated policies, which have a large-scale impact on the environment and ultimately on human health. Indeed, climate, poverty, social inequity, demographic factors, and educational levels may be drivers of faecal-orally transmitted waterborne diseases [161];

Pressures resulting from the driving forces exerted on urban areas (public, domestic, and human), considering that the public area affects the domestic area and the domestic area in turn affects the individual area. Pressures are generated by economic activities, agriculture, housing, social attitudes, and the release of pollutants, waste, and pathogens into the environment [162];

States or quality/degradation of the urban area under the effect of the exerted pressures. Changes in the urban environment can affect the public area through unplanned urbanization and inadequate environmental sanitation, as well as the domestic area through overcrowded housing, contaminated water storage, unsanitary latrines, and ultimately, the individual area through contaminated drinking water and food;

Exposures in urban areas to environmental hazards (waterborne pathogens) through drinking water or food consumption. People face health risks from exposure to pathogens in drinking water, through food, fingers, and flies, and through recreational activities in a contaminated aquatic environment [163] [164];

Effects, as health effects resulting from exposure to environmental hazards in urban areas (e.g., the burden of diarrhoea in sub-Saharan Africa); Actions, such as the implementation of strategies in urban areas to prevent and control the spread of environmental health hazards.

Actions are based on reducing exposure to waterborne pathogens through the supply of safe drinking water, management of health risks, sanitation policies, and health promotion [165].

