ASSESSMENT OF GROUNDWATER QUALITY IN URBAN AND PERI-URBAN AREAS OF WEBUYE MUNICIPALITY, BUNGOMA COUNTY KENYA

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A thesis submitted to the School of Engineering and the Built Environment in partial fulfillment of the requirement for the award of Degree of Master of Science in Water Resources Engineering of Masinde Muliro University of Science and Technology

November, 2023

DECLARATION

This thesis is my original work prepared with no other than the indicated sources and support and has not been presented elsewhere for a degree or any other award

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CERTIFICATION

The undersigned certify that they have read and hereby recommend for acceptance of Masinde Muliro University of Science and Technology a thesis entitled; '**Assessment of Groundwater Quality in Urban and Peri-Urban Zones of Webuye, Bungoma County Kenya'.**

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DEDICATION

This research is dedicate to my family; Mum, Dad and my sons Amali and Fela for the support they have demonstrated since the beginning of my studies.

ACKNOWLEDGEMENT

I would like to extend my gratitude to my supervisors Prof. Basil Ong'or and Dr. Edwin Kanda for their resourceful guidance throughout development of this Thesis, Dr. Mukolwe and the whole Department of Civil and Structural Engineering for the resourceful support extended to my work. I also acknowledge Eng. Hudson Makhanu for his support in data collection and analysis.

ABSTRACT

Safe water and sanitation are human rights as one of the 17 sustainable development goals. Population growth in urban areas has led to increased occupancy on small pieces of land, where occupants develop groundwater sources, onsite sanitation systems, composting sites and gardens on small pieces of land. This has resulted into entry of pollutants into aquifers because of reduced distance between the pollutants and groundwater sources. Contrary to the traditional perception that ground water is safe and dependable for consumption, groundwater is susceptible to anthropogenically and naturally caused pollution. Accumulation of pollutants in groundwater generates a storage for pathogens which leads to new and emerging infectious diseases. The overall objective for the study was to assess groundwater quality in Urban and peri-urban zone of Webuye, Bungoma County Kenya. The specific objectives were; to determine pollution factors and their risks on groundwater quality in Webuye, to determine chemical, physical, and biological water quality parameters of ground water sources in Webuye, to develop and map water quality index of Urban and urban parts of Webuye and to assess groundwater vulnerability to pollution in Webuye. The data that was used in this research was rainfall, water quality analysis results, upstream condition of water ground water sources, topographical data, land use images, well construction and operational status, waste generation and disposal, water depth and distance of water source from onsite sanitation facility. Slovins's formulae was used to come up with an appropriate sample size of 74 shallow wells and 8 springs. All samples were randomly selected for the study. The analysis was done using DRASTIC indexing method to come up with risk models, Shit Flow Diagram (SFD) analysis was also conducted to assess the sanitation levels, ArcGIS mapping and interpolation methods for development of risk maps and prediction of parameter behaviors and excel for data analysis. The study employed correlational and analytical research design. The results revealed most residents live on small portions of land where they put up onsite sanitation facilities and groundwater points. It was also found that in 48% cases show that there was less than 7 m distance between the sanitation facilities and groundwater sources. The study also reveals that 36% of waste generated is safely managed while 64% is not. The water quality results show that Nitrates, pH, TDS and Electrical Conductivity were high concentrations beyond maximum permissible levels. The study further reveals that water quality index of Webuye urban and peri-urban areas is as follows: Excellent 1%, Good 3%, Poor 11%, Very Poor 16% and water that is Unfit for Consumption 69%. This implies that its only 4% of ground water sources in Webuye that is safe foe consumption. The result of this study is key for policy makers to develop strategies for groundwater pollution management through a practical comprehension of water pollution processes rather than concentrating on pollution sources only. Likewise, it provides information on innovative ways of engaging stakeholders, politicians, sanitation experts and community leaders in an informed dialogue about regulation of sanitation service chain.

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LIST OF ABBREVIATIONS AND ACRONYMS

ASAL	Arid and semi-arid land
DRASTIC	Assessment Method
EC	Electric Conductivity
EC	*Escherichia Coli*
FC	Faecal Coliform
GIS	Geographical Information System
GUI	Geographical User Interface
GW	Groundwater
KEBS	Kenya Bureau of Standards
KNBS	Kenya National Bureau of Statistics
LU	Land use
MCDA	Multi-Criteria Decision Analysis
MODFLOW	Modular finite-difference groundwater flow model
NFS	National Sanitation Foundation
OSS	Onsite Sanitation Systems
OWQI	Oregon Water Quality Index
SDG	Sustainable Development Goals
SDG	Sustainable Development Goals
SFD	Shit Flow Diagram
TDS	Total dissolved soilids
TSS	Total Suspended Solid
UN	United Nations
USEPA	US Environmental Protection Agency
WQ	Water Quality
WQI	Water Quality Index

