Linking land use dynamics, surface water systems, and human health risks in Ghana

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Preface

This thesis is submitted in partial fulfilment of the requirement for obtaining a PhD degree in Natural Sciences at the University of Bonn, Germany. The research study described was conducted at the Department of Geography between October 2017 and December 2021, under the supervision of Prof. Dr. Mariele Evers and Prof. Dr. Thomas Kistemann. The research was conducted as part of the One Health and Urban Transformation project under the One Health Graduate School at the Centre for Development Research (ZEF), University of Bonn. The research was funded by Ministry of Culture and Science of North Rhine-Westphalia (Ministerium für Kultur und Wissenschaft des Landes Nordrhein-Westfalen, MKW), Germany.

This doctoral thesis followed the cumulative dissertation approach, consisting of three manuscripts (Chapters 2 - 4) which have been published in "*Water*" and "*Social Sciences and Medicine*" journals. The details of the manuscripts are presented in the subsequent chapters (2 – 4). The following is the list of paper publications. Additional publications are listed in the publication section.

Ntajal, J., Höllermann, B., Falkenberg, T., Kistemann, T., and Evers, M. (2022). Water and Health Nexus—Land Use Dynamics, Flooding, and Water-Borne Diseases in the Odaw River Basin, Ghana. *Water. 14*(3), 461. https://doi.org/10.3390/w14030461

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Summary

Human-land use-water interactions are multifaceted with linkages to health, particularly the transmission of infectious water-related diseases, via either the ingestion of polluted water or human contact with infected water bodies. In Ghana, especially in the Greater Accra Metropolitan Area, drinking water pollution has been a persistent challenge, leading to the transmission of water-related infectious diseases. However, the existing fragmented interventions, including water and sanitation supply, have often failed, while diseases continue to pose a huge burden on households and the government. The underlying drivers of exposure and risks of diseases are not explored and explicitly understood, due to lack of institutional collaborations, hindering the development of integrated solutions. Therefore, this doctoral research aims at enhancing the understanding of the human-water-health nexus, focusing on the exposure pathways and risks of water-related infectious diseases, including water-borne diseases in the Odaw River catchment and schistosomiasis in the Lower Densu River catchment within the Greater Accra Metropolitan Area. This research is based on the hypothesis that human-land use-water interactions have linkages with water-related infectious diseases, which require the adoption and integration of multi-methods to comprehensively explore and examine the underlying drivers to enhance understanding and support develop integrated and collaborative strategies.

The study employed a mixed-methods approach, integrating a systematic literature review of 54 peer-reviewed research articles published between 1995 and August 2019, to assess the trends and gaps in research on human-water interactions and risks of diseases, surveys household (n=320) and schoolchildren (336), field observations of human-water-contact patterns, and stakeholder participation via four focus group discussions, three workshops, and expert elicitations. Data integration and analysis included qualitative system dynamic modeling and analysis of causal loops of the interactions and pathways of exposure and risks of diseases, land use and land cover change assessment and analysis, using supervised classification in the Odaw River catchment, and bivariate logistic regression analysis and estimation of the probability of schistosomiasis infections.

The key outcome of the systematic literature review indicated that there has been an increase in the number of studies since 2009, however, six studies made explicit linkages between water-land use-diseases. Explicit linkages exist between human–water interaction patterns and the transmission of schistosomiasis. However, weak and complex linkages were found between land-use change and the transmission of water-borne disease, due to its multiple underlying drivers. The literature review further revealed gaps in the application of integrated methods in examining the human-land use-water nexus and the pathways to infectious diseases. Regarding the exposure and risks of water-borne diseases, the results show that communities have access to water and sanitation but the diseases are still prevalent, indicating provisioning only water and sanitation is insufficient to eliminate diseases. In addition, flooding, influenced by poor land use planning and solid waste disposal is a key contributing factor to diarrheal disease outbreaks, via drinking water pollution and the destruction of water and sanitation infrastructure. The risk of urinary schistosomiasis is linked to limited access to improved sanitation and safe water supply, compelling the communities to rely on untreated river water from the river, and open defecation. The probability of schistosomiasis infection was found high, regarding recreational, domestic, and occupational water-contacts. More frequent and longer water-contacts patterns increase the chances of urinary schistosomiasis transmissions.

The key highlights from this doctoral research indicate that human-water interactions have multiple pathways to water-related infectious diseases in the Greater Accra Metropolitan Area. The pollution of drinking water and unimproved sanitation services are basic sources of risk of water-borne diseases. Human contact with schistosome-infected water bodies is the key exposure pathway to schistosomiasis transmission.

To enhance further understanding of the human-water-health nexus, this doctoral thesis emphasizes the integration of multiple methods, including multidisciplinary and transdisciplinary approaches for investigating complexities and linkages among land use, surface water quality, and water-related infectious diseases are important. The qualitative system dynamic models and the causal diagrams developed supported the identification of complex linkages and multiple feedback loops of disease outbreaks. Preventive measures must focus on breaking the disease transmission cycle. Thus, providing sufficient safe drinking water supply, and improved sanitation and hygiene can form a barrier to halting the transmission. Precautionary measures such as protective clothing ought to be used during frequent and longer water-contact activities. While these measures can be effective, they are no guarantee for reducing the risk of water-borne diseases. As revealed in this study, integrated land use planning and management are also needed to combat water-related infectious diseases. Thus, the study contributes to multi-sectoral collaborations through the development of integrated and collaborative strategies, including land use plans, awareness campaigns, human behavioral change, flood risk reduction, law enforcement, improved waste management, and water quality monitoring to be inclusively implemented at the community, district, metropolitan, and national levels to reduce the risks of diseases and promote a clean environment and human health.

Zusammenfassung

Die Wechselwirkungen zwischen Mensch, Landnutzung und Wasser sind facettenreich und stehen in engem Zusammenhang mit dem Thema Gesundheit und hier insbesondere mit der Übertragung von wasserbedingten Infektionskrankheiten, die entweder durch die Aufnahme von verschmutztem Wasser oder durch den Kontakt des Menschen mit infizierten Gewässern entstehen. In Ghana, speziell in der Metropolregion Accra, ist die Verschmutzung von Trinkwasser eine anhaltende Herausforderung, die zur Übertragung von wasserbedingten Infektionskrankheiten führt. Die vereinzelt und sektoral geplanten Maßnahmen, einschließlich der Maßnahmen in der Wasser- und Abwasserversorgung, scheitern jedoch häufig und wasserbedingte Krankheiten stellen weiterhin eine große Belastung für die Haushalte und die Regierung dar. Die hierfür zugrunde liegenden Treiber für Exposition und Krankheitsrisiken wurden aufgrund mangelnder institutioneller Zusammenarbeit noch nicht ausreichend untersucht oder explizit verstanden und schränken darüber hinaus die Entwicklung integrierter Lösungen ein. Daher zielt diese Doktorarbeit darauf ab, das Verständnis des Nexus Mensch-Wasser-Gesundheit zu verbessern. Der Schwerpunkt liegt auf der Identifizierung von Expositionspfaden und Risiken wasserbedingter Infektionskrankheiten am Beispiel des Einzugsgebiets des Odaw-Flusses und mit besonderem Fokus auf Bilharziose im Einzugsgebiet des Lower Densu-Flusses im Großraum Accra. Die Forschungsarbeit basiert auf der Hypothese, dass die Wechselwirkungen zwischen Mensch, Landnutzung und Wasser einen großen Einfluss auf wasserbedingte Infektionskrankheiten haben. Dies erfordert die Anwendung und Integration multipler Methoden, um die zugrunde liegenden Faktoren und Treiber umfassend zu erforschen und zu untersuchen, das Verständnis zu verbessern und die Entwicklung integrierter und kooperativer Strategien zu unterstützen.

Die Studie verwendet einen Multi-Methodenansatz. Um Trends und Lücken in der Forschung zu Wechselwirkungen zwischen Mensch und Wasser sowie Krankheitsrisiken festzustellen, fand eine systematische Literaturauswertung von 54 begutachteten Forschungsartikeln, die zwischen 1995 und August 2019 veröffentlicht wurden, statt. Die Situation vor Ort wurde durch Umfragen in Haushalten (n=320) und bei Schulkindern (336) eruiert. Darüber hinaus wurden Feldbeobachtungen von Mensch-Wasser-Kontaktmustern sowie vier Fokusgruppendiskussionen, drei Workshops und Expertenbefragungen mit Beteiligung von Interessenvertretern durchgeführt. Die Datenintegration und Analyse umfasste eine qualitative Systemmodellierung und eine Analyse der Kausalschleifen sowie der Wechselwirkungen und Wege der Exposition und Krankheitsrisiken. Darüber hinaus wurden Landnutzungs- und Landbedeckungsveränderungen im Einzugsgebiet des Odaw-

Flusses klassifiziert, analysiert und bewertet. Mittels bivariater logistischer Regressionsanalyse wurde eine Schätzung der Wahrscheinlichkeit für Bilharziose-Infektionen vorgenommen.

Die Kernaussage der systematischen Literaturauswertung ist, dass die Zahl der Studien seit 2009 zugenommen hat, wobei nur in sechs Studien ein ausdrücklicher Zusammenhang zwischen Wasser, Landnutzung und Krankheiten hergestellt wurde. Es bestehen eindeutige Zusammenhänge zwischen den Interaktionsmustern zwischen Mensch und Wasser und der Übertragung von Bilharziose. Dagegen wurden nur schwache und gleichzeitig komplexe Zusammenhänge zwischen Landnutzungsänderungen und der Übertragung von durch Wasser übertragenen Krankheiten festgestellt, was auf die zahlreichen zugrundeliegenden Faktoren zurückzuführen ist. Lücken bei der Anwendung integrierter Methoden zur Untersuchung des Zusammenhangs zwischen Mensch, Landnutzung und Wasser sowie der Wege zu Infektionskrankheiten wurden festgestellt. Bezüglich der Exposition und den Risiken gegenüber durch Wasser übertragbaren Krankheiten zeigen die Ergebnisse, dass die Gemeinden zwar Zugang zu Wasser und sanitären Einrichtungen haben, die Krankheiten aber immer noch weit verbreitet sind. Dies deutet darauf hin, dass die Bereitstellung von Wasser und sanitären Einrichtungen allein nicht ausreicht, um Krankheiten zu beseitigen. Darüber hinaus tragen Überschwemmungen, die durch schlechte Flächennutzungsplanung und die Entsorgung von Abfälle beeinflusst und begünstigt werden, zur Verschmutzung des Trinkwassers und zur Zerstörung der Wasser- und Abwasserinfrastruktur wesentlich bei und damit auch zum Ausbruch von Durchfallerkrankungen. Das Risiko der Schistosomiasis der Harnwege hängt mit dem eingeschränkten Zugang zu verbesserten sanitären Einrichtungen und einer sicheren Wasserversorgung zusammen. In diesen Fällen sind Gemeinden dazu gezwungen auf unbehandeltes Flusswasser zurückzugreifen und offene Defäkation zu betreiben. Dies gilt für Aktivitäten in allen Lebensbereichen (Beruf, Haushalt und Freizeit) und erhöht die Wahrscheinlichkeit des Infektionsrisikos. Insgesamt erhöhen häufigere und längere Wasserkontakte die Wahrscheinlichkeit einer Übertragung von Schistosomiasis der Harnwege.

Die Kernergebnisse dieser Doktorarbeit deuten insgesamt darauf hin, dass die Wechselwirkungen zwischen Mensch und Wasser auf vielfältige Weise zu wasserbedingten Infektionskrankheiten in der Metropolregion Accra führen. Die Verschmutzung des Trinkwassers und die unzureichende Abwasserentsorgung sind die Hauptrisikofaktoren für wasserbedingte Krankheiten. Der Kontakt der Menschen mit Bilharziose-infizierten Gewässern ist der wichtigste Expositionspfad für die Übertragung von Bilharziose.

Um das Verständnis des Nexus Mensch-Wasser-Gesundheit zu verbessern, legt diese Doktorarbeit den Schwerpunkt auf die Integration verschiedener Methoden, einschließlich multidisziplinärer und transdisziplinärer Ansätze zur Untersuchung der Komplexität und der Zusammenhänge zwischen Landnutzung, Oberflächenwasserqualität und wasserbedingten Infektionskrankheiten. Die qualitativen systemdynamischen Modelle und die entwickelten Kausaldiagramme unterstützten die Identifizierung komplexer Zusammenhänge und multipler Rückkopplungsmechanismen von Krankheitsausbrüchen. Vorbeugende Maßnahmen müssen darauf abzielen, die Krankheitsübertragungszyklen zu unterbrechen. Eine ausreichende Versorgung mit sicherem Trinkwasser sowie verbesserte sanitäre Einrichtungen und Hygiene können als Barriere gegen die Krankheitsübertragung wirken. Bei häufigem und längerem Wasserkontakt sollten Vorsichtsmaßnahmen wie beispielsweise Schutzkleidung getroffen werden. Während die genannten Maßnahmen effektiv sein können, sind sie kein Garant für die Reduzierung des Risikos, sondern – wie diese Studie zeigen konnte – auch integrierte Landnutzungsplanung und Landnutzungsmanagement sind Hauptfaktoren die zur Eindämmung von wasserbedingten Krankheiten beitragen. Die vorliegende Doktorarbeit leistet daher einen Beitrag zur Sektor-übergreifenden Zusammenarbeit, die durch die Entwicklung integrierter und kooperativer Strategien, einschließlich Flächennutzungsplänen, Sensibilisierungskampagnen zur Verhaltensänderungen der Menschen, Verringerung des Überschwemmungsrisikos, Gesetzvollzug, verbesserter Abfallbewirtschaftung und Qualitätsüberwachung zur Verringerung des Krankheitsrisikos beitragen. Diese Sektor-übergreifende Zusammenarbeit kann auf Gemeinde-, Bezirks-, Großstadt- und nationaler Ebene umgesetzt werden, um eine saubere Umwelt und die menschliche Gesundheit zu fördern.

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List of abbreviations

Abbreviation	Full meaning
EC	Electrical Conductivity
FGDs	Focus Group Discussions
LULC	Land use and Land Cover
WRID	Water-Related Infectious Diseases
WHO	World Health Organization
NGOs	Non-Governmental Organization
OR	Odds Ratio
OD	Open Defecation
BOD	Biochemical Oxygen Demand
DO	Dissolved Oxygen
COD	Chemical Oxygen Demand
GAMA	Greater Accra Metropolitan Area
WASH	Water, Sanitation, And Hygiene
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
TSS	Total Suspended Solid
TDS	Total Dissolved Solids
QSD	Qualitative System Dynamics
CLDs	Causal Loop Diagrams
NTDs	Neglected Tropical Diseases
MDA	Mass Drug Administration
VIP	Ventilated Improved Pit Latrines

1. Introduction

1.1. Background

One of the main challenges of the earth today is water pollution, mainly due to anthropogenic activities (Zessner et al., 2017; Wijesiri et al., 2018). Human-water interactions are pluralistic and the associated impacts on water systems are multifaceted (Addae & Oppelt, 2019; Evers et al., 2017). As socio-cultural, economic, political, cultural, and ecological systems become closely interconnected through land use and urbanization, pressure (e.g., pollution) on water systems intensifies (Addae & Oppelt, 2019; Maassen & Galvin, 2019). The influences of these interactions on water systems can have detrimental impacts on public health through diverse interconnected and complex pathways, leading to the emergence and transmission of water-related infectious diseases (WRID) (Sclar et al., 2013; Zhu et al., 2016). Globally, the frequently reported infectious diseases are commonly linked to water quantity and quality, indicating that, while water plays important role in the survival of humans and the functioning of ecosystems, it can be a medium for the emergence and transmission of diseases (Anthonj et al., 2014).

In Asia, Middle-East, Africa, and Latin America, WRID are widespread and has been one of the leading causes of death, particularly among children under five years, contributing to a huge disease burden on households and the governments (Ali et al., 2015; Prüss-Ustün et al., 2019). In addition, to access to safe water, sanitation, and hygiene (WASH), it has been extensively recognized that land use, waste management, flooding, and water pollution form part of the underlying drivers of exposure to and the risks of WRID worldwide, particularly in poor regions with limited investment in water quality monitoring and sanitation (Anthonj et al., 2014; Ferreira et al., 2016; Miller & Hutchins, 2017). Different land use types have varying influences on human-water interaction patterns, water pollution pathways, and the risks of WRID (Anthonj et al., 2019; Magana-Arachchi & Wanigatunge, 2020; Mastel et al., 2018). New threats to human health, for example, the emergence of COVID-19 Coronavirus have become major issues perceived to be associated with human-land use-water interactions, leading to major disturbances to the pathogen reservoirs and spillovers (Plowright et al., 2021).

Different patterns of human-water interactions exist and the pathways of exposure to water-borne pathogens and parasites can be intricately linked. The outcome of the interconnectedness between human-water interactions and health becomes explicit when the associated impacts contribute to promoting health or outbreaks of diseases (Anthonj et al., 2014). Scholars have revealed that WRID are transmitted through two major exposure pathways, including drinking polluted water and human contact with infected water (via skin) (Magana-Arachchi & Wanigatunge, 2020; Ntajal et al., 2021). The WHO (2011) further underlined that diarrheal diseases are commonly linked to drinking water polluted with fecal matter, and contact with infected water bodies. Water-borne pathogens thrive in polluted water (e.g., Escherichia *coli* in fecal matter, or urine), and people are exposed to the pathogens via drinking or preparing food with water from polluted sources, bathing, or through water-contact activities such as swimming (Ding et al., 2017; Magana-Arachchi & Wanigatunge, 2020).

Human contacts with schistosoma-infected water systems via skin can pose higher exposure to the parasitic flatworms, which cause schistosomiasis (e.g., urinal, intestinal) (Ciddio et al., 2017; Kulinkina et al., 2019a; Ntajal et al., 2021). The freshwater snails, which act as the intermediate hosts (e.g., *Bulinus* snails) feed on the fecal matter in water bodies for survival. Studies reported that freshwater snails can be infected via fecal matter from schistosomiasis-infected persons. Niu et al. (2018) reported that environmental factors such as the weather (e.g., water temperature) and hydraulics (e.g., water level, flow, turbidity, etc.) affect the survival and reproduction of freshwater snails and the parasites (cercariae) in a given area. However, human-water contact types and patterns (e.g., duration and frequency) influence exposure to parasites and the risk of schistosomiasis infections (Angelo et al., 2018; Ntajal et al., 2021). Without developing and implementing sustainable barriers such as water quality monitoring and provisioning improved safe drinking water and sanitation to break the causal loops and the transmission cycles, WRID will continue to be a global burden, particularly in poor and developing regions (Soni & Trend, 2019; Alpanakateja, 2016; Ahmed & Shafique, 2019).

In Sub-Saharan Africa, due to anthropogenic activities such as poor land use planning, siltation of drains with solid waste, floods have killed hundreds, displaced thousands of people, and contributed to the spread of cholera, via pollution of drinking water (Kamba et al., 2016; Yira et al., 2016). While studies have identified positive impacts of floods such as renewal of wetlands and the deposition of fertile soils in floodplains, supporting the cultivation of food crops, conversely, devastating and cascading impacts on human health have been widespread, due to fragile systems. These include the destruction of water supply and sanitation facilities, sewage disposal systems, critical infrastructure, and healthcare systems (Adu-Gyamfi et al., 2021; Rui et al., 2018). Water pollution has been a persistent challenge in Ghana, including the Greater Accra Metropolitan Area (GAMA) with varying impacts on humans and environmental health, partly due to poor wastewater treatment and flooding, influenced by poor land use planning and waste disposal. WRID are still a major challenge in Ghana, particularly in poor and flood-prone urban communities in

Accra and Kumasi, mainly in areas with limited access to safe WASH. For example, flooding of the Odaw River in Accra was reported to have washed sewage containing pathogens into water systems, leading to water pollution (at the point-of-use) and outbreaks of diarrheal diseases, weeks after floods in 2014 and 2015 (Songsore, 2017; WHO, 2016).

In Ghana, reports indicate that access to drinking water and sanitation has relatively increased nationwide in the past years, however, multiple outbreaks of WRID, particularly cholera and water-related Neglected Tropical Diseases (e.g., schistosomiasis) are still reported every year (Eduful et al., 2020; Tahiru et al., 2020). Reported cases of water-borne diseases in communities in the Odaw River basin within GAMA are partly linked to poor sanitation and frequent flooding events, due to human activities (Owusu & Agbozo, 2019). In addition, urinary schistosomiasis is still a huge health challenge in peri-urban areas in Accra, including communities in the Lower Densu River basin in GAMA (Kulinkina et al., 2019a; Martel et al., 2019; Nyarko et al., 2018). This indicates that the dynamics and complexities of WRID in GAMA extend beyond the accessibility to only water and sanitation facilities. Additionally, it raises critical questions about our level of understanding of the drivers and dynamics of transmission and the existing interventions for disease control.

A systematic literature review by Ntajal et al. (2020) revealed that achieving drinking water safety involves the development of solutions including multi-barriers for protecting drinking water safety from the supply source till it is finally ingested. However, the provisioning of drinking water in Ghana is often done with limited focus on underlying factors that pose challenges to water systems within river catchments, and water storage behaviors at homes (Eduful et al., 2020). As the response of water systems to individual stress emanating from both natural and human activities are often been investigated and partly understood, there is limited knowledge and awareness of the combined dynamics and impacts of the interactions among different drivers of WRID in GAMA, particularly among the local communities (Abeka et al., 2019; Abu & Codjoe, 2018; Songsore, 2017). This highlights the need for comprehensive exploration and investigation of human-water interactions, and the risks of WRID with a specific focus on the underlying drivers and their cascading impacts to support the development of integrated solutions and collaborative implementation.

Human-water interaction is rooted in the pluralistic water research concept, which argues for the adoption of interdisciplinary and transdisciplinary research and systems approach to develop integrated solutions (Evers et al., 2017). Water-health nexus via the linkages between land use dynamics, flooding, water pollution, and the consequences of their combined impacts on WRID can be complex and therefore require integrated approaches including multidisciplinary and transdisciplinary collaborations to investigate and develop integrated solutions (Katz, 2001; Bammer, 2013). It has been argued that assessing and modeling interactions between complex system components with qualitative designs require the application of system thinking and system dynamics approaches (Coyle, 2000; Powell et al., 2016; Sterman, 2002). System dynamics allow the integration of different methods, including stakeholder participation, surveys, spatial data integration, and qualitative and quantitative analysis (Coyle, 2000; Powell et al., 2016).

Studies have highlighted that fragmented interventions for controlling and preventing WRID have failed, due to lack of institutional collaborations and stakeholder cooperation. As a result, integrated and sustainable solutions are not developed and implemented to promote health in GAMA. Additionally, evidence on holistic studies exploring human-water interactions and risks of WRID was missing (Adu-Gyamfi et al., 2021; Ntajal et al., 2020). To enhance the understanding of the human-water-health nexus and support the development of integrated and collaborative strategies, it is important to comprehensively assess and examine human-water interactions and the underlying drivers of exposure and risks of WRID, including flooding, land use dynamics, water pollution, and human water-contact types and patterns in GAMA. Specifically, this thesis focused on the human-water interactions and the risks of water-borne diseases in the Odaw River catchment, and the risks of urinary schistosomiasis in the Lower Densu River catchment, using integrated and mixed-method approaches.

1.2. Aim and research questions

It has been identified that the response of water systems to the impacts of individual stress has been partially explored and understood, indicating limited knowledge of the combined impacts of the interactions among different drivers of WRID in GAMA. Additionally, lack of collaboration and adoption of integrated approaches in investigating and developing solutions, fragmented strategies to address WRID have often failed. Therefore, it is important to extend our understanding of the exposure and risks of WRID beyond the accessibility to only WASH, specifically focusing on human-water interactions, the underlying drivers, and their cascading impacts on water and health to inform decision-making and policy formulation. Thus, the main aim of this study is to contribute towards the understanding of the human-water-health nexus, focusing on the exposure pathways and risks of water-related infectious diseases including water-borne diseases (e.g., diarrheal diseases) and water-based diseases (e.g., schistosomiasis) within GAMA. In this study, it has been hypothesized that human-water interaction and its underlying drivers contribute to the exposure and risks of WRID in Ghana. Therefore, the key research questions addressed in this thesis include:

Question 1: What are the trends and scientific gaps in research, regarding the influences of human–water interactions on water-related infectious diseases?

Question 2: What are the causes and underlying drivers of exposure to and the risks of water-borne diseases in the Odaw River catchment?

Question 3: What are the key influences of human–surface water interactions on the transmission of urinary schistosomiasis in the Lower Densu River catchment?

1.3. Summary of the methodological steps

Water-health nexus via human and water systems interactions forms part of the pluralistic research concept and cuts across various sectors and disciplines. Therefore, integration of interdisciplinary and transdisciplinary research perspectives, using mixed methods is required to investigate and understand the various dimensions of human-water interactions and drivers of exposure and risks of water-related infectious diseases in GAMA. These also included qualitative system dynamic modeling and spatial LULC change assessment and analysis, using a supervised classification (maximum likelihood) approach.

The mixed-method approach was found suitable for identifying the research gap and consolidating the existing scientific evidence on the given topic, identifying variables, developing the qualitative system dynamic modeling, and developing collaborative interventions to protect water systems and promote health. The data elicitation techniques adopted included a systematic literature review, household and schoolchildren surveys, field observation of human-water contact patterns, and stakeholder participation via stakeholder workshops, focus group discussions, and expert elicitation. The study participants included the members of the communities, schoolchildren, experts in water and health, NGOs, members of academia, and representatives from the government organizations and institutions at the district, municipal, metropolitan, and regional levels. Further details of the methods are integrated into subsequent chapters (2 – 4). Figure 1 presents a summary of the research design.

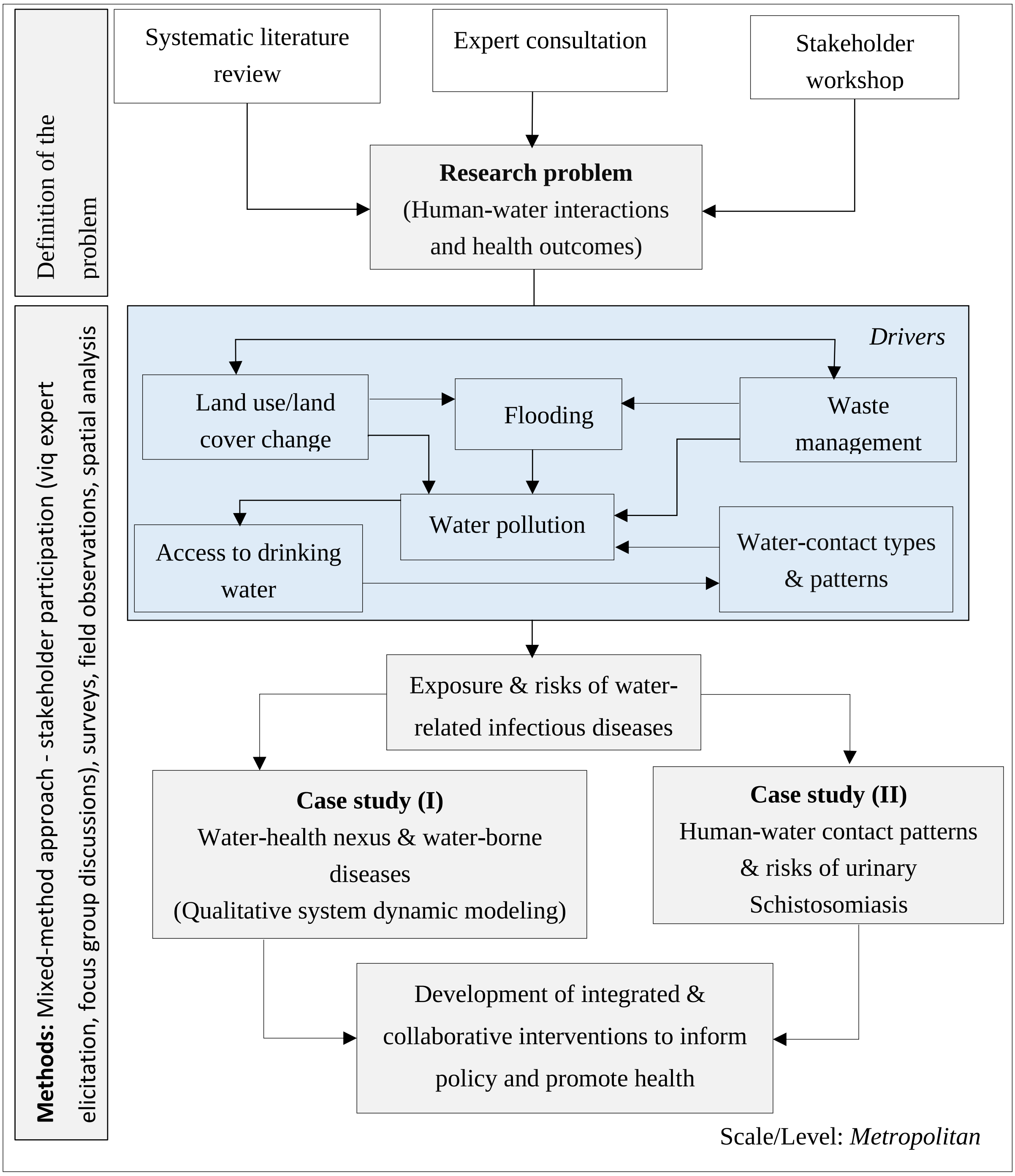

Figure 1. Summary of the research design

Source: Authors own illustrations, 2021.

In figure 1, the research design indicates an integration of various dimensions including the assessment of interactions of multiple drivers. To capture the multiple drivers and interactions, which influence the exposure and risks of WRID, it is crucial to adopt a mixed-method approach for eliciting, integrating, and analyzing data from various sources. Additionally, developing integrated and collaborative interventions requires multi-level stakeholder participation, which allows multi-sectoral collaborations and interactions to develop solutions for solving common and complex problems (Bammer, 2013; Mitchell et al., 1997; Schiller et al., 2013). The QSD was found suitable for this study as it allows stakeholder participation, multi-sectoral collaborations, and integration of data from qualitative and semi-quantitative sources for the development of QSD and causal loop diagrams (CLDs). The FGDs, surveys, and field observations allow comparison, validation, and harmonization of data from different sources. Employing a single method limits the capabilities and flexibility of capturing and integrating data from diverse sources. The integration of the systematic literature review, assessment of the basic and underlying drivers of risks of water-borne diseases, and the assessment of human-water contact patterns and schistosomiasis outcomes is intended to broaden and enhance a holistic understanding of the water-health nexus with multiple pathways.

1.4. The study area

Ghana is a coastal country in West Africa with huge water quality issues, partly contributing to outbreaks of WRID. Through consultations with stakeholders in the water and health sectors and literature review, it was identified that human-water interactions and limited access to WASH are potential drivers of water pollution and WRD in Ghana. However, comprehensive investigations exploring and examining these interactions as well as developing collaborative intervention strategies are missing, particularly in poor and flood-prone urban areas, including the Greater Accra Metropolitan Area (GAMA). Therefore, this doctoral research was conducted in GAMA in a coastal region (Greater Accra) of Ghana (See Figure 2) to support identify solutions. The largest city within GAMA is Accra, which is also the national and administrative capital city of Ghana. Rapid urbanization in Accra has led to tremendous transformations of the city over the decades (Ghana Statistical Service, 2021; Kpienbaareh & Luginaah, 2020). However, land use and infrastructure development placed less attention on the urban surface water systems (Frazier, 2011). The current land use is characterized by increasing paved surfaces, industrial space, road networks, encroachment into wetlands, mangroves, and building in watercourses, which have increased stormwater runoff and the vulnerability of the socio-ecological systems to the frequent flush and riverine flooding.