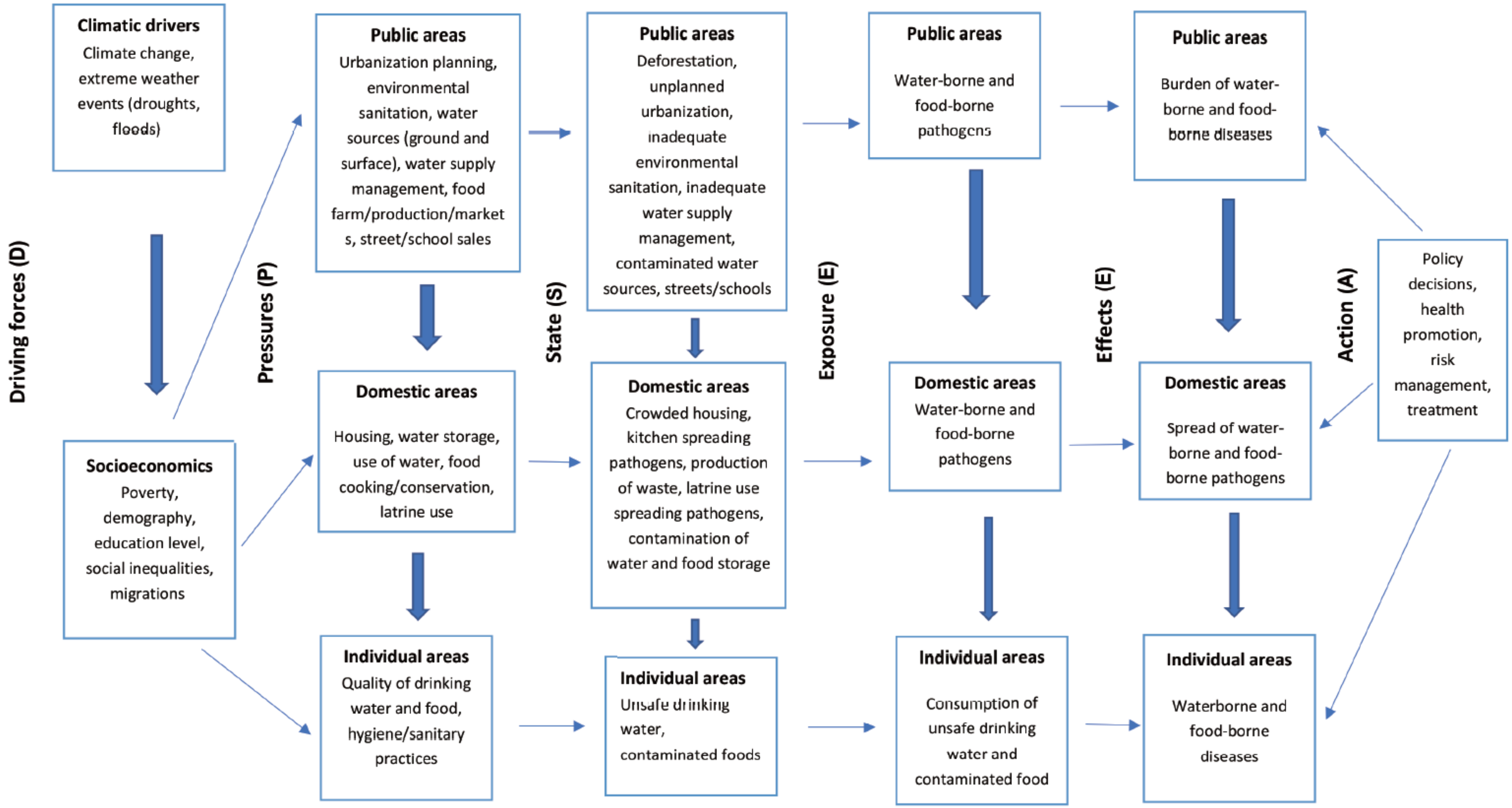


Figure 22:Conceptual framework driving force–pressure–state–exposure–effect–action (DPSEEA) for urban waterborne disease. Source: Own elaboration.

4.6. Conception of diagram for faecal-oral infections transmission in urban areas

Urban areas of faecal-oral diseases transmission

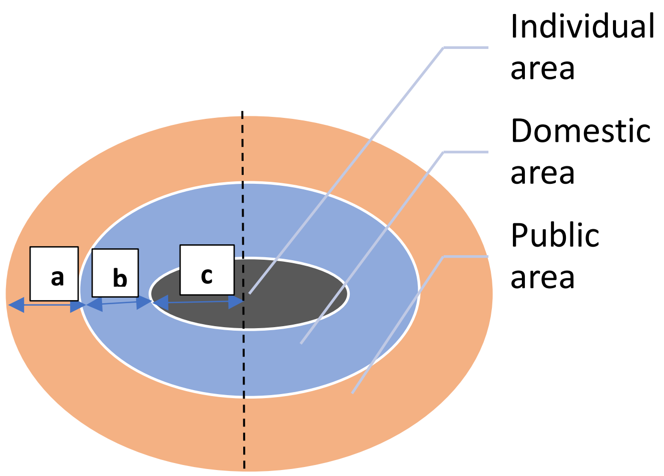


Figure 23:Urban areas for faecal-oral diseases transmission. Source: Own elaboration.

