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Water and Health Nexus—Land Use Dynamics, Flooding, and Water-Borne Diseases in the Odaw River Basin, Ghana

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Abstract: Water pollution is a major issue in Ghana with direct impacts on human health. However, the underlying drivers of exposure and risks are not comprehensively explored and understood, while the diseases continue posing huge burdens. The key question addressed is: what are the key drivers influencing the water–health nexus, particularly water-borne disease risks in the Odaw River basin, Ghana? Multiple approaches were integrated: qualitative system dynamic modeling and urban land-use change assessment. Multi-level stakeholder participation, including household surveys, focus group discussions, and workshops were employed in developing and identifying indicators and feedback loops. The results revealed that communities have access to water and sanitation, but water-borne diseases are still prevalent. Flooding influenced by poor land use planning and solid waste disposal are key risk factors, contributing to water pollution and disease outbreaks. The major land-use change is the conversion of natural to built-up areas, resulting in decreased urban vegetation cover and increased soil sealing, partly contributing to flood risk. Complex linkages and multiple feedback loops between land use, flooding, water pollution, and water-borne disease risks were identified. In addition to supplying safe drinking water and sanitation, multi-sectoral collaborations are required to co-design and implement integrated interventions, including flood risk reduction, urban land use plans, and improved waste management to reduce disease risks and promote health.

Keywords: urban land use; flood; water quality; water-related diseases; Odaw catchment

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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 [1]. Human–water interactions have become progressively multifaceted with varying impacts on water quality, particularly urban surface water systems [2,3]. The influences of these interactions on water systems have varying impacts on public health through diverse interconnected and complex pathways, leading to the emergence and transmission of water-borne diseases [4,5]. Globally, frequently reported infectious diseases are commonly linked to water quantity and quality, indicating that, while water plays an important role in the survival of humans and the functioning of ecosystems, it can be a medium for the emergence and transmission of diseases [6]. Predominantly, water-borne diseases are reported in areas with limited access to safe drinking water and improved sanitation infrastructure [6–8].

Increasing human population growth and human mobility have driven urbanization and the transformation of cities and their peripheries across the globe. As socio-cultural, economic, political, and ecological systems become closely interconnected through land use and urbanization, the pressure on water systems intensifies through water pollution, floods, and droughts [2,9]. Scholars and public health experts have recognized that "too much water" and "too little water" both have varying impacts on human health and the environment [10]. 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 [10]. In 2019, global reports collated by the WHO show that diarrhea accounted for over 370,000 deaths in children under five years of age. As of 2020, 1.3 to 4.0 million cases of cholera have been estimated annually and about 21,00 to 143,000 deaths are reported annually in all WHO regions worldwide, due to infections linked to water, poor sanitation, and hygiene, with their underlying drivers [10].

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 water-borne diseases, particularly in poor regions with limited investment in water quality monitoring and sanitation [6,11,12]. Different land use types have varying influences on human–water interaction patterns, water pollution pathways, and the risks of water-related infectious diseases (WRID) [1,13,14]. Land use and land cover (LULC) changes have impacts on the capacity of urban aquatic ecosystems to provide services that promote health. It has been projected that, in the face of climate change, population growth, and uncontrolled urbanization, the pollution of water systems will continue to increase, particularly in poor and developing regions without sustainable land use planning and safe waste management systems [6,15]. In many urban areas in Sub-Saharan Africa, the horizontal expansion of cities and poor spatial land use planning without improved drainage are observed as important drivers, which trigger flood disasters and their associated impacts on water systems and diseases [16]. It has been reported that floods facilitate the transportation of viruses, parasites, and bacteria into drinking water systems, leading to outbreaks of water-borne diseases when water and food from these contaminated sources are ingested [13].

In Ghana, access to drinking water and sanitation has increased over the past years; however, multiple outbreaks of diarrheal diseases are still recorded each year in flood-prone communities, particularly in the Odaw catchment within the Greater Accra Metropolitan Area (GAMA) [17]. The annual incidence rate of diarrheal diseases (including cholera, typhoid, and dysentery) within GAMA was approximately 25.6% until 2016 [18,19]. For example, in 2014 over 28,974 cases and 243 deaths from cholera were reported in Ghana, and more than 98% of the cases and deaths were recorded in the Greater Accra Region, particularly in the Odaw River catchment, including the Accra Metropolitan Area [18,20]. The underlying causal factors are partly linked to the contamination of food and water, poor hygiene, and sanitation. Water-borne diseases in GAMA have multi-causal pathways, and the underlying drivers influencing outbreaks are complex and far beyond the current traditional understanding. While the responses of water systems to individual stress emanating from both natural and human activities have often been investigated and partly understood, there is limited knowledge and awareness of the combined impacts and dynamics of the interactions among different drivers of water-borne diseases in GAMA.

The usual interventions, including drinking water supplies and the provision of sanitation services, are likely not sufficient to eliminate the diseases. Previous studies have raised concerns regarding the influences of 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, thereby contributing to a low level of awareness among the local population [15,21,22]. This highlights the need for a 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.

Identifying the underlying drivers and impacts of their interactions on risks of water-borne diseases is crucial for the development of relevant interventions [23]. However, due to fragmented interventions and a lack of multi-sectoral collaboration, sustainable solutions have not been developed and implemented, while the complex water–health nexus continues to pose human and environmental health problems. Reviewing the numerous studies related to WRID, evidence of studies designed to explicitly identify the underlying drivers of water-borne diseases besides the supply of WASH was found to missing [23]. Therefore, the key research question that this study addresses is: what are the key drivers influencing the water–health nexus, particularly the exposure to water-borne pathogens and risks of disease in the Odaw River catchment within GAMA? Additionally, given the growing interest among policy makers and the scientific community in adopting interdisciplinary and transdisciplinary approaches, this study further highlights the suitability of the research approach of integrating multi-level stakeholder participation, spatial analysis, and the modeling of intricate interactions between water and human health.