OPERATIONAL DEFINATION OF KEY TERMS

Groundwater	This term was used to refer to springs and shallow wells
Onsite Sanitation System	Refers to waste collected, stored and treated on the plot
Urban	This is the town centre/commercial area of Webuye town
Peri-urban	The residential areas surrounding the urban areas of Webuye

CHAPTER ONE

INTRODUCTION

1.1 Background information

Access to water and sanitation is a human right, acknowledged through various initiatives, including United Nation's 17 sustainable development goals (Sadoff, Borgomeo, & Uhlenbrook, 2020). It is barely 19% of population worldwide that has access basic drinking water services (Mukherjee, Bhanja, & Wada, 2018). Groundwater exploration has lately increased due to its preserved water quality status as compared to surface water. Groundwater is extensively available and highly reliable as compared to surface water in extreme climate change events (B. Das & Pal, 2020). Groundwater usage is dependent of the region. Japan and Northern parts of Europe are highly humid and groundwater is mainly used in industries and for domestic purposes (T. Shah et al., 2007). Countries that are away from humid inter-tropical zone, and other parts of the world; Saudi Arabia, Pakistan, USA, Mexico, India, and China use groundwater mainly for irrigation (Zektser & Everett, 2004). Efficiency in abstraction has increased groundwater usage risking overexploitation (T. Shah et al., 2007).

Groundwater usage in Africa supersedes surface water even in regions that are well-endowed in surface water (M. Kumar, Ramanathan, Rao, & Kumar, 2006). South Africa receives rainfall approximately 450 mm/yr (Binns, Illgner, & Nel, 2001), while Papua New Guinea and Congo are rich in freshwater resources, but they are classified as water stressed countries. Ethiopia is the water tower of Eastern Africa. It is endowed with nine major river basins but it still has water shortages. This is due to the increased water demand and deteriorating water quality of surface sources. Utilization of groundwater in the African region is motivated by its dilatory response to extreme weather variability and its convenience to develop within points of need (Calow, MacDonald, Nicol, & Robins, 2010).With improved pumping efficiencies, electricity network coverage and exploration of solar energy, groundwater extraction worldwide has doubled from 312 km^3/year in 1960s to approximately 743 km^3/year in 2000 (Wada et al., 2010). It is reported that half of urban domestic water demand is satisfied by groundwater (Giordano, 2009). Recent research findings acknowledge that world population expansion and urbanization are worthy of attention in the 21st century. These trends affect economic stability of the globe, energy usage, use of natural resource and the well-being of human (Lederbogen et al., 2011; McDonald, Kazemi, & Kavanagh, 2013; Wong & Brown, 2009). According to the (Dorling, 2021), roughly 55% of global population world's population dwell in urban areas, and this will increase to 68% by 2050. This population will definitely build pressure on groundwater in various aspects, including depletion and loss of quality.

In Kenya, approximately 17 million people live in ASALs. The paucity of surface water and unpredictable rainfall in these areas leaves groundwater as the main sources of water (Mumma et al., 2011). Groundwater usage in Kenya is envisaged to rise further based on population growth and unreliable water quality of surface water resources (Mumma et al. 2011). Groundwater has been the best alternative for poor surface water quality, unreliable rains and high costs of water treatment. However, human activities including waste generation and disposal has continuously resulted into groundwater quality degradation (Döll et al., 2012; Asoka et al., 2018).

Groundwater contamination results from various components combining to contaminate or create an enabling environment for contaminants to reach the aquifers. These components are; distance of groundwater source from dumpsites, pit latrines, location of sources of contamination upstream or downstream of groundwater source, human activities around groundwater sources and groundwater design factors. Human activities use of onsite sanitation systems, urban agriculture, wastewater leakage, land use practices, human waste generation and disposal are serious threat to groundwater quality risking its reliability (Nagkoulis & Katsifarakis, 2022). This study therefore was undertaken to assess groundwater quality in urban and peri-urban areas of Webuye, Bungoma County Kenya.

1.2 Statement of the Problem

Surface water supply is becoming unreliable in recent times because of the cost involved in purification. This is due to its susceptibility to pollutants and effects of climate change. Nzoia Water Services company is the main water service provider in Webuye Town and its environments. Water is abstracted from River Nzoia adjacent to Nabuyole falls. The supply is interrupted in both dry and wet season where reduced water levels at the abstraction point reduce optimum abstraction as per the plant design capacity while in wet season, abstraction is interrupted due to high levels of turbidity making water treatment prohibitively expensive. The water service provider may need to develop measures to maintain or even increase water supply for the growing demand. The most definite option will be developing more water sources such as groundwater which is considered reliable due to its perceived proof against contamination and effects of climate change. According to Nzoia Water Services Company Ltd. water and sanitation coverage (2021) in Webuye

15% population within the study area is served by the sewerage network while remaining 85% rely on on-site sanitation disposal methods. This ends up threatening the water quality status of groundwater.