Urban exposomes for faecal-oral diseases

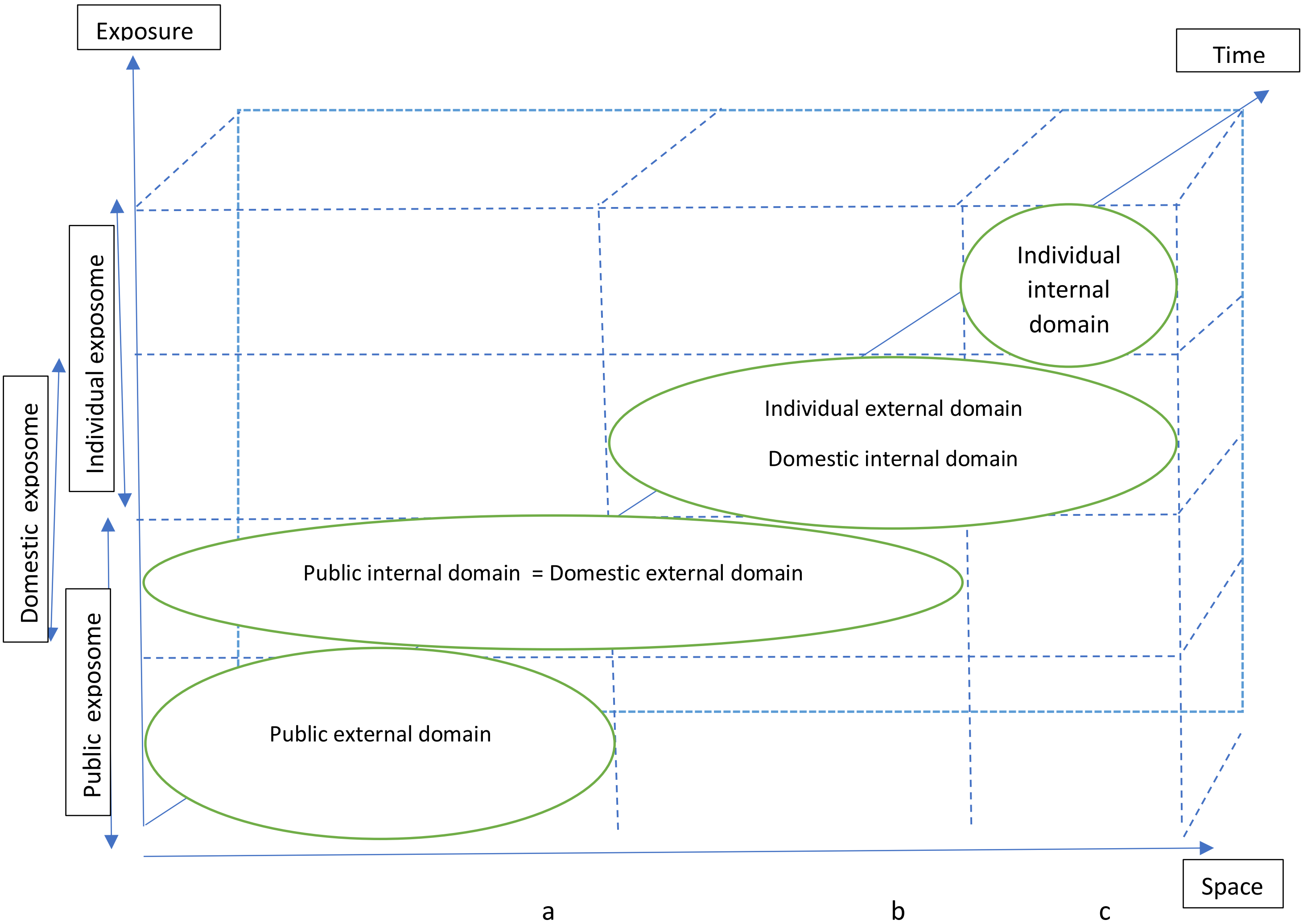


Figure 24:Urban exposome for faecal-oral diseases in sub-Saharan Africa. Source: Own elaboration.