2. Materials and Methods

2.1. 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 (Figure 1). The annual average temperature is about 26 °C, characterized by a tropical savanna climate [24]. The rainfall shows a bimodal pattern, with the highest rainfall recorded between April and July and the lowest between September and October, with an average annual rainfall of 730 mm [25,26]. 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 [27,28]. Rainfall in the Odaw catchment occurs in the form of short but intensive storm events, which cause localized flash and riverine floods in areas with poor and choked drainage systems [29]. Historical flood disaster records show major flood events in GAMA where the Odaw River has been the hotspot following extremely high rainfall intensities, since 2001 with recent events in 2010, 2011, 2013, 2014, and 2015 [30]. The 3 June 2015 flood disaster is often used as a reference flood year, due to the combined impacts of the flood and a fire outbreak at Odawna [28,31]. In any given year, Accra has over a 20% chance of experiencing floods, given an extremely high rainfall, and is vulnerable to a 10-year flood with a 10% probability of occurrence [31]. Intermittent droughts are observed in the Odaw catchment; however, this does not pose major exposure problems and risks of water-borne disease, as the area is largely urbanized and the households do not depend on the Odaw river for their drinking water supply. However, droughts contribute to reduced water volume, leading to a higher concentration of pollutants in the stagnant waters, which are washed into drinking water systems via floodwaters [27,32].

The Odaw River and its tributaries are polluted with domestic and industrial effluents, contributing to food and drinking water pollution via poor hygiene, sanitation, and floodwaters [33]. Besides the well-recognized impact of floods such as the destruction of critical infrastructure in the vulnerable communities in the area, floods contribute to the transportation of sewage and effluents via floodwaters into drinking water systems, which is an important environmental and health issue in the area [30].

The study selected four communities within the catchment for household surveys: Agbogba, Alajo, Nima, and Odawna (Figure 1). These communities were purposively selected based on their proximity to the main drains of the Odaw River (within 100 m buffer), which partly influences their level of interaction with the river, exposure to frequent floods, and the risk of water-borne diseases [15,20]. 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 industries in Accra are located within the Odaw catchment [34]. Along the drains of the river are micro-retail shops, auto-mechanic shops, refrigerator repair shops, etc. [34]. These businesses, located along watercourses, contribute to the blockage of the drainage systems, leading to flooding in the area.

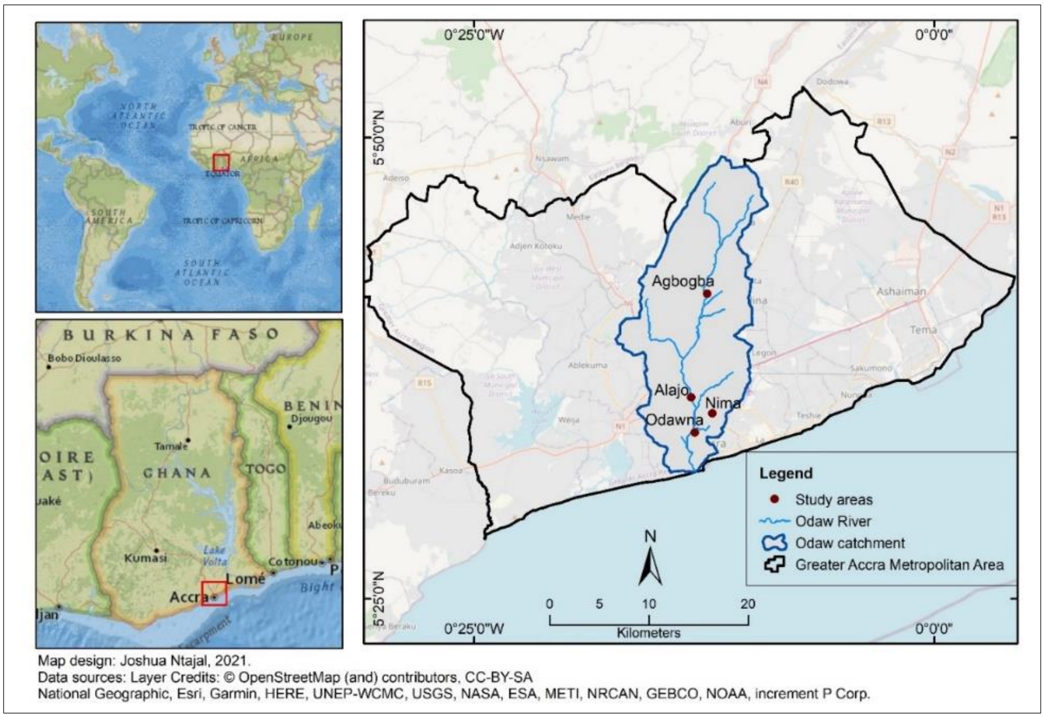

Figure 1. Map of the study sites in the Odaw River basin.

2.2. Methodological Approach

The study adopted a mixed-method approach, including qualitative system dynamics (QSD) modeling. In order 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 held. 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 2 presents the methodological steps.

2.3. 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 [35]. Qualitative System Dynamics (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) [36].

The causal loops 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 [35,37]. In CLD analysis, the relationship between variables is depicted using positive (+) and negative (−) signs, placed beside the arrowheads to indicate the polarity [36,38]. 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.