Research carried out by KfW, water and sanitation hygiene sensitization in Webuye, shows that a significant number of landlords and developers have limited financial resources or reluctant to mobilize resources to install proper water supply and sanitation for their tenants (KfW, 2006). For lack of developed water sources and low water coverage in the area by Nzoia Water Services Company, the residents end up going for shallow wells which are less costly to develop and operate. Areas with high groundwater utilizations, wastewater is managed onsite, in some places very close to abstractions points. Research conducted by Obala et al (2013) in Webuye found a that 46.1% of the residents in Webuye use shallow wells as their main sources of water. The study also found that there were 52.3% (417 cases out of 797 samples) prevalence of intestinal parasite prevalence of 52.3% which was attributed to poor hygiene and low access to potable water. According to Health and Demographic Surveillance System (HDSS) of Webuye, the residents have access to contaminated water water sources contaminated (HDSS, 2019). Pathogens leak from onsite sanitation systems to groundwater reserves, creating a reservoir for pathogens. The clean-up process of groundwater requires advanced technologies, time consuming, expensive and the impacts of pollution persists for years, decades, or even centuries it is therefore easier to prevent groundwater pollution than restoring polluted groundwater resources. This study aimed at carrying out an assessment of groundwater quality in rural and peri-urban zone of Webuye, Bungoma County Kenya. The study was used to come up with a tool for decision support to create awareness on the quality situation of ground water in Webuye for safe water planning.

1.3 Objectives of the Study

1.3.1 Main Objective

The overall objective for the study was to assess groundwater quality in Urban and peri-urban zone of Webuye Municipality, Bungoma County Kenya.

1.3.2 Specific Objectives

i. To determine pollution risk factors on groundwater quality in Webuye Municipality

ii. To determine chemical, physical, and biological water quality parameters of ground water sources in Webuye Municipality

iii. To develop and map water quality index of Urban and urban parts of Webuye Municipality

iv. To assess groundwater vulnerability to pollution in Webuye Municipality

1.4 Research Questions

i. What are pollution risk factors on groundwater quality in Webuye Municipality?

ii. What is the water quality of ground water sources in Webuye Municipality?

iii. What is the water quality index of Urban and urban parts of Webuye Municipality?

iv. What is the vulnerability of groundwater to pollution in Webuye Municipality?

1.5 Significance of the Study

Increased population in the urban areas has risen needs beyond the planned thresholds. On the other hand, increased population has put pressure on the available resources through pollution and over exploitation. Webuye municipality is neither new or exceptional to these challenges. Increased use of onsite sanitation facilities in areas with low coverage of water and sanitation has necessitated this study, in order to establish the relationship with the quality of groundwater, therefore the vulnerability of the aquifer. Through the results of this study, water quality index was established and mapped out in Webuye Municipality area. The results of this study were crucial to policy makers and municipality infrastructural management, for planning purposes. This study remains important information to Nzoia Water Services Company Ltd. for planning purposes. With increased demand in the service area, the company may seek to exploit more water sources and groundwater is the most suitable option.

1.6 Scope and Limitation

The study focused on assessment of groundwater quality in Webuye Municipality. The data was collected from 53 groundwater sources: 7 springs and 46 water wells in urban and peri-urban areas of Webuye Municipality. Water samples were analyzed for chloride, phosphates, Electrical Conductivity (EC), Total Dissolved Solids (TDS), nitrates, salinity, pH, turbidity, Total Suspended Solids (TSS), sulphates, and Total and Fecal coliforms. In the first sample period, in dry season, the study did not sample all the 74 groundwater samples because 28 shallow wells were dry at the time of sample collection.

CHAPTER TWO
LITERATURE REVIEW

2.1 Introduction

Water has become a main concern at policy level at a global level, this is evident in the report of the 3rd United Nations World Water Development (United Nations World Water Assessment Programme (WWAP, 2009). The report warns that if water is inequitably and unsustainably used momentous consequences may result. Inequitable and unsustainable water result into security and economic risks. The global energy threat closely becoming coupled up with an emerging water crisis. The energy, food and water linkages which are expressed through the impact of water use on consumption of energy (Grafton & Horne, 2014; Hoff, 2011; Pahl-Wostl, 2019).

Today, recognition of accessibility water and sanitation as a human right is seen in various initiatives like in the resolution 64/292 of the United Nations (UN) (Assembly & Committee, 2010) and in SDG (The United Nations, 2018). There are efforts to increase access to improved water and sanitation services, however, it's only 19% of the global population have access basic drinking water services (Mukherjee, 2018). The quality of the water is determined by the attributes of the source. Surface water sources provide drinking water for approximately 50% of population, but its quality is generally require extensive treatment. The other 50% population is provided by the groundwater which is considered safe though prone to contamination among others, solid waste landfills and onsite sanitation systems.