The two research case studies were conducted in two different river catchments within GAMA: the Odaw River catchment in Accra and the Densu catchment in the periphery of Accra. These areas were selected based on human interactions with the rivers and reported public health outcomes in the communities. The assessment of exposure to and risks of water-borne disease in the context of urban transformation was conducted in the Odaw River basin, while assessment of the impacts of human-surface water interactions, and the risks of schistosomiasis infections was conducted in the Lower Densu River catchment, a peri-urban area with a rapidly increasing population, due to urban expansion pressure from Accra. The communities in the Lower Densu catchment in the Ga West and South municipalities literally have limited access to improved WASH. In addition, the urbanized communities in the Odaw River catchment, characterized by poor land use planning and poor waste management, which partly contributes to situations where “every place” including built-up (residential areas) and waterways in the communities are turned into waste disposal sites, leading to water and environmental pollution. The improper discharge of wastewater contributes to water pollution, while solid waste disposal causes siltation of the drainage systems, leading to flooding.

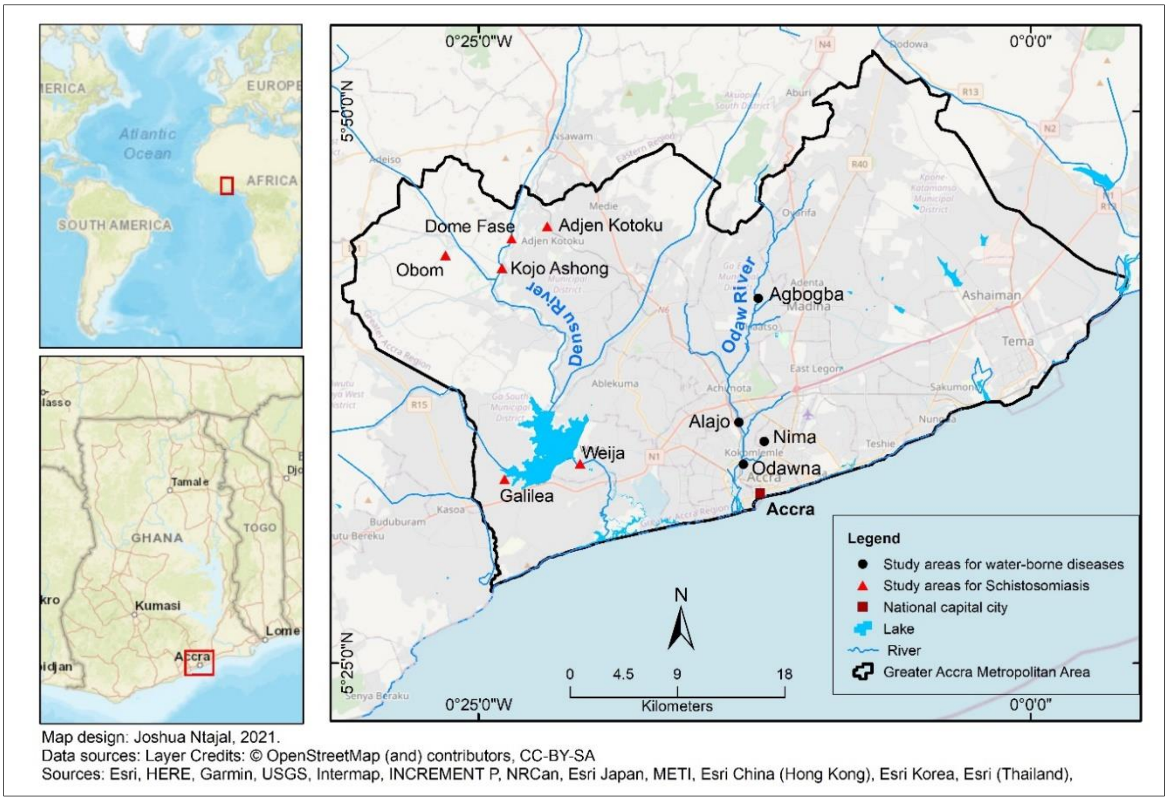

Figure 2. Map of the study areas within the Greater Accra Metropolitan Area

1.5. Overview of the research questions, methods, and key highlights of the study

An overview of the key research questions addressed, the methods employed, and key highlights from the study are summarized in Table 1. It further summarizes the contributions to the understanding of the exposure and risk of WRID associated with human-water interactions and its underlying drivers. Each research question was addressed and presented as an individual chapter (2 - 4). Chapters two (paper 1), chapter three (paper 2), and chapter four (paper 3) have been published in peer-review journals (see Table 1).

Table 1. Overview of the research questions, methods, and key highlights of the study

#	Research question	Methods	Key highlights	Key contributions to the field	Paper status
Paper 1	What are the trends and research gaps, regarding the influences of human–water interactions on the risks of water-related infectious diseases?	A systematic review of literature, following the "Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA)" procedure. 54 papers were retrieved from web databases (e.g., Google Scholar, PubMed, Science Direct, etc.) from 1995 to 2019	• There has been an increase in scientific research on LULC and WRID globally (2011-2019) • There exist relatively complex and weak linkages between land-use dynamics and water-borne diseases • There is an explicit linkage between human water-contacts and risk of schistosomiasis infections • Other drivers (access to WASH, floods, etc.) have influences on WRID • Lack of inter-transdisciplinary research collaborations on LULC & WRID	• Identified the trend and gaps in research including lack of integrated approach in assessing linkages between land use, water pollution, and human health risk • Recognized the need for investigating and addressing underlying drivers of exposure and risks of WRID, in addition to access to WASH and sensitization	Published in "*Water*" DOI: 10.3390/w12030631
Paper 2	What are the causes and underlying drivers of exposure to and the risks of water-borne diseases in the Odaw River catchment?	Mixed-method approach: • Household surveys (n=320) • Focus group discussions (4) • Stakeholder workshops (3	• Communities have access to drinking water and unimproved sanitation • Provisioning of drinking water and sanitation is not a stand-alone solution to water-borne diseases	• Development of qualitative system dynamic models for water-borne diseases risks • Development of integrated and collaborative strategies for flood risks reduction,	Published in "*Water*" DOI: 10.3390/w14030461

		workshops) & expert elicitation • Qualitative system dynamics modeling - participatory	• Flooding has impact on the outbreaks of water-borne diseases • Multi-sectoral collaborations and cooperation are important to co-design and inclusively implement integrated strategies	LULC planning, waste management, water quality monitoring, and human health promotion • Stakeholder participation and multi-sectoral collaborations contributed to human capacity building	
Paper 3	What are the key influences of human–surface water interactions on the transmission of urinary schistosomiasis?	Mixed-method approach: • Survey of schoolchildren (n=336) • Human water-contact observations • Expert elicitation	• There is limited access to improved sanitation and safe water, compelling communities to depend directly on river/streams • Water-contact activities, including domestic, recreational, and occupational are practiced by all children, creating widespread exposure patterns • Frequent and longer water-contacts contribute to high odds of blood in the urine • Supplying improved WASH in addition to sensitization is important to reduce exposure to pathogens	• Identification of human-water contact types and patterns, which form key exposure pathways and risks of urinary schistosomiasis transmission • Development of sustainable solutions including improved WASH, awareness campaigns, and discourage contacts with infected water bodies, as barriers to break the schistosomiasis infection cycle	Published in *"Social Science and Medicine"* DOI: 10.1016/j.socscimed.2020.113546

1.6. Thesis organization and overview of the chapters

The thesis is organized into five chapters including the general introduction (Chapter 1). Chapter two covers the systematic literature review of the trends and gaps in research. Chapter three focuses on the first case study of exposure to and the risks of water-borne diseases in the Odaw River catchment. Chapter four focused on the second case study on the influences of human-water interactions on the transmission of urinary schistosomiasis in the Lower Densu River catchment. Chapter five provides the general conclusion of the thesis, including key findings, recommendations for further research, and the outlook. A summary of the thesis organization is presented in figure 3.

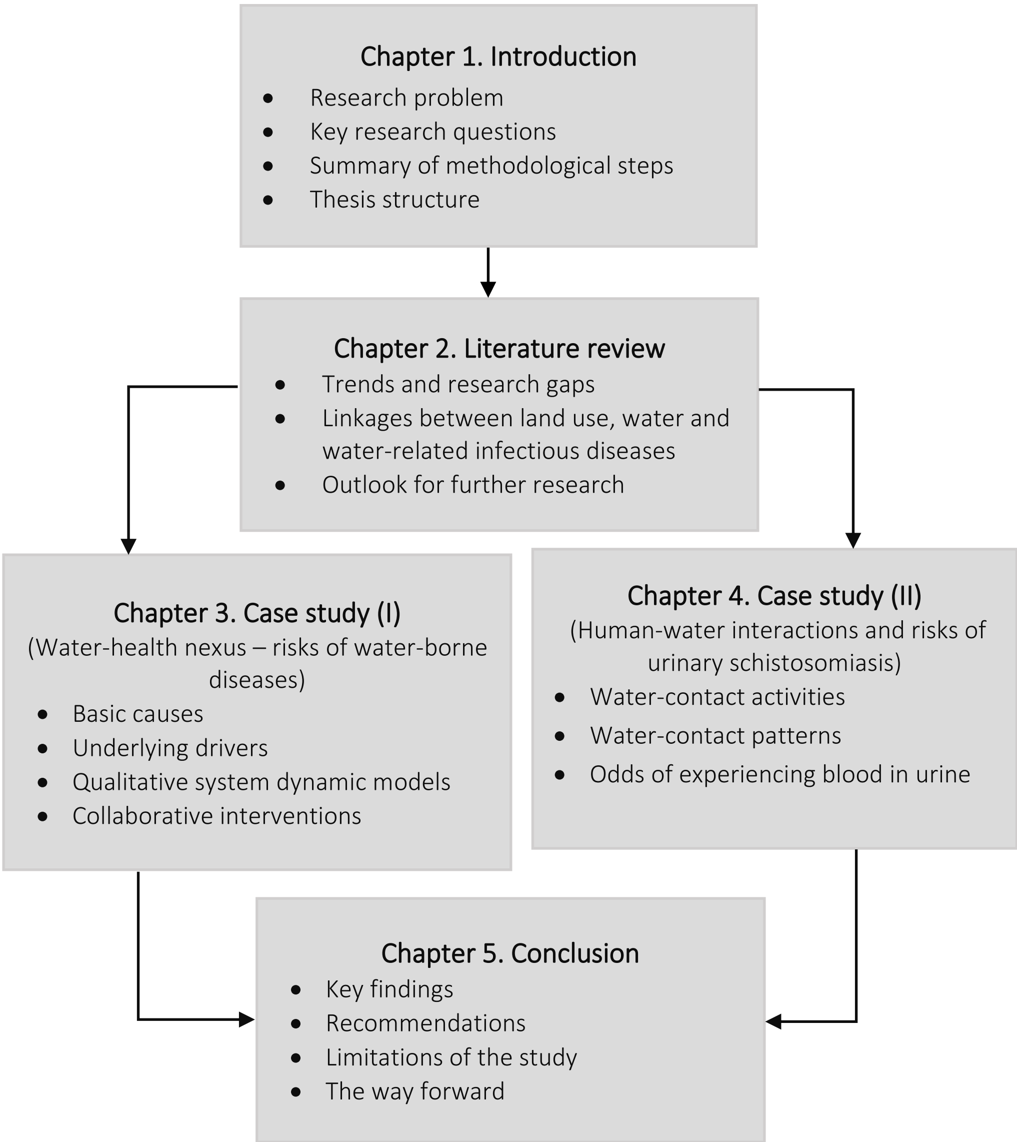

Figure 3. Organization of the thesis
Source: Authors' own illustrations, 2021

As illustrated in figure 3, the following (chapters 2 – 5) presents the details of the thesis, including the outcome of the systematic literature review of the trends and gaps in scientific research on the linkages among land use, water pollution, and the transmission of WRID (chapter 2). The next chapter (i.e., chapter 3) presents results from the first case study (I), which explored the water-health nexus, particularly the influences of land use, flooding, and water pollution on the exposure to water-borne pathogens and the risks of water-borne diseases in the Odaw River catchment. Chapter four covers the second case study (II) on the influences of human-surface water interactions on the risks of urinary schistosomiasis among communities in the Lower Densu River catchment. The final chapter (i.e., chapter 5) covers the general conclusion of the thesis, highlighting the key findings, the importance of integrating multi-methods in this thesis, reflections on the research approach and limitations, recommendations for policy formulation and further research, and key contributions to science and the understanding of the linkages between water-land use-health interactions and the risks of WRID.

2. Influences of land use dynamics and surface water systems interactions on water-related infectious diseases - a systematic review[1]

Abstract

Human interactions with surface water systems, through land-use dynamics, can influence the transmission of infectious water-related diseases. As a result, our study explored and examined the state of scientific evidence on the influences of these interactions on water-related infectious disease outcomes from a global perspective. A systematic review was conducted, using 54 peer-reviewed research articles published between 1995 and August 2019. The study revealed that there has been an increase in the number of publications since 2009; however, few of these publications (*n=6*) made explicit linkages to the topic. It was found that urban and agricultural land-use changes had relatively high adverse impacts on water quality, due to high concentrations of fecal matter, heavy metals, and nutrients in surface water systems. Water systems were found as the common "vehicle" for infectious disease transmission, which in turn had linkages to sanitation and hygiene conditions. The study found explicit linkages between human–surface water interaction patterns and the transmission of water-based disease. However, weak and complex linkages were found between land-use change and the transmission of water-borne disease, due to multiple pathways and the dynamics of the other determinants of the disease. Therefore, further research studies, using interdisciplinary and transdisciplinary approaches to investigate and enhance a deeper understanding of these complexities and linkages among land use, surface water quality, and water-related infectious diseases, are crucial in developing integrated measures for sustainable water quality monitoring and disease prevention.

Keywords: review study; land-use change; water quality; diarrhea; schistosomiasis; infectious diseases

[1] This chapter (2) was originally published as: Ntajal, J., Falkenberg, T., Kistemann, T., Evers, M. (2020). Influences of Land-Use Dynamics and Surface Water Systems Interactions on Water-Related Infectious Diseases—A Systematic Review. *Water 12*(3), 631. https://doi.org/10.3390/w12030631

2.1. Introduction

The emergence of historical civilizations, human settlements, agricultural and trade activities along rivers, lakes, and deltas illustrates the spatial distribution of water and its importance to humans (Adedire, 2017; Briassoulis, 2005). Usually, the quality of water from these sources is deteriorated by human activities (Briassoulis, 2005; Dwarakish et al., 2015). The status of water resources (quality and quantity) is largely influenced by human activities such as water abstraction and water pollution, which are partly related to land use change (Serpa et al., 2017). Land use and land cover change (LULC) influence numerous elements within water systems at diverse spatio-temporal scales (Ding et al., 2016; van der Hoven et al., 2017). LULC within watersheds has effects on stormwater runoff and flooding, which are major processes in the transportation of domestic and industrial effluents, sediments, and nutrients into surface water systems (Henderson et al., 2014).

Land use (LU) is generally described as the type of human activities that occur on the land, towards the achievement of socio-economic growth and development. In urban and peri-urban settings, land use is described as the spatial, socio-economic, and institutional usage of the land and its entrenched resources for infrastructure development (Henderson et al., 2014). Land use change refers to the modifications or complete conversion of land into another type, due to changes in human activities. In forested and cultivated or vast vegetated areas, land cover (LC) is usually the appropriate term to adopt, as it describes the physical characteristics of a place, e.g., grasses, trees, wetlands, or human artifacts. LULC is influenced by multiple drivers of urban and rural transformation processes such as population growth, culture, climate change, migration, and politics on diverse levels, which influence the quality (and quantity) of water resources (Henderson et al., 2014; Kleemann et al., 2017). In terms of urban transformation, LULC is entwined in the urbanization processes (United Nations, 2019).

Urbanization is described as a complex socio-economic, environmental, and societal process, which transforms the built environment through the conversion of rural settlements into urban settlements (United Nations, 2019). Besides the economic and infrastructure development, the urbanization process is perceived as a megatrend of LULC (Gerten et al., 2019). As reported in the 2018 Revision of World Urbanization Prospects of the United Nations, more than half (55%) of the world's population lived in urban areas as of 2018, as against 30% of the urban population in 1950 (United Nations, 2019). It was projected that by 2050, more than 68% of the global population will be urban, where a larger portion of the population will be concentrated in Africa (1.2 billion) and Asia (3.3 billion) (Gerten et al., 2019; United Nations, 2019). In low and middle-income countries, where the rate of urbanization is faster than infrastructure development and spatial land use planning, challenges with water systems, waste management, sanitation, and hygiene will likely be aggravated (Gerten et al., 2019; United Nations, 2019).

Urban surface water systems are increasingly facing stress from pollution in most developing countries in Asia, Africa, and Latin America, as a result of land use change, lack of wastewater treatment, and poor water quality monitoring (Monney, 2013; Rietveld et al., 2016; Schwarzenbach et al., 2010). Threats to human health, particularly the emergence and spread of water-related infectious diseases (WRID) and sanitation have been the focus of many research studies in South-East Asia and Sub-Saharan Africa, however, such studies focused less on the interactions between LULC and diseases (Ahmed and Shafique, 2019; Kamba et al., 2016; Schwarzenbach et al., 2010). Water pollution can have detrimental influences on the transmission of WRID (Mackinnon et al., 2019; Mari et al., 2018; United Nations Water, 2016).

A limited number of studies have taken the linkage among LULC, water quality, and WRID into account from an interdisciplinary perspective, in terms of research content and methodology (Mastel et al., 2018; van der Hoven et al., 2017). This illustrates the need for comprehensive investigations into the underlying human-water-disease interactions (Lalande et al., 2014; United Nations Water, 2016). Therefore, there is a need for a systematic review of the literature to assess and consolidate the current scientific evidence on the influences of human-surface water interactions on WRID outcomes.

2.2. The conceptual linkages among land use, water quality, and WRID

2.2.1. LULC and surface water quality

In most urban areas in Asia, Latin America and Sub-Saharan Africa floods pose huge challenges to water resources, due to poor urban land use planning (Gentry-Shields and Bartram, 2014). Construction of buildings in wetlands and choking of drainage systems with waste increases the likelihood of river and flash floods, given extreme rainfall and stormwater flow (Rain et al., 2011). Watersheds with a large percentage of developed urban areas and agriculture fields, tend to have higher contaminant concentrations (Hwang et al., 2016). Expansion of human settlements, as well as the expansion of cultivated areas into natural forests and grasslands near river catchments for drinking water, are risky land cover changes (Barton, 2009; Gentry-Shields and Bartram, 2014). Conversion of a land cover type into built-up areas, roads, or parking grounds can increase stormwater runoff and the transportation of pollutants into water bodies (Deilami et al., 2017; Monney, 2013).

2.2.2. Water-related infectious diseases

According to the Protocol on Water and Health, water-related diseases could be described as “any significant adverse effects on human health, such as death, disability, illness or disorders, caused directly or indirectly by the condition, or changes in the quantity or quality, of any waters” (Kulinkina et al., 2016)(p. 1). The Bradley Classification categorizes WRID into water-borne, water-based, water-washed, and water-related vector-borne diseases (Kulinkina et al., 2016; WHO, 2011; White et al., 1972). Water-borne diseases (e.g., diarrheal diseases) are transmitted via water and occur through the ingestion of water with high fecal pollution. On the other hand, water-washed diseases (hygiene-related) occur due to insufficient water supply for the maintenance of adequate hygiene. The pathogens are transmitted person-to-person through body contact (Daly et al., 2013; Gara et al., 2017; Mondal et al., 2014; Rietveld et al., 2016). Insects, such as mosquitoes, which breed and feed in or near water cause vector-borne diseases (e.g., malaria and dengue). Water-based diseases (e.g. schistosomiasis and buruli Ulcer) are caused by parasites (e.g., worms), which require an aquatic host (e.g. snails) to complete their life cycle (Kulinkina, et al., 2016; Nyarko et al., 2018). In this study, WRID includes all classes of infectious diseases stated above.

2.2.3. Influences of water quality on WRID

Pollution of surface water sources can increase the exposure of humans to water-related pathogens (Previsich et al., 2017). Poor water quality, sanitation, and hygiene are reported as the leading causes of health problems in developing countries (Clasen et al., 2014). Globally, reports indicate that nearly 15% of deaths among children below 5 years are linked to diarrheal diseases (WHO, 2020a). The number of reported deaths of cholera to the World Health Organization (WHO) increased between 2015 and 2017. For example, in 2015, 172,454 cases of cholera and 1,304 deaths were reported to the WHO. In 2017, 1,227,391 cases with 5654 deaths were reported to the WHO worldwide (WHO, 2020a). In contrast, 499,447 cases with 2990 deaths were reported in 2018, indicating a global decrease in the case numbers and deaths of cholera (WHO, 2020a). It was argued that the discrepancies in the reported deaths between 2017 and 2018 were likely an indication of improvements in safe water supply, sanitation, and hygiene behavior, and increased cholera vaccination coverage. However, the distribution of the reported cases in the cholera endemic regions raised concerns about the challenges with the disease surveillance system and the fear of implications the disease can have on trade and tourism in countries of such regions. Figure 4 illustrates the transmission pathways of diarrheal diseases including cholera.

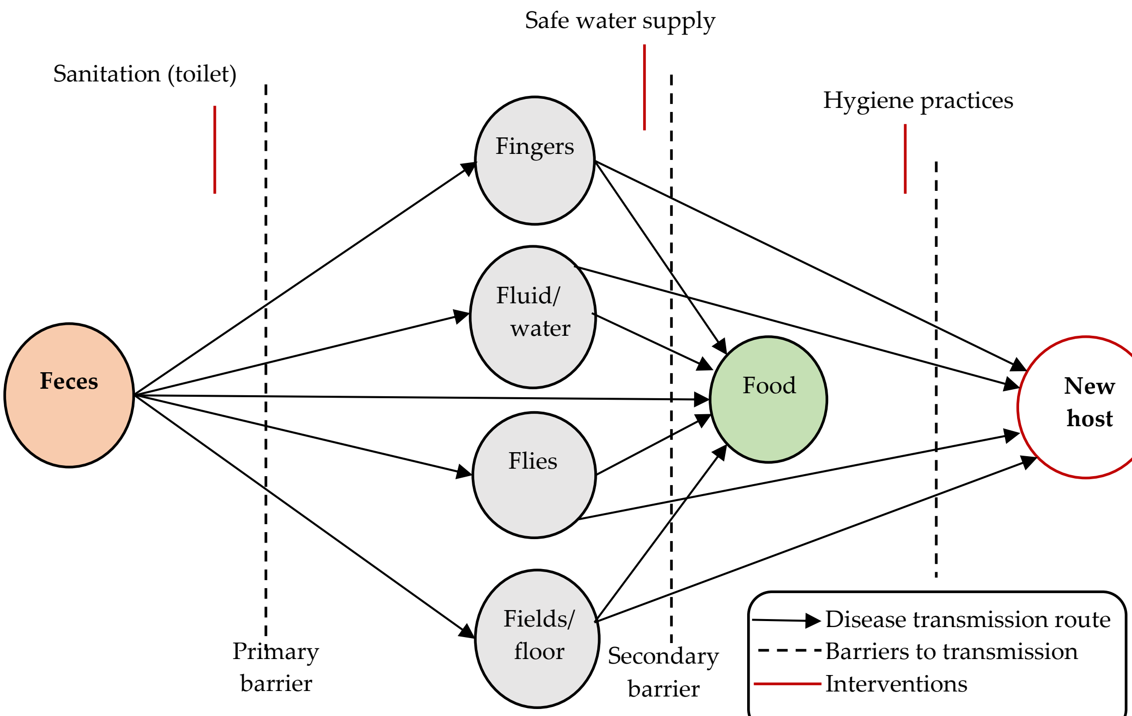

Figure 4. Diarrhea transmission pathways through polluted water sources
Source: adapted from Wagner and Lanoix (1958).

Human factors such as sanitation, hygiene, and health-seeking behaviors play major roles in diarrhea transmission, as usually illustrated, using the F-Diagram (Falkenberg et al., 2018). The F-Diagram illustrates the different transmission pathways through which fecal pathogens are transferred from an infected person to a new host (see Figure 4) (Wagner and Lanoix, 1958; Water 1st International, 2015). The starting point is the release of fecal pathogens into the environment through open defecation or unimproved sanitation facilities. The transmission occurs through unclean hands (failure to wash hands after using the toilet), polluted drinking water, flies, or contaminated food. Consuming food prepared with water from polluted sources or consuming fresh vegetables from irrigated fields exposes households to pathogens (WHO, 2020a).
Diarrheal disease transmission pathways in Tanzania, Senegal, Uganda, Ghana, and Nigeria, where recurrent cases of diarrheal diseases are reported, followed the illustrations in the F-diagram (Anthonj et al., 2018; Forstinus et al., 2016; Soller et al., 2014). Similar examples were reported in poor and water-deprived communities in Pakistan, Iran, Indonesia, India, and Vietnam (Ahmed & Shafique, 2019; Ahmed et al., 2016; Falkenberg et al., 2018; Kulinkina, Mohan, et al., 2016). In most cases, water serves as a vehicle for infectious disease transmission. Land use, in all forms and at all scales, as well as sanitation and hygiene practices are critical underlying risk factors. The importance of the F-Diagram is found in its application in the identification of potential barriers and interventions, which can be used to control and break the cycle of diarrheal disease transmission.

The interactions between humans and surface water systems can have complex linkages to health, through interrelated processes within watersheds (Vrebos et al., 2017). However, the literature reveals that these interactions and their resultant influences on WRID have more often been examined separately without explicit linkages (Anthonj et al., 2018; van der Hoven et al., 2017). To protect water resources, research studies recommended the assessment of land use influences on water quality, taking into consideration residential development and waste disposal among others (Anthonj et al., 2018; Näschen et al., 2018). In this review paper, our objective was to explore and examine the state of scientific evidence in this area from a global perspective and identify gaps in knowledge.

2.3. Methodology

In conducting the systematic review, we adopted the "Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA)" approach (Moher et al., 2009). A thorough search of the literature was performed, following the systematic, quantitative, and qualitative assessment approach (Gottdenker et al., 2014; Pickering and Byrne, 2014). This approach includes 1) identification of the key research question, 2) identification of relevant articles, 3) selection of the relevant articles, 4) charting and tabulating of data, and 5) reporting and summarizing the results. The advantage of this procedure is that it reduces the chances of omitting critical aspects of literature reviews (Arksey and O'Malley, 2005). It was argued that this approach is relatively easy to use and offers more insights than the 'traditional narrative' approaches (Pickering and Byrne, 2014). The approach has been widely adopted in systematic literature review studies (Cui et al., 2016; Gottdenker et al., 2014; Mastel et al., 2018; Wright et al., 2004). In this review, we combined both the systematic quantitative and the 'traditional narrative' approaches, as the traditional narrative approach offers the flexibility of extracting common themes from key findings (Gottdenker et al., 2014; Mastel et al., 2018).

2.3.1. Identification of the key research question

This review study aims to answer the following question: what is the current state of evidence on the interactions between land use dynamics and surface water systems, and the transmission of WRID? The review scope and the review process were conducted on a global scale.

2.3.2. Identification of relevant articles

Prior to the selection of the relevant peer-reviewed articles, a comprehensive search of the scientific literature was conducted, utilizing the online bibliographic databases: Google Scholar, PubMed, Public Library of Science, Science Direct, and Web of Science. We developed an online search query, using a combination of the key terms, concepts, and phrases related to the topic under investigation (land use, land use change, water quality, sanitation and hygiene, WRID) (see Table 2). We further explored the references of these articles, using the 'ancestry' approach (the screening references of other studies for eligibility of inclusion) (Wright et al., 2004). Searching and identification of the relevant literature involved a multi-step approach. During the initial search, 1,303 articles were retrieved.

Bibliographic information from Google Scholar was extracted using web search engines. The citations of the relevant papers were exported into the reference management system. If the citation link was unavailable, the PDF file of the paper was imported into Zotero, which automatically extracts the information. The information was double-checked for errors and completeness.

Table 2. Keywords and syntax used for the literature search

Land use	Water Quality	Infectious WRID	Combined Search
"land use" OR "land use change" OR "built-up areas" OR "bare-grounds" OR "cultivated areas" OR "farm" AND.	"water pollution" OR "Physicochemical" OR "fecal pollution" OR "solid wastes" OR "wastewater" AND.	"health" OR "water-borne" OR "water-related" OR "diarrhea" OR "cholera" OR "fever" OR "malaria" OR "schistosomiasis" OR "Buruli ulcer" OR "bacteria" OR "parasite" OR "pathogen" AND.	"1" AND "2" AND "3"

2.3.3. Selection of the relevant articles: inclusion and exclusion criteria

The selection of relevant articles was done by a thorough skimming of the peer-reviewed articles between 1995 and August 2019. The papers, which did not have relevant information on land use, water pollution, and WRID were excluded. Similarly, review articles and thesis of PhD studies were excluded from the review. Advancement in the literature review was made by reading the abstracts, the key findings, and relevant text of the articles for the final selection of the eligible studies. The selected studies were uploaded on a desktop referencing system for full-text analysis and data extraction. The relevant information and metadata were extracted, tabulated, and tallied for qualitative and quantitative analysis. These included land use, key parameters of water quality, water-related infectious diseases (diarrheal diseases, schistosomiasis, etc.), and the pathways through which LULC influences surface water pollution. The PRISMA diagram, illustrated in Figure 5, summarizes the steps adopted for the selection of eligible research studies.

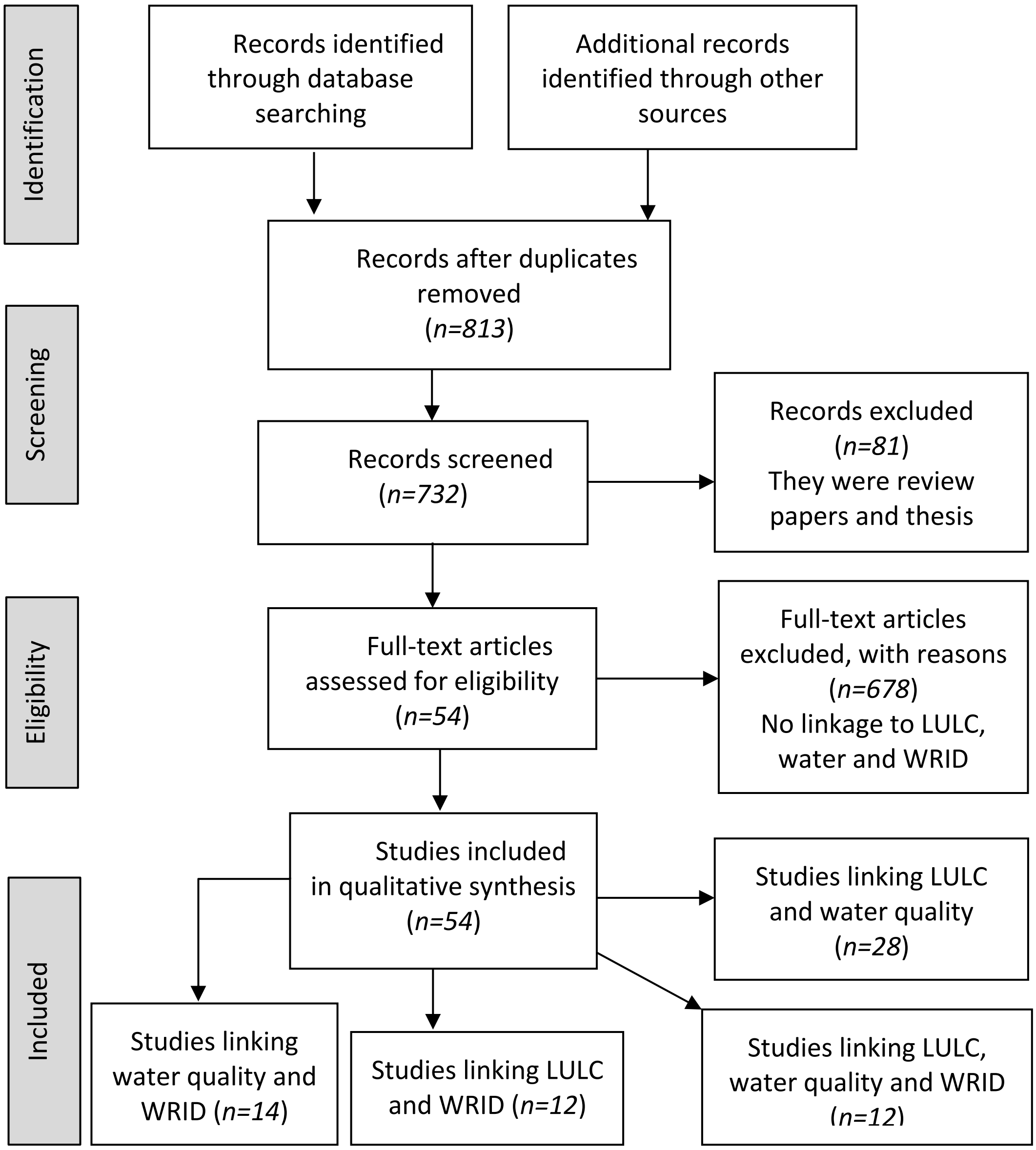

Figure 5. PRISMA flow diagram for the selection of the eligible studies
Source: Adapted from Moher et al. (2009).