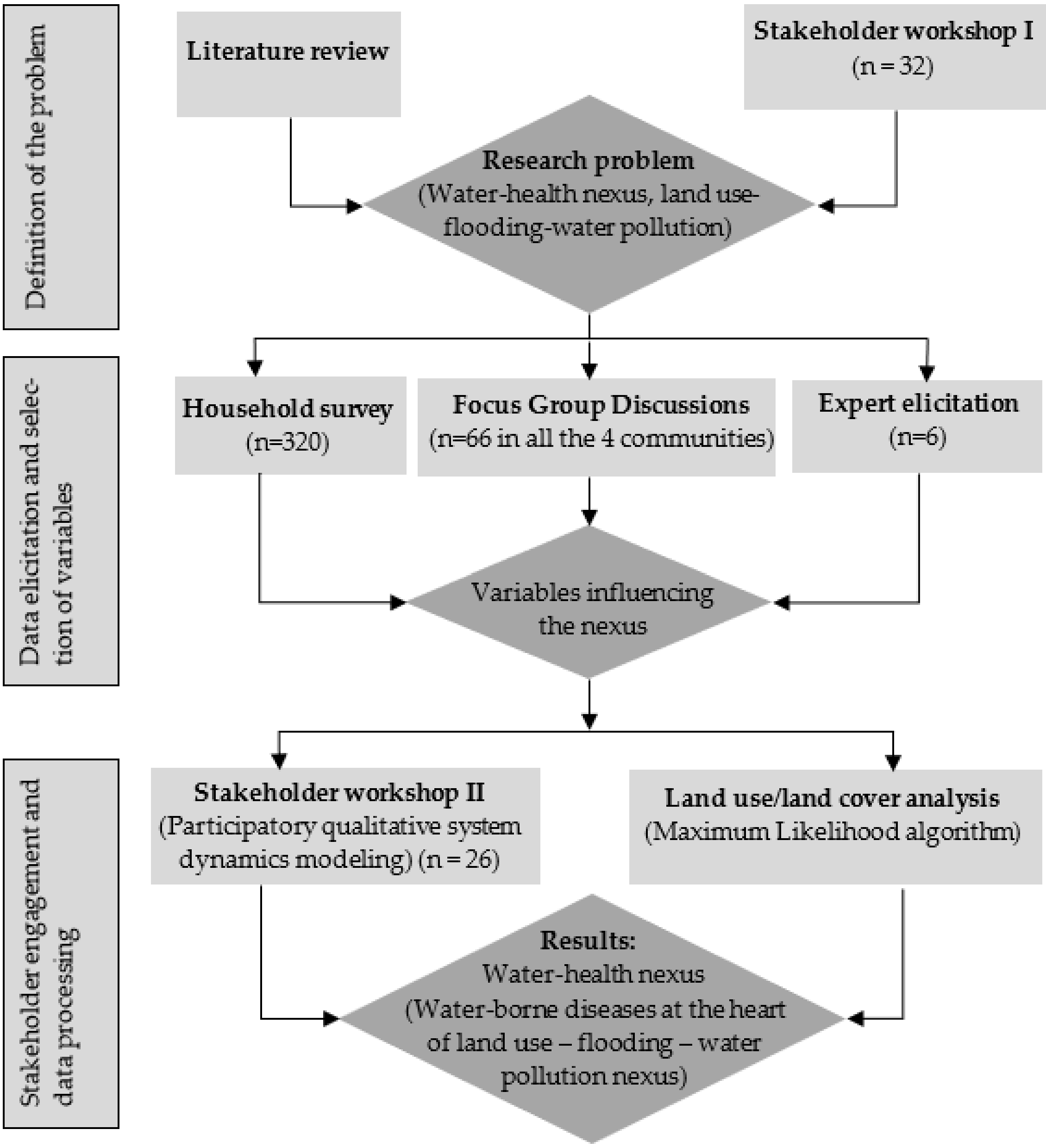

Figure 2. Flowchart showing the methodological steps. Source: Authors' own work (2021).

2.4. Methods

2.4.1. Stakeholder Workshop I

The first stakeholder workshop was organized in November 2018 to define the research problem and discuss data sources. A snowball sampling approach was used to identify the participants for the stakeholder workshop, following the stakeholder theory and participant identification procedure of "those affected and those involved in decision making" [39,40]. 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 such as the Physical Planning Department of the Accra Metropolitan Assembly, Ministry for Water and Sanitation, Community Water and Sanitation Agency, Environmental Protection Agency, Water Resources Commission, Water Research Institute, Department of Public Health of the University of Ghana, Ghana Health Service, National Disaster Management Organization, etc. 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 with the workshops was found crucial, as they are the beneficiaries and mediators of the systems as well as potential the actors influencing the dynamics in the QSD models that were developed. The engagement of the stakeholders allowed the identification of key variables and the development of relevant interventions to promote health.

2.4.2. Sampling and Sample Size Estimation for Household Surveys

To obtain data on the exposure to and risks of water-borne diseases, household surveys were conducted in February 2019. The four communities identified for the survey were purposively selected due to their proximity to the main Odaw River, exposure to vulnerability to floods, and frequently reported cases of water-related infectious diseases [15,27]. The sample size was estimated using the method stated:

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

where n is the sample size, Z is the statistic corresponding to the level of confidence (1.96), P is the annual incidence rate of diarrhea (25.6%) [18,19] and d is precision (95%), which is widely used [41]. Therefore,

$$n = \frac{(1.96)^2 \times 0.256(1-0.256)}{(0.05)^2} = \frac{3.8416 \times 0.744}{0.0025} = 293$$

Therefore, a sample size (n) of 293 households was estimated for the survey. Adding a 10% buffer ($0.1 \times 293 = 29.3$) of the estimated sample size to compensate for a possible non-response rate, the final estimated sample size was 322 households.

The anonymity of the respondents was assured and their consent to participation was sought prior to the survey (using personally drafted consent forms). Given the sample size of 322, a total of 320 households granted their consent to participate in the survey. The sample (n = 320) was equally distributed among the four purposively selected communities (Alajo, Agbogba, Odawna, and Nima) within the Odaw River catchment. In each of the communities, 80 households were randomly selected to participate in the survey. This is because the communities exhibited similar physical, socio-cultural, and economic characteristics, and the differences in household characteristics were of no particular importance to the study. The survey was digitally coded and personally administered using tablet computers. The survey was structured and the key topical issues covered included: access to water and sanitation, risks of water-borne diseases, impacts of floods on outbreaks of water-borne diseases, and underlying drivers and pathways of water pollution such as floods, land use, and household waste management areas.

2.4.3. Focus Group Discussions and Expert Elicitation

The focus group discussions (FGDs) were conducted to gain an understanding of the research problem from the perspectives of groups and communities. 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 of the FGDs included the chiefs of the respective communities, assembly members, representatives from the Market Women Associations in the communities, Community Health and Sanitation Officers, and elderly persons, all of whom 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 memories and local information retrieval experiences. The key issues related to the water–health nexus and the underlying driving forces were discussed. The participants were engaged in identifying and discussing the potential variables. Flipcharts were provided for the documentation and illustration of linkages between variables highlighted by the participants. The potential variables identified were again presented to the groups in each of the study communities at the end of the exercise for further discussion and validation. The final set of variables was considered valid only when the participants reached a consensus.