2.1.1 Groundwater resources

The competition for water has taken shape across the globe, and this is fueled by the growing population, increased industrial, agricultural activities and economic development. Groundwater is approximately 20% of the global water use. Regions with high humidity like northern Europe and Japan, groundwater is mainly for industrial and domestic use (T. Shah et al., 2007). In many countries away from the humid inter-tropical areas, groundwater is used to satisfy agricultural water demand (Zektser & Everett, 2004). Over exploitation of large aquifers to support agricultural water demand in India, Saudi Arabia, USA, Pakistan, China and Mexico, are under threat (Gleeson, Wada, Bierkens, & Van Beek, 2012). The rate of groundwater use supersedes the use of surface water globally; and with efficiency in drilling and pumping, and the growing awareness, the rate of groundwater usage is expected to increase further (T. Shah et al., 2007).

Groundwater is a very important resource even in Countries that receive a substantial amount of rainfall or even has well-endowed in surface water, where groundwater still supplies 85% of rural and 50% of urban water needs respectively (M. Kumar et al., 2006). Groundwater usage in Africa supersedes surface water even in regions that are well-endowed in surface water (Kumar et al. 2006). South Africa receives rainfall approximately 450 mm/yr (Binns et al. 2001), while Congo and Papua New Guinea are rich in freshwater resources, but they are classified as water stressed countries. Ethiopia is the water tower of East Africa. It is endowed with nine major river basins but it still has water shortages. This is due to the increased water demand and deteriorating water quality of surface sources. Utilization of groundwater in Africa is motivated by; its slower response to extreme weather variability and its convenience to develop within points of need (Calow et al. 2010).

It is approximated that in Kenya, 17 million people living in Arid and Semi-Arid Lands (ASALs). These residents get their water from groundwater resources; due to the fact that surface water is scarce and the area has varying and unpredictable rainfall patterns (Mumma, Lane, Kairu, Tuinhof, & Hirji, 2011). With progressive population growth in Kenya and continuous depletion of surface water resources, demand for groundwater is expected to rise (Mumma et al., 2011). There has been tremendous progress towards human development of late this has continuously resulted into groundwater degradation and depletion from climate change and human activities (Asoka, Wada, Fishman, & Mishra, 2018; Döll et al., 2012).

2.2 Groundwater pollution

Contamination of groundwater is caused by various components combining to contaminate or set up polluted environment for contaminants to reach the aquifers. Some of factors considered for both springs and wells are; distance of spring from dumpsites, pit latrines, location of sources of contamination (upstream or downstream of the well or springs, human activities around wells and springs and groundwater design factors. The agricultural activities and waste handling methods are the most common sources of contamination of groundwater. Use of fertilizers in irrigated agriculture can degrade water quality increased chances of nitrate and salinity contamination (Homoncik, MacDonald, Heal, Dochartaigh, & Ngwenya, 2010; Scanlon, Jolly, Sophocleous, & Zhang, 2007).

2.2.1 Onsite sanitation systems

Urban and peri-urban communities living in areas not covered by municipal sewer lines or high costs of installation, largely depend mostly on on-site sanitation systems (OSS) which are steadily growing in use and awareness as part of the wastewater facilities (Gunady, Shishkina, Tan, & Rodriguez, 2015; White, Bradley, & White, 2002). (Kiptum & Ndambuki, 2012) attributes the increased use of onsite sanitation systems in Eldoret to low water and sanitation coverage by the local Water Service Provider and the fact that these facilities are cheap in installation and operation. OSS have been in use for a long-time, however, poor installations and operational inefficiency in treatment processes is compromised therefore discharging untreated or partially treated effluent to the environment (Heinonen-Tanski & Matikka, 2017; Utne-Palm, 2002). Installation defaults and their distance to groundwater abstraction points is one big undoing of these systems (Palamuleni & Akoth, 2015), especially for unlined or semi-lined systems, they increase the chances of groundwater contamination through leachates to the aquifer (Shivendra & Ramaraju, 2015). Most OSS used especially in developing world are either unlined or semi-lined therefore, not watertight, thus allowing the wastewater to leach to aquifers. In most urban set up pit latrines are commonly located in short distances from the groundwater abstraction points (Deepnarain et al., 2020). In such cases, groundwater cannot be directly used for consumption without proper treatment.