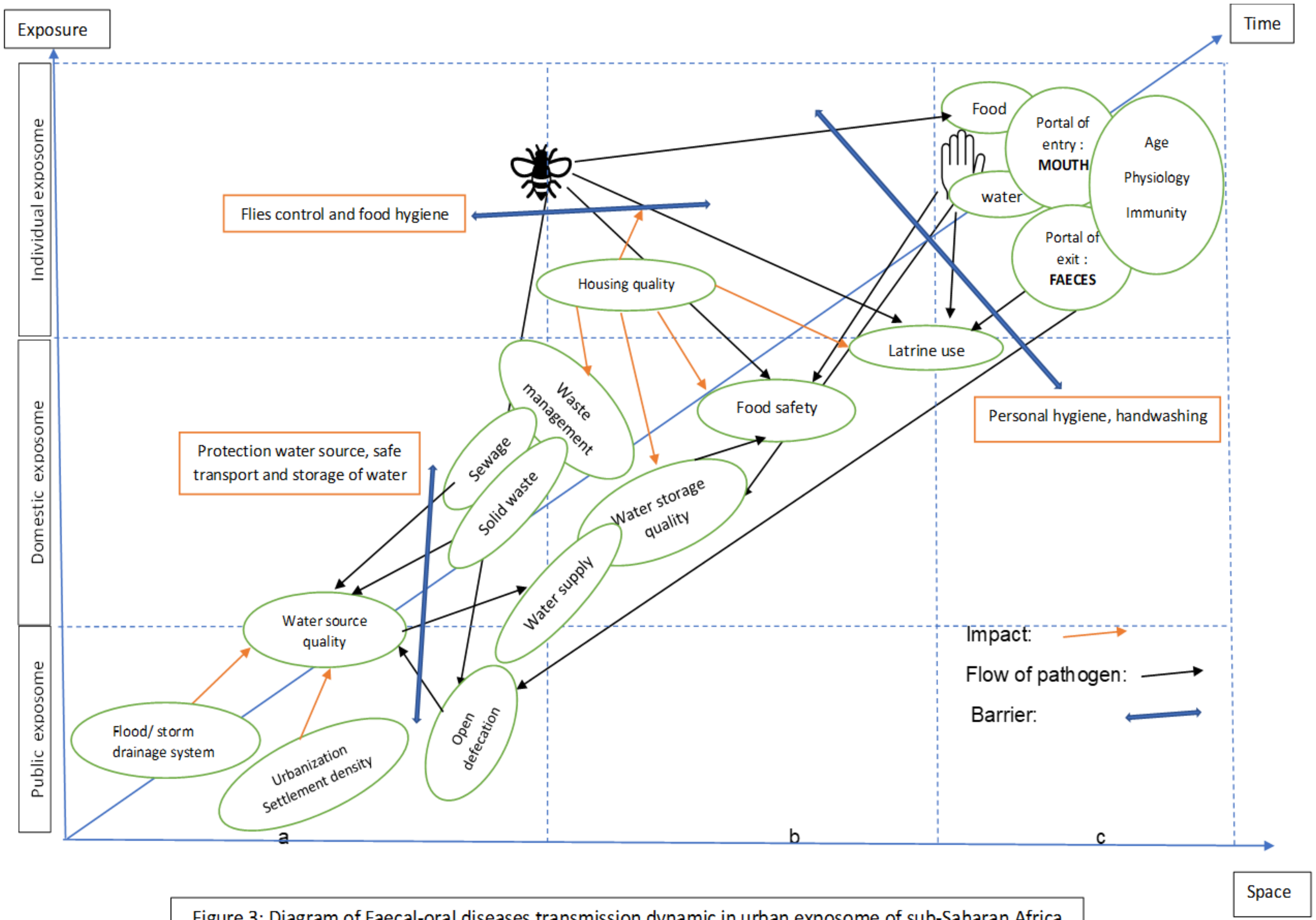


Figure 3: Diagram of Faecal-oral diseases transmission dynamic in urban exposome of sub-Saharan Africa

Figure 25:

Public exposome

As an exposome related to exposure in area under control of "*public places of work, schooling, commerce and recreation as well as the streets and fields*", the disease transmission occurs through faecal contamination of the environment, soil and water source [166]. Therefore, the measure to interrupt the chain of infection would be the prevention of faecal contamination of the environment and water sources. A public environmental sanitation policy is more appropriate [167].

Domestic exposome

The transmission occurs when contaminated water is used in food preparation, washing utensils and drinking water storage containers [168]. Furthermore, flies frequent both faeces and food, so they can contribute to the transmission of FOD as a vehicle of the pathogen [153].

Domestic exposome as exposure in area under control of household, food hygiene (food handling, preparation and storage practices) may interrupt the chain of transmission because food acts as a vehicle in the spread of FOD [167]. In addition, safe excreta disposal prevents faecal-oral pathogens from entering the household environment [167].

Individual exposome

The spread of faecal-oral pathogen may occur through contaminated fingers and hands. Then an ingestion of contamination of drinking water and contamination of food expose to FOD, if there are not practice of personal hygiene [168].

Individual exposome refers to exposure in an area under the control of individuals, such as behavioral practice (personal hygiene in the case of FOD), but also the non-genomic factors such as immunity and physiology that play a role in susceptibility to infection [169].Personal hygiene such as handwashing before eating and after defecation may break the chain of transmission of faecal oral infections [167].

4.7. Potential application of the diagram: surveillance of faecal-oral diseases in sub-Sahara Africa

Surveillance of FOD helps to prevent outbreaks or reduce the burden of these infections in urban areas. One of the potential applications of this diagram is the surveillance of FOD which mainly involves monitoring indicators of faecal contamination.

Indeed, the faecal contamination is the cornerstone of the spread of FOD, so monitoring indicators of this contamination reveals its state, the performance of the existing water sanitation and hygiene (WASH) services and interventions to be taken.

The Faecal environmental Contamination Index (FAECI) is based on eight indicators of the WHO-UNICEF and is suitable for monitoring indicators of faecal contamination and WASH services [170]. The indicators of this index are: (i) For water: basic drinking water services (W_1) and safely managed drinking water services (W_2); (ii) For sanitation: open defecation (S_1), basic sanitation services (S_2), safely managed sanitation services (S_3) and community coverage with basic sanitation services (S_4); and (iii) For hygiene: basic handwashing facilities (H_1) and handwashing with soap after potential faecal contact (H_2).