2.4.4. Stakeholder Workshop II: Development of the QSD—Causal Loop Diagrams

To allow collaborations and stakeholder participation in the development of the QSD models, a second stakeholder workshop was organized in April 2019 in Accra, Ghana. A total of 26 participants from the first stakeholder workshop participated in the second workshop, due to their level of interest in the research problem and their critical contributions during the first workshop. 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 "effect" relationships between the variables, the QSD and 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. The process of variable identification and the QSD modeling exercise was a learning process for the participants of the workshops, including the experts in the fields of water, health, and spatial planning, members of local communities, and the researchers.

2.4.5. 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 were cleaned and examined for errors and completeness. The descriptive statistics highlighted the potential variables, influencing households' exposure to pathogens and the risks of waterborne 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 diagrams 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 causes and effects within the QSD sub-models. The CLDs were systematically traced and the feedback loops were identified. Feedback loops exist when the arrows flow in the same direction (clockwise) or opposite direction (counter-clockwise) in a circular manner [36,38]. The feedback loops were either reinforcing (R) or self-balancing (B) [42]. 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 m. 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 variance and correlation of spectral values of the different bands, based on the specified spectral signature [43]. The training samples for each group of pixels were created for all the images to generate their spectral signatures required for the maximum likelihood classification. The LULC types in the area 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. Results

3.1. Basic Factors Contributing to Water-Borne Diseases

3.1.1. Access to Water and Sanitation

In each of the four selected communities, 80 households were surveyed, with a response rate of 100%. The results of the household survey revealed that more than 80% of the households in all 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 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, household members had to pay and often queue for an average of 10 min 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 (Table 1). 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%). In contrast, the flush toilet facility was mainly used at Agbogba (44%), which is occupied by residents within low- to middle-income classes.

Table 1. 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

Data source: based on primary data collection, using household surveys in the Odaw River catchment in Ghana, in April 2019.

It was noted that the Pan latrines and 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 a usage fee, these public sanitation facilities in Odawna, Nima, and Alajo were found in deplorable conditions and poorly maintained, which discourages 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 to be rare in all the communities; however, the FGDs revealed that it was significantly practiced in and around the Odaw drains and could be a major source of water pollution with fecal matter and *E. coli*, inducing water-borne disease risks when ingested. Further analysis revealed that household wastewater management contributes to the water-borne disease risk in addition to WASH.

3.1.2. Household Wastewater Management

The management of wastewater generated from sanitation, laundry, cooking, bathing, etc. is crucial for 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 (Figure 3), while 26% of the households discharged their wastewater on the open spaces outside their homes, which was found to attract houseflies and rodents into homes. 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.

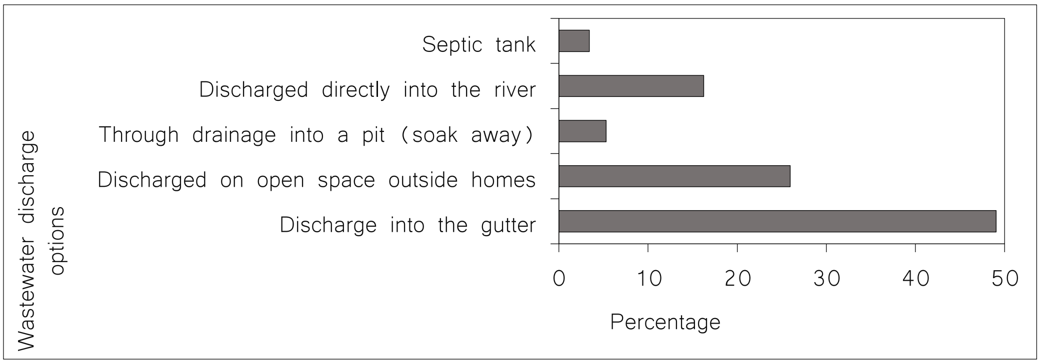

Figure 3. Wastewater management named by households. Data source: based on primary data collection, using household surveys in the Odaw River catchment in Ghana, in April 2019.

3.1.3. Exposure Pathways and Risks of Water-Borne Diseases

In Figure 4, 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 of diseases (e.g., cholera, typhoid, etc.). Limited access to water and sanitation, as well as poor hygiene practices among households contributed to the pollution of water with fecal matter via unsafe wastewater discharge and open defecation practiced by infected persons, thereby reinforcing the feedback loop. Another reinforcing feedback loop (R2) was identified, as wastewater from households and industrial areas is used for irrigation in urban agriculture to meet the growing demand for food (Figure 4). The irrigation activities, in turn, generate wastewater with nutrients and chemical loads from the farms, through the application of fertilizers.

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 of water-borne diseases (Figure 4). Further, the death rate among persons infected can increase, given limited access to healthcare services. The long-term effects may result in a decrease in population growth, although interruptions such as time delays and interventions from the government are expected. An increase in the 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.