2.3.4. Charting and tabulating of data

The authors created excel spreadsheets, where data extracted from the selected peer-reviewed articles were listed. These included the names of the authors, the title of the paper, year of publication, country of the study, land use-water interactions, WRID, and summary of key results.

2.3.5. Reporting and summarizing the results

Descriptive statistics were utilized for analyzing and synthesizing data. Regarding content analysis, qualitative and narrative approaches were used in presenting and discussing the results. The results from the descriptive statistics and the spatial distribution of the studies are presented in the following sections in the form of graphs, maps, and tables.

2.4. Results

This section presents the results of 54 peer-reviewed research articles included in this review. These studies were categorized based on the linkages between land use and surface water systems, land use and WRID, surface water pollution and WRID, and influences of land use, surface water quality, and WRID on a global scale. The review considered only original peer-reviewed research studies, which made explicit linkages among land use, surface water, and WRID.

2.4.1. Trends in the scientific studies on LULC, surface water quality, and WRID

The review (see Figure 6) revealed an increase in the scientific literature on the research problem over the past decade (2009-2019). Scientific studies related to either land use, water quality, or infectious diseases exist since 1995, however, these studies have not made explicit linkages among the key research concepts from a global perspective. It was observed that scientific evidence on the interactions between LUCL and surface water quality increased from 2011 to 2019. This can be linked to the increasing challenges of limited access to clean drinking water, sanitation, and hygiene, which contribute to the outbreak of infectious diseases in the fast-growing urban areas and poor rural communities in developing regions.

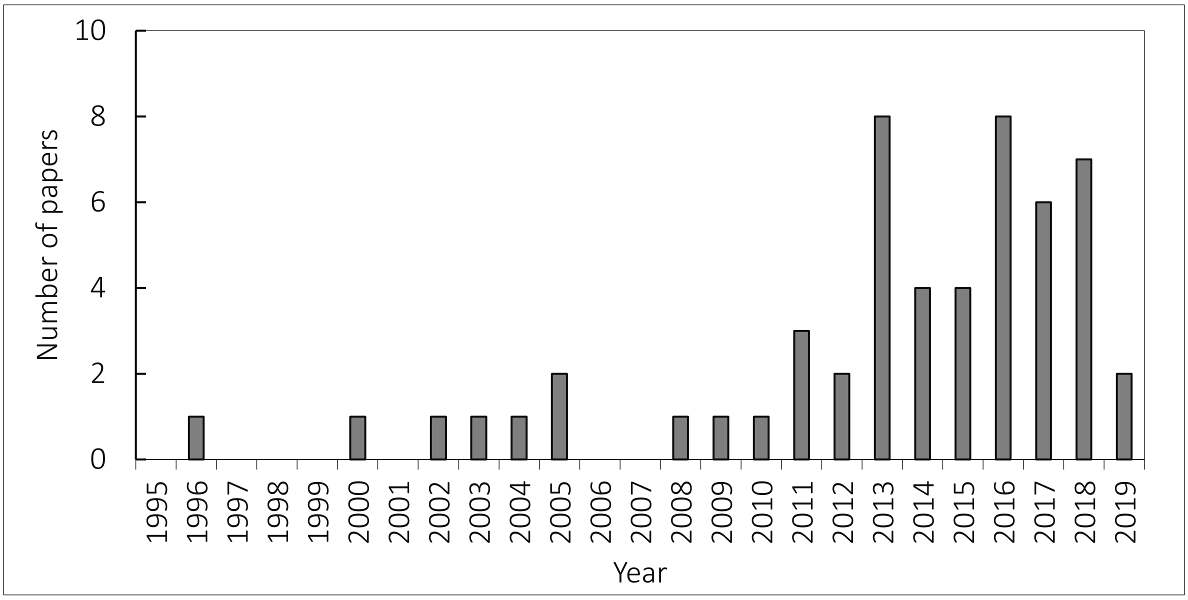

Figure 6. Number of studies between 1995 and August 2019

2.4.2. Distribution of studies by country/region

The assessment of literature on the global scale provided a broader perspective on the distribution of scientific studies linking land use change, surface water quality, and infectious diseases (see Figure 7). It was found that 20.37% (*n=11*) of studies were conducted in the People's Republic of China, while about 11% (*n=6*) were conducted in the United States of America and Ghana respectively. On average, it was observed that a higher number of the included studies were from countries classified as developing regions such as Sub-Saharan Africa, Asia, and Latin America, where there is limited potable drinking water, poor wastes management, poor water quality monitoring, unsustainable agricultural practices, and limited access to funds for scientific research. There are many studies on water quality and diseases, however, these studies lacked explicit linkages to WRID (Cui et al., 2016; Wijesiri et al., 2018).

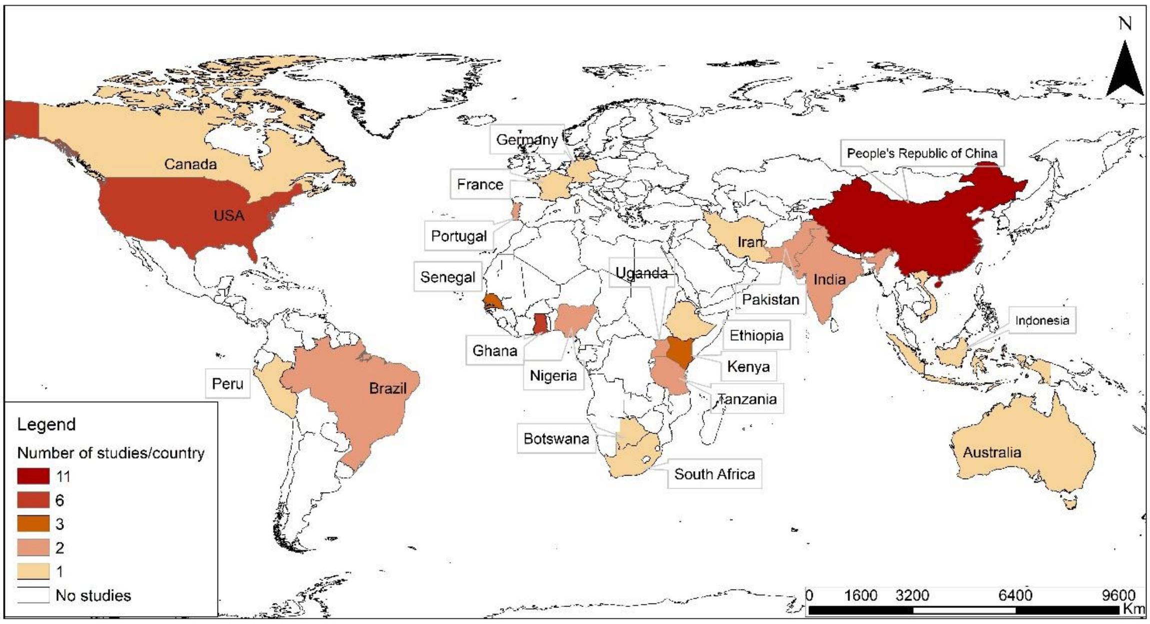

Figure 7. Distribution of reviewed studies by country/region (1995–2019)
Source: author's own illustrations (2020).

2.4.3. Land use and land cover classification

Land use and land cover are characterized or classified based on the aim of a specific study. However, there are similarities among the various classes (Wilson, 2015). Land use patterns as described in the various studies were broadly classified into nine (9) classes (see Figure 8). It was found that a higher number of studies (*n=28*) focused on the links between agricultural land use change, surface water pollution, and the emergence of water-borne disease. These included both point-source and non-point-source pollution of water from cultivated lands and livestock-raising sites (Ribolzi et al., 2011). Human settlement expansion including urban sprawl, and expansion of peri-urban and rural areas were factors that resulted in the conversion of natural forestlands, grasslands, and wetland reserves into residential areas (Dai et al., 2017; Wijesiri et al., 2018). Urbanization has formed the center of most land use studies due to its contribution to the pollution of surface water systems, notably in poor countries, where sanitation and sewage systems were poorly developed (Lambin et al., 2010; Saravanan, 2013). It was recorded that land use change characterized by built-up areas such as urban, peri-urban, and rural residential areas was found in most of the studies (*n=26*). Similarly, twenty-six studies (*n=26*) focused on water bodies as a crucial class of land use and land cover. Deforestation (*n=17*) was found as an equally important land use change pattern, which influenced the transportation of nutrients, sediments, and other chemical contaminants into surface sources, through stormwater runoff, flooding, and windstorms (Ding et al., 2016; Meneses et al., 2015; Patz et al., 2004).

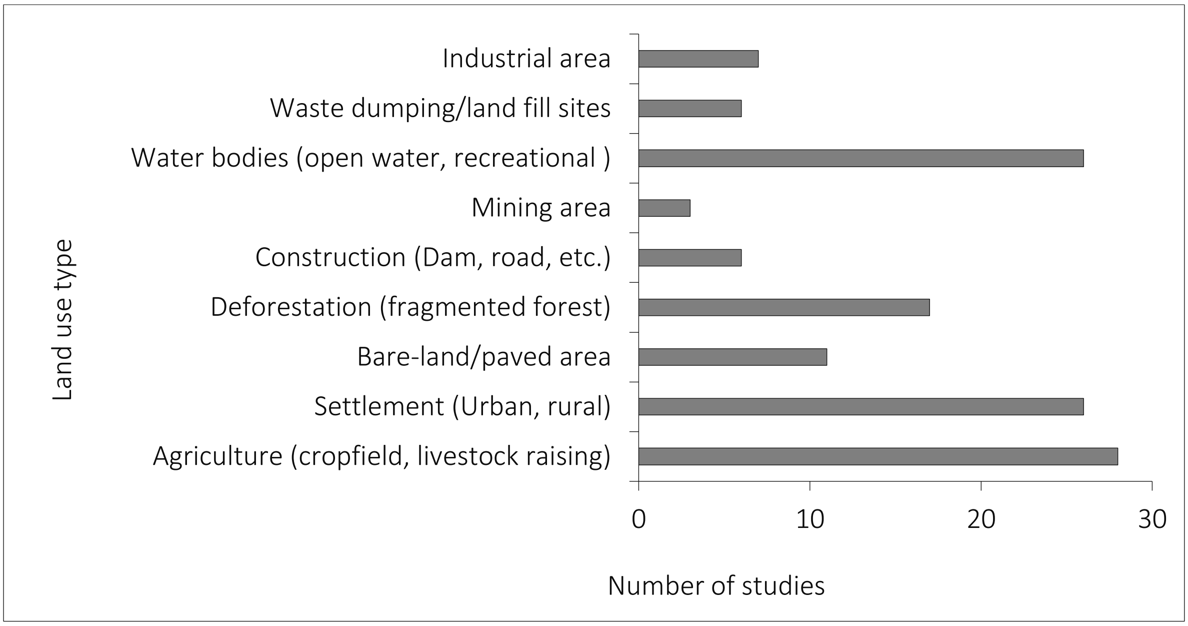

Figure 8. The general classification of land use and land cover types
Source: author's own illustrations with data from the literature review.

2.4.4. Identified water-related infectious diseases

It was found in the reviewed studies that there is a complex link between land use and infectious diseases due to the dynamics involved in the emergence and transmission of the diseases (Ahmed et al., 2016; Khan et al., 2018; Lambin et al., 2010). A few studies (*n=6*), which made explicit linkages between land use change and surface water pollution identified some common infectious water-related diseases (see Figure 9). Relatedly, water-borne diseases appeared in 22 studies in Africa and Asia (Khan et al., 2018; Oguntoke et al., 2009; Ohene-Adjei et al., 2017). Schistosomiasis (*n=16*) was commonly examined as a result of its emergence and transmission through direct human interaction with water (body contact with polluted water and the infected intermediate snail host). Buruli ulcer and hookworm, which were classified as Neglected Tropical Diseases emerged in studies (*n=5*) in Africa, with devastating health impacts and economic burden on households (Quarcoo et al., 2015; Webster et al., 2016). The study revealed that the number of studies on schistosomiasis had increased globally between 2013 and 2016 (Anthonj et al., 2018; Nyarko et al., 2018). Further, studies on diarrheal diseases such as cholera and dysentery linked to land use and water quality fluctuated from year to year, however, a steady increase was observed between 2013 and 2018, with a high number of studies in 2017. The number of studies on malaria with explicit linkages to LULC and water quality has not changed over the years, since 2013. Further, there were missing studies in the literature on malaria with links to LULC in 2016 and 2017. It was identified that studies on hookworm were found only in 2016 (Grimes et al., 2016).

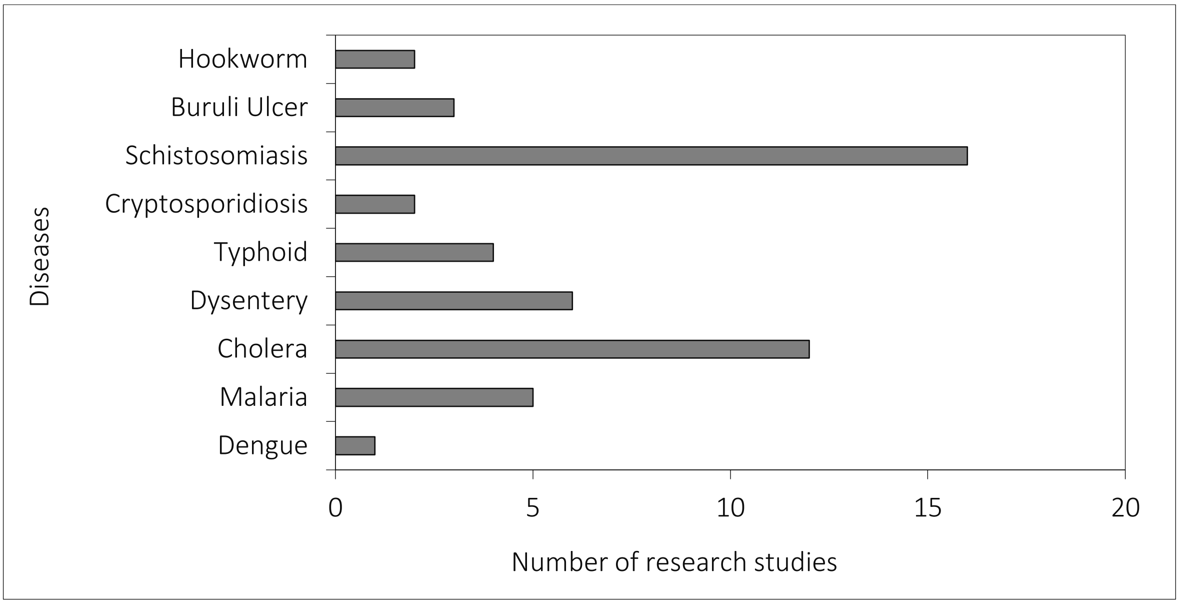

Figure 9. Infectious diseases related to land-use change and surface water quality
Source: author's own illustrations with data from the literature review.

2.4.5. Land-use change and surface water pollution pathways

The review revealed various mechanisms influencing land use change and surface water pollution. Water pollution occurred through point-source, non-point-source, and point-of-use (Laurent and Mazumder, 2013). Well-documented processes such as stormwater runoff, flooding, and direct dumping of domestic and industrial effluents into surface water systems were identified in the studies as the major water pollution pathways. These mechanisms are summarized in terms of the given land use classes and water quality parameters (see Table 3). Dida et al. (2014), Ahmed et al. (2016), and Saravanan (2013) reported that deforestation within river catchments exacerbated the process of erosion and increased surface runoff, which facilitated the transport of nutrients (nitrogen and phosphorus) and sediments into water systems. These lead to the siltation of the water channel and reservoirs through sedimentation, as well as eutrophication due to the supply of nutrients from agricultural fields (Dai et al., 2017; Ding et al., 2016; Grimm et al., 2008; Patz et al., 2004). It was identified that fast industrialization in China has resulted in the discharge of organic pollutants into rivers, severely affecting water quality. Examples were the high chemical oxygen demand (COD) found in water bodies in industrial cities such as Anshan, Liaoyang, Fushun, and Shenyang in China (Li et al., 2012).

Table 3. Linking land use/land cover and surface water pollution

Land use classifications	Mechanisms of water pollution	Water quality parameters tested.	Citation
Agriculture (cropland, livestock raising)	Pollution with sediments and nutrients from farms, through stormwater runoff and flooding	pH, EC, DO, N, K, TN, TP, TSS	(Attua et al., 2014; Halstead et al., 2018; Kistemann et al., 2012; Ribolzi et al., 2011; Wilson, 2015)
Settlement (Urban, rural)	Point-source and non-point-source pollution due to poor sanitation and waste management	Heavy metals, fecal coliform, E. *coli*, temperature,	(Aglanu and Appiah, 2014; Chen et al., 2016; Daly et al., 2013; Laurent and Mazumder, 2013; Wilson, 2015)
Deforestation (fragmented forest)	A decrease in vegetation cover exposed water to extreme heat, led to sedimentation and eutrophication	Temperature, Turbidity, pH, COD, BOD, DO, TSS, EC heavy metals	(Dida et al., 2014; Head et al., 2016; Lindblade et al., 2000; Wilson, 2015)
Industrial area	Industrial and domestic effluents pollute water	Turbidity, pH, COD, BOD, DO, TSS	(Meneses et al., 2015; Wilson, 2015; Zhang et al., 2013)
Bare-land/paved area,	Pollution of water through stormwater	N, P, Fecal coliform, E. *coli*	(Alvani et al., 2011; Tong and Chen, 2002)
Water bodies (open water, recreational)	Pollution with fecal matter	E. *coli*, fecal matter, C. *parvum oocysts*, Giardia *duodenalis* cysts	(Daly et al., 2013; Jacob et al., 2015; Nyarko et al., 2018; Tong and Chen, 2002)
Mining area	Point-source pollution through stormwater runoff from mining areas	N, P, COD, DO, heavy metals	(Dida et al., 2014; Chen et al., 2016; Cunha et al., 2016)
Waste dumping/landfill sites,	Wastewater solid waste disposal	EC, pH, DO, Cu, lead	(Aglanu and Appiah, 2014; van der Hoven et al., 2017)

pH = Potential of Hydrogen; EC = Electro Conductivity; DO = Dissolved Oxygen; COD = Chemical Oxygen Demand; BOD = Biochemical Oxygen Demand; TSS = Total Dissolved Solids; N = Nitrogen; P = Phosphorus; K= Potassium; Cu = Copper

2.4.6. Water quality parameters and the potential water-related infectious diseases

It is often difficult to understand the complete disease ecology and the underlying causes of exposure, due to the complexities involved in the transmission dynamics of pathogens. It is worth noting that studies *(n=14)* have established some level of agreement in the identification and characterization of some potential WRID, which are commonly associated with changes in water quality parameters (see Table 4) (Lindblade et al., 2000). It was reported that changes in water temperature, turbidity, and pH influenced the survival and abundance of the Anopheles mosquito, which transmits malaria (Lindblade et al., 2000). Relatedly, it was recorded that higher concentrations of E. *coli* and fecal matter in drinking water were associated with diarrheal diseases (cholera and dysentery) (Ahmed et al., 2016;

Saravanan, 2013). In the same fashion, schistosomiasis was associated with polluted surface water systems in Kenya and Senegal, due to the presence of fecal matter in the water, which promotes the survival of the intermediate snail host (Dida et al., 2014; Ciddio et al., 2017; Codjoe and Larbi, 2016; Nyarko et al., 2018; Picquet et al., 1996; Wang et al., 2005).

Table 4. Summary of water quality parameters and the potential infectious diseases

Water quality parameters	Diseases	Sources
Temperature, turbidity, pH,	Dengue	(Lindblade et al., 2000)
Temperature	Malaria	(Johnson, 2008; Lindblade et al., 2000; Patz et al., 2004)
E. *coli*, fecal coliform,	Cholera	(Ahmed et al., 2016; Alexander et al., 2018; Jacob et al., 2015; Khan et al., 2018; Oguntoke et al., 2009)
E. *coli*, fecal coliform, turbidity, pH,	Dysentery	(Ahmed, 2014; Khan et al., 2018; Oguntoke et al., 2009)
E**.** *coli*, fecal coliform	Typhoid fever	(Khan et al., 2018; Oguntoke et al., 2009)
E. *coli,* fecal coliform, BOD, Temperature, DO,	cryptosporidiosis	(Jacob et al., 2015; Kistemann et al., 2012)
Fecal coliform,	Schistosomiasis	(Angelo et al., 2018; Dida et al., 2014; Chadeka et al., 2017; Ciddio et al., 2017; Head et al., 2016; Picquet et al., 1996; Tetteh-quarcoo et al., 2013)
E. *coli*, fecal coliform, Temperature, turbidity	Buruli Ulcer	(Picquet et al., 1996)
E**.** *coli*, fecal coliform, Temperature, DO, BOD, TSS, turbidity	Hookworm	(Chadeka et al., 2017)

pH = Potential of Hydrogen; DO = Dissolved Oxygen; BOD = Biochemical Oxygen Demand; TSS = Total Suspended Solid

2.4.7. Studies linking land use, water, and major WRID

The reviewed literature revealed that a few studies (n=6) highlighted explicit linkages among land use change, surface water quality, and WRID as mentioned above. These studies were found in SSA (n=3), Europe (n=2), and India (n=1) with a special focus on diarrheal diseases and neglected tropical diseases (i.e., schistosomiasis and buruli ulcer). This was due to the dynamics and the multiple pathways involved in the transmission of infectious diseases, as well as the complex interrelated factors such as individual's perception of diseases, access to sanitation and hygiene, and consistent and adequate supply of potable water (Anthonj et al., 2018; Briggs, 2003; Oguntoke et al., 2009; Quarcoo et al., 2015; Ribolzi et al., 2011). These factors do not have well-established direct links with land use change, as in the case of changes in water quality (Quarcoo et al., 2015; Ribolzi et al., 2011). A combination of interactions among various types of LULC was found to have differential effects on specific water quality parameters and WRID (Anthonj et al., 2018; Ding et al., 2015). A summary of these interactions and the key results highlighted in the corresponding countries are presented in Table 5.

Table 5. Combined influences of land use and land cover (LULC) types on water quality and water-related infectious diseases (WRID)

LULC	Water quality parameters	WRID	Summary of key findings	Country	Source
Cultivated lands, swamps, forests, open water	Temperature	Malaria	Replacement of natural swamp vegetation with irrigated rice and vegetable farms led to an increase in temperature and breeding of Anopheles mosquitos. LULC also reduced the breeding of mosquitoes.	Uganda	(Gabiri et al., 2019; Lindblade et al., 2000)
Cropland, urban expansion	pH, Turbidity, TDS, DO, BOD, COD, E. *coli*	Cholera	A high concentration of E. *coli* correlated with cholera cases in areas along the river, with a high rate of urbanization and waste disposal in the river	India	(Marale et al., 2012; Saravanan, 2013)
Dam construction, streamside pool, swamps	Temperature, turbidity, DO, EC, pH	Schistosomiasis	The distribution of the intermediate snails varied with the variation in vegetation cover, turbidity, and pH of water and soil	Tanzania	(Angelo et al., 2018; Dida et al., 2014)
Grassland, croplands forest, livestock farming	Clostridium *perfringens* and E. *coli*	Cryptosporidiosis	The erratic occurrence of Cryptosporidium in the streams was mainly attributed to diffuse pollution. Recreational activities increased the exposure and risk factors	Germany	(Jacob et al., 2015; Kistemann et al., 2012)
Cropland, forest, urban area, water bodies	Cryptosporidium *parvum* oocysts, Giardia *duodenalis* cysts, E. *coli.*	Cholera	Pollution of surface water with C. *parvum* and G. *duodenalis*, due to fecal pollution from wastewater treatment plants and croplands	France	(Jacob et al., 2015)
Croplands, recreational waters	Fecal coliform	Schistosomiasis	Recreational activity was the major exposure and risk factor for schistosomiasis transmission	Ghana	(Nyarko et al., 2018; Tetteh-quarcoo et al., 2013)

pH = Potential of Hydrogen; EC = Electrical Conductivity; DO = Dissolved Oxygen; COD = Chemical Oxygen Demand; BOD = Biochemical Oxygen Demand

2.5. Discussion

The study identified various linkages between land use dynamics and surface water quality, and the consequent influences on WRID in different countries across the globe. This allowed the categorization of land use and land cover types into various classes, the identification of water quality parameters, and the relevant WRID. Several research studies have demonstrated the influence of land use on E. *coli* concentration in drinking water. For example, Marale et al. (2012) reported that an increase in E. *coli* concentration at the downstream of River Indrayani in India was linked to land use in communities located upstream of the river.

Similarly, during winter, van der Hoven et al. (2017) identified that the levels of E. *coli*, EC, DO and TDS in the Klein Jukskei River were beyond the recommended drinking-water standards in sections of the river close to industrial and informal settlements in South Africa. This was attributed to the upstream discharge of domestic and industrial effluents into the river. Similar results were found in Ghana, Senegal, Indonesia, and Iran (Alvani et al., 2011; Ciddio et al., 2017; Deilami et al., 2017; Ohene-Adjei et al., 2017).

The influence of rainfall and stormwater runoff during winter and summer are crucial pathways of water pollution. The study identified a positive relationship between urban floods and E. *coli* concentration in flood retention ponds in Botswana (Alexander et al., 2018). Agricultural land use such as the cultivation of crops was linked to an increase in N and P in the Fuxian Lake in China (Dai et al., 2017). This led to eutrophication and a decrease in DO in the lake (Dai et al., 2017). In addition, a significant negative relationship was found between forested areas and the amount of Ammonia, N, and COD in the Fuxian Lake (Dai et al., 2017; Water 1st International, 2015). This illustrated the influences of forestland cover on the rate of stormwater runoff and the transportation of parent materials and nutrients into water systems.

It is worth noting that the various linkages between LUC and surface water quality and the resultant influences on the transmission of infectious diseases were identified, however, the studies focused entirely on the negative aspects of land use change. The potential positive influences of LUC on water quality and disease ecology were found missing in the literature (Cui et al., 2016; Dai et al., 2017; Mastel et al., 2018; Patz et al., 2004; Wijesiri et al., 2018). This indicates a potential direction for future research investigations to explore the positive influences of LUC on water quality at different scales in relation to WRID ecology (Henderson et al., 2014). It was also observed that LULC classification studies oversimplified the concept of LU and did not provide adequate information on LU characteristics at a finer resolution. For example, cultural and recreational aspects of land use were not included in the classification of LULC. These types of LU will likely aid the investigations on human-water interactions and disease outcomes.

2.5.1. Influences of water quality on WRID

Water plays a major role in the emergence and transmission of infectious diseases, through direct and indirect pathways (Jacob et al., 2015). In 2017, flooding in Botswana resulted in an increased concentration of fecal coliforms at the downstream of Chobe River, which contributed to an increase in reported cases of diarrheal diseases by 16.7% with 4 weeks lag among children under 5 years (Alexander et al., 2018). Areas with high population density, frequent flooding, bare-soils, and built-up areas were linked to higher reported cases of cholera and typhoid in Semarang City in Indonesia (Deilami et al., 2017). A significant positive relationship between limited access to potable water and sanitation infrastructure and diarrhea morbidity was observed in 2015 in Accra, Ghana (WHO, 2014).

In addition, the reviewed studies revealed that the most direct interactions between humans and water, which resulted in water-based disease outbreaks were through human skin contact with polluted water (Anthonj et al., 2018; Ciddio et al., 2017; Nyarko et al., 2018). Relatedly, the probability of being infected depends on the frequency and patterns of human-water contacts. Helminthic diseases such as schistosomiasis, hookworm, and buruli ulcer are classical examples of diseases transmitted through direct contact with polluted water, soil, and infested snail hosts (Dida et al., 2014; Halstead et al., 2018; Wang et al., 2005). Lack of sanitation and hygiene facilities compelled households in remote communities in Tanzania to practice open defecation in and around water bodies, which resulted in high levels of fecal coliform concentration in water and increased the survival rate of intermediate snail hosts of S*. haematobium* (Angelo et al., 2018). It was argued that differences in the spatial distribution of the S*. haematobium* are influenced by the spatial connectedness of land use types, water pollution patterns, and risk and exposure factors (Chadeka et al., 2017).

2.5.2. Directions for further research

This review study has deepened our understanding of the interactions and the linkages among land use, surface water systems, and the transmission of WRID. It provided credible grounds for identifying the gaps in knowledge and scientific evidence on these linkages. In regions such as Sub-Saharan Africa, South Asia, and the Middle East, where WHO reported as the hotspot of WRID, interdisciplinary studies exploring the influences of land use and water quality on WRID outcomes have not been comprehensively explored (WHO, 2020a). Therefore, the adoption of multidisciplinary, interdisciplinary, and transdisciplinary research perspectives is required to deepen the understanding of LULC, water, and WRID nexus. The understanding of disease ecology extends beyond a single discipline. System-thinking and complex network analysis can be adapted to identify the interactions and linkages among the various drivers of LULC and water pollution. System-thinking and network analysis, employing mind-mapping approaches such as “Driving forces-Pressure-State-Impacts-Response” frameworks and Multi-Criterial Decision Analysis are recommended for structuring and characterizing the interactions.

2.5.3. Limitations

The review study depended mainly on peer-reviewed papers that were published in the English language, and it was considered a major limitation. Many peer-reviewed papers in French, Spanish and Portuguese were retrieved from literature but were not considered in the review, due to the language barrier. It is likely that such papers contain vital information and data, which could be of immense importance to our review. In addition, the review focused on studies, which made explicit linkages to LULC, surface water, and WRID. There were other important studies, which made significant contributions to scientific research but focused on either land use change, surface water systems, or only WRID. The exclusion of such studies from the review was found as a limitation. Relatedly, the review strictly considered studies, which focused on only surface water systems. Studies, which made linkages to groundwater sources such as boreholes and wells, and rainwater harvesting, were excluded from the review.

2.6. Conclusion

The review study explored the current state of scientific evidence on the influences of land use dynamics and surface water systems interactions on WRID. There has been an increase in scientific research on LULC and WRID globally. LULC types have differential impacts on water quality, especially in agricultural land use and human settlement areas, where there is poor water quality monitoring, and land use planning. There are linkages between land use dynamics and WRID outcomes, however, these linkages are relatively complex and weak. On the other hand, there is an explicit linkage between water quality and water-borne diseases with multiple transmission pathways. Human-water interactions have influences on WRID, however, other determinants of health and exposure factors such as individual and community's perception of diseases, and health-seeking behaviors play a major role in the transmission of WRID. This was an indication of a lack of interdisciplinary and transdisciplinary research collaborations on LULC and WRID.