These indicators could be linked to the components of the diagram and be monitored over time in public, domestic and individual areas of transmission of FOD as shown in Table 1. Thus, a FAECI index could be obtained for each area of transmission of FOD (public, domestic and individual). Therefore, faecal contamination and WASH services conditions could be known. Accordingly, appropriate interventions could be taken at the public, domestic or individual level.

Table 4: Exposure and FAECI indicators. Source: Own elaboration.

	Exposure	FAECI indicators
Public	Open defecation	S_1
	Urbanization, Water source quality, drainage system	S_4
Domestic	Housing quality	H_1
	Water storage and supply	W_1, W_2
	Waste management, food safety, latrine use	S_2, S_3
Individual	Food consumption, drinking water	H_2

5. DISCUSSION

"Research is to see what everybody else has seen and to think what nobody else has thought"

Albert Szent-Gyorgyi

5. Discussion

5.1. Vector-borne diseases dynamic complexity in SSA urban areas

Urban areas are human-modified environments that can create conditions to the spread of pathogens and become a public health challenge [9] [171] [172]. These conditions are the result of the interactions between the pathogens, the urban environment, and the residents, which is a dynamic complexity because several elements of human and natural systems interact over time [173]–[175]. Indeed, the aetiology of these infections appears to be a combination of complex non-linear interactions between socioeconomic and urban environmental factors, living conditions, and public health policies [9]. Furthermore, SD modelling is an effective tool for perceiving and analyzing the dynamic complexity of a public health problem by observing the pathways of interactions as a whole, rather than isolated parts of the system [176].

As a system dynamic tool, the CLD visually describes the interconnections and interactions between the factors that make up the entire system [177]. With CLD I and II (Figures. 15 and 16), the dynamics of risk transmission factors for VBD and LF have been shown and portrayed, and the following emerges: (i) There is an interaction between location and socio-economic status which generates socio-spatial inequalities and deprivation and poses a threat to public health [178]. This occurs in the urban transmission of VBD and LF; (ii) The areas with high population density, poor quality housing, migration from rural areas endemic to LF, poverty, and low level of education involve a lack of means for prevention and protection. These socio-economic factors lead to a risk of LF transmission in SSA urban areas [159].

Moreover, the transmission of LF in a community depends on three conditions: the prevalence of infected individuals and their microfilaremia, the density of mosquitoes and their vectorial capacity, and finally, the frequency of human-mosquito contact [179].

Anopheles is the main vector of transmission of *Wuchereria bancrofti* in Africa, but in urban areas, *C. quinquefasciatus* is the vector [180]. *C. quiquefasciatus* is an urban vector, which may be due to the fact that anopheles need relatively clean water to reproduce, whereas *C. quiquefasciatus* can adapt to water with high organic content, such as water in poor urban environments [181]. Indeed, in poor urban areas, there is a lack of environmental sanitation and poor sanitation and drainage, such as stagnant water, waste water pool, wet pit latrines, and flooded soils, all conditions that favor the reproduction of vectors such as *C.quinquefasciatus* [159].

With CLD III (Figure 17), the public health intervention and vector control of urban LF were represented and depicted. It follows that: (i) LF elimination is possible by interrupting its transmission cycle. This is possible by providing treatment in a large-scale endemic community to reduce microfilaremia and vector control to reduce vector density and prevent human-mosquito contact. In addition, there should also be the management of diseases in infected people.

Referring to this, the WHO launched in 2000 the ‘‘Global Program to Eliminate Lymphatic Filariasis” (GPELF), which is based primarily on two strategies: (1) Stopping the spread of infection (interruption of transmission by MDA and vector control) and (2) Alleviating the suffering of the affected population (control of morbidity) [160].

With an STD, a model of LF transmission was conceptualized for the simulation. This simulation model shows the dynamics of LF transmission over time (Figs. 18 and 19).

The stock and flow diagram shows how the system evolves over time and allows the quantification of the simulation [182]. Moreover, long delays between cause and effect are most often characteristics of a dynamic complexity problem [183]. Such a situation is the case in LF as a public health issue.