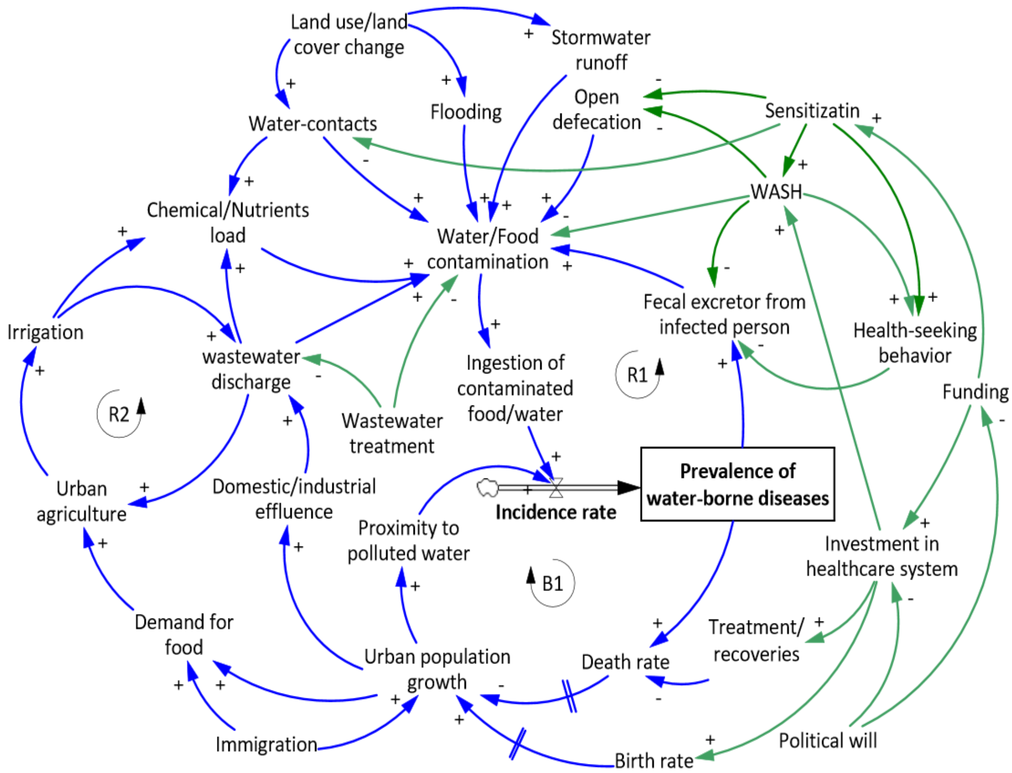

Figure 4. Water-borne diseases sub-model. The blue arrows show the connections between the variables, while the green arrows indicate the interventions altering the state of these variables. Data source: based on primary data collection in the Odaw River catchment in Ghana, in April 2019.

3.2. Flooding, Water Pollution, and Water-Borne Diseases Pathways

The household survey on water-borne diseases associated with major flood events in the study communities was based on the 3 June 2015 flood disaster, due to its widespread impacts ranging from the loss of lives and livelihoods, destruction of critical infrastructure, and subsequent outbreaks of diarrheal diseases about 14 days after the disaster. The results of the household survey revealed that, while diarrheal diseases are usually associated with an inadequate supply of safe drinking water and access to improved sanitation as well as poor hygiene, major flood events including the 3 June 2015 flood disaster contribute to acute drinking water pollution and consequent outbreaks of cholera 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%), diarrheal diseases including cholera (35%), typhoid fever (18%), and dysentery (7%), were noted as the most common and frequently reported water-borne diseases 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 record-keeping habits at both the household and the district levels, as well as stigmatization. The results of the QSD modeling and CLD show the interactions between the underlying causes of flooding, such as LULC change and solid waste disposal, and the exposure pathways to pathogens are captured in Figure 5.

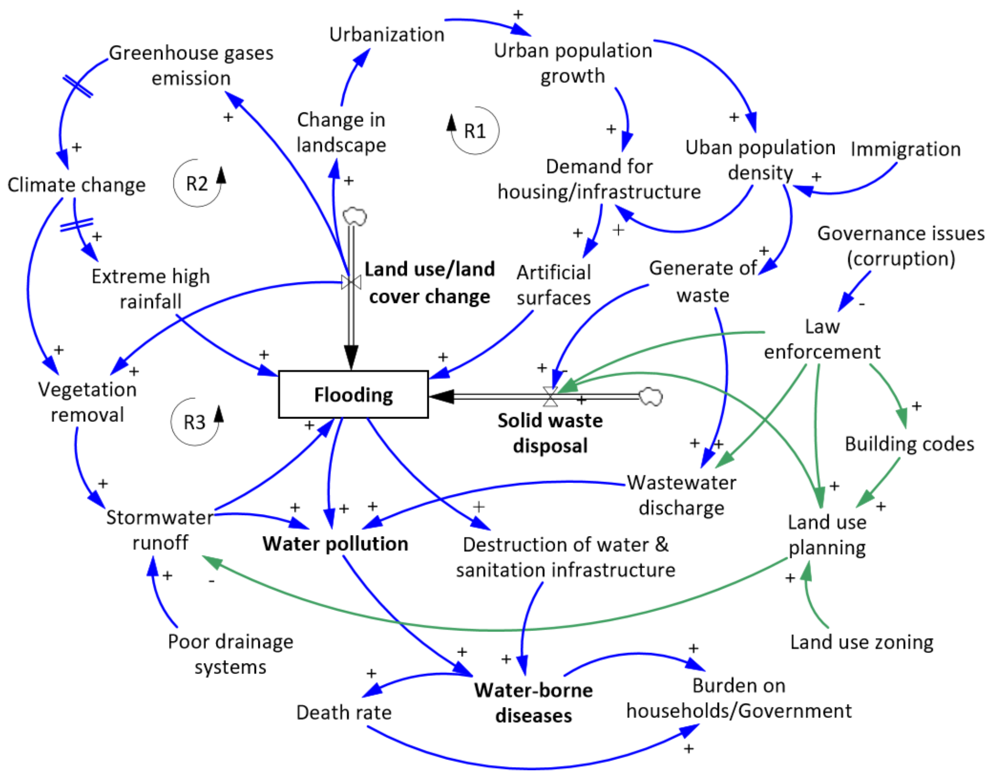

Figure 5. Flood sub-model. The blue arrows show the connections between the variables, while the green arrows indicate the interventions altering the state of these variables. Data source: based on primary data collection in the Odaw River catchment in Ghana, in April 2019.

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, artificial surfaces and soil sealing have increased, facilitating 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. Furthermore, an increase in urban population density increases the amount of solid waste produced, which, improperly disposed of, contributes to siltation of the drains and consequent localized flash floods after even short durations of extreme high rainfall. These result in devastating flood events such as the 3 June 2015 flood at Odawna in Accra, and other major flood events (e.g., 2010, 2011, and 2014).

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 is reinforced by LULC change (R2). The influences 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 our understanding of their influence on flooding.