3. Water and health nexus – Land use dynamics, flooding and water-borne diseases in the Odaw River basin, Ghana[2]

Abstract

The study focused on understanding the key drivers of exposure and risks of water-borne diseases, including flooding, land use, and waste management in the Odaw River basin within the Greater Accra Metropolitan Area in Ghana. Water-borne diseases in Ghana are frequently reported within major cities, particularly in flood-prone communities in Accra. Fragmented interventions, including drinking water supply, have often failed, while water-borne diseases continue to pose a huge burden on households and the government. The underlying drivers of exposure and risks of diseases are not explored and explicitly understood. An integrated approach, including qualitative system dynamic modeling and spatial analysis of land use change, was adopted. Household surveys, expert elicitation, and multi-level stakeholder participation using focus group discussions and stakeholder workshops were employed in identifying indicators, developing qualitative system dynamic models, and identifying key feedback loops. The results show that communities have access to water and sanitation but water-borne diseases are still prevalent. Poor wastewater management systems posed higher health risks. In addition to limited access to safe drinking water and improved sanitation, floods, influenced by poor land use planning and solid waste disposal is a key contributing factor to drinking water pollution and the destruction of water and sanitation infrastructure, leading to outbreaks of water-borne diseases. Qualitative system dynamic modeling supported the identification of complex linkages and multiple feedback loops among land use, flooding, water pollution, and risks of water-borne diseases. Provisioning only water, sanitation, and hygiene are insufficient to eliminate diseases. Multi-sectoral collaborations are required to co-design and inclusively implement integrated and strategies, including flood risk reduction, land use plans, and improved waste management to reduce risks of diseases to promote a clean environment and human health.

Keywords: land use; flood; water quality; water-related diseases; qualitative system dynamics

[2] This chapter (3) has been published as: Ntajal, J.; Höllermann, B.; Falkenberg, T.; Kistemann, T.; Evers, M. (2022). Water and Health Nexus—Land Use Dynamics, Flooding, and Water-Borne Diseases in the Odaw River Basin, Ghana. *Water 14*(3), 461. https://doi.org/10.3390/w14030461.

3.1. Introduction

Water forms a crucial part of the ecosystem with multiple health benefits, however, it can pose detrimental health challenges, including water-borne diseases, when excessively polluted (Magana-Arachchi & Wanigatunge, 2020). Water-borne diseases are still a huge burden on households and governments across the globe, particularly in vulnerable areas in Africa, the Eastern Mediterranean region, and Southern Asia, partly due to low investment in water and sanitation infrastructure, under the already growing threats posed by climate change, conflicts, drought, and frequent flood disasters (WHO, 2020a). Scholars and public health experts have recognized that "too much water" and "too little water" both have varying impacts on health (WHO, 2020a). In 2019, global reports collated by the WHO show that diarrhea accounted for over 370,000 deaths in children under five years. As of 2020, 1.3 to 4.0 million annual cases of cholera have been estimated and about 21,00 to 143,000 deaths are reported annually in all the WHO regions worldwide, due to infections linked to water, sanitation, and hygiene, with their underlying drivers (WHO, 2020a).

In Ghana access to drinking water and sanitation has relatively increased over the past years, however, multiple outbreaks of diarrheal diseases are still recorded each year in flood-prone communities in the Odaw catchment within the Greater Accra Metropolitan Area (GAMA) (Owusu & Agbozo, 2019). Water-borne diseases in the GAMA have multi-causal pathways and the underlying drivers influencing outbreaks are complex and far beyond the current traditional understanding. The usual interventions, including drinking water supply and provision of sanitation services are likely not sufficient to eliminate the disease. Previous studies have raised concerns regarding the influences of land use and land cover (LULC) change, flooding, and risk of water-borne diseases, however, these factors have not been comprehensively explored and explicitly understood in urban environments in Ghana, contributing to low level of awareness among the local population in particular (Abu & Codjoe, 2018; Owusu-Ansah, 2018; Songsore, 2017).

Identifying the underlying drivers and impacts of their interactions on risks of water-borne diseases is crucial for the development of relevant interventions (Ntajal et al., 2020). However, due to fragmented interventions and lack of multi-sectoral collaborations, sustainable solutions are not developed and implemented, while the complex water-health nexus continues to pose human and environmental health problems. Reviewing the numerous studies related to water-related diseases, evidence on studies designed to explicitly identify the underlying drivers of water-borne diseases besides the supply of water, sanitation, and hygiene (WASH) was missing (Ntajal et al., 2020). Therefore, the key research questions this study addresses are: what are the key drivers influencing the water-health nexus, particularly the exposure to water-borne pathogens and risks of diseases in GAMA? Additionally, given the growing interest among policy-makers and the scientific community to adopt interdisciplinary and transdisciplinary approaches, this study further highlights the suitability of the research approach for integrating multi-level stakeholder participation, spatial analysis, and modeling intricate interactions between water and human health.

3.2. Study area

The study was conducted in the Odaw River catchment, a small urban river system, which drains the central part of Accra. The Odaw catchment falls within the Greater Accra Metropolitan Area (GAMA), which is the business and industrial hub of the Greater Accra region, with an approximate area of 271 km^2 (see Figure 10). The annual average temperature is about 26°C, characterized by a tropical savanna climate (Codjoe & Larbi, 2016). The rainfall portrays a bimodal pattern with the highest rainfall recorded between April and June and lowest between September and October with an average annual rainfall of 730 mm (Gimba, 2009; Simister, 2010). The catchment is densely populated with more than 60% of the population of Accra, where about 30% of the residents are exposed to flood risk (Ackom et al., 2020; Owusu & Obour, 2021). The Odaw River and its tributaries are polluted with domestic waste and industrial effluents (Karikari et al., 2009).

The study selected four communities within the catchment for household surveys: Agbogba, Alajo, Nima, and Odawna (see Figure 10). These communities were purposively selected based on their proximity to the main drains of the Odaw River (within 100 meters buffer), which partly influences their level of interactions with the river, exposure to frequent floods, and the risk of water-borne diseases (Abu & Codjoe, 2018; WHO, 2016). The selected communities formed part of the urban poor communities in GAMA with high exposure to water-borne diseases. The main economic activities within the catchment are retail marketing and small businesses. Over 80% of the industries in Accra are located within the Odaw catchment (Ministry of Works and Housing Ghana, 2019). Along the drains of the river are micro-retail shops, auto-mechanic shops, refrigerator repair shops, etc. (Ministry of Works and Housing Ghana, 2019). These businesses located along watercourses contribute to the blockage of the drainage systems, leading to flooding in the area.

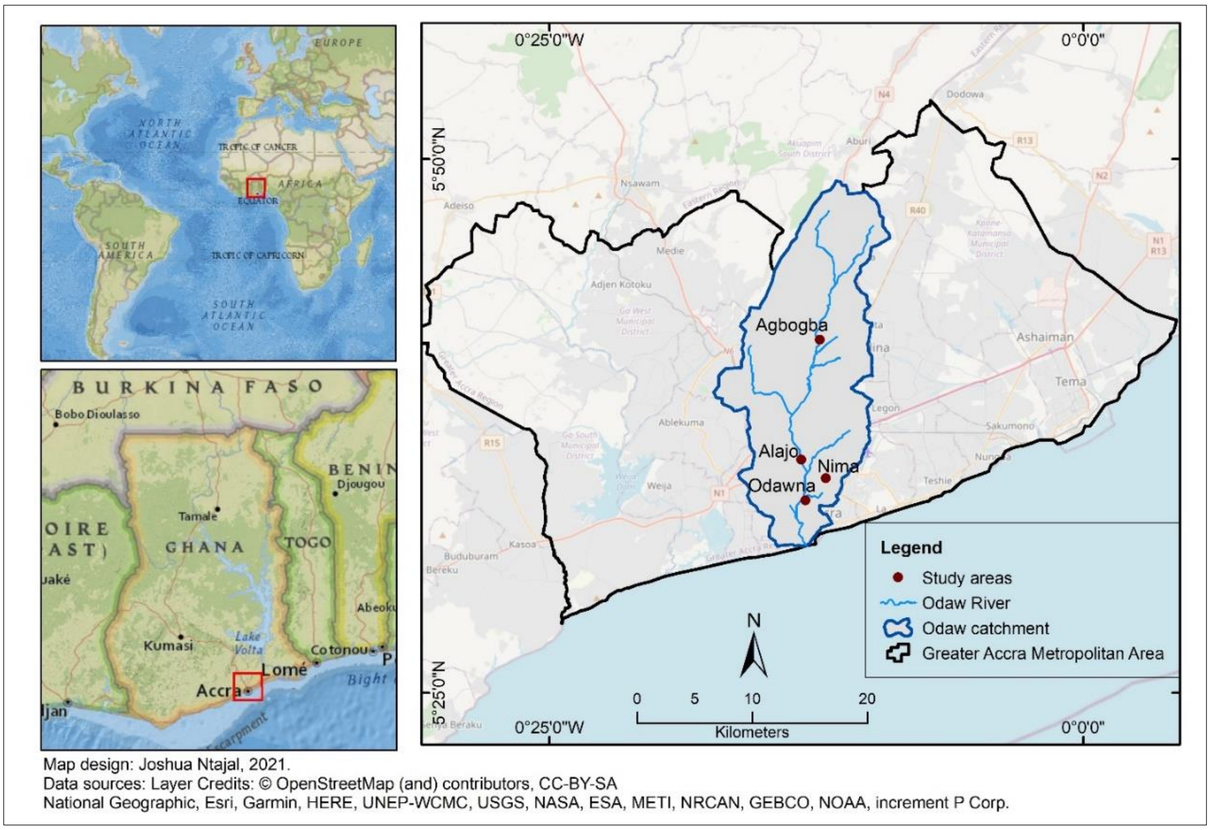

Figure 10. Map of the study sites in the Odaw River Catchment

3.3. Materials and methods

3.3.1. Methodological approach

The study adopted a mixed-method approach, including qualitative system dynamics (QSD) modeling. To assess the key causes of water-borne diseases and identify variables for the QSD modeling, household surveys and stakeholder participation through focus group discussions (FGDs), expert elicitation, and workshops were conducted. The supervised classification (e.g., maximum likelihood) was performed to assess the extent of decadal changes in land use and land cover from 1991 to 2020, using Landsat satellite images. Figure 11 presents the methodological steps.

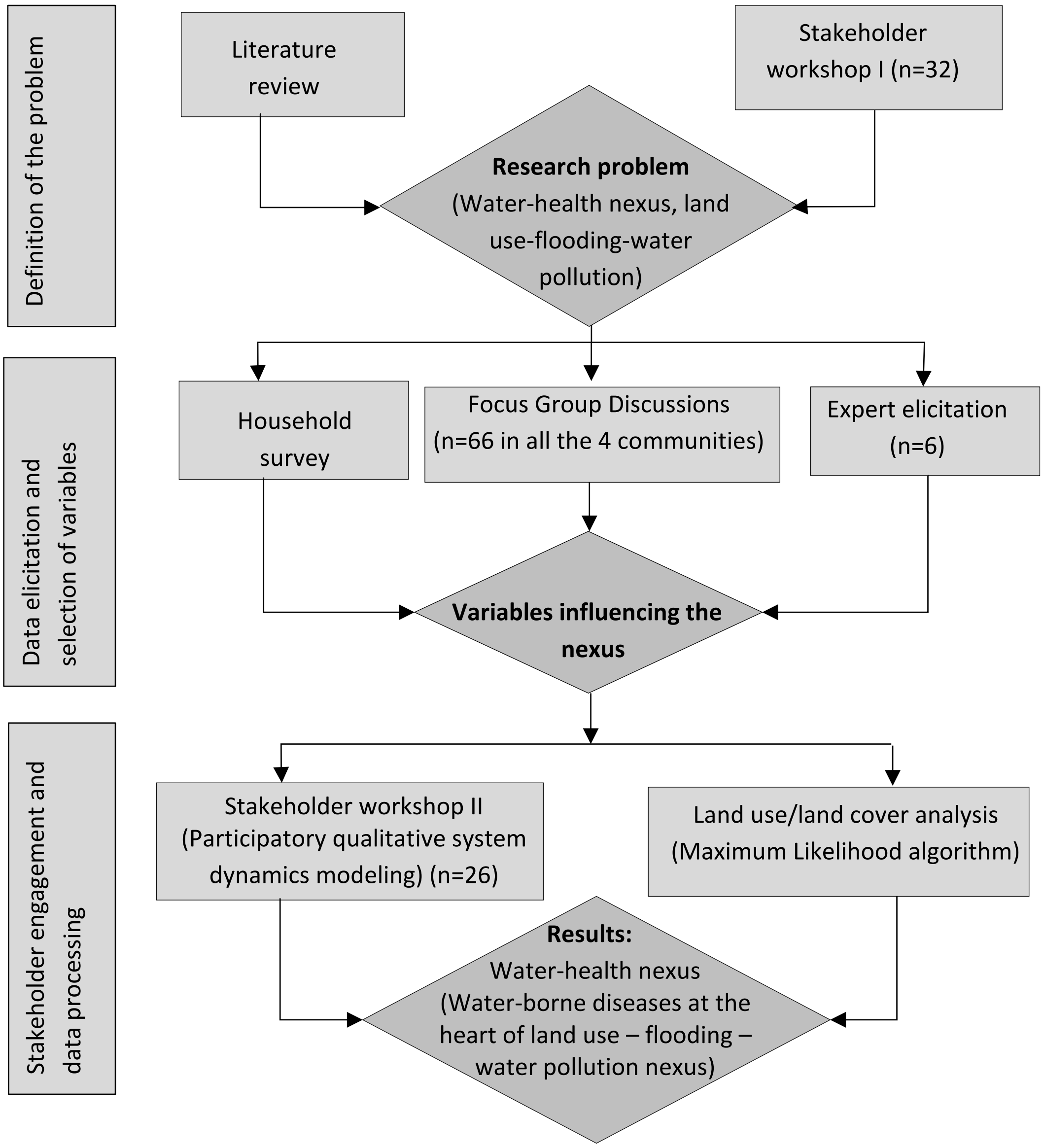

Figure 11. Flowchart showing the methodological steps
Source: authors' own illustrations (2021).

3.3.2. System dynamics – qualitative system dynamics

System dynamics (SD) is an important component of the systems approach, which has long been applied in several domains to model the behavior of complex systems and translate outcomes into policies and actions, using quantitative and qualitative models (Coyle, 2000). Qualitative System Dynamic (QSD) involves the representation of interactions between components of systems (stocks-and-flows), using feedback loops, without rigorous formulation of mathematical equations and computer simulations. QSD is rooted in the fact that knowledge about complex systems needs to be integrated and harmonized to enhance a deeper understanding of how system components and variables are connected and function in the real world, using causal loop diagrams (CLDs) (Powell et al., 2016).

The causal loop diagrams, also denoted as feedback loops, are flexible tools used to illustrate the linkages among variables within systems with arrows from a "*cause*" to an "*effect*" or vice versa (Coyle, 2000; Powell & Coyle, 2005). In CLD analysis, the relationship between variables is depicted, using positive (+) and negative (-) signs, placed beside the arrowheads to indicate the polarity (Powell et al., 2016; White, 2011). The QSD was found suitable to conceptualize, assess, integrate, and understand complex interactions among LULC change, flooding, surface water pollution, and the risks of water-borne diseases. It supported stakeholder participation and the creation of qualitative models, using qualitative variables such as health-seeking behaviors, waste management practices, and perception of health risk factors, which are difficult to quantify and integrate into the models.

3.3.3. Methods

3.3.3.1 Stakeholder workshop I

The first stakeholder workshop was organized in November 2018 to define the research problem and discuss data sources. The snowball sampling approach was used in identifying the participants for the stakeholder workshop, following the stakeholder theory and participants identification procedure of "those affected and those involved in decision-making" (Hansen & Baun, 2015; Schiller et al., 2013). The participants (n=32) of the workshop included for example; representatives from Non-Governmental Organizations, members of academia, opinion leaders from the communities, and government agencies and institutions. As part of the workshop activities, the initial research concept was presented in a plenum to guide the discussion with the stakeholders. This allowed the definition of the research problem, focusing on the water-heath nexus in the Odaw River catchment within GAMA. The engagement of the stakeholders from the workshops was found crucial as they are the beneficiaries, mediators of the systems as well as the potential actors influencing the dynamics in the QSD models that were developed.

3.3.3.2 Household surveys

To obtain data on the exposure to and risks of water-borne diseases, household surveys were conducted in February 2019. A total number of 320 households were randomly selected and equally distributed among the four purposively selected communities (Alajo, Agbogba, Odawna, and Nima) within the Odaw River catchment. This is because the communities exhibit similar physical, socio-cultural and economic characteristics, and the differences in household characteristics were of no particular importance to the study. In each of the communities, 80 households were randomly selected to participate in the survey. The key topical issues covered in the survey included but were not limited to access to water and sanitation, risks of water-borne diseases, and underlying factors such as floods, household waste management, and water pollution pathways in the Odaw River.

3.3.3.3 Focus group discussions and expert elicitation

The focus group discussions (FGDs) were conducted to gain an understanding of the research problem from group and communities' perspectives. One FGD was conducted in each of the four selected communities between February and March 2019 with a total of 66 participants: Alajo (n=16), Nima (n=17), Odawna (n=18), and Agbogba (n=15). The participants included the chiefs, assembly members, representatives from the Women Associations, community health and sanitation officers, and elderly persons, who have lived in their respective communities for at least 30 years. The threshold of 30 years of residence was required to obtain historical information about LULC dynamics and flooding within the Odaw catchment, based on their memory recall and local information retrieval experiences. The key issues related to the water-health nexus and the underlying driving forces were discussed. Flipcharts were used to document all the variables highlighted by the participants. The variables identified were presented to the groups at the end of the discussion in each of the communities for review and selection of potential variables.

3.3.3.4 Stakeholder workshop II: development of the QSD – Causal loop diagrams

To allow collaboration and stakeholder participation in the development of the QSD models, a second stakeholder workshop was organized in April 2019 in Accra. Prior to the development of QSD models and the CLDs, the potential variables identified via household surveys and FDGs were collated and presented during the workshop for review and selection of the final set of variables. Through collective intelligence and group consensus decision-making, based on the "*cause*" and "*effects*" relationships between the variables, QSD and the CLDs were created using flipcharts. The next step was the digitalization of the CLDs and the identification of the feedback loops within the sub-models developed. The final draft of the QSD and CLDs was shared with the stakeholders to check for errors, consistency, and validation.

3.3.3.5 Data integration and analysis

The study adopted descriptive statistics for the analysis of household surveys and LULC change data. As part of the preliminary data analysis, the survey data was cleaned and examined for errors and completeness. The descriptive statistics highlighted the potential variables, influencing households' exposure to pathogens and the risks of water-borne diseases. The variables identified from the household survey and expert elicitation were merged and presented during the second stakeholder workshop for final review and selection for developing the QSD sub-models. The QSD models developed were analyzed by exploring their linkages to understand the interconnectedness between variables. For example, examining the sub-models, identifying the polarity of the variables, and feedback loops. The key feedback loops identified from the sub-models were further merged to provide an overview of the key interactions between systems to guide the discussion.

The causal loop diagram analysis

The QSD models were examined and interactions between variables were identified. In addition, the polarity (+/-) of each variable was identified by the participants of the stakeholder workshop to support the understanding of the *cause* and *effects* within the QSD sub-models. The CLDs were systematically traced and the feedback loops were identified. Feedback loops existed when the arrows flow in the same direction (clockwise) or opposite direction (counter-clockwise) in a circular manner (Powell et al., 2016; White, 2011). The feedback loops were either reinforcing (R) or self-balancing (B) (Sterman, 2002). Blue arrows were used to indicate the connections between variables, while the green arrows indicated interventions altering the state of the variables by either mitigating the *cause* or reducing the impacts of the *effects* within the models.

Spatial data analysis – land use and land cover change

The Landsat images for the years; 1991, 2002, 2011, and 2020 were obtained from the United States Geological Survey online database with a spatial resolution of 30 meters. The images were obtained from Landsat 4, Landsat 7 Thematic Mapper (TM), Landsat 7 Enhanced Thematic Mapper Plus (ETM+), and Landsat 8 Operational Land Imager (OLI). The satellite images were geometrically corrected as part of the image preprocessing. The supervised image classification was performed, using the maximum likelihood algorithm. The maximum likelihood has been widely adopted based on its theoretical basis and robustness in calculating the total number of variance and correlation of spectral values of the different bands, based on the specified spectral signature (Dadashpoor et al., 2019). The training samples for each group of pixels were created for all the images to generate the spectral signatures required for the maximum likelihood classification. The images were classified into four classes: built-up areas (settlements, industrial areas, transport infrastructure, etc.), vegetation (protected forest, grassland, shrubs, etc.), bare-land, and water bodies (e.g., rivers, lakes, ponds, lagoons, etc.).

3.4. Results

3.4.1 Basic factors contributing to water-borne diseases

3.4.1.1 Access to water and sanitation

It was found that more than 80% of the households in all the four study communities have access to water, though, the quality of the water was not further examined. The main source of water at home is via piped water obtained from the water supply or vending points within the communities, while bottled water including sachet water (i.e., water stored in plastic sachet bags) was the main source of drinking water outside their homes. However, members of the households had to pay and often had to queue for an average of 10 minutes to have access to water at the water supply or vending points within the communities. Further, the results show that various types of sanitation facilities exist in the study communities (see

Table 6). The sanitation facilities were mainly public, and a usage fee was required to gain access. For example, Pan latrine was mainly used in Nima (58%), Odawna (56), and Alajo (48%). Relatively, the flush toilet facility was mainly used at Agbogba (44%), which is occupied by residents within low to middle-income class.

Table 6. Types of sanitation facilities in the study communities in Accra

Community	Pan latrine (%)	Ventilated improved pit latrine (%)	Open defecation (%)	Flush toilet (%)	Total
Alajo	38 (48)	34 (43)	2 (3)	6 (8)	80
Nima	46 (58)	29 (36)	2 (3)	3 (4)	80
Odawna	45 (56)	31 (39)	2 (3)	2 (3)	80
Agbogba	32 (40)	13 (16)	0 (0)	35 (43)	80
Total	161	107	6	46	320

Source: based on primary data collection in the Odaw River catchment in Ghana, in April 2019.

It was found that the Pan and the Ventilated Improved Pit (VIP) latrines were the main facilities used in the communities, except in Agbogba, where the flush toilet was mainly used in addition to the Pan latrine. Besides paying the usage fee, these public sanitation facilities in Odawna, Nima, and Alajo were found in deplorable conditions and poorly maintained, which discourage their usage, contributing to open defecation practices in the communities (e.g., Odawna). The survey results show that the self-reported practice of open defecation was found low in all the communities, however, the FGDs revealed that it was significantly practiced in and around the Odaw drains, and can be a major source of water pollution with fecal matter and *E. coli.*, leading water-borne diseases when ingested. Further analysis revealed that household wastewater management contributes to the basic causes of water-borne diseases in addition to WASH.

3.4.1.2 Household wastewater management

The management of wastewater generated from laundry, cooking, bathing, etc. is crucial in the maintenance of good health. The results of the surveys show that households (49%) discharged their wastewater mainly into the nearest gutters to their homes. 26% of the households discharged their wastewater into the open spaces outside their homes, which was found to attract houseflies and rodents (see Figure 12). Additionally, 16% discharged the wastewater directly into the Odaw River. The FGDs further revealed that wastewater discharged, using the reported strategies contributes to the contamination of drinking water and food via the actions of houseflies, rodents, poor hygiene, and most importantly floodwater. Key lessons from the FGDs and expert elicitation revealed that the communities have access to WASH, however, outbreaks of water-borne diseases are still reported in these communities, particularly, within periods of major flood events. This indicates that the risks of water-borne diseases are influenced by additional factors, which are presented in the subsequent sections with the QSD models and the feedback loops to support the understanding of the pathways.

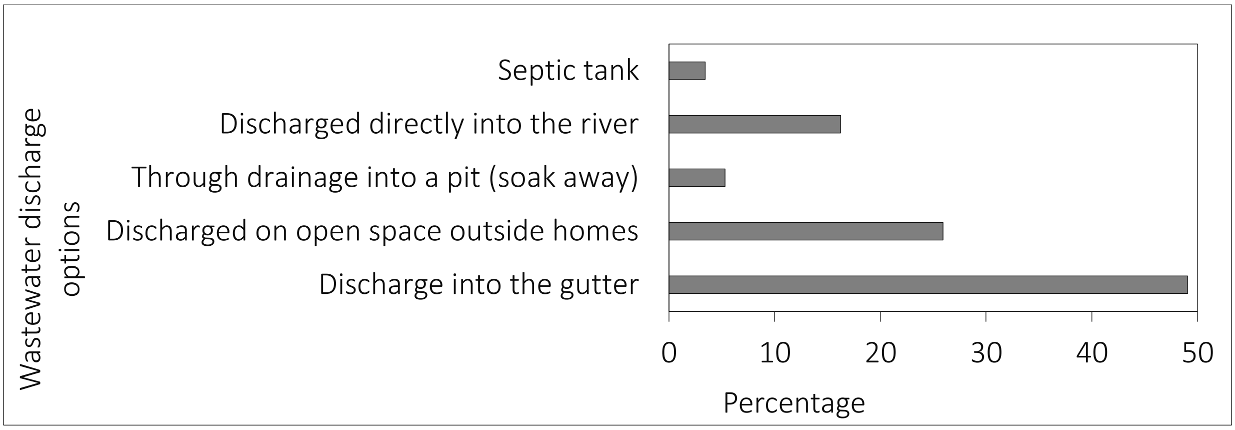

Figure 12. Wastewater management named by households
Source: based on primary data collection in the Odaw River catchment in Ghana, in April 2019.

3.4.1.3 Exposure pathways and risks of water-borne diseases

In Figure 13, the loop (*R1*) shows reinforcing feedback, where the *ingestion of contaminated food and water* due to poor hygiene and sanitation practices leads to an increase in the *incidence rate* of diseases (e.g., cholera, typhoid). Limited access to water and sanitation, and poor hygiene practices among households contributed to the *pollution of water* with fecal matter via *wastewater discharge* and *open defecation* practiced by infected persons, thereby reinforcing the feedback loop. A reinforcing feedback loop (*R2*) was identified, as *wastewater* from households and industrial areas is used for *irrigation* to boost *urban agriculture* to meet the growing demand for food (see Figure 12). Further, the *irrigation* activities, in turn, generate *wastewater* with nutrients and chemical loads from the farms, through the application of fertilizers.

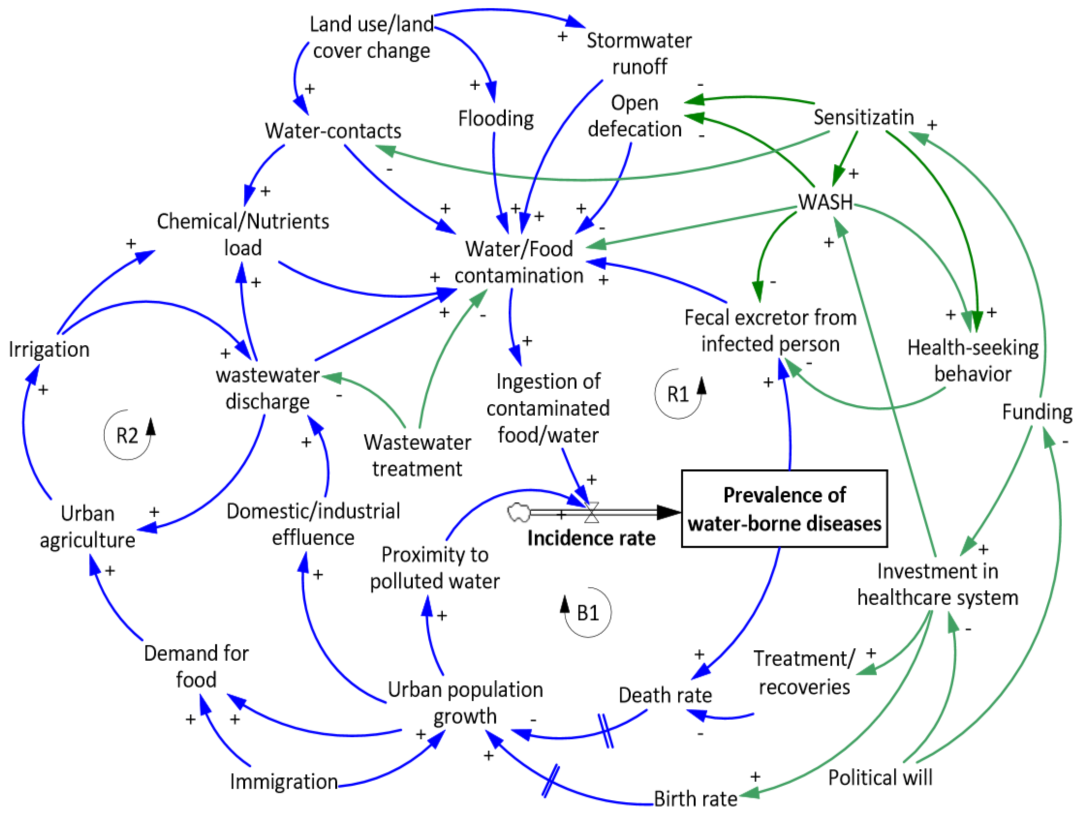

Figure 13. Water-borne diseases sub-model

The blue arrows show the connections between the variables, while the green arrows indicate the interventions altering the state of these variables.
Source: based on primary data collection in the Odaw River catchment in Ghana, in April 2019.

In addition, a balancing feedback loop (*B1*) was identified as *urban population growth* compelled the urban poor to settle on the unoccupied spaces around the river. However, *proximity to the river* increases their interactions with the *polluted water*, particularly during flooding events, leading to drinking water pollution and the *incidence rate* of water-borne diseases (see Figure 13). Further, the *death rate* among persons infected can increase, given limited access to healthcare services. The long-run effects can result in a decrease in population growth, although interruptions such as time delays and interventions from the government are expected. An increase in *birth rate* can counterpoise the unfavorable balancing effects in *B1* with respect to time. Interventions such as sustainable wastewater treatment and the construction of sewer systems are perceived to reduce water pollution through the removal of contaminants from the wastewater.

3.4.2 Flooding, water pollution, and water-borne diseases pathways

It was found that while diarrheal diseases are usually associated with an insufficient supply of safe drinking water and access to improved sanitation, major flood events were found as key drivers in the Odaw catchment. The transmission pathways were concomitant to the pollution of drinking water at the point-of-use during and after floods. The results of the household survey show that besides malaria (38%), which is commonly associated with LULC types, water, and the weather, diarrheal diseases. Cholera (35%), typhoid fever (18%), and dysentery (7%) were identified as the most common and frequently reported water-borne diseases in the communities, following flood events. Key lessons elicited from expert interviews revealed that the number of unreported cases of diarrheal diseases, and flood-related deaths are far beyond the figures documented, due to poor recording keeping habits at both the households and the district levels, and stigmatization. The results of the QSD modeling and CLD show the interactions between the underlying causes of flooding such as LULC and solid waste disposal, and the exposure pathways to pathogens are captured in figure 14.

The feedback loop (*R1*) shows the impacts of *LULC change* on *landscape change* and *urbanization,* due to the conversion of vegetated lands into residential areas and the development of infrastructure such as roads, parking lots, and pavements, leading to an increase in artificial surfaces, which facilitate stormwater runoff and flooding. In addition, the urbanization of GAMA has contributed to rural-urban migration and *population growth,* increasing *urban population density.* This increases the *demand for housing and infrastructure,* which in turn, contributes to changes in *LULC.* Further, an increase in urban population density increases the amount of solid waste disposal contributing to *siltation* of the drains, riverine, and localized flash floods, with a short duration of extreme high rainfall.