Poorly installed and operated on-site sanitation systems are potential sources of pathogens and nutrients which lowers the water quality standards of natural waters and increasing risks to public health. Furthermore, poorly designed, constructed and maintained on-site systems lead to inadequate function and under performance (Gunady et al., 2015). Such systems release partially or untreated effluents into the environment leading resulting into microbial contamination of ground water sources (Čapek et al., 2018).

(Graham & Polizzotto, 2013) indicated that misconceptions on suitability of groundwater for drinking purposes still exist. A study carried out in India on groundwater pollution awareness revealed that barely 3–4% of the research sample was had knowledge on groundwater pollution (S. Das et al., 2019). Study shows that approximately 1.77 billion people fully use pit latrines as primary mode of sanitation (Graham & Polizzotto, 2013). Watertight OSS's are relatively costly but if installed, they can partly address this type of groundwater contamination. These systems are therefore, not applied for sanitation purposes in the developing world especially by the urban poor.

In Kenya, instances of groundwater pollution is as a result of municipal wastes, agricultural chemicals from industrial wastes and fertilizers (Little, Hayashi, & Liang, 2016). Cases of associating groundwater pollution with onsite sanitation systems; septic tanks and soak pits in urban and peri-urban areas have been researched and reported in groundwater of Mombasa and Kwale as early as 1997 (Tole, 1997). This phenomenon has attracted more recent studies in Kenya. Research carried out by (Kanda, Odiero, Lutta, & Ong'or, 2018) established a significant relationship between onsite sanitation systems and groundwater contamination in rural areas owing to design failures and inadequate operational capacity. The overwhelming challenge of groundwater pollution is that the purification process is time consuming, expensive, requires advanced technologies and the impacts of pollution persists for years, decades, or even centuries (Mileham, Taylor, Todd, Tindimugaya, & Thompson, 2009).

2.2.2 Agricultural Factors

Population growth has led to increased demand for food and therefore expansion of irrigation fields, for food production. It is approximated that 70% of diverted freshwater intended for human use is used in agricultural production. This is set to increase due to the expansion of irrigated agriculture (Stoichev, Alexandrova, Raikova, Angelov, & Stoicheva, 1999). Farming and other human activities have several impacts on the soil leading to deposits of organic compounds, microbial contaminants and fertilizers. These impacts affect the quality of soil, affecting plant productivity (Stoichev et al., 1999). Non-point pollution sources are moved from the earth surface by surface runoff and groundwater pathways. In this kind of pollution, pollutants do not originate from a particular source, but to undefined contributing area (Liu, Wu, & Zhang, 2005).

Population growth has been projected to have an impact on increases food demand and therefore discharge of nutrients into the water sources. However, its important to note that population increase puts pressure on available water and sanitation facilities. Municipal water and sanitation services take a lot of time and resources to cater for new or unexpected demands. This leads to open defecation, increased pit latrines and increased water borne diseases.

2.2.3 Groundwater sources design and construction factors

Water wells in residential locations in urban areas may be vulnerable to contamination because they are sited near sources of contaminant, and they often draw water from unconfined aquifers. Observation shows that in most cases wells are constructed just next to OSS and are not well maintained. The lack of well maintenance can result in unsanitary conditions and poor water quality. Suitable well design can greatly reduce chances of pollution by providing proof.

Study carried out by Kanda (2023) in Vihiga County Kenya on assessment of groundwater quality, reported that it is important to minimize groundwater pollution from onsite sanitation systems especially in areas where hydrogeological features support easy infiltration of contaminants. This can be done through proper site oriented well design and capacity building users on safe well operations (Kanda et al., 2023). The well design should ensure that the apron slab of the well contains surface water splashed ensuring that it does not flow back into the well. To ensure this, the slope of the circular apron should be not less than 0.9m in radius from the middle of the well, with raised edges (75-100mm) and smooth surface finishing. The apron should slant into a folded drainage with a slope of 1:50. Well lining should also be installed to protect it from subsurface contamination. Well linings can be easily constructed using locally available material like burnt bricks, galvanized iron rings and sinking caissons. Well construction regulations specify a minimum separation distance 30 m between wells and onsite sanitation facilities (Ndoziya, Hoko, & Gumindoga, 2019). However, they are usually located relatively close to each other because they must both be located on one piece of land and closer to the house (DeSimone, Hamilton, & Gilliom, 2009).

Shallow aquifers are prone to pollution due to the almost direct effects of human activities on the earth surface (Embrey and Runkle, 2006). A study by (Arnade, 1999) in Florida, USA, established an inversely Proportional relationship between wells and septic tanks where if the distance between domestic wells and septic tanks is reduced, there will be increase in concentrations of fecal coliform. Other study findings have reported that domestic wells in areas practicing agriculture have a higher risk of bacterial contamination (Conboy & Goss, 2000; Goss, Barry, & Rudolph, 1998).