3.2.1. Causes of Flooding in the Odaw River Catchment

To identify the linkages between flooding and water pollution within the catchment, the causes of flooding were explored. The results from the household surveys show that poor solid waste disposal was found as a major contributing factor to flooding, except in the upstream area, Agbogba, where the construction of infrastructure (e.g., houses, auto-mechanic shops, etc.) on watercourses was the key factor (Figure 6).

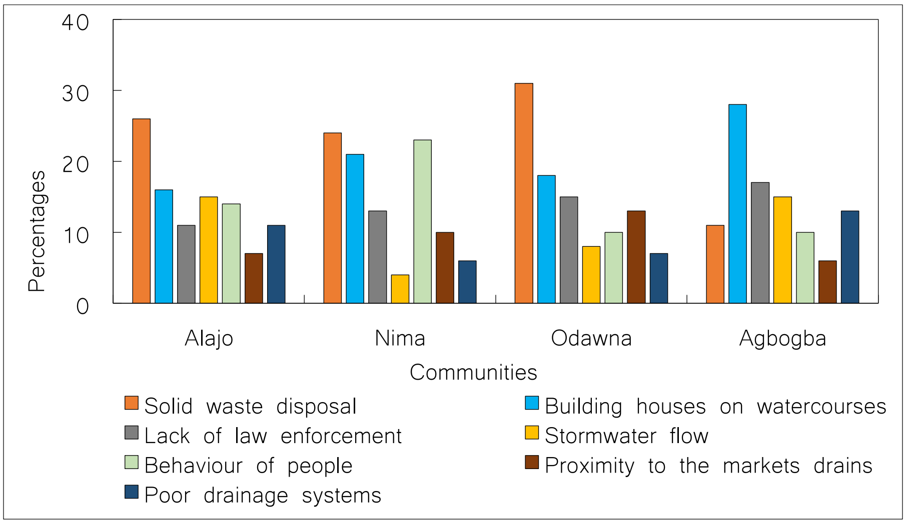

Figure 6. Contributing factors influencing flooding in the Odaw catchment. Data source: based on primary data collection, using household surveys in the Odaw River catchment in Ghana, in April 2019.

Furthermore, the building of houses on watercourses as well as a lack of law enforcement were found relevant in all communities. The behavior of residents and 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 a relevant factor. The proximity of markets to the drains of the Odaw River system was noted 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 change and solid waste disposal, influenced by the lack of law enforcement and the behavior of the people.

3.2.2. 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 (Table 2). Similarly, 30% of the households relied on "house-to-house" private waste collection services. Although these options were dominant in the communities, these 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 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 community.

Table 2. 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)

Data source: based on primary data collection, using household surveys in the Odaw River catchment, Ghana, in April 2019.

3.2.3. Land Use and Land Cover Change

The results show significant changes in LU and LC 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 noted between 2011 and 2020 (Table 3). The vegetation cover including protected forests, grasslands, and shrubs has decreased from 70% in 1991 to 21% in 2020. The built-up area has increased over the past four decades from 19% in 1991 to 65% in 2020. In contrast, 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 that 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. The major LULC changes such as expanded built-up areas (urban expansion) and reduced vegetation cover are partly due to urban population growth, urban transformations, increased demand for infrastructure, and uncoordinated urban environmental protection measures.

Table 3. 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

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

A negative relationship between vegetation cover and built-up areas is evident. As the built-up areas expanded, vegetation cover including forest, grasslands, and mangroves decreased. 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 could potentially increase stormwater runoff and flood events, particularly given the 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 changes and stormwater runoff were the major contributing factors to recurrent annual floods in Accra. The visual impressions from the LULC change assessment (Figure 7) 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 were 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.

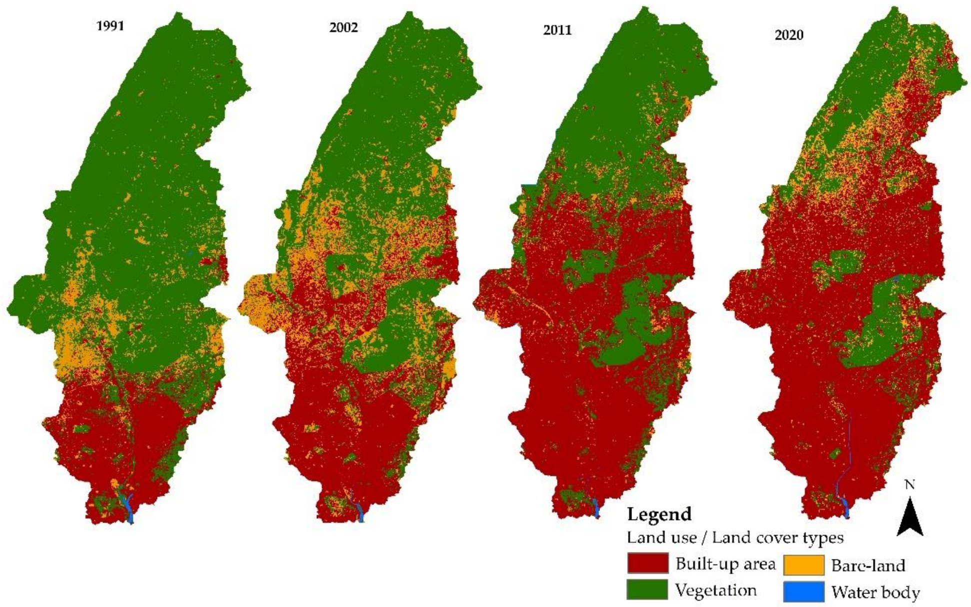

Figure 7. The results of the LULC change assessment in the Odaw River catchment from 1991 to 2020. Source: own LULC change assessment by the authors.