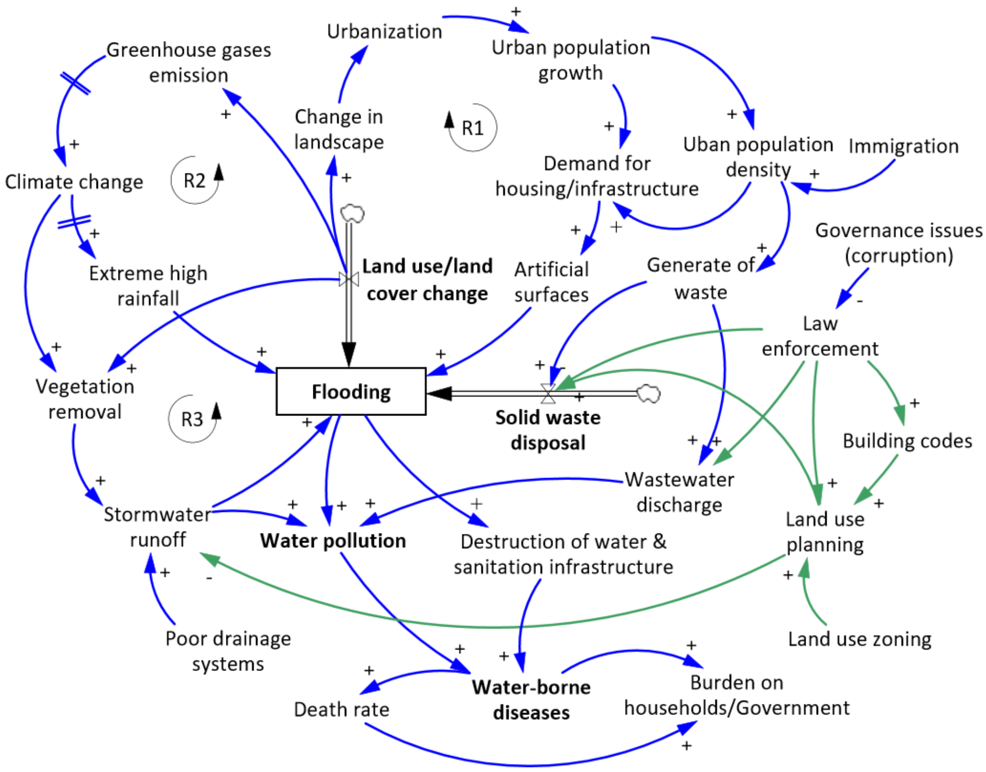

Figure 14. Flood sub-model

The blue arrows show the connections between the variables, while the green arrows indicate the interventions altering the state of these variables.
Source: Based on primary data collection in the Odaw River catchment in Ghana, in April 2019.

Besides extreme high temperatures, *climate change* has contributed to extreme weather events such as *high rainfall*, leading to excessive *stormwater runoff* and *flash floods* in Accra, which reinforces *LULC change* (*R2*). The influence of LULC and waste management play key roles in devastating flood disasters within the catchment, resulting in *drinking water pollution* and outbreaks of *water-borne diseases*. LULC change and household solid waste disposal strategies within the catchment were further assessed in the subsequent sections to enhance the understanding of their level of influence on flooding.

3.4.2.1 Causes of flooding in the Odaw River catchment

To identify the linkage between flooding and water pollution within the catchment, the causes of flooding needed to be explored. The results from the household surveys show that poor solid waste disposal was found as a major contributing factor to flooding, except at Agbogba in the upstream, where construction of infrastructure (e.g., houses, auto mechanic shops, etc.) on watercourses was the key factor (see Table 7).

Table 7. Contributing factors influencing flooding in the Odaw catchment

	Communities			
Waste disposal options	Alajo	Nima	Odawna	Agbogba
Solid waste disposal (%)	21 (26)	19 (24)	24 (30)	9 (11)
Building house on watercourses (%)	13 (16)	16 (20)	14 (17)	22 (28)
Lack of law enforcement (%)	9 (11)	10 (13)	11 (14)	14 (17)
Stormwater flow (%)	12 (15)	3 (4)	7 (9)	12 (15)
Behavior of people (%)	11 (14)	18 (23)	8 (10)	8 (10)
Proximity to the markets drains (%)	6 (7)	8 (10)	10 (13)	5 (6)
Poor drainage systems (%)	9 (11)	5 (6)	6 (7)	10 (13)
Total (%)	80 (100)	80 (100)	80 (100)	80 (100)

Source: based on primary data collection in the Odaw River catchment in Ghana, in April 2019.

Further, building houses on watercourses as well as lack of law enforcement was found relevant in all the communities. The behavior of some of the residents and the hawkers emerged quite strongly in all communities, particularly at Nima (23%) and Alajo (14%). In addition, 15% of the households in Alajo, and 13% in Agbogba found stormwater runoff as a relevant factor. The proximity of markets to the drains of the Odaw River system was identified mainly at Odawna (13%) and Nima (10%). The waste generated from the markets is reportedly deposited directly into the drains, contributing to siltation and flooding. The causes of flooding were mostly related to LULC and solid waste disposal influenced by lack of law enforcement and the behavior of the people.

3.4.2.2 Impacts of household solid waste disposal on flooding

It was found that 37% of the households relied on some designated public waste collection locations marked by the Accra Metropolitan authorities (see Table 8). Similarly, 30% of the households relied on "house-to-house" private waste collection services. Although these options were dominant in the communities but were found not sustainable as the transfer of the waste to the final recycling or landfill sites was often delayed. This contributes to the already existing indiscriminate waste disposal habit (9%), which poses huge hygiene and health challenges, besides the *siltation of drains*. In addition, 5% of the households disposed of their waste directly into the Odaw drains. The main focus of the analysis in this section was placed on the waste management options as a whole and not segregated by communities.

Table 8. Solid waste disposal options named by household

Waste disposal strategies	Number of households	(%)
Public waste collection points	119	(37)
Burn solid wastes	48	(15)
Private house-to-house collection service	97	(30)
Bury the waste	12	(4)
Indiscriminate waste disposal	28	(9)
Direct dumping into the river/gutter	16	(5)
Total	320	(100)

Source: based on primary data collection in the Odaw River catchment in Ghana, in April 2019.

3.4.2.3 Land use and land cover change

The results show significant changes in LULC within the Odaw River catchment. Mainly, the built-up areas including urban and peri-urban residential areas have increased by 46% from 1991 to 2020, with a significant decrease in vegetation cover. A higher proportion (21%) of the urban expansion occurred between 2002 and 2011, while an increase in the density of built-up areas including urban settlements and infrastructural development within the catchment was found to have occurred between 2011 and 2020 (see Table 9). The vegetation cover including protected forests, grasslands, and shrubs has decreased from 70% in 1991 to 21% in 2020. The built-up areas have increased over the past four decades from 19% in 1991 to 65% in 2020. On the contrary, the cover vegetation has decreased by 62.65 km^2 (23.6%) from 1991 to 2002, 17.07 km^2 (6.43%) from 2002 to 2011, and 51.03 km^2 (17.53%) from 2011 to 2020. The decadal change analysis shows the total area of the built-up area has increased by 13.6% from 1991 to 2002, 21% from 2002 to 2011, and 10.5% from 2011 to 2020.

Table 9. Area and percentage changes in LULC classification types between 1991 and 2020

Year	Area coverage	Water	Vegetation	Built-up area	Bare-land
1991	Area (Km^2)	0.45	187.91	51.16	25.81
	Area (%)	0.17	70.82	19.28	9.73
2002	Area (Km^2)	0.25	125.26	87.34	52.48
	Area (%)	0.09	47.21	32.92	19.78
2011	Area (Km^2)	0.44	108.19	143.45	13.24
	Area (%)	0.16	40.78	54.07	4.99
2020	Area (Km^2)	0.31	57.16	171.24	32.80
	Area (%)	0.12	21.54	64.54	12.00
1991-2002	Area change (Km^2)	-0.20	-62.65	36.18	26.67
	% change	-0.07	-23.61	13.64	10.05
2002-2011	Area change (Km^2)	0.19	-17.07	56.12	-39.24
	% change	0.07	-6.43	21.15	-14.79
2011-2020	Area change (Km^2)	-0.13	-51.03	27.79	19.56
	% change	-0.05	-19.23	10.47	7.01

Source: own land use and land cover (LULC) assessment by the authors.

A negative relationship between vegetation cover and the built-up areas. As the built-up areas increases, the destruction of vegetation including forest, grasslands, and mangroves for housing and infrastructural development without mass tree planting, contributed to a significant reduction in the percentage of vegetation cover. The observed increase in built-up areas together with bare-land can potentially increase stormwater runoff and flood events, given the existing inefficient drainage systems in GAMA. Bare-lands with compacted soils reduce infiltration and increase stormwater runoff. The engagement with the stakeholders and experts revealed that LULC and stormwater runoff were part of the major contributing factors to recurrent annual floods in Accra. The visual impressions from the LULC change assessment (See Figure 15) show that the extent of the catchment covered by water bodies was found insignificant, partly due to the low resolution of the satellite images, and the season in which the satellite data was captured. In addition, the river is mostly filled with solid waste and sediments, which have significant influences on the spectral reflectance from the water bodies.

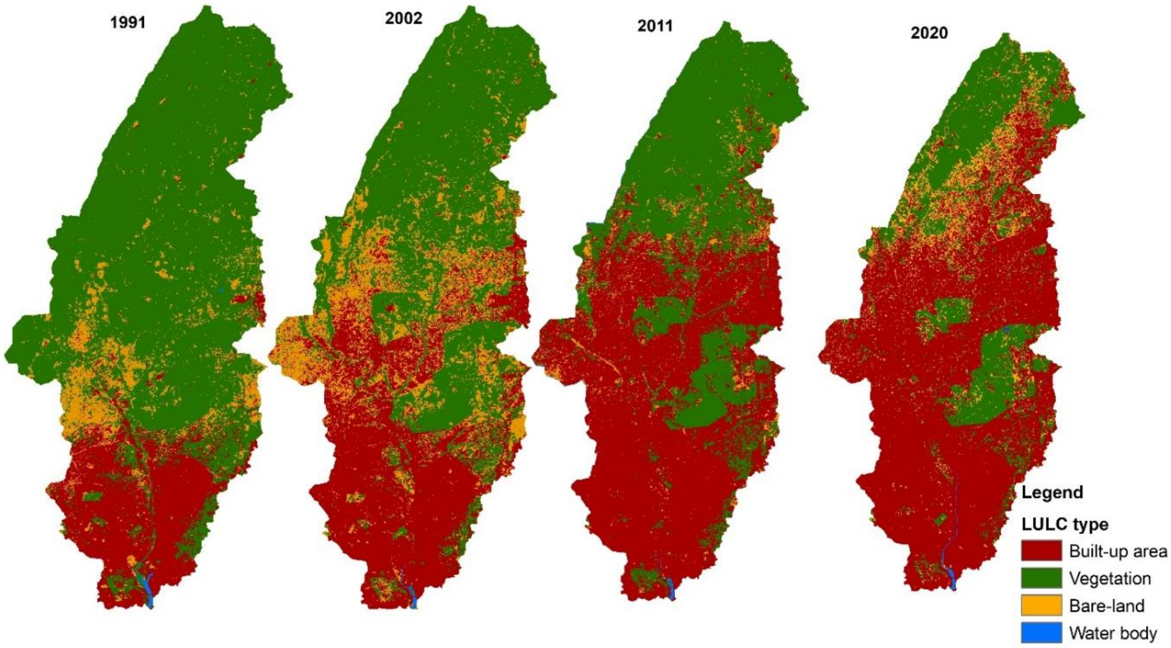

Figure 15. The results of the LULC assessment in the Odaw River catchment from 1991 to 2020
Source: own land use and land cover (LULC) assessment by the authors.

An interview with urban development experts revealed that the urban transformation processes in GAMA have contributed to the growth of the local economy, improvement in the healthcare systems, and the standard of living, which attracted the migration of people, while housing and infrastructural facilities deficits continue to increase exponentially. The unplanned land use and transformation process together with poor waste management systems can pose huge threats to surface water systems, resulting in health-related risks and outbreaks of diseases. Having explored the exposure pathways and the risk of water-borne diseases in the Odaw catchment, there is the need to identify the existing measures adopted in the communities to reduce the risk of diseases and promote health.

3.4.3 The existing interventions and prevention strategies

Health promotion and water-related disease prevention measures: interventions for epidemics and related disasters were done by providing immunization and relief items, which are often short-term interventions. The lessons from FGDs indicate that the supply of WASH facilities in the communities has been the ultimate goal of the local government, private investors, and Non-Governmental Organizations over the decades, however, there is a growing pressure on the available WASH facilities, due to the increasing population in the communities. In addition, these facilities are mostly destroyed or rendered inaccessible during devastating floods. In addition, the outcome of the FGDs in Alajo, and Odawna revealed that the programs failed due to inadequate cooperation from the communities during the implementation of the programs as they felt excluded in the projects' inception stages.

Flood risk reduction measures: the expert interviews and research reports show that over the past years, there have been intervention measures such as early warning systems and dredging of the Odaw-Korle drainage systems. In addition, there are ongoing projects from 2019 to 2025 (Greater Accra Resilient and Integrated Development Project) to dredge the Odaw-Korle drainage systems, build human capacity, and create flood retention ponds within the catchment, however, the preliminary reports highlighted challenges with funding and noncompliance from the communities and institutions (Owusu & Obour, 2021).

3.4.4 Intervention measures proposed by the stakeholders

The QSD models and the CLDs integrated some intervention measures to support reducing the impacts and the cascading effects of the causal factors, and break the negative reinforcing feedback loops in the systems. Through the engagement of stakeholders and community representatives, an intervention framework was developed to be implemented at both local communities and governmental levels to support surface water protection, clean city, and promote health. The drafted framework was validated, using a stakeholder workshop in Accra (see Figure 16). The framework was found relevant due to the specification of roles for both the communities and the government, as lessons from the FGDs revealed that the local communities were fond of shifting community responsibilities to only the government and NGOs. It is strongly recommended for inter-sectoral and multi-sectoral collaborations and sharing of experiences and feedback for the sustainable implementation of the proposed measures.

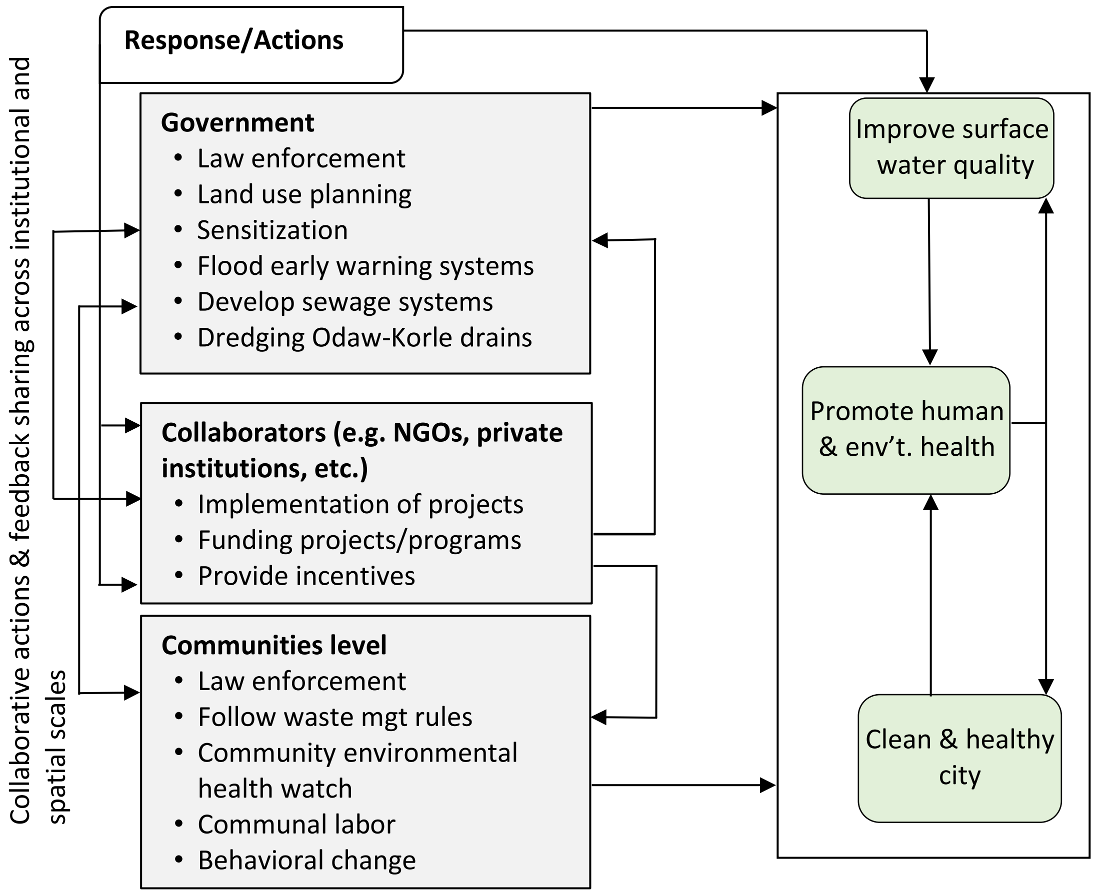

Figure 16. Proposed collaborative strategies to support water quality monitoring and promote health
Summary of proposed collaborative strategies to support water quality monitoring, clean city, and human and environmental health. Here, collaborators may act as a bridging element between the different spatial and institutional scales.
Source: based on expert elicitation and stakeholder interactions in workshops in Ghana between 2018-2019.

3.5. Discussion

Adopting an integrated approach including qualitative system dynamic modeling, proved expedient to enhance the understanding of the complexities of the water-health nexus and its underlying multifaceted drivers. The qualitative system dynamic (QSD) modeling allowed the exploration of the underlying drivers including flooding, LULC change, waste management, and water pollution, which contribute to the risk of water-borne diseases. To enhance the

understanding of the pathways of exposure to and the risks of water-borne diseases, our discussion focuses on accessibility to WASH and wastewater management, and the key feedback loops and interactions consolidated from the QSD sub-models developed.

3.4.5 Access to WASH and wastewater management – impacts on water-borne diseases

The households in the communities have access to drinking water, mainly piped and sachet water. The sachet water is sold in the communities by private individuals and hawkers. The households revealed that the piped water in the communities was directly used for drinking and cooking without additional treatments, but samples were not tested in the laboratory to further determine the quality of the water. The communities have access to sanitation, which are mainly public facilities, however, open defecation practice was identified. Similarly, to accessibility to water, households are required to pay usage fees to gain access to sanitation services, while the facilities were poorly mainly maintained thereby discouraging users. This, in addition to the usage fees, partly compelled the practice of open defecation along the drains. Besides the flush toilets, the existing public sanitation facilities are unimproved, leading to exposure to pathogens, through poor hygiene practices. Given the accessibility to WASH, water storage behaviors and hygiene practices play key roles in the outbreaks of diseases (Falkenberg et al., 2018). Studies in India and the Democratic Republic of Congo show that drinking water can be contaminated with *E. coli* at the point-of-use, when proper hygiene and safety measures are not observed (Falkenberg et al., 2018; Kamba et al., 2016). Falkenberg et al. (2018) underscored the adoption of health-seeking behaviors such as the practice of good hand hygiene in addition to accessibility to safe drinking water to efficiently prevent water-related infectious diseases.

Another basic risk factor is wastewater management in the communities. Wastewater management strategies including the direct discharge of wastewater into the Odaw River, gutters, open spaces outsides homes, etc., were widespread. In addition, the industries along the main drains of the catchment discharge their effluents directly into the river. These management strategies are not sustainable and can pose higher exposure to pathogens and health risks as the pollutants can in turn contaminate drinking water and food via the actions of houseflies, rodents, wind, and floodwater. Grytdal et al. (2018) highlighted that exposure to untreated wastewater containing harmful microorganisms can lead to gastrointestinal infections such as diarrhea. This indicates that in GAMA, the underlying drivers influencing the outbreaks of these diseases extend beyond the supply of only drinking water and sanitation infrastructure. Studies on the benefits of WASH intervention programs in Kenya, Zimbabwe, and Bangladesh revealed that providing WASH has no significant impact on the prevention of diarrheal diseases, due to additional impacts caused by the spatio-temporal dynamics of disasters (e.g. floods, droughts, conflicts, etc.) and health-seeking behaviors (Pickering et al., 2019).

The risks of water-borne diseases via WASH, wastewater management, and additional key drivers including flooding are further discussed in the subsequent sections using the key feedback loops from QSD models developed. To enhance the understanding of the pathways of exposure to and the risks of water-borne diseases, our discussion focuses on the key feedback loops and interactions obtained from the developed QSD sub-models (see Figure 17) and spatial LULC change analysis. The exposure and risk factors are complex with cascading linkages to health, therefore, the important pathways ought to be traced to identify the key areas that require rapid intentions.

3.4.6 Water pollution and the risk of water-borne diseases – influences of floods, waste management, LULC change, and waste management

It was found that besides accessibility to WASH, the prevalence of water-borne diseases is influenced by several interconnected factors including flooding and water pollution through LULC change and waste management, under the dynamics of urbanization in GAMA. A simplified CLD of the interconnections between the underlying drivers of water-borne disease in addition to WASH is presented in Figure 17. For example, the usage of untreated wastewater for urban agricultural activities to avoid overreliance on the unpredictable rainfall pattern in the region pose high risks to health via drinking water pollution. As illustrated in a balancing loop (*B1*), the polluted water in the Odaw River is not suitable for irrigation, and when it is used for cropping as indicated in the loop (*R5*), the food produced can pose health risks via direct ingestion without washing with safe water. This increases the exposure of households to pathogens, leading to an increase in the incidence and prevalence rates of water-borne diseases.

The fecal matter from infected persons without proper hygiene practice leads to pollution of drinking water (see loop *R6*). Interventions such as provisioning safe drinking water and improved sanitation promote good hygiene and reduce open defecation practices (see loop *R7*). The loop (*R7*) is reinforced where an increase in open defecation practice creates environmental and sanitation nuisance. Related scenarios have been reported to have caused major outbreaks of water-food-borne diseases in Ghana (including Accra and Kumasi), Kenya, Mozambique, Bangladesh, and the United Kingdom (Miller & Hutchins, 2017; Ohene-Adjei et al., 2017; Okaka & Odhiambo, 2018; WHO, 2020a).

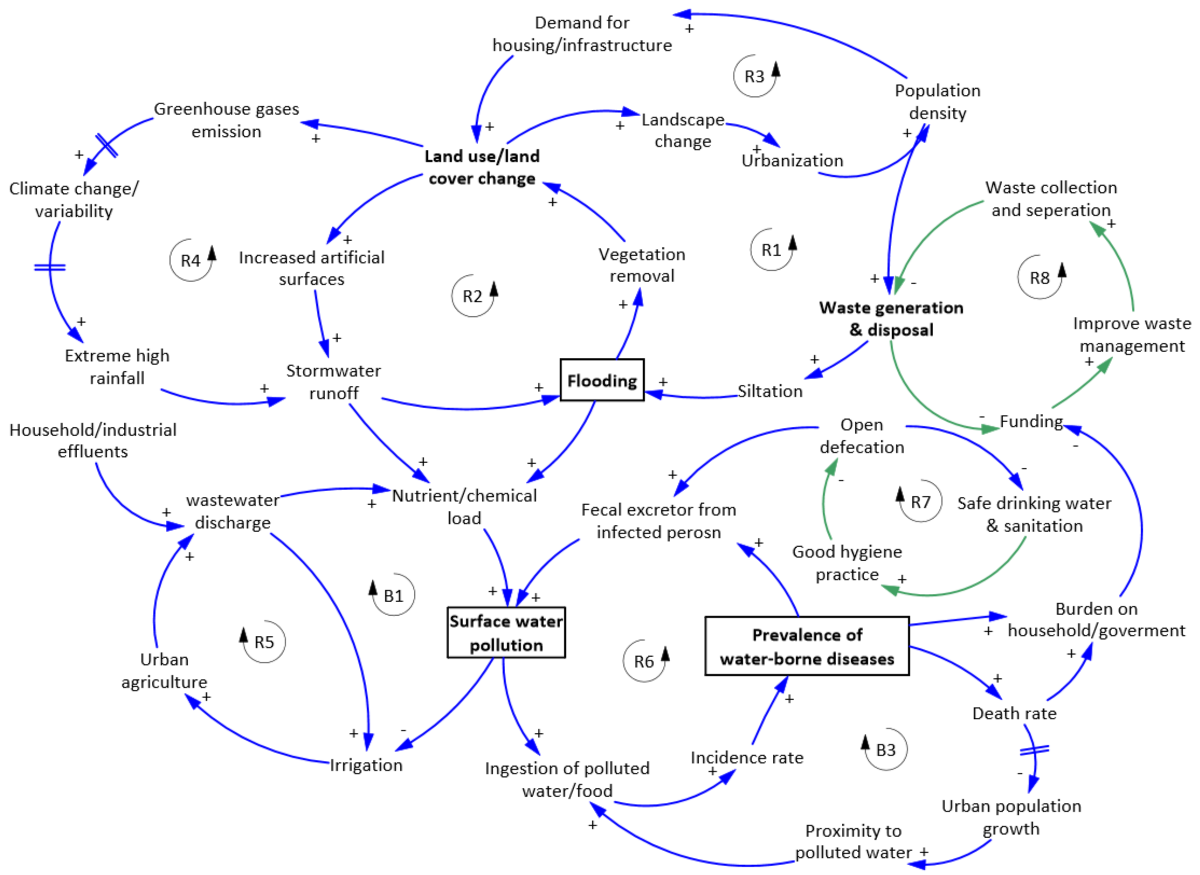

Figure 17. Integrated CLD obtained from the key feedback loops in the sub-models developed

The blue arrows show the connections between the variables, while the green arrows indicate the interventions altering the state of these variables.
Source: based on primary data collection in the Odaw River catchment in Ghana, in April 2019.

In our study, flooding was found as a major driving factor influencing frequent outbreaks of water-borne diseases in GAMA, through the pollution of drinking water and the destruction of WASH infrastructure. Given the global impacts of climate change and variability, flooding in the Odaw catchment is mainly caused by human-induced factors such as poor land use planning, solid waste disposal, and lack of law enforcement. Major outbreaks of diarrheal diseases following flood events have been repeatedly reported in communities along the Odaw River in Accra (Abu & Codjoe, 2018). Okaka and Odhiambo (2018), and Abu and Codjoe (2018) revealed that besides the destruction of critical infrastructure, including water supply systems, sanitation, and hygiene facilities, floods in Ghana and Kenya have contributed to the pollution of drinking water at the point-of-use, through the transportation of pathogens, leading to the risks of diseases. For example, a cumulative sum of 618 cases with 6 deaths was reported as of June 14, 2015, following the June 3 flood disaster in Accra in 2015 (WHO, 2016). Similarly, study reports show that flood events have contributed to the outbreak of diarrheal diseases in Southern Asia and Sub-Saharan Africa countries including Bangladesh, Kenya, and Mozambique (Mboussou et al., 2019; Okaka & Odhiambo, 2018; WHO, 2020a).

In addition, evidence from the surveys, and expert elicitations, indicate that solid waste disposal is a major contributing factor to flooding in the Odaw River catchment, through siltation of the drainage system. The feedback loop (*R1*) indicates that an increase in urban population density increases the generation and disposal of solid waste, leading to the siltation of drainage systems and flooding. Interventions such as improved waste management play crucial roles in the causal loop of flooding. Providing funds to improve waste management contributes toward reducing the amount of solid waste disposed into drains (see loop *R8*). Reports show that as of 2018, about 4.7 million people generate over 1.6 million tons of solid waste annually within GAMA, and more than half of the solid waste ends up in the surface water drainage systems. Lessons from waste management strategies in Rwanda revealed that sustainable and innovative waste management in addition to environmental law enforcement yielded significant improvements in water quality and environmental health in major cities in Rwanda (Mukanyandwi et al., 2019).

Land use and land cover change, partly due to an increase in built-up areas and reduction in vegetation cover between 1991 and 2020, play crucial roles in flooding. Increased artificial surfaces including bare-lands reduce infiltration thereby facilitating stormwater runoff and flooding, given the poor engineering of drainage systems in the area. A reinforcing loop (*R3*) shows that an increase in the urban population increased demand for housing and infrastructure, leading to urban LULC changes. Similarly, LULC changes contribute to climate change and its associated long-term impacts such as extreme high rainfall and flooding (see *R4*). LULC can also affect water quality directly with chemicals in wastewater from urban agricultural activities.

Key lessons from the interview with experts at the Physical Planning Department of the Accra Metropolitan Area revealed that poor LULC planning, lack of law enforcement, and corruption, coupled with the challenges of the traditional land tenure system in Ghana contribute to the development of housing and unauthorized infrastructure on watercourses. This hinders the smooth flow of water, leading to flooding, given extreme high rainfall. Previous studies in Ghana have attributed these to lack of implementation of urban land use plans and environmental protection (Akubia & Bruns, 2019). LULC change and stormwater runoff play a major role in the transportation of nutrients and chemicals from farmlands, grease from auto mechanic shops, and residential areas into *water systems* and soils. However, the concentration of chemicals and heavy metals in the water and soils above the recommended standard levels can render the water unclean for agricultural activities, and the food produced using polluted water can pose significant health risks. Research studies in the United Kingdom, Kenya, and the Democratic Republic of Congo indicate that unplanned infrastructure development including roads, parking lots, and sidewalks can increase stormwater runoff and flooding, facilitating the transportation of pollutants, viruses, and bacteria from the landscape into water sources (McGrane, 2016; Miller & Hutchins, 2017; Okaka & Odhiambo, 2018).

3.4.7 The way forward

The study identified that the provision of only WASH is not sufficient to prevent water-borne diseases in Ghana. It calls for the development of integrated solutions, covering land use planning, improved waste management systems, behavioral change, and flood disaster risk reduction, through multi-sectoral collaborations. For example, sustainable land use planning and implementation of building codes, surface water and environmental protection, supply of adequate WASH, designing of sensitization program in collaboration with the communities, creating awareness on the dynamics between floods, water pollution and the outbreak of water-borne diseases, public-private partnership, and provision of sufficient funds for flood and waste management projects are proposed intervention for GAMA. The development of flood risk adaption strategies is associated with adaptation co-benefits, as these strategies will not only reduce flood risks but indirectly reduce flood-induced water-related diseases in GAMA.

3.4.8 Limitation of the study

Water quality sampling and laboratory analysis were not conducted in this study, due to limited resources and the short duration of the fieldwork activities in Ghana. This could allow quantitative analysis of the correlation between water quality and the outbreak of water-borne diseases. Nonetheless, the adoption of the and QSD modeling and stakeholder participation provided relevant information to enhance our understanding of interactions and linkages between water pollution and the important pathways to water-borne disease in GAMA. Though QSD models are limited in terms of mathematical simulations and quantification of *cause* and *effects* within systems, however, as the study is qualitatively oriented, the CLDs and the feedback loops created were sufficient for the development of interventions and inform decision-making. In addition, the Landsat satellite images used (30 m spatial resolution) has relatively low pixel values, which are not suitable for a detailed assessment of LULC, however, the results obtained were useful for our analysis as the study focused mainly on the extent of built-up areas and vegetation cover in the Odaw catchment.

3.6. Conclusion

The study assessed the water-health nexus, using an integrated approach to explore the interactions and linkages between water pollution and the risk of water-borne diseases in the Odaw River catchment within the Great Accra Metropolitan Area in Ghana. It was revealed that the communities have access to drinking water and sanitation, however, the sanitation facilities are poorly maintained. Wastewater management strategies in the communities are not sustainable and rather pose higher health risks. Water-borne diseases are still prevalent in GAMA, particularly following flood events. Supplying only drinking water and sanitation is not a stand-alone solution as water-borne diseases in the area have multi-causal pathways. The underlying drivers of the disease include water flooding and pollution, influenced by different interrelated factors such as poor land use planning, poor waste management, lack of law enforcement, and corruption at all levels of governance. Sustainable management of these drivers by a single sector or institution can be extremely challenging. Multi-sectoral collaborations and cooperation are important to co-design and inclusively implement integrated strategies together with the local communities to promote a clean environment and human health. The applied integrated research approach supported the understanding of the complexity of the water-health nexus, and further helped to identify strategies to inform policy formulation and decision-making.