During spring construction, protection area of not less than 100m in radius should be established. Springs need protection against inflows of contaminants for upstream environment. Spring protection can be enhanced through construction of a spring box, spring tapping and drainage provision. Surface water can be controlled by a drainage ditch constructed upstream and around the spring to control pollution from surface runoff (Bubuya, Mwambutsa, & Scott, 2008). Further, (abdalla, makokha, & maalim, 2021) advice that spring areas should be fenced in the radius of 10 – 20 m to protect the spring from human activities such as farming and grazing.

2.2.4 Excreta Generation and Disposal

As outlined in the Sustainable Development Goals (SDG's) goal number 6 promotes access to water and sanitation as part of UN's blueprint for a more sustainable future for all. With all the efforts geared towards promoting access to improved sanitation facilities, the risk of exposure to pathogens present in human excreta must be reduced. Several studies (Conboy & Goss, 2000; Fewtrell et al., 2005) show that technologies in sanitation have reduced the prevalence of diarrheal disease and helminth infections.

The measures put in place by various stakeholders to attain this goal No. 6 of the SDG are only focused household. However, it is very important to comprehend the status of human excreta starting from point of generation to the point of disposal or containment, the entire sanitation chain. This can help to ensure a preventing human from excreta contact within and beyond the household premises (Peal, Evans, Blackett, Hawkins, & Heymans, 2014).

2.2.5 The Sanitation Chain Assessment

Urban sanitation process is a complicated system and requires skilled technical competency to handle. The urban sanitation set up needs interconnected networks systems to address domestic, commercial and open defecation. To be able to put in proper measures in handling sanitation issues in urban set up, the current sanitation situation must be understood well (Baum, Luh, & Bartram, 2013; Sato, Qadir, Yamamoto, Endo, & Zahoor, 2013; Williams & Overbo, 2015). The simplest way to understand the sanitation stages; (containment, emptying, transport, treatment and disposal) is finding a way to track waste from generation to disposal, however, methods of assessment has been a gap for a long time, because of the complexity of the sanitation chain especially in urban areas.

However, efforts that have been recently developed to fill these gaps. There are several systems developed to solve the water and sanitation imbalance in urban set up. Systems like the Performance Assessment System (PAS) was developed and tested in India to benchmark for water supply and sanitation services (Carolini & Raman, 2021). There was also AQUASTAT, and the International Benchmarking Network (IBNET) (2018), developed to assess the urban sanitation status in extensive areas. AQUASTAT and IBNET have been found unreliable since they fail to include systems that are not the main water and sanitation service providers or large utilities in areas of study outside of those provided by large scale utility service providers. On the other hand, Performance Assessment System (PAS) deals with almost all players of water and sanitation and the system is used in parts of India. World Health Organization also developed Sanitation Safety Planning (SSP) to assesses poor sanitation risks so as to build on their principle for wastewater re-use (Pittet, Allegranzi, Boyce, & Experts, 2009). However, of all these systems, none has been widely applied in simulation of sanitation chain in urban and peri-urban areas.

To complete the assessment of sanitation chain including all players be it public or large utilities and private a method for assessment of urban sanitation service delivery was developed, and as described by (Peal et al., 2014) this model performs this assessment through assessment service delivery stages and a fecal waste flow diagram (also known as a shit-flow diagram, SFD, or (SFD) Graphic). SFD model has the ability to visibly depict sanitation chain failures stages in the sanitation service delivery. It particularly points on waste treatment, disposal and reuse, (Peal et al., 2014). The “shit-flow diagram” or SFD method has been widely accepted and used. It is now being used as a tool for pointing out political dynamics and technical effort play around in solving the sanitation status in an urban set up. The SFD was recommended in the 2018 World Health Organization guidelines on sanitation and health (Pittet et al., 2009).

World Bank's Water and Sanitation Program facilitated research on fecal sludge management in 12 cities for the purpose of developing tools for promoting knowledge on the flow of excreta through the cities in 2012–2013. Since then, a number of excreta management bodies began collaborating in June 2014 to improve the SFD (Mitra, Narayan, & Lüthi, 2022). Majority of urban dwellers, especially those in low-income areas, use non-sewered sanitation options because of unplanned settlements. This results into rise of sanitation challenges for growing urban areas in developing countries, and many of these countries need to develop or relook into their sanitation strategies in response to their respective population growth. The use of shit flow diagram helps sanitation organizers and the stakeholders to see challenges facing their sanitation systems, and propose for practical improvements. The graphical presentation is made simple to start dialog excreta management. SFD's have been used in 140 cities in the developing world and the information has been used to direct resources (Peal et al., 2014).