Interviews with urban development experts revealed that urban transformation processes in GAMA have contributed to the growth of the local economy, improvement of the healthcare systems, and the standard of living, which attracted migration, while housing and infrastructural facility deficits continue to increase exponentially. The unplanned land use and urban transformation process, together with poor waste management systems in GAMA, pose huge threats to surface water systems, resulting in health-related risks and outbreaks of water-borne diseases. Further interactions with the Spatial and Urban planning Department of the Accra Metropolitan Area revealed that uncontrolled deforestation and land cover conversion within the catchment were linked to the complex land ownership system in Ghana, a poor human attitude towards urban ecosystems, and inadequate knowledge of the importance of urban green spaces to health. Adequate vegetation cover serves as a retention mechanism, which facilitates infiltration, reduces stormwater runoff, and consequently reduces the chances of flooding. In the case of decreased vegetation cover and poor land use planning, as found in the Odaw catchment, an increase in stormwater runoff and a higher probability of flooding are expected, which is amplified by poor drainage engineering and the blockage of drains with solid waste. Having explored the exposure pathways and the risk of water-borne diseases in the Odaw catchment, it was found necessary to identify the existing interventions adopted for responding to flood disasters, reducing the risk of water-borne diseases, and promoting health in GAMA.

3.3. Interventions for Reducing Disease Risks and Prevention Strategies

3.3.1. The Existing Interventions and Prevention Strategies

Health promotion and water-related disease prevention measures for responding to epidemics and related disasters are performed by providing immunization and relief items, which are often short-term interventions. The results 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 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 inception stages of the projects.

Regarding 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 [28].

3.3.2. Intervention Measures Proposed by the Stakeholders

The QSD models and CLDs integrated some intervention measures to support reducing the impacts and the cascading effects of the causal factors, and to break the negative feedback loops in the systems. Through the engagement of stakeholders and community representatives, an intervention framework was developed to be implemented at both the local community and governmental levels to support surface water protection, a clean city, and promote health. The drafted framework was validated using a stakeholder workshop in Accra (Figure 8). 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 the government and NGOs. Inter-sectoral and multi-sectoral collaborations and the sharing of experiences and feedback for the sustainable implementation of the proposed measures are strongly recommended.

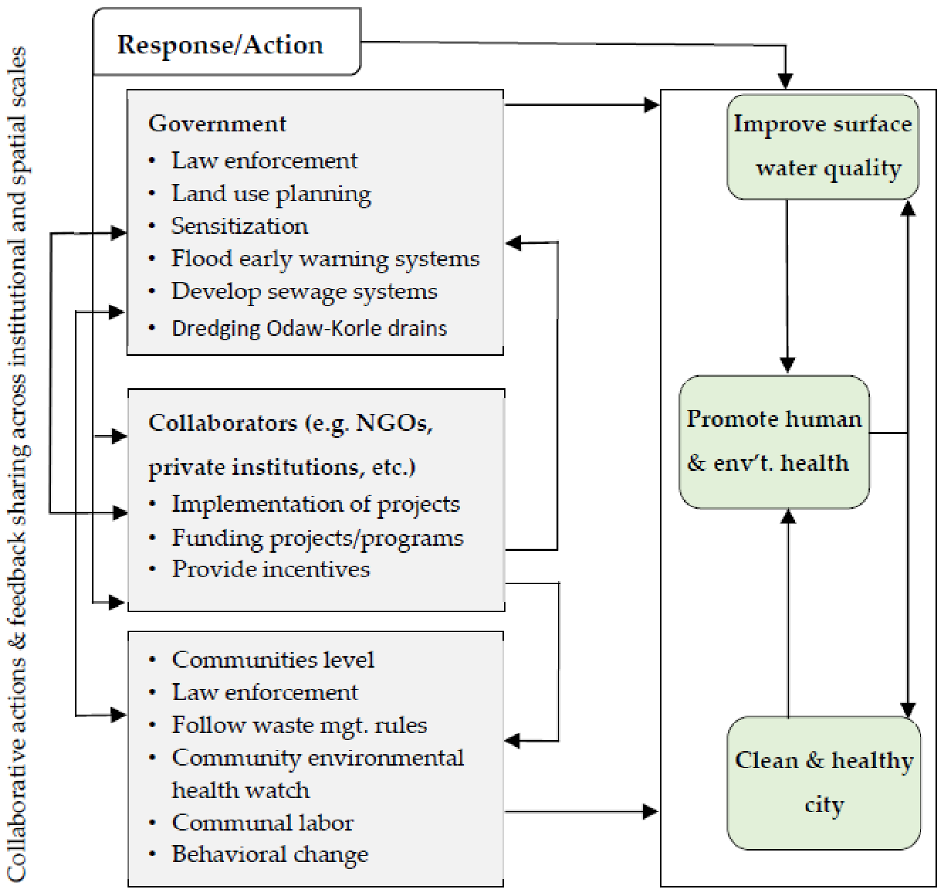

Figure 8. Proposed collaborative strategies to support water quality monitoring and promote health. Summary of proposed collaborative strategies to support water quality monitoring, clean city, and human and environmental health. Here, collaborators may act as a bridging element between the different spatial and institutional scales. Source: based on expert elicitation and stakeholder interactions in workshops in Ghana, 2018–2019.

4. Discussion

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

4.1. Access to WASH and Wastewater Management—Impacts on Water-Borne Diseases

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 the water quality was not determined in this. The communities have access to sanitation facilities, which are mainly public. However, open defecation practice was noted. Similarly to accessibility to water, households are required to pay usage fees to gain access to sanitation services, while the facilities were poorly maintained, thereby discouraging use. 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 [44]. Studies in India and the Democratic Republic of the 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 [44,45]. Falkenberg et al. [44] underscored the importance of good hand hygiene in addition to accessibility to safe drinking water to efficiently prevent water-related infectious diseases.

Another risk factor is inadequate 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 high exposure to pathogens and toxic substances via the contamination of drinking water and food. Grytdal et al. [46] 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 outbreaks of these diseases extend beyond the supply of safe drinking water and sanitation infrastructure. Studies on the benefits of WASH intervention programs in Kenya, Zimbabwe, and Bangladesh noted that providing WASH had no significant impact on the prevention of diarrheal diseases, due to the additional impacts caused by spatio-temporal dynamics of disasters (e.g., floods, droughts, conflicts, etc.) and health-seeking behaviors [47].

4.2. Water Pollution and the Risk of Water-Borne Diseases—Influences of Floods, Waste Management, and 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 9. For example, the usage of untreated wastewater for urban agricultural activities to avoid overreliance on the unpredictable rainfall pattern in the region poses high risks to health. 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 the direct ingestion of contaminated food. This increases the household's exposure to pathogens, leading to an increased incidence and prevalence of water-borne diseases.