4. Influence of human–surface water interactions on the transmission of urinary schistosomiasis in the Lower Densu River basin, Ghana[3]

Abstract

Human interactions with surface water systems have complex linkages to health through interrelated processes, with particular impacts on the transmission pathways of diseases including schistosomiasis. The objective of the study was to assess the influence of human-surface water interactions on the transmission of urinary schistosomiasis in the Lower Densu River basin, Ghana. A cross-sectional survey was conducted among 336 schoolchildren between the ages of nine and fifteen in six basic schools, from six communities. In addition, field observation of human-water-contact patterns was conducted twice per week in the six communities. The study utilized descriptive statistics and bivariate logistic regression for data analysis. The bivariate logistic regression was used to calculate the odds ratios. The study found limited access to improved sanitation and safe water supply, which compelled the communities to rely on open defecation and untreated river water sources. It was found that male children had 5.5 times the odds of blood in urine compared to female children. The odds of blood in urine doubled from children of 13 years (OR=1.7) to 15 years and above. Elevated odds ratios were found for recreational, domestic, and occupational water-contact activities. In addition, the study found that more frequent and longer water-contacts contributed to elevated odds of blood in the urine. The preventive effect of Mass drug administration shows that children receiving treatment had lower odds (R=0.4) of blood in the urine. To reduce the exposure and the risk of the disease, preventive measures must focus on breaking the transmission cycle of schistosomiasis. Providing sufficient safe drinking water supply, and improved sanitation and hygiene can form a barrier to halting the infection. Collaborative implementation of sensitization campaigns to reduce frequent and longer water-contacts, and prevent open defecation are sustainable strategies to tackle schistosomiasis.

Keywords: Water pollution; water-contacts; *schistosoma haematobium;* snail host; schoolchildren; Ghana

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4.1. Introduction

Human interactions with surface water systems are reflections of humanities' dependence (directly or indirectly) on water resources for survival (Massuel et al., 2018; Tanaka et al., 2016). These interactions influence the pollution pathways of surface water systems and the exposure of humans to water-related infectious diseases (e.g., schistosomiasis) (Ciddio et al., 2017; Kulinkina et al., 2019). Schistosomiasis is one of the Neglected Tropical Diseases (NTDs) that pose a huge economic burden and health challenges in tropical and subtropical regions (Kulinkina et al., 2019; Rostron et al., 2019). Schistosomiasis, a water-based infectious disease, is a parasitic disease of considerable medical and veterinary significance, which is caused by flatworms of the genus Schistosoma (Gower et al., 2017; Webster et al., 2013).

Schistosomiasis has a complex lifecycle (see Figure 18) that requires freshwater snails (*Bulinus*), which serve as the intermediate host in which the parasite undergoes development, and the definitive hosts (humans and animals) in which the parasite matures (French et al., 2018; Tchuem-Tchuenté et al., 2017). Schistosomiasis transmission depends on water-contact patterns as well as the presence and distribution of infected intermediate snail hosts within watercourses (Chadeka et al., 2017; Grosse, 1993; John M. Hunter, 2003). The cercariae, a parasitic fluke released from the snails, penetrate the skin of humans and animals, transform into *schistosomula* and enter the bloodstream or the urinary system, mature, pair up and begin to produce eggs after about two weeks (Ciddio et al., 2017; Grimes et al., 2016; Tchuem-Tchuenté et al., 2017).

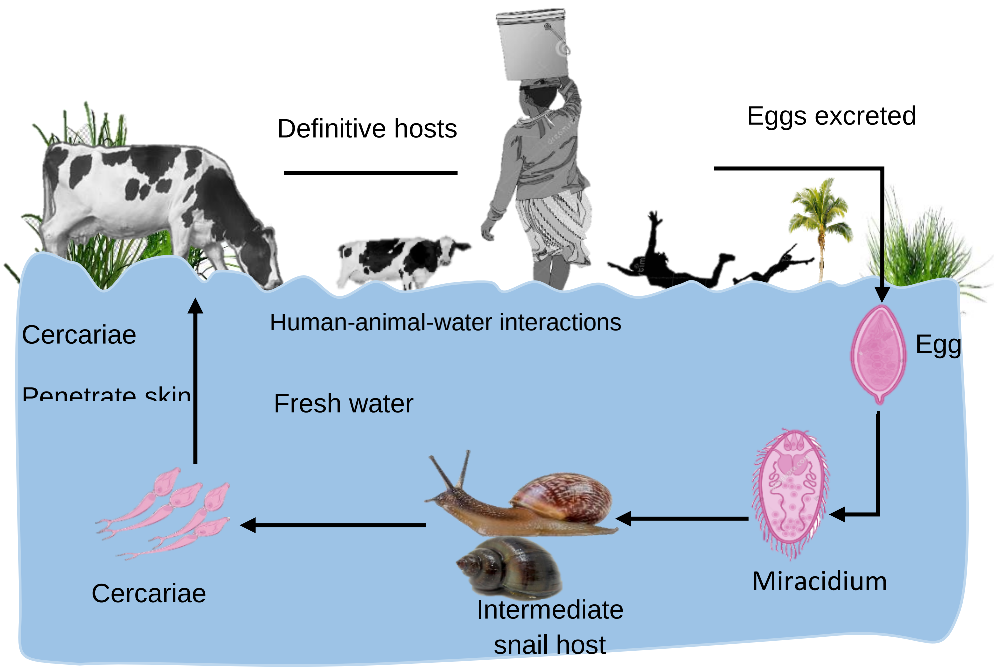

Figure 18. Schistosoma transmission lifecycle.
Source: adapted from Ciddio et al. (2017) and McManus et al. (2010).

Ecological and human factors play major roles in the epidemiology of the disease (Hunter et al., 1983; Hunter, 2003). Ecological changes resulting from the construction of dams, ponds, or irrigation canals, along with the hydrological dynamics of a given environment, influence the survival, dispersal, distribution, and abundance of the cercariae and the snail hosts, due to changes or modifications to the habitat conditions (Ciddio et al., 2017; Hunter, 1981).

Further, the risk of human infection depends on the degree of exposure (water-contacts), host immunity, and hygiene and sanitation conditions, particularly open defecation (Angelo et al., 2018; Schmidlin et al., 2013). The pollution of surface water with human excreta containing schistosoma eggs is the key driver of schistosomiasis transmission in most endemic areas across the world, particularly in Sub-Saharan Africa (Kulinkina et al., 2019b; J. P. Webster et al., 2016). Given the underlying risk and exposure factors, schistosomiasis-infected persons can experience some general symptoms, including blood in urine, pains (in the abdomen and joints), and whole-body sicknesses, such as itching, skin rashes, fatigue, fever, and weight loss. The occurrence and severity of these symptoms depend on the immune systems of the definitive host (Tchuem-Tchuenté et al., 2017).

As of 2018, the number of people suffering from schistosomiasis worldwide was approximately 252 million, and it was estimated that between 4,400 and 200,000 people die annually from the disease (Niu et al., 2018). Over the past decades, it has been reported that about 90% of global schistosomiasis cases are reported in Sub-Saharan Africa (Anyan et al., 2019; Hughes & Hunter, 1970; WHO, 2020b). Among the numerous species of schistosoma discovered in the tropics and sub-tropical regions, S. *haematobium* and S. *mansoni* are most commonly reported for human infections in Sub-Saharan Africa (Stadley et al., 2012). In many West African countries, including Senegal, Mali, Ghana, Burkina Faso, Niger, and Nigeria, schistosomiasis is considered endemic (Kulinkina et al., 2019; Martel et al., 2019; Walz et al., 2015; Woodall and Kramer, 2018).

In Ghana, schistosomiasis is not a new disease, instead, it has become a permanent health challenge, since the construction of dams and ponds for hydropower, irrigation, and community water supply in the early 1950s (Grosse, 1993; Hughes & Hunter, 1970; Hunter, 2003). It has been reported as the most neglected among the Neglected Tropical Diseases, which is widespread in the peri-urban and rural communities of Ghana, where access to clean water, improved hygiene, and sanitation is limited (Kulinkina et al., 2019; Martel et al., 2019; Nyarko et al., 2018). S. *haematobium* is the most commonly reported schistosome species in Ghana, which causes urinary schistosomiasis (Anyan et al., 2019; Kulinkina et al., 2019; Martel et al., 2019). In 2018, the proportion of schistosomiasis among all reported cases of water-related infectious diseases in Ghana was approximately 52%, while the prevalence rate was 27.5% (Anyan et al., 2019; Martel et al., 2019; Nyarko et al., 2018). The underlying exposure and risk factors associated with such cases were not explicitly highlighted, although control measures such as mass drug (praziquantel) administration (MDA) were implemented (Martel et al., 2019; Nyarko et al., 2018). Praziquantel is described as an anti-worm drug used to prevent the newly hatched schistosoma worms from multiplying in the human body (Vale et al., 2017).

Despite the interventions, including the mass drug administration and schistosomiasis sensitization programs by the Government of Ghana and the World Health Organization (WHO), schistosomiasis continues to be a stern health challenge in the country (Kulinkina et al., 2018, 2019; Tetteh-Quarcoo et al., 2013). Reports of research studies in the southern part of the country revealed that the prevalence and the impacts of the disease have often been underestimated (Anyan et al., 2019; Kulinkina et al., 2019b; Martel et al., 2019). The current evidence illustrates that research studies on schistosomiasis in the Densu River basin focused mainly on the prevalence, parasitic egg counts, intensity, environmental factors, and the control measures (Anyan et al., 2019; Martel et al., 2019; Nyarko et al., 2018). There is a need for comprehensive investigations, from a transdisciplinary perspective, to understand the human-water contact patterns and exposure factors that reinforce the schistosoma lifecycle and its transmission. Specifically, the study explored and examined the influence of the availability and accessibility to safe drinking water and improved sanitation, the places of open defecation, and the type and pattern of human-water interactions on the transmission pathways of urinary schistosomiasis in the Lower Densu River catchment in Ghana.

4.2. Study area

The study was conducted in the Ga South and Ga West Municipal Assemblies in the Lower Densu River catchment in Ghana, a coastal country located in West Africa. The Densu catchment occupies an area of about 2,490 km^2 with a total population of over 600,000 people spread over 200 settlements, equating to a population density of 240 persons per km^2 (Ghana Statistical Service, 2014). The catchment is located in the southeastern part of Ghana, which stretches between longitudes 0°10' W - 0°40' W and latitudes 5°30' N - 6°15' N (see Figure 19).

The area experiences a bimodal rainfall pattern. The average annual rainfall is about 800 mm, with higher monthly rainfall in June and July (Nkrumah et al., 2014). The annual temperature ranges between 23°C and 33°C with the hottest periods between February and April (Codjoe & Larbi, 2016). The source of the river lies in the Atewa mountain ranges and flows for about 116 km southwards into the Weija reservoir, before entering the sea at the Gulf of Guinea (Attua et al., 2014). The Densu reservoir serves as a drinking water source for most parts of the city of Accra and its peri-urban areas (Karikari & Ansa-Asare, 2009; Yorke & Margai, 2007).

The communities along the Densu river depend directly on the river and its tributaries as a source of livelihood and domestic water supply, which exposes them to water-related pathogens and parasites (Tetteh-Quarcoo et al., 2013; Nyarko et al., 2018). The major occupation and livelihood activities in the communities are subsistence farming, fishing, and petty trading.

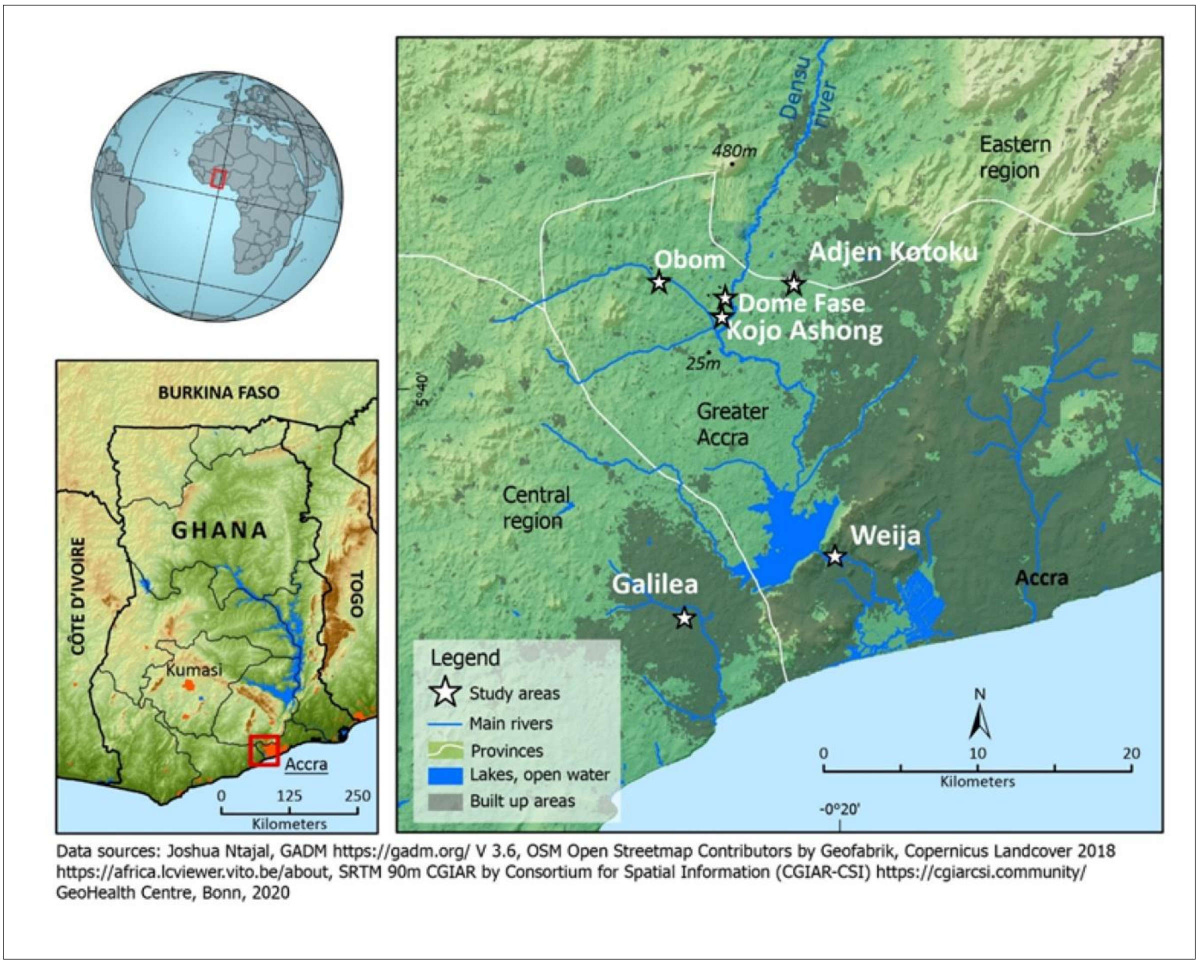

Figure 19. Map of the study area

4.3. Materials and methods

4.3.1. Sampling and sample size estimation for the survey

The minimum sample size determination approach of Pourhoseingholi et al. (2013) as stated in $Equation$ 1 was used to determine the sample size of 306 for the cross-sectional survey

$$n = \frac{Z^2 P(1-p)}{d^2} \qquad Equation\ 1$$

Applying a buffer of 10% to account for potential non-response, 337 schoolchildren were randomly sampled from the six schools (see Appendix I). The selection of the sampling sites was based on the proximity of the respective communities to surface water bodies (rivers, streams, and ponds), the communities' interactions with surface water, and the prevalence of schistosomiasis (Attua et al., 2014; Codjoe & Larbi, 2016; Kulinkina et al., 2019; Nyarko et al., 2018). The public schools with the largest number of schoolchildren were selected as they were all part of the "free and compulsory" basic schooling program of Ghana, which gives equal opportunity to all residents to acquire basic education. The six selected schools were found to be homogeneous and the targeted sample frame was made up of children with similar demographic characteristics, including the same age groups, hence, the total sample size of 336 was equally distributed among the selected schools (see Zimmerman, 1996). The names of the schools were coded with letters (i.e., A, B, C, etc.) to protect their privacy.

Through consultation with the Schistosomiasis Control Program at the Center for NTDs in Accra, Ghana, schoolchildren aged between nine and fifteen years, who have spent at least five years within their respective communities, were considered eligible to take part in the survey. These eligibility criteria are based on the experiences of the Center for NTDs, indicating that a minimum of five years of residency is required to ensure that recorded prevalence rates can be attributed to community-level exposure factors. To ensure the data collected in this study is compatible with the existing schistosomiasis database in Ghana, the eligibility criteria of the Center for NTDs were followed. A systematic random sampling approach, using the school attendance record book with the names of the pupils, was used to select the participants. The list of schoolchildren was segregated by gender (to obtain a gender-balanced sample) and the names of the children were numbered from one to the n^{th} person. The first participant was randomly selected and subsequently, every fifth student on the list was selected until the required sample size was obtained. The consent to participate in the study was granted by 336 schoolchildren, hence, 56 schoolchildren (28 males and 28 females) were sampled from each of the six basic schools.

4.3.2. Data collection

Prior to conducting the surveys, gatekeepers (assembly members, school staff, and chiefs of the communities) were consulted to gain full entry and access to the communities and the basic schools. In addition, research practice partners (i.e., key stakeholders and institutions, which supported the fieldwork and data collection process) including experts in water and sanitation research, disease control officers of the various health centers in the communities, school staff, and experts of schistosomiasis research were identified and consulted to support the design and data collection activities.

A cross-sectional survey was conducted to obtain primary data on the pattern of human-water interactions, access to clean water, sanitation and hygiene facilities, self-reported experiences of schistosomiasis (blood in urine), and the perceptions on the exposure and risk factors. An expert interview was conducted to obtain data on disease control and preventive measures. The collection of blood, stool, or urine samples was not included in this study due to logistics and financial constraints. The different types of water-contact activities in the communities were classified according to the reasons for engaging in such activities. Therefore, all water-contact activities were classified into four major categories: domestic, occupational, recreational, and cultural/religious.

4.3.3. Water-contact observations

In order to complement the self-reported water-contact patterns, on-site observation of the water-contact activities was conducted at the major water-contact points in each community twice per week over three months (February to April). The water-contact activities, the people (i.e., age group and gender) involved, and the duration of water-contacts were the key items of the observation.

4.3.4. Statistical analysis

The study utilized descriptive statistics and bivariate odds ratios for data analysis. In order to identify the predictors of S. *haematobium* infection, an analysis of the Spearman rank correlation test was performed. The output of the test allowed the selection of the most potent factors that can likely explain infection. In addition, a bivariate logistic regression was performed, calculating odds ratios. The results were considered statistically significant at a *P-value* of *0.05* or less.

4.3.5. Ethical issues

Ethical approval was obtained from the Ethical Committee at the Center for Development Research (ZEF), University of Bonn in Germany. In addition, ethical approval was obtained from the Ethical Clearance Committee at the University of Ghana, and the Ghana Education Service. A letter of approval to conduct the study was obtained from the education offices of the Ga South (Weija) and the Ga West (Amasaman) Municipal Assemblies. The ethical clearance letter, together with a copy of the consent form and a sample of the questionnaire was presented to the school staff to also seek their approval. One week before the commencement of the survey, copies of the consent forms were given to the participants (schoolchildren) and their parents or guardians to obtain their informed consent. The researcher received the endorsed copies of the consent forms before the commencement of the study. The participants were informed that they are free to withdraw their consent or discontinue their participation in the study at any point and for any reason. An identification number (ID) was assigned to each respondent to ensure their anonymity.

4.4. Results

4.4.1. Demography and WASH characteristics

4.4.1.1 Gender and age distribution

In each of the six schools, 28 males and 28 females took part in the survey, resulting in a response rate of nearly 100% with a total sample size of 168 males and 168 females. Further, the age of the study participants ranged from 9 to 15. The highest number of the children was found within the age group of 11 and 12 years (144), while the lowest number of children was within the age group of 15 years and above (14) (see Table 10).

Table 10. Age distribution of the sampled children in the surveyed schools

Age group	A	B	C	D	E	F	Total
09 – 10 years	10	12	26	13	15	23	99
11 – 12 years	18	22	22	33	32	17	144
13 – 14 years	21	18	7	8	9	16	79
15 and above	7	4	1	2	0	0	14
Total	56	56	56	56	56	56	336

Source: based on primary data collection in Ghana between February 2019 and April 2019.

4.4.1.2 Availability and accessibility of sanitation facilities

The availability and accessibility of sanitation facilities were found to be a challenge in the selected schools and their respective communities. In all the selected schools in the Ga West and Ga South municipal assemblies, public toilet facilities, commonly known as “Ventilated Improved Pit latrines” (VIP) were available and accessible to all schoolchildren, however, these facilities were poorly maintained. At home, 53% of the schoolchildren depended on public toilet facilities, which were also found in poor condition. This compelled 33% of the schoolchildren and other members of their households to practice open defecation (see Table 11). One of the reasons for engaging in open defecation was the usage fees of the VIP. In addition, the distance between the home and the nearest toilet facility, on average between two and four-minute walk, was identified as a common reason for not utilizing these facilities. Lack of improved sanitation facilities compelled 61% of the schoolchildren to practice open defecation at Kojo Ashong. Similarly, limited access to improved sanitation and hygiene was identified as the motivating factor for open defecation among 55% of the schoolchildren in Obom. Communities such as Weija, Adjen Kotoku, and Galilea are peri-urban areas with relatively high access to sanitation facilities compared to the rural communities: Obom, Kojo Ashong, and Dome Fase.

Table 11. Access to sanitation facilities in the communities

Community	Public (VIP)	Private pit latrine	Private flush toilet	Open defecation
Obom	16 (29%)	8 (14%)	1 (2%)	31 (55%)
Kojo Ashong	18 (32%)	4 (7%)	0 (0%)	34 (61%)
Weija	34 (61%)	5 (9%)	3 (5%)	14 (25%)
Adjen Kotoku	46 (82%)	6 (11%)	3 (5%)	1 (2%)
Galilea	41 (73%)	11 (20%)	2 (4%)	2 (4%)
Dome Fase	24 (43%)	4 (7%)	0 (0%)	28 (50%)
Total	179 (53%)	38 (11%)	9 (3%)	110 (33%)

Source: based on primary data collection in Ghana between February 2019 and April 2019.

4.4.1.3 Places of open defecation

Despite the global and national efforts to end open defecation (OD), rural communities in Ghana, including those in the lower Densu River catchment, still practice OD. It was found that 33% of the children were compelled to practice OD, due to limited access to improved sanitation at home. The crucial aspect of OD in this study was the places it is practiced (see Figure 20). Importantly, 48% of OD was practiced in and around the Densu River (and its tributaries). The uncleared bushes and grasses around the buildings were the next suitable OD sites for 32% of the children. Other places such as public dumping sites and uncompleted buildings were also identified as places for OD, particularly at night, when the surrounding environment becomes dark.

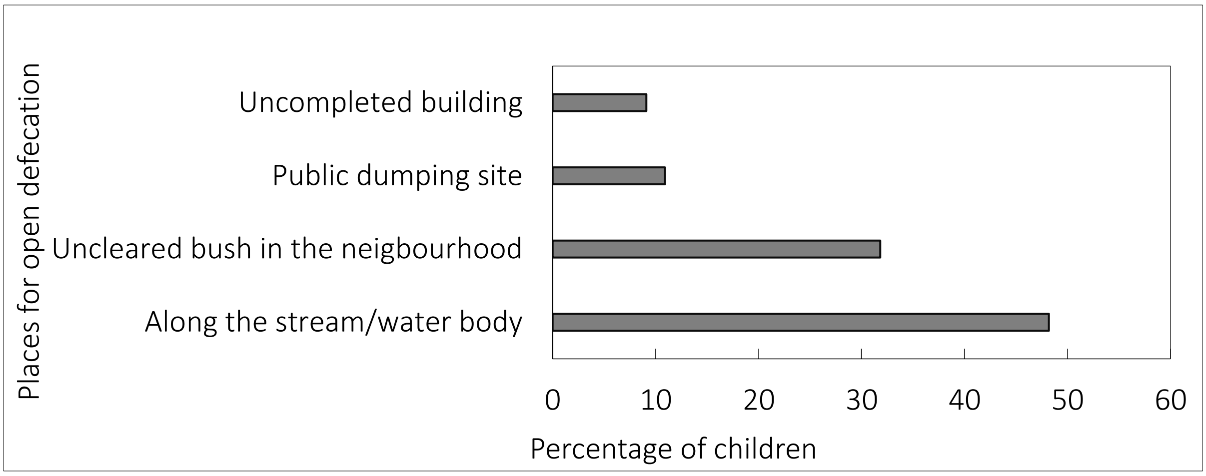

Figure 20. Places of open defecation in the communities
Source: based on primary data collection in Ghana between February 2019 and April 2019.

4.4.1.4 Sources of drinking water

In schools of the peri-urban communities, the main source of drinking water was bottled (or sachet) water. However, in rural communities, the main source of drinking water at school was piped water, which is tapped from the main Municipal Water Supply System (from the Weija Dam). For example, 43 out of 56 schoolchildren at Weija depended on bottled (or sachet) water. The bottled (or sachet) water is sold on the schools' premises, hence the schoolchildren, who could not afford it, as was the case at Dome Fase, had to rely on river water at school. At home, the schoolchildren in communities such as Dome Fase, Kojo Ashong, and Obom depended on unimproved water sources (directly from Densu River and its tributaries) as their main source of drinking water (see Figure 21). Although, the municipal water supply (piped water) was available in all selected communities but was not affordable to all households. In communities such as Obom, where the Densu River is relatively difficult to access, 28 out of 56 of the schoolchildren revealed that their households depended on the *Ponpon* stream, a tributary of the Densu River.

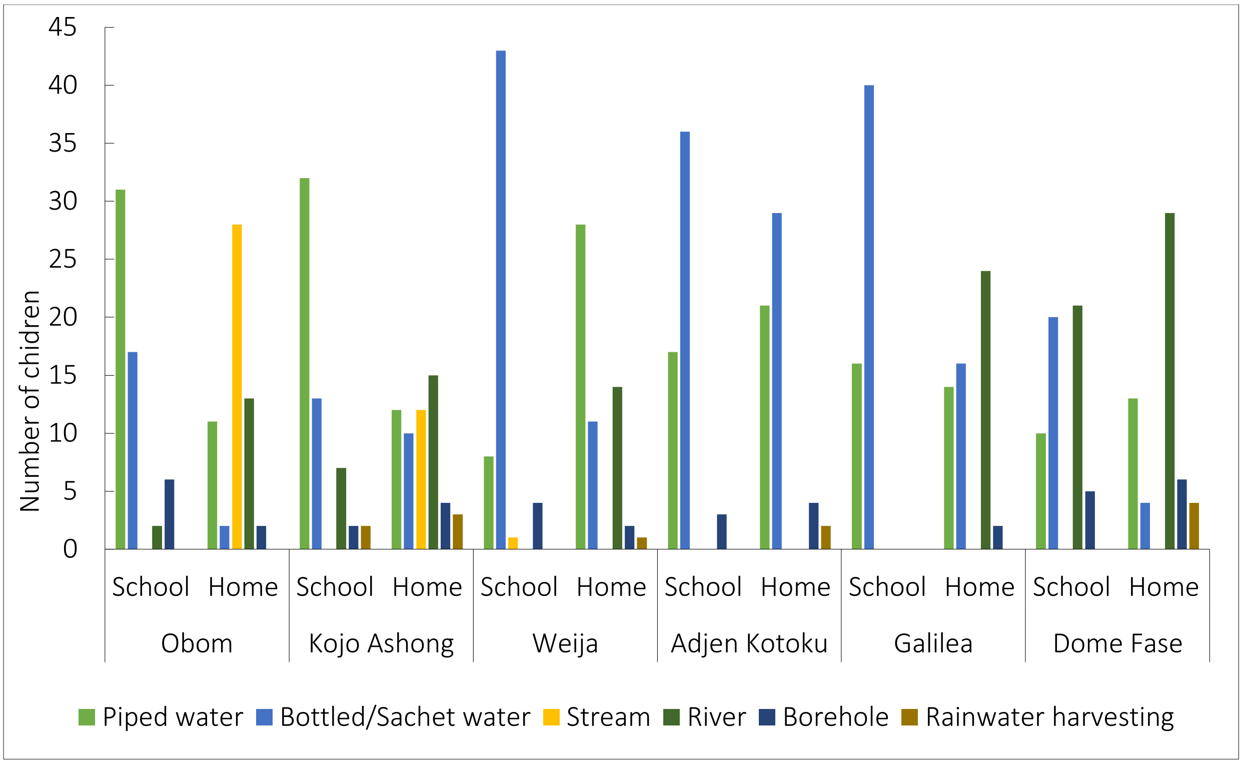

Figure 21. Sources of drinking water at school, and home
Source: based on primary data collection in Ghana between February 2019 and April 2019.

4.4.2. Water interaction and contact patterns

4.4.2.1 Self-reported water-contact activities

Human contacts with polluted surface water systems that contain the infected intermediate snail host are crucial in the transmission cycle of *S. haematobium*. Water-contact activities at the community level give a holistic view of human interactions with surface water. For example, the major water-contact activity in all the communities was recreational (53%), primarily swimming (see Table 12). 28% and 18% of the schoolchildren were engaged in domestic and occupational water-contact activities, respectively. Only one percent of the entire sample population had water-contact for cultural/religious reasons, e.g., during the "holy baptism". Water-contact activities, such as assisting parents in fishing, crossing the river to reach school, or irrigating crops, were the common occupational activities among the children. Further, a gender difference was found, with 34% of males engaging in recreational water-contact activities compared to only 19% of females. On the other hand, 20% of females were involved in domestic water activities, whereas only 8% of males indicated such water-contact activities.

Table 12. The outcome of the self-reported water-contact activities in the communities

	Water-contact activities								
	Recreational		Domestic		Occupational		Cultural		
Gender	Male	Female	Male	Female	Male	Female	Male	Female	Water type
Obom	22	10	4	13	2	4	0	1	River & stream
Kojo Ashong	20	15	3	11	5	2	0	0	River
Weija	17	12	4	8	7	6	0	2	River
Adjen Kotoku	16	8	4	11	8	9	0	0	Ponds
Galilea	18	9	7	13	2	6	1	0	River
Dome Fase	21	11	4	12	3	5	0	0	River
Sub total	114 (34%)	65 (19%)	26 (8%)	68 (20%)	27 (8%)	32 (10%)	1 (0.3%)	3 (0.9%)	
Grand total	179 (53%)		94 (28%)		59 (18%)		4 (1%)		

Source: based on primary data collection in Ghana between February 2019 and April 2019.

4.4.2.2 Age distribution of water-contact activities

The segregation of the water-contact activities by age groups (see Table 13) shows that recreational activities are the most common water-contact activity practiced by children of all age groups, with an increasing proportion of older age groups. Whilst 45% of 9-to-10-year-old children engage in recreational water activities, 62% and 71% of children aged 13 to 14 and above 15 years engage in the behavior, respectively. Interestingly, it was found that younger children, i.e., age groups 9 to 10 years and 11 and 12 years, are more frequently engaged in occupational and domestic water-contact activities compared to the older children. In fact, 23% of the 9-to-10-year-old children indicated being involved in occupational water-contact activities, whilst only 10% of the older children (13 years and above) indicated such behavior. It is thus indicated that with increasing age the children are less engaged in domestic and occupational water-contact activities and more engaged in recreational water activities.

Table 13. Cross-tabulation of age groups and water-contact activities

	Water-contact activities			
Age group	Recreational	Domestic	Occupational	Cultural
09 – 10 (n=99)	45	30	23	1
11 – 12 (n= 144)	75	41	26	2
13 – 14 (n=79)	49	20	9	1
15 & above (n=14)	10	3	1	0
Total (n=336)	179	94	59	4

Source: based on primary data collection in Ghana between February 2019 and April 2019.

4.4.2.3 Self-reported versus the observed water-contact activities

Comparing the outcomes of the self-reported with the observed water-contacts at the community level (see Figure 22A), both methods revealed that children were most commonly engaged in recreational activities in all communities except at Galilea, where the observed domestic water-contact activities were similarly common to the recreational activities. Segregating the water-contact activities by gender (see Figure 22B), confirms that males are more frequently engaged in recreational activities compared to females. The observational data further confirms that females are more frequently engaged in domestic water activities compared to males, however, the observations revealed a slightly higher proportion of males than the self-reported results (28% and 34%).