The Shit Flow Diagram (SFD) was used to model the chain of excreta management throughout the sanitation service chain. The idea was to understand the unsafely managed excreta through asking key informants from Nzoia Water Services Company Ltd and sanitation data by Kenya National Bureau of Statistics (2019) to give data of the questions listed below:

(i) Exhausted (emptied) human wastes but not delivered to the plants

(ii) The contents of pits and tanks which are emptied but not delivered for treatment

(iii) contents of pits and tanks which are not emptied and are overflowing, leaking, or discharging to the surrounding environment

(iv) wastewater in sewers not delivered to treatment

(v) fecal sludge and supernatant delivered to treatment but not treated

(vi) wastewater delivered to treatment but not treated

2.5 Pollution Risk Assessment

Risk is defined as the product of an event and the impact (Thornton, Pearce, & Kavanagh, 2011). Pollution risk assessment is the evaluation of quantitative and qualitative risks humans and environment are exposed to, by exposure to pollutants. Groundwater pollution risk' is the likely consequence on the groundwater arising from a specific point source through a subsurface pathway. Risk is the measure of a hazard to turn into a source or medium of contamination and therefore affecting human health, as well as reducing the reliability on groundwater. Pollution hazard was used to refer to a condition through which an aesthetically objectionable or degrading material could enter groundwater sources. In order to carry out this assessment, the potential level of harmfulness for every hazard should be considered. It is determined by the quantity of toxic substances and the toxicity level released to the environment, should a pollution even occur (Thornton et al., 2011).

The profile is represented in two main categories level I and level II. Category I are the main hazards in the hazards inventory. The presented Level II Categories is a representation of likelihood of a risk; additional criterion, which discerns hazards based on source of groundwater contamination, activities or status likely to cause pollution, with their respective range of possible pollutants as shown in Table 2.1. Other than the nature and quantity of harmful substances essential to a hazard, the security measures, level of maintenance, the surrounding conditions, and technical status are considered fundamentals when carrying out assessment of probability contaminant. The weights are multiplied across the level II category to get risk factors (RF), which are then categorized into desirable risk index (RI). The risk indices (RI) should be classified into Risk classes (Viban et al., 2021).

Table 2. 1: General groundwater pollution factor categories

No.	Level I categories of hazard	Level II categories (risks)
1	Environmental conditions	Sewer overflows/ Stagnant water
1.1		Municipal solid waste dumping
1.2		Waste drainage status lined/unlined
2	Location of septic tanks/toilets/dumpsites	Upstream of the water source
2.1		Distance to water sources
2.2		Topography
2.3		Type of toilet
2.4		status, cracked, lined, unlined
2.5		Household waste dumping
3	Human activities	Human waste transport and dumping
3.1		Farming & washing around the well
3.2		Open defecation
4	Onsite sanitation systems	Proximity to water wells and springs
4.1		Lining
4.2		Rope and bucket
5	Geological properties	Type of soil
5.1		Infiltration
5.2		Hydraulic status
6	Status of the well	Abstraction methods
6.1		Well lining, well depth and cover

2.6 Water Quality Index (WQI)

Water quality index (WQI) is a simple way of explaining complex water quality data by providing a range of percentage which gives the general water quality of a particular location and time, in conformity with several water quality parameters so as to make the information simplified and usable by the public. Water quality is a significant attribute of water supply sources and help to assess various options in water abstraction (Ouyang, 2005). The other essence of water quality indexing helps in providing information that is important in monitoring the sources of water for the purposes of supply. This information is important for conservational and economic growth since water demand is on the rise while availability continues to shrink. Water quality index helps to identify the source (s) of contamination and develop a strategic water quality protection to reduce potential public health risks (Carroll, Dawes, Goonetilleke, & Hargreaves, 2006).

There are many water quality index calculation methods. Many of the water quality indices depend on systemizing, data parameter by parameter in accordance with anticipated concentrations and definition of 'good' versus 'poor' concentrations. Parameters are allocated weight in the order of their significance to the general water quality. The water quality index is predetermined as the weighted average of all observations of interest (Katyal, 2011; Liou, Lo, & Wang, 2004; Pesce & Wunderlin, 2000; Sargaonkar & Deshpande, 2003). Water quality is calculated based on human consumption standards as recommended by (WHO, 2004). The methods presume that weights given to parameters is inversely proportional to the recommended standards for the corresponding parameters (Mishra & Patel, 2001; Naik & Purohit, 2001). The following sections represents formulae be used to calculate WQI.

2.6.1 National Sanitation Foundation-Water Quality Index (NSF-WQI)

This is a widely applied water quality index (WQI) method which was developed by National Sanitation Foundation (NSF) in 1970 (Brown, McClelland, Deininger, & O'Connor, 1972). This method was arrived at in order provide a homogenized method for contrasting the water quality for different of water bodies. NSF-WQI includes nine water quality parameters: BOD, nitrate, DO, total solids, pH, turbidity, temperature, total phosphorus, and fecal coliform (Ewaid, 2017). Every parameter confers varying contribution upon the moderation of the water quality, a distinct weight while calculating the NFS-WQI index is attributed to each of the parameters listed in Table 2.2 below.