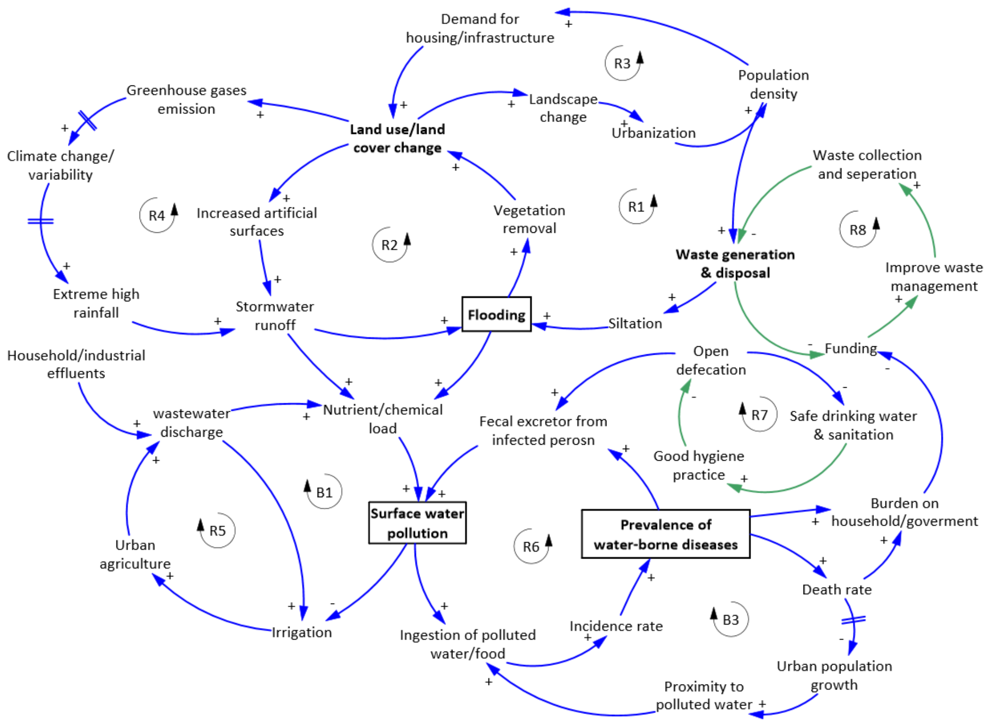

Figure 9. Integrated CLD obtained from the key feedback loops in the sub-models developed. The blue arrows show the connections between the variables, while the green arrows indicate interventions altering the state of these variables. Source: based on primary data collection in the Odaw River catchment in Ghana, in April 2019.

Fecal matter from infected persons without proper hygiene practices leads to pollution of drinking water (see loop R6). Interventions such as the provisioning of safe drinking water and improved sanitation promote good hygiene and reduce open defecation practices (see loop R7). The loop (R7) is reinforcing, 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 [10,12,18,48].

In our study, flooding was found to be a major driving factor influencing frequent outbreaks of water-borne diseases in GAMA, through the destruction of WASH infrastructure and the consequent pollution of drinking water. 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 [15]. Okaka and Odhiambo [48] and Abu and Codjoe [15] noted 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. For example, a cumulative sum of 618 cases with 6 deaths was reported as of 14 June 2015, following the 3 June flood disaster in Accra in 2015 [20]. Similarly, study reports show that flood events have contributed to outbreaks of diarrheal diseases in Southern Asia and Sub-Saharan African countries including Bangladesh, Kenya, and Mozambique [10,48,49].

In addition, evidence from the household survey 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 siltation of the 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 towards a reduction in 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. 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 [50].

Land use and land cover change, partly due to an increase in built-up areas and a reduction in vegetation cover between 1991 and 2020, play crucial roles in flooding. Increased artificial surfaces, including soil sealing and bare lands, reduce infiltration, thereby facilitating stormwater runoff and flooding. A reinforcing loop (R3) shows that an increase in the urban population increased the 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 via the influx of chemicals in wastewater from urban agricultural activities.

Key lessons from expert interviews with the Physical Planning Department of the Accra Metropolitan Area revealed that poor LULC planning, a 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 extremely high rainfall. Previous studies in Ghana have attributed these challenges to a lack of implementation of urban land use plans and environmental protection [16]. LULC changes and stormwater runoff play a major role in the transportation of nutrients and chemicals from farmlands, grease from auto-mechanic shops, and waste from 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 unsafe for agricultural activities, and food produced using polluted water can pose significant health risks. Research studies in the United Kingdom, Kenya, and the Democratic Republic of the 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 [12,48,51].

4.3. The Way Forward

The study noted that the provision of WASH alone is not sufficient to prevent water-borne diseases in Ghana. As highlighted in the WHO's 'Health in all Policies' strategies, the development of integrated solutions, covering land use planning, improved waste management systems, behavioral change, and flood disaster risk reduction through multi-sectoral collaborations, is holistically crucial for promoting health [52]. For example, sustainable land use planning and the implementation of building codes, surface water and environmental protection, supply of adequate WASH, designing of a sensitization program in collaboration with communities, creating awareness on the dynamics between floods, water pollution and the outbreak of water-borne diseases, public-private partnership, and the provision of sufficient funds for flood and waste management projects are proposed interventions 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.

4.4. Limitations 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 QSD modeling and stakeholder participation provided relevant information to enhance our understanding of the interactions and linkages between water pollution and the important pathways to water-borne disease in GAMA. QSD models are limited in terms of mathematical simulations and the 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 to inform decision making. In addition, the Landsat satellite images used (30 m spatial resolution) have relatively low pixel values, which are not suitable for 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.

5. Conclusions

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 noted 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 in fact 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 flooding and water pollution, influenced by different interrelated factors such as poor land use planning, poor waste management, a 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. According to the 'Health in all Policies' strategy of the WHO, 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 improved understanding of the complexity of the water-health nexus, and further helped to identify strategies to inform policy formulation and decision making.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

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