5.2. WASH coverage and health ill in SSA urban areas

Despite the low coverage of WASH in SSA, urban areas have better WASH services than rural areas. Southern SSA has the best urban WASH coverage, followed by western and middle regions. A low WASH coverage is noted for its contribution to mortality associated with diarrheal diseases across SSA, since diarrheal diseases may originate from inadequate access to WASH services. Indeed, for the year 2019, 7.75% (CI95%

5.99–9.7%) of all deaths in SSA from diarrheal diseases were attributable to unsafe WASH with a RFA of 95.93% (CI95% 91.94–98.24%).

Unless actions are taken to improve WASH access in SSA, theoretical estimates do not predict much progress in reducing the mortality of diarrheal diseases attributable to unsafe WASH services by 2030. Indeed, diarrheal diseases are expected to be the cause of 6.77% (CI95% 2.39–15%) of all deaths with a RFA of 93.15% (CI95% 82.8–98.13%). In fact, many SSA countries are predicted to show a negative progress in WASH coverage by 2030.

In the context of low WASH coverage and associated health burden in the SSA region, urban areas were not spared from this issue. Even though WASH coverage is better in urban areas than in rural areas, social inequalities in urban areas have implications for access to WASH services and health risks associated with inadequate WASH [48]. Therefore, poor urban areas have low coverage of WASH services relative to wealthy urban areas; consequently, poor urban residents are at a higher risk for transmission of WASH-related infections such as diarrhea [184]. However, it is difficult to obtain data on the88ealthh burden in poor urban areas, since there are no disaggregated data available for urban health in SSA [28].

Fecally transmitted infections are often the result of poor WASH. Indeed, inadequate WASH access enables the interlinked pathways in the Wagner F diagram [fluids (or water), field (or soil), flies, fingers, and food] for transmission of fecal–oral diseases, such as diarrheal diseases, to flourish [185] [186].

5.3. Proposition of conceptualisation

Cairncross et al. [186] discussed public and domestic domains regarding disease transmission, while Andrianou & Makris [20] discussed urban and human levels in relation to the concept of the exposome. A division of urban areas into public, domestic, and individual areas is of interest for considering the dynamics and specificities of exposomes in and between these urban areas. Another point of interest in this restructuring of urban exposomes is the potential for more targeted and effective interventions, which would be particularly relevant for waterborne disease-related issues in sub-Saharan African urban areas.

The DPSEEA framework determines the source and causes of the spread of waterborne pathogens by analysing interconnections between changes in the urban environment and the burden of waterborne diseases [187]. This framework is helpful for taking a proactive approach that targets actions to be taken earlier in the causal chain of the framework. Such actions will subsequently contribute to the reduction of environmental occurrence of waterborne pathogens and the risk prevention for related diseases [188].

Urbanization in SSA generates a combination of conditions including environmental degradation, populated areas and economic deprivation, all conducive to unsafe sanitation and exposure to faecal-orally transmitted diseases (FOD) [189].

FOD mainly result from oral contact with water, food, and other vehicles contaminated with faecal matter [153] [169]. These infections, caused by various bacterial, viral and protozoan pathogens, are preventable by interrupting the faecal-oral transmission pathways [189].

Many models are developed to represent the faecal-oral route, among them the most important is the “F diagram” of Wagner and Lanoix [190]. This diagram illustrates the transmission of faecal-oral diseases and it could be useful to also describe water, sanitation and hygiene (WASH) interventions acting as barriers in the flow of faecal-oral pathogens [189]. However, this diagram does not take into account the different domains of disease transmission (public, domestic and individual) discovered after [166] [191].

Displaying the “F-diagram” throughout the urban domains of diseases transmission can provide an alternate pattern and specify by domain the components of this diagram and the barriers acting as interventions. This diagram allows the panorama of factors of exposure to FOD throughout the urban exposome, these factors can then be quantified and measurable over time as components of the exposome [192].

This diagram also presents the barriers to break the transmission of FOD in each of the urban transmission areas (public, domestic and individual). Therefore, it shows where the WASH interventions could take place and what type of interventions. An advantage of this diagram is the potential surveillance of FOD in urban areas with the faecal contamination indicators (FAECI) [170].

The FAECI indicators could be monitored In public, domestic and individual areas to get the status of the WASH services and the effectiveness of the interventions. Indeed, these indicators are related to water (W_1, W_2), sanitation (S_1, S_2, S_3, S_4) and hygiene (H_1, H_2) and may be monitored over time in public, domestic and individual areas.