The gender distribution of the occupational water contact category differed between the observational and self-reported data, while the self-reported results indicated that more females were engaged in occupational water interactions, the observation showed a higher proportion of males engaging in such activities. Similarly, more males were observed engaging in cultural water interactions, whilst the results of the self-reports indicated that more females were engaged in such an activity. As the number of both reported and observed cultural water activities was very low, the gender distribution in this category is not robust and should therefore be ignored. Additionally, it should be noted that the surveyed children were asked to indicate their primary water contact activity, which may have led some males to omit their engagement in occupational water contact activities. Further, it cannot be excluded that some reporting bias was evident during the survey.

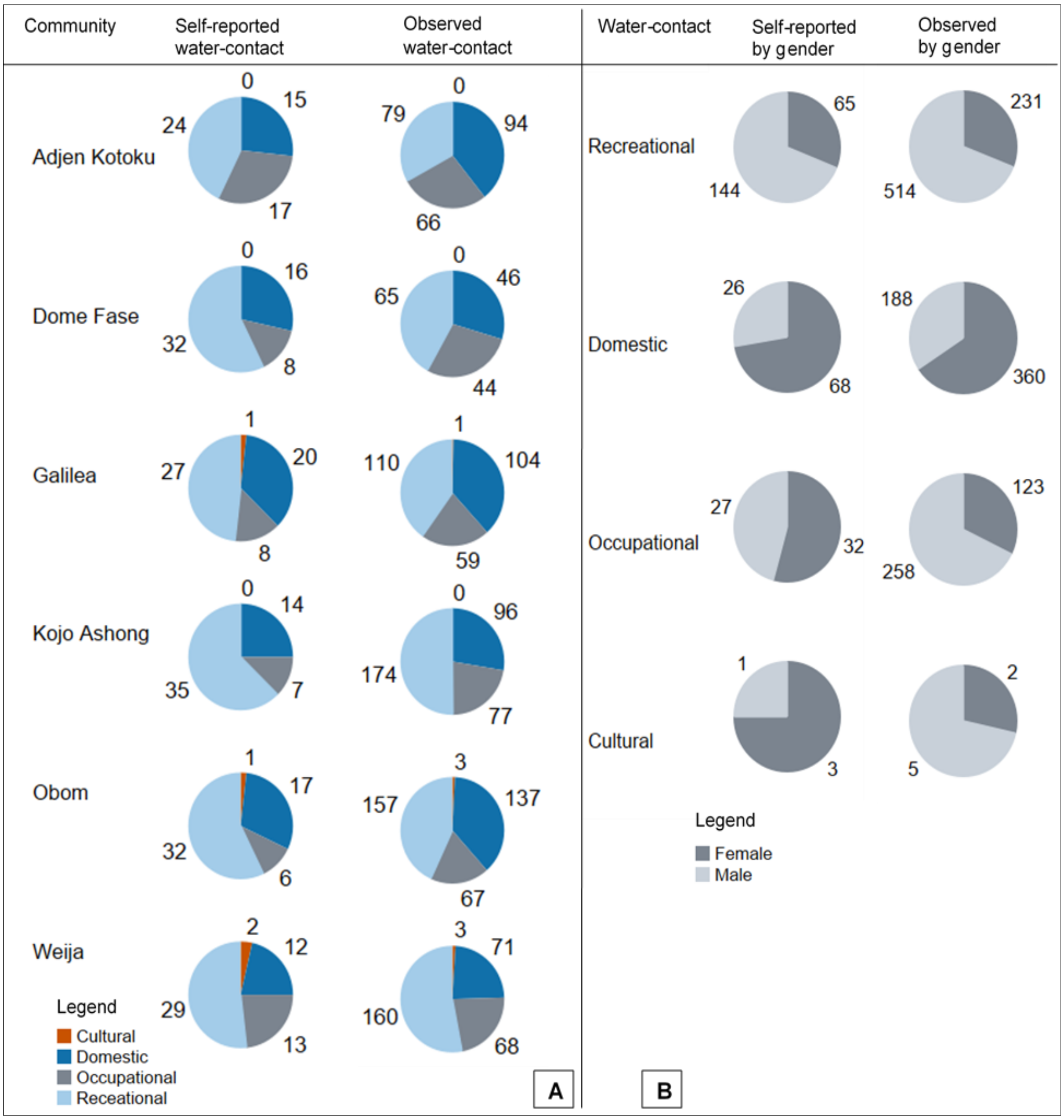

Figure 22. A: self-reported versus observed water-contact activities; B: gender distribution of water-contact activities
Source: based on primary data collection in Ghana between February 2019 and April 2019.

4.4.2.4 Frequency and duration of water-contacts

Thirty-two percent of the children indicated in the survey to have water-contacts more than twice per week (see Table 14). For example, children who were involved in fetching drinking water to be used at school and/or at home in Dome Fase and Galilea. In addition, it was found that recreational activities occurred once per week (only on weekends) at Adjen Kotoku, Weija, and Obom, and more than twice a week at Kojo Ashong and Galilea.

The water contact duration was categorized as either more than or less than 30 minutes. Both the self-reported and the observational data indicate a higher proportion of children engaging in water contact activities for less than 30 minutes. The self-reported results showed a higher percentage of children engaging in longer water-contacts (42%) compared to the results of the observed data (31%). This difference may be attributed to the aggregation of water contact durations. While the observation recorded the duration of a single water-contact event (e.g., duration of a single swimming event), the respondents of the survey may have aggregated the total water-contact duration (i.e., duration of multiple swimming events).

Table 14. Frequency and average duration of water-contacts

	Frequency of water-contacts	Number of children	Percentage
Self-reported	Less than twice a week	205	61%
	More than twice per week	131	39%
	Total	336	100%
Self-reported	Less than 30 minutes	194	58%
	More than 30 minutes	142	42%
	Total	336	100%
Observed	Less than 30 minutes	1162	69%
	More than 30 minutes	519	31%
	Total	1681	100%

Source: based on primary data collection in Ghana between February 2019 and April 2019.

4.4.3. The occurrence of self-reported blood in the urine

The results of the self-reported occurrence of blood in urine among the schoolchildren revealed that 98 children (76 males and 22 females) reported blood in their urine, representing 45% and 13% of the total male and female sample population respectively. Overall, a strong gender effect is evident, with more males reporting blood in urine compared to females. On the community level, Kojo Ashong recorded the highest case count of 19 male children and 7 female children (see Figure 23A), followed by Obom with 21 cases. Weija and Dome Fase had relatively moderate case counts among the male children. Adjen Kotoku had the lowest number of cases, which was partly due to the type of water body (pond) in the area and the corresponding water-contact patterns.

Further, computing the percentage of children with reported cases of blood in the urine for each age group, the results show that 57% of the older children within the age group of 15 years and above reported blood in the urine (see Figure 23B). Similarly, 47% of the children aged 13 to 14 years reported blood in urine, compared to 23% of the children of 10 years and below. This result shows that older children (13 years and above) experienced more cases of blood in the urine.

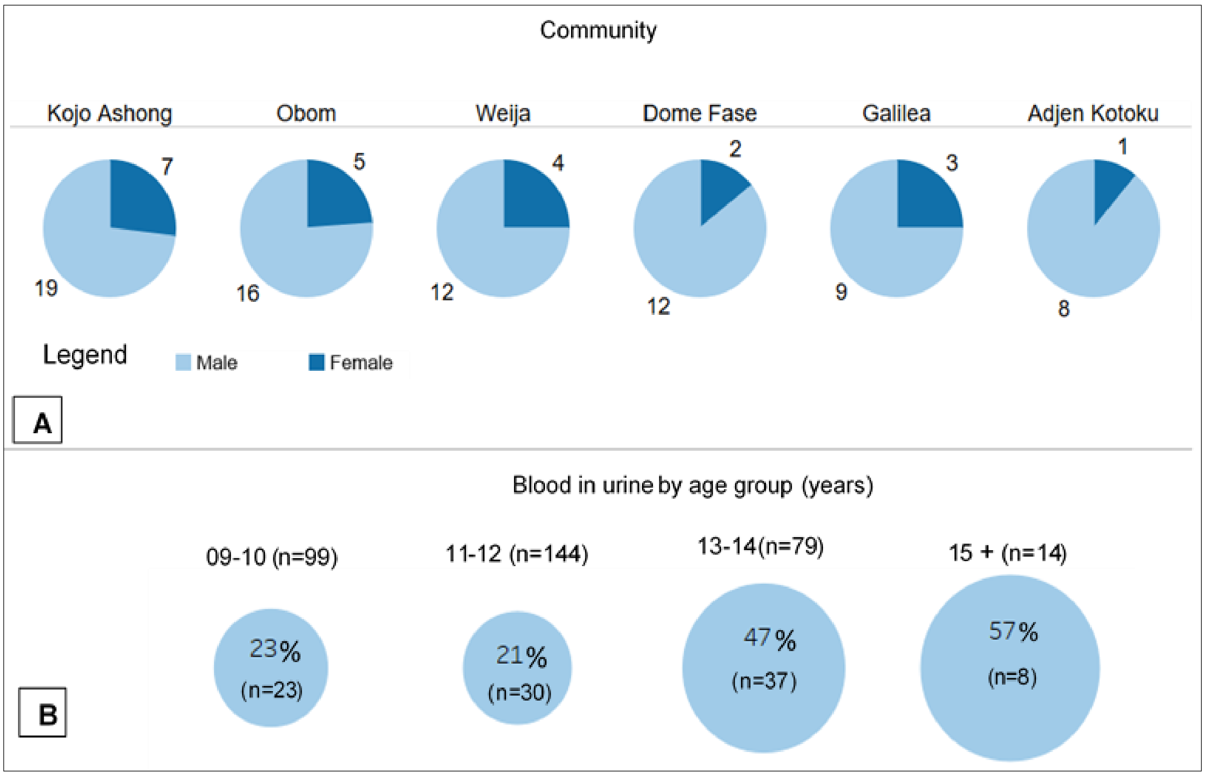

Figure 23. A: self-reported cases of blood in urine in the communities by gender; and B: self-reported cases of blood in urine in each age group

The blood in urine segregated by age group was calculated, using the total number of self-reported cases of blood in urine in each age group divided by the total number of children in that age group. Source: based on primary data collection in Ghana between February 2019 and April 2019.

4.4.4. Perceived exposure factors among schoolchildren

Knowledge about places of exposure to cercariae is imperative for the control and prevention of schistosomiasis. This study found that 55% of the schoolchildren perceived that frequent swimming in polluted water is the cause of blood in urine, while 10% of the children did not know any exposure factors, and 2% perceived schistosomiasis as a spiritual issue or punishment from the gods (see Figure 24). It could be observed that the majority of the schoolchildren were aware of some exposure factors, such as fetching water and fishing in the *Bulinus*-dominated water.

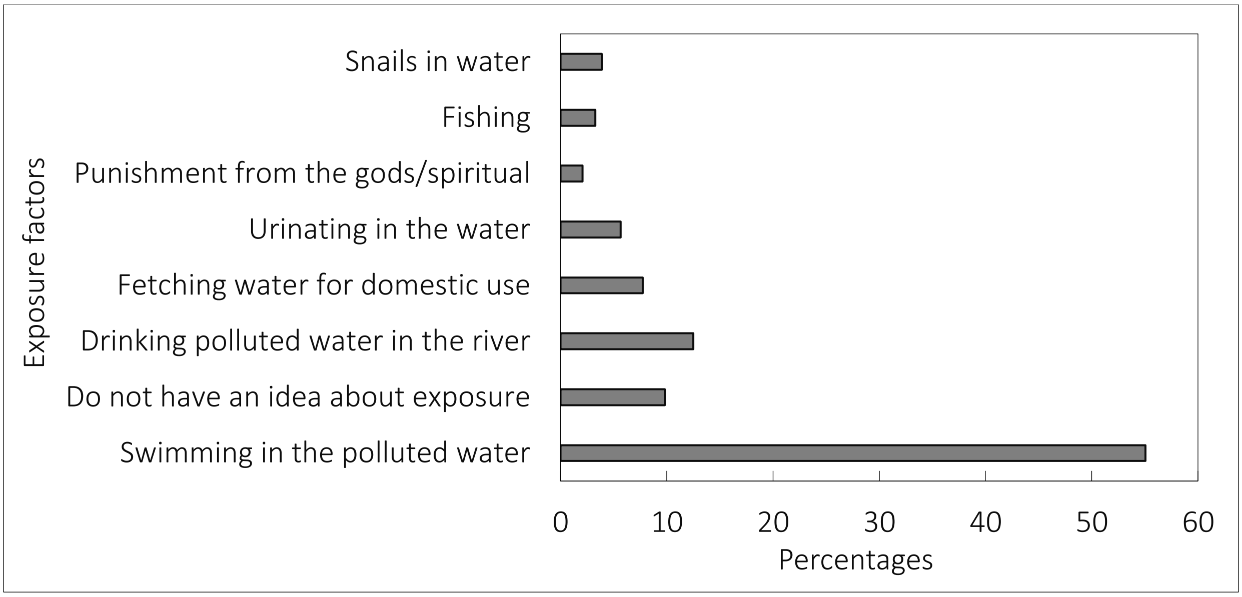

Figure 24. Perceived exposure factors
Source: based on primary data collection in Ghana between February 2019 and April 2019.

4.4.5. Odds ratios of blood in urine and water-contact activities

The output of the correlation analysis (see Appendix II, Table 16) revealed that blood in urine is correlated with recreational, domestic, and occupational water-contact activities, as well as frequency and duration of water-contacts, whilst these also correlate with each other, leading to issues of collinearity. Therefore, a bivariate analysis (calculation of odds ratios) was performed between blood in urine and each of the exposure variables (see Table 15).

A strong gender effect is evident with males having 5.5 times the odds of blood in urine compared to the female children. Additionally, an age effect was found with significantly elevated odds of blood in urine among the 15 years and above (OR=3.4) and 13 to 14 years (OR=1.7) age group. The three dominant water-contact activities, domestic, recreational, and occupational, all show significantly elevated odds of blood in the urine. The highest odds ratios were found for recreational water-contact activities followed by occupational and domestic activities. More frequent and longer water-contacts also led to elevated odds of blood in the urine. Considering the interactions between these variables, it was found that children involved in domestic activities are more likely to have more frequent water-contacts, i.e., more than twice per week, while recreational and occupational water-contacts are linked to longer water-contact durations, i.e., more than 30 minutes. Additionally, the results indicate a preventive effect of mass drug administration (MDA), where children receiving the treatment show 0.4 times lower odds of blood in urine compared to children not receiving the treatment.

Table 15. Bivariate regression analysis showing odds ratios of self-reported blood in the urine

Variable	Odds ratio	Significance	95% CI
Gender	5.482	0.000	3.190 – 9.422
Improved water supply	0.733	0.202	0.455 – 1.181
Open defecation	1.287	0.317	0.786 – 2.109
Domestic	2.749	0.001	1.490 – 5.073
Recreational	4.202	0.000	2.466 – 7.158
Occupational	3.634	0.002	1.588 – 8.318
Cultural	1.238	0.854	0.127 – 12.052
Water-contact more than twice a week	1.857	0.014	1.131 – 3.051
Water-contact more than 30 minutes a week	2.898	0.000	1.785 – 4.705
Mass drug administration	0.439	0.001	0.272 – 0.710
09 – 11 years	1.530	0.123	0.891 – 2.627
11 – 12 years	1.347	0.226	0.832 – 2.180
13 – 14 years	1.702	0.050	0.999 – 2.897
15 years and above	3.437	0.026	1.160 – 10.183

The variables were considered statistically significant at a *P-value* of *0.05* or less.
Source: all the variables were self-reported in the survey conducted in Ghana between February 2019 and April 2019.

4.4.6. Control and prevention measures

The outcome of the key informant interviews with the disease control officers in the various health centers of the communities revealed that the common schistosomiasis control measure was MDA with praziquantel. In addition, an interview with the school staff at Obom and Galilea revealed that sensitization programs were organized occasionally for awareness-building, and to discourage swimming in the polluted water, however, such programs did not yield significant positive results.

4.5. Discussion

The interactions between humans and surface water systems influence urinary schistosomiasis, particularly, regarding the type of water-contact behavior, availability of safe drinking water supply, and sanitation. The direct dependence on unimproved water sources, i.e., surface water, increases the chances of exposure to contaminated water and thus, the risk of S. *haematobium* infection. This study found that peri-urban and rural communities (e.g., Dome Fase and Weija) directly depend on surface water from the Densu River and the Weija Lake to supplement their domestic water supply. Consequently, these surface water sources are extensively used for washing, cooking, personal hygiene, and for drinking. This is of particular concern, as open defecation (OD) is widespread in these communities. Although sanitation facilities generally exist, poor conditions of these, the required usage fees, and relatively long distances between homes and public sanitation facilities were key factors driving community members to engage in open defecation.

In this study, it was identified that OD is commonly practiced along the watercourse, leading to fecal contamination of the surface water systems and thus contributing to the transmission of fecal-oral diseases, including schistosomiasis. While OD was not statistically significant in this study, Schmidlin et al. (2013) found it as a statistically significant risk factor of S. *haematobium* in the Taabo area of south-central Côte d'Ivoire. Poor hygiene and sanitation linked to the practice of OD play crucial roles in the transmission cycle of S. *haematobium*, as the schistosome eggs are released into water systems via feces and urine (Schmidlin et al., 2013). The eggs released from infected humans hatch and infect the snails (intermediate hosts), which in turn release the parasites to infect humans (Kulinkina et al., 2019; Martel et al., 2019). OD forms a precondition for infecting *Bulinus* snails with S. *haematobium*. A related study on schistosomiasis in other peri-urban communities of the Ga West and Ga East Municipal assemblies highlighted that the schistosomiasis risk of children was linked to limited access to safe drinking water, swimming activities, and low investment in improved hygiene and sanitation infrastructure (Nyarko et al., 2018). Therefore, eradicating OD can contribute greatly to breaking the S. *haematobium* transmission cycle.

4.5.1. Human-water interactions and occurrence of blood in the urine

It was found that all children engage in some kind of water-contact activity, the most common were recreational water-contacts (53%), followed by domestic (28%) and occupational water-contacts (18%). Direct water contact exposes the children to the cercariae and thus places them at risk of infection. Ajakaye et al. (2017) reported that individuals, who directly depended on freshwater as a source of livelihood had higher exposure to the cercariae in Nigeria. Similarly, Codjoe and Larbi (2016) highlighted that children with relatively high levels of exposure to the cercariae in the Densu Basin in Ghana were those engaged in frequent water-contacts, such as fetching water for household use. Occupational water-contacts, such as fishing or crossing water, were reported as exposure factors in the Eastern region of Ghana and the Migori county in Kenya, where schoolchildren cross water bodies with bare-feet to and from school (Martel et al., 2019; Ng'ang'a et al., 2016). It is therefore evident that water contact is common and, in many cases, unavoidable.

Additionally, it was identified that the type of water-contact activity is related to the frequency and duration of the water-contact, which in turn correlates with the level of exposure. Whilst, domestic water-contact activities are linked to more frequent (but rather short) water-contact activities, recreational water-contact activities occur less frequently but usually for longer durations. Similar patterns were observed in a study in the Shinyanga

District of Tanzania, where swimming activities were positively correlated with longer water-contact durations, thereby increasing the exposure to schistosomiasis (Angelo et al., 2018). In addition, studies in Senegal revealed that the exposure of women and children to the cercariae was influenced by the frequency of water-contacts, the duration, and the proportion of the human body exposed to the cercariae (Ciddio et al., 2017; Webster et al., 2013). This indicates that the type of water interaction is an important factor mediating the exposure to the cercariae and the risk of schistosomiasis. As swimming activities usually involve longer water-contact durations as well as full submersion of the body, it is not surprising that our data indicates these recreational water-contact activities as having the highest odds of experiencing blood in the urine. Similarly, the variables of more frequent water-contacts (more than twice per week) and longer water-contact durations (more than 30 minutes) showed significant increases in the odds of blood in the urine.

4.5.2. Control and preventions measures

The identified control measure in the communities was mass drug administration (MDA), which does produce some degree of protection against blood in urine, however, the degree of protection appears to be low. While studies have demonstrated the vital role of praziquantel in the control of human schistosomiasis, other reports highlighted its weaknesses regarding the development of resistance (Chai, 2013; Vale et al., 2017). For example, studies in Ghana show a wide coverage of MDA in schistosomiasis-prone communities, however, health centers in these communities continue to record new and recurrent cases of schistosomiasis (Martel et al., 2019; Nyarko et al., 2018). Additionally, It was discovered that the drug has side effects, including increasing allergic and hypersensitivity reactions (Chai, 2013). This is an illustration that MDA is insufficient to eliminate the disease, therefore, measures to tackle the underlying causal factors, open defecation, and limited access to safe drinking water are required alongside awareness-building campaigns.

4.5.3. Level of awareness of schistosomiasis risk factors

Our study found that 88% of the children are aware of the risk and exposure factors of schistosomiasis, nonetheless, these children still engage in these risky behaviors. Interestingly, reports on schistosomiasis in the northern part of Ghana and southern Burkina Faso from the 1950s and 1960s, already indicated that these water-contact behaviors were the drivers of schistosomiasis transmission (Hunter et al., 1983; Hunter, 1981; 2003). The findings of these reports and the results of our study show that there has not been a significant change in the water-contact behavior of children over the past decades, despite successful awareness-raising campaigns (as indicated by the relatively high level of awareness of key risk behaviors among the children). This is an important finding with a significant policy implication, highlighting that awareness-raising is insufficient to sustainably change behavior or reduce schistosomiasis transmission. There is a pressing need for the development and implementation of more efficient and sustainable strategies that target the root causes of schistosomiasis transmission such as the provision of functioning primary barriers (i.e., sanitation facilities). In the hot Ghanaian summers, it will be unavoidable that children engage in recreational water activities and occupational utilization of water resources form important components of local livelihood strategies. Avoiding water contacts can therefore not be a solution to schistosomiasis transmission, but what is required is the establishment of effective primary barriers. Additionally, the provision of safe and sufficient drinking water supply can significantly reduce exposure, particularly among populations that rely on these surface water systems for drinking water or domestic water uses.

4.5.4. Limitations

The study relies on self-reported cases of blood in the urine, hence, some degree of reporting bias must be expected. Particularly the gender and age effects should be viewed with great caution. Although all children engage in multiple water-contact activities, only the dominant water-contact activity was reported. This may affect the respective effects of the individual water-contact activities. The study design is based on the assumption that all children have some degree of exposure, therefore there was no control group, thus not allowing robust case-control analysis.

4.6. Conclusion

This study assessed human water interactions and their influences on schistosomiasis prevalence. There is limited access to improved sanitation and safe water supply, which compels the communities to rely on open defecation and untreated river water, reinforcing the schistosomiasis transmission cycle. Particularly, open defecation along the waterways forms a precondition for schistosomiasis transmission. Water-contact activities, including domestic, recreational, and occupational activities, are practiced by all children, therefore creating a widespread exposure pattern. The type of water-contact activity influences the frequency and duration of water-contact, which in turn determines the level of exposure. Higher frequencies and longer durations are linked to a higher prevalence of blood in the urine.

The majority of children are aware of the underlying exposure factors, yet still engage in these risk behaviors. It is therefore indicated that awareness-raising campaigns are insufficient to break the schistosomiasis transmission cycle. Next to such campaigns, the common schistosomiasis control measure is mass drug administration. Although significant preventive effects were identified, the effect size was found to be rather low. Current control strategies target the human definitive host by promoting behavior change and preventive treatment. However, these strategies failed to sustainability break the transmission cycle, as these do not tackle the underlying causal factors. Ensuring a sufficient and safe drinking water supply is needed to reduce the requirement to utilize surface water for domestic purposes, which thus reduces the frequency of exposure. Additionally, sensitization campaigns are required for occupational users, to ensure adequate protective gear is being utilized during prolonged water contact, also contributing to exposure reduction. However, the transmission cycle cannot be broken by exposure reduction but requires the development of effective primary barriers. The provision of improved sanitation facilities can form an effective strategy by halting infection of the intermediate snail host. In order to sustainably tackle schistosomiasis, the transmission cycle needs to be broken by preventing open defecation through the provision of improved sanitation facilities.

5. Conclusion and recommendations

The study aimed to contribute towards the understanding of human-water-health nexus via land use and water interactions, and the risks of WRID, including water-borne diseases and urinary schistosomiasis. It employed a mixed-method approach and integration of methods, including surveys, field observations, and stakeholder participation, using focus group discussions, workshops, and expert elicitation to develop qualitative system dynamic models, identify and analyze the exposure and risks of WRID, and development of collaborative interventions to promote human and environmental health in GAMA. The study identified and highlighted key outcomes and the importance of integrating multi-methods for investigating and analyzing the human-land use-water nexus. In the following sub-sections, a summary of key highlights from this study, including reflections on the outcomes from the systematic literature review and the two case studies (see chapters 2 – 4) are presented. The importance of this study reflects in its major contributions towards a deeper understanding of the trends and gaps in research (see 5.1.1), noting the basic causes and underlying drivers of exposure and risks of water-borne diseases such as cholera, dysentery, and typhoid (commonly classified as diarrheal diseases) (see 5.1.2), and contributions to the understanding of the influences of human-water contact types and patterns on the risks of urinary schistosomiasis transmission in GAMA (see 5.1.3). Additionally, the study recognized the importance of employing and integrating multi-methods in addressing the key research questions (see 5.2).

5.1. Key findings

5.1.1. Trends and gaps in research on the influences of human–water interactions and water-related infectious diseases

The study identified that the number of scientific evidence (between 1995 and August 2019) on the influences of human-water interactions on the emergence and transmission of water-related infectious diseases has increased, particularly between 2011 and 2020. A higher number of the studies are found in China (20%). On the other hand, the study found limited evidence in the frequently reported global hotspots of WRID, which can be partly attributed to limited access to funds for investment in scientific research and publication of research outcomes. The study revealed that water serves as a vehicle for the transmission of WRID, particularly in areas with limited access to safe and improved WASH, and low levels of investments in drinking water infrastructure development.

The study revealed longer causal pathways and weak linkages between LULC, human-water interactions, and risks of water-borne diseases, including diarrheal diseases (cholera, dysentery, and typhoid), due to additional underlying drivers and their cascading impacts (e.g., flooding). However, explicit linkages are found between human interactions with surface water systems and the risks of water-based diseases such as schistosomiasis, through various types and patterns of water-contacts. The study identified gaps in the adoption of transdisciplinary and integrated research approaches to capture and address the complexities between LULC, surface water systems interactions, and WRID. Comprehensive assessment, using integrated and systemic approaches, including stakeholder participation was further emphasized to enhance a deeper understanding of the nexus and support informed decision-making, and the development of relevant solutions.

5.1.2. Basic causes and underlying drivers of the exposure and risks of water-borne diseases

The communities in the Odaw River catchment within GAMA have access to water and sanitation. However, usage fees are required to gain access to the services. It is further revealed that in addition to the usage fees, the sanitation facilities were poorly maintained, creating an environmental nuisance, which discourages their usage. This compels households to engage in open defecation practices along the drains of the river. The wastewater management strategies in the communities are unimproved, unsustainable, and rather increase the exposure of the households to pathogens and additional environmental health risks. Given the accessibility to drinking water, diarrheal diseases are still prevalent, partly caused by frequent flood events. The QSD models show that supplying only WASH is not enough to prevent water-borne diseases when additional underlying drivers (e.g., floods, waste management, etc.) contributing to the exposure and risks of diseases are not tackled. It was identified that flooding plays a key role in the outbreaks of diarrheal diseases, via pollution of drinking water at the point-of-use, leading to diseases when the water is directly ingested without proper treatment.

It was revealed that flooding in the area is caused by key factors such as poor land use planning and the siltation of drains with solid waste from the metropolis. These are linked to lack of law enforcement, behaviors of people towards the environment and water systems, lack of compliance, and corruption at all levels of governance. Further, analysis of LULC change revealed that urban expansion (built-up areas) in the Odaw catchment has increased significantly by 46% from 1991 to 2020, while the vegetation cover has decreased significantly from 70% in 1991 to 21% in 2020. The implications of these significant changes in LULC, given the existing inefficient drainage systems, are increase in stormwater runoff and flooding, which sweeps pollutants including viruses and pathogens in fecal matter and wastewater into drinking water systems. This increases the exposure of households, particularly children to pathogens and the risks of diseases.

To support establishing relevant barriers for disease prevention, collaborative strategies are important. The collaborative strategies developed via stakeholder engagements emphasized the key roles designated to be implemented at various levels from the government (local, regional and national) and the community levels with support from collaborators and funding agencies such as Non-Governmental Organizations, private institutions, etc. The key factors highlighted for immediate and aggressive interventions included flood prevention, improved

WASH, improved waste management systems, implementation of land use plans, human behavioral change, and law enforcement.

5.1.3. Influences of human–surface water interactions on the transmission of urinary schistosomiasis

The accessibility to safe drinking water, sanitation, and the influences of human water-contacts types and patterns on the risks of urinary schistosomiasis are explored and examined. It was found that there is limited access to improved water supply and sanitation, compelling the communities to rely directly on untreated river water and open defecation, which reinforces the schistosomiasis transmission cycle. The major human-water contact activities and predictors of schistosomiasis infections are recreational, domestic, and occupational. Besides water-contact activities, patterns of water-contacts play a key role. Thus, longer durations and frequent water-contacts are additional determinants of exposure to the parasite and the risks of schistosomiasis infections.

The children are aware of the risks of infections for engaging in water-contact activities but still engage in such risky behaviors, indicating that the sensitization campaigns are not sufficient. The Male children are mainly engaged in recreational water-contacts (e.g., swimming) with higher odds of infections. Conforming to the findings of this study, research reports show that human water-contact types among children in the Northern part of Ghana have not changed since1950s (Hunter, 1981). The common control measure of the disease is mass drug administration with praziquantel from the government and NGOs, however, reports show that their effect size is relatively low. The praziquantel protects only humans and does not tackle the underlying drivers of human water-contacts and the cercariae hosts (e.g., snails, animals, etc.). Recreational water-contacts such as swimming should be monitored, or strongly discouraged in infected water bodies.

To sustainably eliminate schistosomiasis, efforts must be targeted at breaking the transmissions cycle. The points of contact between humans and the infected snail (intermediate hosts) or the cercariae infected water should be broken or disconnected. Sustainable interventions must be targeted at breaking the schistosomiasis transmission cycle, with a particular focus on reducing the chances of water-contacts among the vulnerable population. Therefore, the development and implementation of interventions such as supplying safe WASH and collaboratively designing and implementing public sensitization campaigns on the precautionary measures such as the usage of protective gears during longer water-contact activities are required to reduce the exposure and risks of infections.

5.2. Importance of the integrated research approach to the study

Further, the study identified the importance of an integrated approach, for data elicitation and analysis, including multi-level stakeholder participation in the conceptualization, assessment, identifying variables, QSD modeling, and developing collaborative solutions. This contributed to a better understanding of the intricate interactions among drivers such as land use, flooding, surface water systems, waste management, WASH, and the exposure pathways and risks of WRID. The QSD models and CLDs supported the understanding of the human-water-health nexus and further highlighted important barriers for breaking the disease transmission loops. The models revealed that water-borne diseases have multi-causal feedback loops with multiple pathways. It underscores the key linkages between flooding and its cascading impacts on health (particularly WRID) and the environment, indicating the need for multi-sectoral collaborations to sustainably tackle the health problems. In addition, the multi-level stakeholder participation contributed to the development of integrated and collaborative strategies to tackle the problems of persistent failures of the existing fragmented strategies developed to eliminate WRID in GAMA. Further, combining surveys, interviews, expert elicitation, and field observation of human-water contact types (e.g., recreational, domestic, and occupational) and patterns (e.g., frequency and duration of water-contacts) in the communities supported the detection of reporting bias and validation of survey results regarding exposure and risks of schistosomiasis transmission.

5.3. Reflections on the research approach and limitations

The study made valuable contributions to the understanding of WRID risks associated with human-water interactions in both urban and peri-urban settings in GAMA. However, some limitations, particularly related to the methodology are expected. Despite the efforts made to reduce the level of predispositions in the selection of eligible scientific papers for the review, some level of bias was found in the criteria of selecting literature. For example, the systematic review was based on studies focusing on only surface water systems, hence, studies with linkages to groundwater sources, such as boreholes and wells, as well as rainwater harvesting, were excluded from the review, thereby limiting the integration of additional perspectives related to WRID in the investigations. However, it was necessary to focus on surface water systems as the research design focuses on surface processes and dynamics, including drivers such as LULC, waste management, flooding, and human-water contact types and patterns (e.g., swimming, laundry, farming, etc.), and the pathways to the risks of WRID, which are mainly dependent on surface processes and interactions.

In addition, water quality sampling, and laboratory testing were not performed, and further quantitative assessment of the relationship between water quality and diseases or estimation of odds of diarrheal diseases in Accra was not conducted. The analysis of exposure and risks was based on self-reported survey data from the households' perspectives, thereby highlighting expectations of reporting bias. Nonetheless, the identification of the drivers of exposure and risks are critical for understanding the pathways of WRID risks and developing relevant interventions to support close the gap of missing evidence on the combined impacts emanating from the interactions among the drivers of WRID in GAMA. While QSD modeling allowed multi-level stakeholder participation and integration of data from varying sources, it was unable to quantify the amount of the *cause* and *effects* of interactions between variables within the models developed. However, the outcome of QSD modeling was found crucial to inform decision-making, and also established the basis for future research collaborations and quantitative system dynamic modeling to further quantify and estimate the *cause* and *effects* of interactions between variables within human-water-health systems in Ghana.

LULC change assessment was performed, using Landsat satellite images with a spatial resolution of 30 m, having relatively low pixel values, are not ultimate for detailed assessment and characterization of land use patterns, particularly in urban areas in Ghana without standard spatial planning and land use zonation. The results of the land use assessment were relatively general with limited focus on cultural and socioeconomic land use patterns such as slum or informal settlements, low-income areas, residential, industrial, agricultural lands, etc. However, the outcome of the LULC assessment was sufficient for the analysis as the study mainly focused on the extent of expansion of residential areas (built-up areas) and vegetation cover, which have critical influences on the key drivers (e.g., surface water runoff, sediments, and pathogen transportation, etc.) and central focus of the study (e.g., flooding, and water pollution) under urbanization processes.

Investigations on human-water interactions and risks of urinary schistosomiasis relied on self-reported experiences of blood in urine, a major symptom of urinary schistosomiasis can be subjected to reporting bias, possibly due to fear of stigmatization. This was managed by assuring the participants their confidentiality and anonymity. Additionally, only communities pre-identified as hotspots were included in the study. Nonetheless, the pre-definition of the study area was necessary to define the study boundaries and research focus. The proximity of communities to water bodies and the reported prevalence of urinary schistosomiasis was considered as additional criteria for the selection of the study communities.

5.4. Recommendations for future research

It has been extensively acknowledged that this thesis has extensively explored the exposure to and the risks of WRID associated with human-water interactions to enhance our understanding and support developing relevant strategies to protect water systems and promote human and environmental health. However, further research studies focusing on water quality testing and laboratory analysis are crucial to identify the statistical relationship between water and WRID, given the expected frequent flooding events in GAMA, which has similar characteristics with other major metropolitan areas in Sub-Saharan Africa. Additionally, research studies on sustainable flood risk management and the co-development of integrated flood mitigation strategies are required. The QSD and CLD for flood sub-model in this study identified potential adaptation co-benefits associated with flood disaster risk mitigation, reducing impacts on WASH infrastructure, water pollution, and the risks of WRID. Further investigations, highlighting the impacts of governance issues and accessibility to sewage or wastewater treatment systems are required to support the understanding of the WRID risk factors in the GAMA.

Additionally, Livestock was excluded in the study, while evidence shows that they share and interact with humans in the same water bodies. Therefore, further studies on risks of human-animal (e.g., livestock) interactions with surface water systems and the risks of schistosomiasis infections are important. Studies in Senegal highlighted that animal (the definitive hosts) play major roles in the hybridization (genetic mutations) of the schistosomes. For example, mixing of the *s. haematobium*, which infects humans and the *s. mansoni* that infects animals can lead to the emergence of new species or hybrids of schistosomes, posing huge challenges to the interventions exclusively developed to tackle only *s. haematobium*, which infects only humans.

5.5. Contributions to science and understanding of WRID risks

The study recognized that the human-water-disease nexus is complex, partly due to the interconnectedness between water and human systems with multiple underlying driving forces, including poor land use planning, human behavioral issues, urbanization dynamics, flooding, poor waste management systems, governance issues, etc. Human-water interactions and disease pathways extend beyond the boundaries and influences of a single driver at a given spatio-temporal scale. The exposure to and risks of WRID extend beyond only WASH and can be challenging for a single intuition or sector to sustainably manage, with limited resources. The key pathways through which human-water interactions affect health via the pollution of drinking water systems, limited access to safe WASH, human-induced water-related disasters, and injuries (e.g., floods). Similarly, the key pathways of exposure and risks of WRID are through drinking fecally polluted water and human-contacts (via skin) with pathogen-infected water bodies.

The uncontrolled physical urban transformation, due to lack of land use planning and implementation, lack of sewage systems, unsustainable waste management and limited access to WASH, and strong interconnectedness between human and water systems have long-term adverse impacts on water and health systems. It is important to note that strong interconnections between the drivers of WRID can potentially pose challenges to developing barriers to disease transmission cycles when the explicit linkages are not identified and addressed. Therefore, the application of transdisciplinary and multidisciplinary approaches is required for comprehensive assessment and robust analysis to inform sustainable policy formulation. Water serves as a connection among many sectors, which partly explains the multi-causal pathways of WRID across different sectors. Therefore, multi-sectoral collaborations are necessary to co-design and implement interventions to tackle its related diseases.

The water-land use-health systems are interconnected: why not develop integrated solutions? Integrated, sustainable, and collaborative solutions, targeting land use planning and implementation, flood risk reduction, innovative waste management, and provision of improved WASH are important to reduce WRID transmissions. Hence, incorporating water-health nexus into pluralistic water research approaches, including transdisciplinary and multidisciplinary research is important for building capacity and developing integrated solutions at the local, regional, and national scales for tackling and reducing the risks of WRID.

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7 Appendices

7.1 Appendix I. Sample size estimation for schoolchildren surveys

The sample size was estimated, using the method stated in $Equation\ 1$.

$$n = \frac{Z^2 P(1-p)}{d^2} \qquad Equation\ 1$$

Where n is the sample size, Z is the statistic corresponding to the level of confidence (1.96), P is the prevalence rate of *S. Haematobium* (27.5%) (Nyarko et al., 2018) and d is precision (95%), which is widely used (Pourhoseingholi et al., 2013).

Therefore:

$$n = \frac{(1.96)^2 * 0.275(1-0.275)}{(0.05)^2} = \frac{3.8416 * 0.766}{0.0025} = 306$$

As a result, the sample size (n) is 306. Using a buffer of 10% ($0.1 * 306 = 30.6$) of the estimated sample size as a non-response rate, the final estimated sample size was 337.

7.2 Appendix II. Correlation matrix of S. haematobium predictors

Table 16. The correlation matrix of S. *haematobium* predictors

	Blood in urine	Gender	Improved water supply	Open defecation	Domestic	Recreational	Occupational	Cultural	Water-contact more than twice	Water-contacts more than 30 min	Vaccination	10 – 11 yrs.	11 – 12 yrs.	13 - 14 yrs.
Gender	.354**													
Improved water supply	-.070	.067												
Open defecation	.055	-.038	-.162**											
Domestic	.181**	-.265**	.043	-.011										
Recreational	.299**	.280**	-.099	.107	.665**									
Occupational	.176**	-.055	.070	.122*	.288**	.493**								
Cultural	.010	.000	.033	-.018	-.068	-.117*	-.051							
Water-contact more than twice	.134*	-.139*	.035	.079	.209**	.376**	.226**	.073						
Water-contacts more than 30 min	.239**	.153**	-.014	.119*	-.172**	.259**	.144**	.025	-.334**					
Vaccination	-.185**	.060	.159**	.058	-.108*	.167**	-.095	.009	-.008	.134*				
10 – 11 yrs.	.084	-.007	.016	-.131*	.034	-.101	.096	-.011	.085	-.062	-.123*			
11 – 12 yrs.	.066	-.229**	-.012	.011	.010	-.021	.011	.016	-.091	-.002	-.024	-.560**		
13 - 14 yrs.	.107*	.232**	.047	.107	-.033	.097	-.090	.004	-.031	.046	.110*	-.358**	-.480**	
15 yrs. & above	-.128*	.089	-.105	.045	-.030	.076	-.057	-.023	.094	.047	.107*	-.135*	-.181**	-.116*

Source: All variables were self-reported in the survey conducted in Ghana between February 2019 and April 2019.
The output of the correlation analysis showing correlation between blood in urine and recreational, domestic, and occupational water-contact activities, as well as the frequency and duration of water-contacts

7.3 Appendix III. Research materials and tools

The following are the survey materials used for household survey on human-water-land use nexus and the risk of water-borne diseases in the Odaw basin, and schoolchildren survey on water-contact patterns/types and the risks of urinary schistosomiasis infections in the Lower Densu River basin.

Household survey forms for communities in the Odaw River Basin in GAMA

A- Date of survey

yyyy-mm-dd

A1- Select the district, town etc.

Please select the municipality where you are

- ◯ Alajo
- ◯ Nima
- ◯ Odawna
- ◯ Agbogba

A2- Name of the enumerator

- ◯ Lawrence Odoo
- ◯ William Amedegbe

This questionnaire is designed to obtain data on the driving forces for urbanization through land use change, impacts on surface water in the Odaw River basin, and the consequent health outcomes. It is mainly designed for academic purpose. Therefore, your confidentiality and anonymity are totally assured.

Demography

B1- Age of the respondant

B2- What is the gender of the respondant

- ◯ M
- ◯ F

B3- What is the level of education of the respondant

- ◯ No formal education
- ◯ primary school
- ◯ junior secondary school
- ◯ senior secondary school
- ◯ higher education

12/13/21, 5:12 PM Household survey forms for communities in the Odaw River Basin in GAMA

B5- What is your main occupation?

- ◯ Farming
- ◯ Commerce
- ◯ Fishing
- ◯ Civil servant
- ◯ Artisan
- ◯ Housewife
- ◯ Unemployed
- ◯ Other

Water sanitation

C- Access to water and sanitation

C1-What are the sources of your drinking water?

- ☐ River
- ☐ Dam
- ☐ Stream
- ☐ Bottle/Sachet water
- ☐ Pipe water
- ☐ Borehole
- ☐ Well
- ☐ Rainwater harvesting

C3- Do you use the water in the Odaw River?

- ◯ Yes
- ◯ No

C3.1- If yes, what do you use the water for?

- ◯ Drinking
- ◯ Bathing
- ◯ Washing clothes
- ◯ Watering vegetables
- ◯ Car/motorbike washing
- ◯ Other

https://kf.kobotoolbox.org/#/forms/aQRiSSz5aDiyNcRzvaGMjh/edit 2/7

C4- Do you have dustbins/container for solid waste disposal at home?

- ◯ Yes
- ◯ No

C4.1- If yes, do you practice waste seperation?

- ◯ Yes
- ◯ No

C5- How do you mainly dispose of your household solid waste?

- ◯ House to house private individual solid waste collection
- ◯ Public waste collection container
- ◯ Indiscriminate waste disposal in open spaces
- ◯ Public waste dump site
- ◯ Burn the waste
- ◯ Bury the waste
- ◯ Other

C6- How do you dispose of your household liquid waste (wastewater from the bathing, cooking food, washing clothes, etc.)? (choose the main one)

- ◯ Discharged directly into gutter
- ◯ Discharge into sewage
- ◯ Septic tank
- ◯ Through drainage into a pit (soak away)
- ◯ Discharged on the street/outside houses
- ◯ Other

C7- Do you have any toilet facility in your household?

- ◯ yes
- ◯ no

C7.1- If no, do you have any toilet facility in your community?

- ◯ yes
- ◯ no

C7.1.1- If yes, what is the distance (minutes) from your house to the nearest toilet facility

- Less than 2minute
- 2 – 4 minutes
- 4 – 6 minutes
- 6 – 8 minutes
- 8 – 10 minutes
- More than 10 minutes

C7.1.2- Do you need to pay for the toilet facility in your community before using it?

- Yes
- No

C7.1.2.1- If yes, how much do pay to use the toilet facility?

- 10-20 Pesewas
- 21-40 Pesewas
- 41-60 Pesewas
- 61-80 Pesewas
- 81-100 Pesewas

C8- Which type of toilet facility do you often use?

- WC
- KVIP
- Aqua privy (bucket)
- Open defecation

Driving forces: Flooding and water pollution

D- Driving forces flooding and pollution of water

D1- What do you think of the status of water in the Odaw River?

- Polluted
- Not polluted
- No idea

D2- According to you, what are the main causes of water pollution in Odaw River contributes to?

- ☐ Increase in population
- ☐ Dumping of wastes
- ☐ Proximity to the markets
- ☐ Lack of law enforcement
- ☐ Stormwater runoff
- ☐ Flooding
- ☐ Other

D3- Are there industries/manufacturing companies in your area?

- ○ Yes
- ○ No
- ○ No idea

D3.1- If yes, where do the industries/manufacturing companies dispose of their sewage?

- ○ Into the Odaw river
- ○ Into the sea
- ○ Into the sewage system
- ○ Do not know
- ○ Other

D4- Who contributes more to the pollution of the water in the Odaw River?

- ○ Individual hawkers
- ○ Households
- ○ Industries
- ○ Other

***D5. What are the main causes of flooding of the Odaw River?**

- ☐ Solid waste disposal
- ☐ Building house on watercourses
- ☐ Stormwater flow
- ☐ Behavior of people
- ☐ Poor drainage systems
- ☐ Proximity to the markets drains
- ☐ Lack of law enforcement

12/13/21, 5:12 PM Household survey forms for communities in the Odaw River Basin in GAMA

Health challenges related to water pollution

E- Health challenges with the Odaw river water pollution

E1- Do you think that the current status of the water in Odaw river affect your health?

- ◯ Yes
- ◯ No
- ◯ No idea

E2- Which health challenges in your household can you link to the water in the Odaw River?

- ☐ Diarrheal diseases (Cholera, Dysentery, Typhoid fever
- ☐ Malaria
- ☐ Piles (Kokoo)
- ☐ Skin diseases
- ☐ None
- ☐ Do not know
- ☐ Other

E3- After flooding of the Odaw river, do you experience outbreak of diseases?

- ◯ Yes
- ◯ No
- ◯ No idea

E3.1- If yes, mention the diseases (choose all the applicable options)

- ☐ Cholera
- ☐ Typhoid fever
- ☐ Malaria
- ☐ Dysentery
- ☐ other

Strategies to tackle the water pollution and and health issues

F1- What do you think could be done by your household to reduce water pollution in Odaw River?

- ☐ Avoid dumping of waste into the water
- ☐ Report culprits to law authorities
- ☐ Impose fine on culprits
- ☐ Other

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12/13/21, 5:12 PM Household survey forms for communities in the Odaw River Basin in GAMA

F2- What do you think could be done by your community to reduce water pollution in Odaw River?

- ☐ Community participation in desilting of gutters
- ☐ General town cleaning in the community
- ☐ Enforcement of community bye-laws
- ☐ Sensitization
- ☐ Other

F3- What do you think could be done by the government to reduce water pollution in Odaw River? (choose all the applicable options)

- ☐ Waste recycling
- ☐ Improve the sewage system
- ☐ Dredging of the river
- ☐ Construction of adequate drainage
- ☐ Construct walls on the river banks
- ☐ Enforcement of water monitoring and protection laws
- ☐ Other

Geolocation

Please take the geo point

latitude (x.y °) __________

longitude (x.y °) __________

altitude (m) __________

accuracy (m) __________

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12/13/21, 5:17 PM Urinary Schistosomiasis survey forms for schoolchildren in communities in the Lower Densu River Basin, Ghana

Urinary Schistosomiasis survey forms for schoolchildren in communities in the Lower Densu River Basin, Ghana

A- IDENTIFICATION

A2- Date of survey

yyyy-mm-dd

A6- select the school

Please select the school are now

- ◯ Kojo Ashong
- ◯ Dome Fase
- ◯ Obom
- ◯ Adjen Kotoku
- ◯ Galilea MA/2 Primary School
- ◯ Weija Presby Primary

A7- Name of the enumerator

- ◯ Joshua Ntajal
- ◯ Option 7

This questionnaire is designed to obtain data on the risk factors of urinary schistosomiasis (blood in urine) in the Lower Densu River basin in the Ga South and Ga West municipalities in Accra, Ghana. It is mainly designed for academic purpose. Therefore, your confidentiality and anonymity are totally assured.

Demography

B1- Age of the respondant

B2- What is the gender of the respondant

- ◯ M
- ◯ F

https://kf.kobotoolbox.org/#/forms/axYtTw9K9uHY8E6MwMo6vL/edit 1/7

B3- What is the level of education of the respondant

- ◯ primary school
- ◯ junior secondary school

Water and Sanitation

C1- What are the sources of your drinking water at school?

- ☐ River
- ☐ Dam
- ☐ Stream
- ☐ Bottle/Sachet water
- ☐ Pipe water
- ☐ Borehole
- ☐ Well
- ☐ Rainwater harvesting

C2- What are the sources of your drinking water at home?

- ☐ River
- ☐ Dam
- ☐ Stream
- ☐ Bottle/Sachet water
- ☐ Pipe water
- ☐ Borehole
- ☐ Well
- ☐ Rainwater harvesting

C3- Does your school has a toilet facility?

- ◯ Yes
- ◯ No

C3.1- What type of toilet facility do you often use?

- ◯ WC
- ◯ KVIP
- ◯ Aqua privy
- ◯ Other

12/13/21, 5:17 PM Urinary Schistosomiasis survey forms for schoolchildren in communities in the Lower Densu River Basin, Ghana

C3.2- Is there a toilet facility in the community nearby your school?

- Yes
- No

C4- Is there toilet facility at home?

- Yes
- No

C4.1- Do you have any toilet facility in your community?

- Yes
- No

C4.1.1- What is the distance (minutes) from your house to the nearest toilet facility that you often use?

- Less than 2minute
- 2 – 4 minutes
- 4 – 6 minutes
- 6 – 8 minutes
- 8 – 10 minutes
- More than 10 minutes

C4.1.2- Do you need to pay for the toilet facility in your community before using it?

- Yes
- No

C4.1.2.1- How much do pay to use the toilet facility?

- 10-20 Pesewas
- 21-40 Pesewas
- 41-60 Pesewas
- 61-80 Pesewas
- 81-100 Pesewas

C5- Which type of toilet facility do you often use?

- WC
- KVIP
- Aqua privy
- Open defecation

https://kf.kobotoolbox.org/#/forms/axYtTw9K9uHY8E6MwMo6vL/edit 3/7

C5.1- Where do you practice open defecation?

- along the stream/water body
- in the gutter
- public dumping site
- open space around the house
- uncompleted building
- beside abandoned cars/vihecles
- uncleared bush in the neigbourhood

Experience of blood in the urine among school children

D1- Have you observed blood in your urine in the past?

- Yes
- No
- Do not know

D1.1- When was the last time you observed blood in your urine?

- Past one week
- I am experiencing it now
- Past one month
- Past 6 month
- Past 1 year

D1.2- Who did you report the blood in urine to?

- Parents
- Teachers
- Friends
- No body

D1.2.1- Specify why you did not report the blood in urine issue to anybody

____

D2- Are you aware that seeing blood in urine is a symptom of diseases?

- Yes
- No

D3- What do you think is the main cause of blood in urine in your area?

- ◯ Bathing in river, stream, lake, dam etc.
- ◯ Fishing
- ◯ fetching water
- ◯ Drinking water in the river
- ◯ Through blood transfusion
- ◯ Punishment from the gods/spiritual
- ◯ Other

Water contact activities among children

E1- Do you get into contact with water in the river, stream, dam, lake, irrigation ponds?

- ☐ Yes
- ☐ No

E1.1- Which activities expose you to water contact?

- ◯ Crossing water to and from school
- ◯ Swimming
- ◯ Fetching water
- ◯ Washing car/motrbike
- ◯ Washing clothes
- ◯ Assisting parents in fishing
- ◯ watering/irrigating crops
- ◯ Other (specify)

E1.1.1- Specify other water contact activities

____

E1.2- Do your siblings and your friends also swim, wash clothes, and/or fetch water from the river and dam or stream?

- ◯ Yes
- ◯ No

E1.3- How often do you swim or fetch water from the river, dam or stream etc.?

- ◯ everyday
- ◯ once in a week
- ◯ twice in a week
- ◯ more than twice in a week

E1.4- For how much time do you spend in the water per each water contact?

- 1-10 minutes
- 10-20 minutes
- 30-60 minutes
- 60-120 minutes

E1.5- Do you urinate into water in the river, stream, dam, Lake, etc.?

- Yes
- No

E2- Are there cattle in your area?

- Yes
- No
- No idea

E2.1- Do the cattle drink directly from the water in your area?

- Yes
- No
- No idea

E2.2.1- Do cattle cross the water?

- Yes
- No
- No idea

Interventions in control and preventions for blood in the urine

F- Interventions in control and prevention of blood in urine

F1- Have you been given some vaccination at school or at home to prevent blood urine?

- Yes
- No
- Do not know

12/13/21, 5:17 PM Urinary Schistosomiasis survey forms for schoolchildren in communities in the Lower Densu River Basin, Ghana

F2- Who teaches you about blood in urine and the related danger issues involved?

- ◯ Teacher
- ◯ Parents
- ◯ friends
- ◯ Media (e.g. radio, TV,)
- ◯ No body

Thank you for your patience and willingness to support the study. Your valuable contributions are important for this study.

Geolocation

Please take the geo point

latitude (x.y °)

longitude (x.y °)

altitude (m)

accuracy (m)

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12/13/21, 5:09 PM Water-contact observation forms

Water-contact observation forms

A- IDENTIFICATION

A2- Date of survey

yyyy-mm-dd

A6- Select the observation site

- ◯ Kojo Ashong
- ◯ Adjen Kotoku
- ◯ Obom
- ◯ Dome Fase
- ◯ Galilea
- ◯ Weija

A7- Name of the Enumerator/Observer

- ◯ David Amewu

Observed pattern of water-contacts

B1- Are there water-contacts?

- ◯ Yes
- ◯ No

B1.1- Which category of people are involved in

- ☐ Boys
- ☐ Girls
- ☐ Women
- ☐ Men
- ☐ Hard to know

https://kf.kobotoolbox.org/#/forms/aGB3JKVPMGL4wVkGCZ7vyz/edit 1/3

B1.2- What time of day is the water-contact made?

- [ ] before 06 am
- [ ] 06am - 08am
- [ ] 08:01 - 10am
- [ ] 10:01 - 12 noon
- [ ] 12:01 - 02pm
- [ ] 02:01 - 04pm
- [ ] 04:01 - 06pm

B1.3- what is the average duration per water-contact activity?

- ○ 1-10 minutes
- ○ 10-20 minutes
- ○ 30-60 minutes
- ○ 60-120 minutes

Water-contact types/activities

C- What are the observed water-contacts types/activities?

- ○ Swimming
- ○ Fetching water
- ○ Irrigating crops
- ○ Washing clothes
- ○ Religious/traditional activities
- ○ Crossing the river/stream, etc.
- ○ Others (specify)

12/13/21, 4:52 PM Observation of snails availability in water bodies - Schistosomiasis

Observation of snails availability in water bodies - Schistosomiasis

A- IDENTIFICATION

A2- Date of survey

yyyy-mm-dd

A6- select the observation site

- ◯ Kojo Ashong
- ◯ Adjen Kotoku
- ◯ Obom
- ◯ Dome Fase
- ◯ Galilea
- ◯ Weija

Snail sampling and counting

C- Snail availability in the water

C1- Are snails in the water?

- ◯ Yes
- ◯ No

C1.1-What is the total number of snail sampled at this site?

C2- Do you have some comments?

Measuring water variables

C- Water-contact for other activities/reasons

https://kf.kobotoolbox.org/#/forms/a5xaiwrkECE8mhgmKN7uRA/edit 1/2

12/13/21, 4:52 PM Observation of snails availability in water bodies - Schistosomiasis

C1- Which water body type exist in the sampling site

- ◯ River
- ◯ Stream
- ◯ Pond/dug-out
- ◯ Lake

C2- what is the value of water tmeperature (oC)?

____

C3- what is the average value of pH?

____

C4- what is the average value of turbidity (NTU)?

____

C5- what is the average value for water depth (m)?

____

C6- what is the velocity of water flow (seconds)?

____

Geolocation

Please take the geo point

latitude (x.y °)

____

longitude (x.y °)

____

altitude (m)

____

accuracy (m)

____

https://kf.kobotoolbox.org/#/forms/a5xaiwrkECE8mhgmKN7uRA/edit 2/2

8 Publications

8.1 Peer-reviewed Journal Articles

Ntajal, J., Höllermann, B., Falkenberg, T., Kistemann, T., and Evers, M. (2022). Water and Health Nexus—Land Use Dynamics, Flooding, and Water-Borne Diseases in the Odaw River Basin, Ghana. *Water. 14*(3), 461. https://doi.org/10.3390/w14030461

Ntajal, J., Evers, M., Kistemann, T., Falkenberg, T. (2021). Influence of human–surface water interactions on the transmission of urinary schistosomiasis in the Lower Densu River basin, Ghana. *Soc. Sci. Med. 288,* 113546. https://doi.org/10.1016/j.socscimed.2020.113546

Ntajal, J., Falkenberg, T., Kistemann, T., Evers, M., (2020). Influences of Land-Use Dynamics and Surface Water Systems Interactions on Water-Related Infectious Diseases—A Systematic Review. Water 12, 631. https://doi.org/10.3390/w12030631

Schmiege, D., Perez Arredondo, A.M., **Ntajal, J.,** Minetto Gellert Paris, J., Savi, M.K., Patel, K., Yasobant, S., Falkenberg, T. (2020). One Health in the context of coronavirus outbreaks: A systematic literature review. *One Heal. 10,* 100170. https://doi.org/10.1016/j.onehlt.2020.100170

Leroy, M., Gomez, A., Janet, O., **Ntajal, J.** (2020). International Journal of Disaster Risk Reduction Vulnerability to coastal erosion in The Gambia: Empirical experience from Gunjur. *Int. J. Disaster Risk Reduct. 45,* 101439. https://doi.org/10.1016/j.ijdrr.2019.101439

Yao, K.M.A., Obeng, F., **Ntajal, J.,** Tounou, A.K., Kone, B. (2018). Vulnerability of farming communities to malaria in the Bole district, Ghana*. Parasite Epidemiol. Control 3,* e00073. https://doi.org/10.1016/J.PAREPI.2018.E0007

Ntajal, J., Lamptey, B.L., Mahamadou, I.B., Nyarko, B.K. (2017). Flood disaster risk mapping in the Lower Mono River Basin in Togo, West Africa. *Int. J. Disaster Risk Reduct. 23*. https://doi.org/10.1016/j.ijdrr.2017.03.015

Ntajal, J., Lamptey, B.L., Sogbedji, J.M. (2016). Flood Vulnerability Mapping in the Lower Mono River Basin in Togo, West Africa. *Int. J. Sci. Eng. Res. 7,* 1553–1562.

Ntajal, J., Lamptey, B. L., Mianikpo, J., & Kpotivi, W. K. (2016). Rainfall trends and flood frequency analyses in the lower Mono River basin in Togo, West Africa. *International Journal of Advance Research*, *4*(10).

8.2 Contribution to Newsletters

Ntajal, J., (2020). Human-surface water interactions and the transmission of water-related infectious diseases – schistosomiasis in Ghana. In: Exner, M., Kistemann, T., Rechenburg, A., Grossi, V., 2020. *WHOCC WATER & RISK 30.* 2191-9674. https://www.researchgate.net/publication/343905687_WHOCC_Newsletter_Water_and_Risk_Vol_30

9 Conference contributions (*most relevant*)

9.1 Oral presentations

Ntajal, J., Evers, M., Kistemann, T., Falkenberg, T. (2021). Linking land use dynamics, urban transformation, and surface water systems: identifying human health risks and developing integrated solutions. Symposium for Research and Capacity Development in West Africa - WASCAL and German Partners, University of Wurzburg, September 22 - 23 September 2021, Würzburg, Germany.

Ntajal, J., Evers, M., Kistemann, T., Falkenberg, T. (2021). Land use dynamics, urban transformation and the complexity of surface water pollution: identifying risks and developing integrated solutions to water-borne disease in Accra, Ghana. International Water Resources Association (IWRA) – IWRA 2021 Online Conference on One Water, One Health: Water, Food and Public Health in a Changing World. 7 - 9 June 2021, online.

Evers, M., Almoradie, A., de Brito, M. M., Höllermann, B., **Ntajal, J.,** Lumor, M., Bossa, A., Norman, C., Yira Yacouba, Y. Y., Jean Hounkpe, J. H. (2021). Flood risk management in Ghana: gaps, opportunities, and socio-technical tools for improving resilience, EGU General Assembly 2021, online, 19–30 Apr. 2021, EGU21-12683, https://doi.org/10.5194/egusphere-egu21-12683

Ziga-Abortta, F. R., Kruse, S., Höllermann, B., **Ntajal, J.** (2021). Stakeholder Participation in Flood-Related Disaster Risk Management in Ghana, EGU General Assembly 2021, online, 19–30 Apr. 2021, EGU21-10819, https://doi.org/10.5194/egusphere-egu21-10819

Ntajal, J., Falkenberg, T., Kistemann, T., Evers, M. (2019). Linking land use dynamics and surface water systems in Ghana: human health perspective. DKG - 61st Deutscher Kongress für Geographie in Kiel. 25–30 Sept. 2019, Christian-Albrechts-Universität of Kiel, Germany.

Ntajal, J., Evers, M., Kistemann, T. (2019). Linking human-water interactions and risks of urinary schistosomiasis in Ghana. International Medical Geography Symposium in Queenstown organized by the University of Canterbury. New Zealand. 30–05 July 2019, Heritage, Queenstown.

9.2 Poster presentations

Ntajal, J., Kistemann, T., Falkenberg, T, Evers, M. (2020). Urban land use, spatial transformation, and the complexity of surface water pollution: identifying risks of water-borne disease in Accra, Ghana. One Health Symposium. Center for Development Research. 3 Nov. 2020. University of Bonn, Germany

Ntajal, J., Evers, M., Kistemann, T., Falkenberg, T (2019). Land use, surface water systems, and human interactions in urban river catchments in Ghana: human health outcomes. People-Oriented Urbanization: Transforming Cities for Health and Well-Being - ICUH 2019 in Xiamen. 04 - 08 Nov. 2019, Swiss International Hotel Xiamen, China.

10 About the author

Joshua Ntajal is a Geographer, focusing on Physical, Health and Medical Geography. Specific areas of expertise include; elements of Physical Geography, applied Hydro-climatology, Climate Change, Disaster risk management, One Health, Teaching, Field research, and Geospatial data analysis, using GIS and Remote Sensing. Ntajal is working as a research fellow and PhD student at the Department of Geography, University of Bonn, Germany. His PhD thesis focuses on understanding human-land use-water interactions and the consequent influences on exposure pathways and risks of water-related infectious diseases in Ghana. In his PhD research, Ntajal explored interactions among land use dynamics, flooding, surface water pollution, human water-contact patterns, and risks of water-borne diseases and urinary schistosomiasis. His PhD research contributed towards the understanding of the disease risk pathways and developed integrated, collaborative, and sustainable solutions, using system dynamics and stakeholder participatory approach. In the course of his PhD journey, Mr. Ntajal contributed to science, research, and development through publications in peer-review journals, newsletters, and conference presentations and also served as a peer-reviewer for numerous manuscripts for worldwide renowned journals.