In the public area, public policies could be taken for the municipal management of sanitation, the security of the water supply, while in the domestic area, there could be a community intervention for the promotion of health in household sanitation, water security and food hygiene [170]. In an individual area, there could be a health promotion intervention for personal hygiene such as hand washing to avoid contact and ingestion of faeces, as well as an intervention to treat infections based on physiology, age, and immunity of individuals [169].

Vulnerability to exposure to infections depends on factors such as hygiene behavior, socio-economic status and environment. This vulnerability increases susceptibility to infections by inducing physiological changes in an individual [153] [169]. In the case of FOD, drinking water is a key route through which individuals are exposed to faecal-oral pathogens [167]. Therefore, monitoring of exposomics data on drinking water quality (e.g, E. *coli* per 100 mL) remains important. When in individual exposome, drinking water is highly compromised, water treatment and safe distribution of the public exposome are the main concerns [189]. This diagram also illustrates the possibility to trace the source of an exposure and planning a targeted intervention, because the exposures are interrelated.

5.4. Discussion of research objectives

Regarding **Specific objective 1** (*"To establish the typology of the environmental risk to water and vector-borne diseases in SSA urban areas"),* the SSA urban areas and particularly poor urban areas such as informal settlements home environmental risk for the spread of WBDs and VBDs. During this study, a specific type of risks were distinguished the "everyday health risk" of urban area referring to health risk to which dwellers are permanently exposed.

In the case of WBDs, the risk come from contaminated drinking water and bad hygiene practices, diarrheal disease, cholera, and worm infections are concerned. For the VBDs, an unsafe sanitation, sewage, trash, garbage lead to breeding of vector site and pose the risk of the spread of Malaria, Dengue, zika, Chikungunya.

When considering **Specific objective 2** (*"To determine how the urban environment factors trigger water and vector-borne disease outbreaks"),* an encroachment of people on the sylvatic cycle of pathogen such arbovirus could lead to outbreak. The risk of VBD outbreak come from a combination of factors related to vectorial capacity, environmental suitability, and pathogen mutations. These factors are exacerbated by the climate change phenomenon because vector competence varies spatially with climatic parameters such as relative humidity and temperature.

The risk of outbreak of WBD such as cholera come from proliferation of pathogen in contaminated water, where condition of temperature, salinity, nutriment are favourable. But these environmental factors for proliferation of pathogen with poor sanitation, bad hygiene practices have a seasonal variation in human exposition.

In relation to **Specific objective 3** *"To determine the specificities and contributions of urban environment in the exposure to water and vector-borne diseases"),* from statistical analyse, in 2019 there was 7.75% (CI9% 5.99-9.97%) of total death, all age, all sex, from diarrheal diseases across SSA attributable to unsafe water sanitation and hygiene practices with a risk factor attribution (FRA) of 95.93%(CI95% 91.94 – 98.24%).

Considering **Specific objective 4** (*"To propose a conceptualization of urban environment to face the water and vector-borne diseases risks")*, in this study we proposed to divide urban area in 3 exposomes: public, domestic, and individual. Making urban area as continuum of exposome where internal exposome domain of the higher-level exposome is anchored to the external exposome of the next. Also a conceptual framework was proposed in the application of this subdivision of urban areas in the DPSEEA.

The study revealed that system dynamic are effective for perceiving and analysing the complexity of public health problem by observing the pathways of interactions as a whole, rather than isolated parts of the system.

6. CONCLUSIONS

"A conclusion is the place where you got tired thinking" Martin Fischer

6. Conclusions

1. Urbanization is one of the most important challenges that SSA countries face and should be considered a process of development that can generate specific health risks at the SSA area.

2. The everyday health risk and its socio-spatial distribution through the population in the contextual setting of urban informal settlements in SSA result from a complex interaction between multi-level causative factors. Informal settlements should be considered as a social health determinant in order to capture risk and vulnerabilities in these poor urban areas and bring better public health intervention responses.

3. Emergence of *Aedes*-borne viral infections has been observed in SSA and the potential of an arbovirus to adopt an urban transmission cycle with a competent anthropophilic vector, such as *A. aegypti* or *A. albopictus*, demonstrates the risk to SSA population health. This vector proliferation is intensified by the SSA socio-economic conditions of the population and environmental/climate change factors. The development of an urban transmission cycle poses a potential risk of re-emergence of dengue, *chikungunya*, *Zika*, and yellow fever in the SSA urban population.

4. The SSA region has a poor WASH coverage, leading to WASH-related diseases, with diarrhea being the main health burden. Although urban areas have better overall WASH coverage than rural areas, poor urban areas remain underserved owing to intraurban inequalities in access to WASH services. In addition, there is not much data available on WASH coverage and the associated health burden in poor urban areas. Disaggregated data on urban WASH access could help in inclusive WASH service implementation in poor urban areas.

5. Cholera remains a major scourge for the SSA population and urban areas with inadequate sanitation and limited access to safe water are likely to acquire this waterborne disease as well as spread it. *V. cholerae* exists in natural aquatic environments, and a multidisciplinary approach to investigate the different relationships between the genomic and ecological characteristics of the bacterium and African urban anthropic behavior could be useful in containing the spread of the disease.

6. System dynamics modelling is adapted to understand the complexity of vector-borne diseases and to design an effective holistic intervention. This study shows that the dynamic complexity of risk factors for the transmission of urban LF can be well illustrated by system dynamics modelling. It is a holistic approach to tackle the issues of the interaction of risk factors and eventually proposes interventions to control urban LF in SSA. Modelling system dynamics can be a system thinking approach for public health interventions and policies.

7. The division of urban areas into individual, domestic, and public areas is essential to achieve a better understanding of the specificities of urban exposures to waterborne diseases. This approach implies taking into account the urban exposome in terms of individual, domestic, and public exposomes. This restructuring of urban areas could be considered in the DPSEEA conceptual framework. It shows the interconnections among causes, changes in the sub-Saharan urban environment, and potential public health interventions against the spread of waterborne diseases.

8. The diagram of faecal-oral diseases transmission dynamic in urban exposome gives an overview of the connection between the exposure components of the urban exposome for faecal-orally transmitted disease in sub-Saharan Africa.

9. In the form of an exposome diagram, it allows to measure the exposomics data over time of faecal-orally transmitted diseases in public, domestic and individual areas, thus allowing targeted interventions in these urban exposure areas.

7. List of publications

Zerbo A., Castro Delgado R., Arcos González P. Conceptualization of the transmission dynamic of faecal-orally transmitted diseases in urban exposome of sub-Saharan Africa. *Risk Management and Healthcare Policy.* Under review

Zerbo A, Castro Delgado R, Arcos González P. Conceptual frameworks regarding waterborne diseases in sub-Saharan Africa and the need of a new approach to urban exposomes. *Epidemiology and Health 2021*: e2021079. DOI: https://doi.org/10.4178/epih.e2021079.

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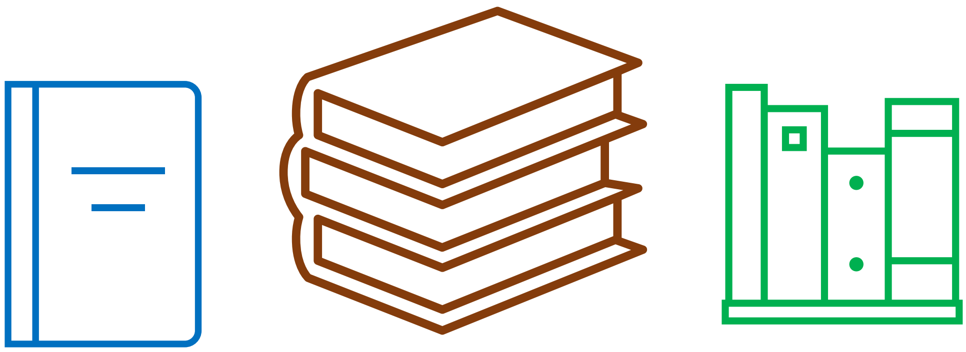
Zerbo A., Castro Delgado R., P. Arcos González P. Vulnerability and everyday health risks of urban informal settlements in Sub-Saharan Africa. *Global Health Journal* 4(2) June 2020 10.1016/j.glohj.2020.04.003

8. REFERENCES

"Each source that I read, I would look through the bibliography and the footnotes, and use that as a map for the next thing I would read"

Alexander Chee



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