Table 2. 2: NFS-WQI standard weight for water

S/no.	Parameter	Weight factor
1	Biochemical Oxygen Demand	0.11
2	Dissolved oxygen (OD)	0.17
3	Coliforms	0.16
4	PH	0.11
5	Temperature	0.1
6	Nitrates	0.1
7	Total Phosphate	0.1
8	Turbidity	0.08
9	Total solids (TDS)	0.07

Source: (Călmuc et al., 2018)

Calculation of WQI in this method is based on the equation 2.1:

$$NSF - WQI = \sum_{i=1}^{n} W_i \, Q_i \qquad (2.1)$$

where:

WQI-NFS value ranging between 0-100;

W_i is the weighting value of parameters in Table 2.2

Q_i is the sub-index of the quality parameter i, (Darvishi, Kootenaei, Ramezani, Lotfi, & Asgharnia, 2016). Upon calculation of the NFS-WQI index, the analyzed water source score is categorized as shown in the Table 2.3.

Table 2. 3: Categorization of NFS WQI

NFS WQI Value	Water Quality
90-100	Excellent
70-90	Good
50-70	Medium
25-50	Bad
0-25	Very Bad

Source: Brown, 1972

The advantage of this method is that it totals up the water quality to one value, faster and objectively in duplicable manner evaluation of water quality can be modified to vary in discrete areas. Additionally, the index value obtained provides information on potential water use. However, this method is limited to specific water quality parameters and in the event of manipulation, some data is lost (Paun et al., 2016).

2.6.2 Oregon Water Quality Index (OWQI)

The purpose Oregon Water Quality Index is to demonstrate a simple method for demonstrating the water quality of Oregon's streams for the purposes of recreation. This method was initially developed in 1970’s, but improved understanding of water quality dynamics overtime has informed modification of this method. The Oregon Water Quality Index (OWQI) expresses water quality of an area through a single number by combining water quality measurements of variables for eight water quality parameters including: temperature, dissolved oxygen, total phosphorus, pH, total solids, biochemical oxygen demand, ammonia+nitrate nitrogen and fecal coliform) (Cude, 2001). The main contrast in this method is in the calculus approach and the weight allocated to each parameter though it’s not taken into consideration. The approach in the arithmetic average method is utilized in this method, and is calculated using the Equation 2.2 (Tyagi, Sharma, Singh, & Dobhal, 2013).

$$\mathrm{OWQI} = \sqrt{\frac{\mathbf{n}}{\sum_{\mathbf{i=1}}^{\mathbf{n}} \frac{\mathbf{1}}{\mathbf{SIi^2}}}} \qquad \textbf{(2.2)}$$

where:

n numbers of parameters (n=8),

S_i is the sub-index of sub-index i^{th} parameter (Darvishi et al., 2016).

When using this method, value of the calculation is then categorized in the ranges of OWQI value as shown in the Table 2.4

Table 2. 4: Categorization of Oregon water quality index

OWQI Value	Water Quality
90-100	Excellent
70-90	Good
50-70	Medium
25-50	Bad
0-25	Very Bad

Source: Darvishi et al., (2016)

This method has the following advantages:

i. it enables one to contrast between sampling points

ii. use of weighted harmonic to combine sub-indexes enables the most impacted parameters to influence the OWQI the most;

iii. The formula is sensitive to environmental changes and significant impacts on water quality.

Disadvantages:

i. it simplifies multiplex methods thus creating chances of information loss
ii. this method is limited in a way it cannot evaluate other water quality parameter: bacteria, metal.

2.6.3 CCME-WQI

Developed by the Canadian Council of Ministers of the Environment (CCME) Water Quality Index (WQI) the purposes was to simplify reporting of water quality (Vijayakumar, Gurugnanam, Nirmaladevi, & Panchamin, 2015). This method was first applied in British Columbia province in Canada before adoption by various other authorities and institutions. The application progress and status of this method was assessed by a CCME WQI technical sub-committee for the purposes of evaluating how it could be applied nationally (Khan, Tobin, Paterson, Khan, & Warren, 2005).

To calculate the WQI in a stream, quite a number of parameters are used in this method: dissolved oxygen (OD), turbidity, temperature, conductivity, color, pH, alkalinity, Ca, Na, Mg, K, SO_4, Cl-, F-, Dissolved Organic Carbon, P, Nitrates, Nitritis, N, SiO2, Al, As, Ba, Be, Cd, Co, Cr, Cu, Fe, Hg, Li, Mn, Mo, Ni, Pb, Se, Sr, V, Zn (Jakovljević, 2012). The CCME WQI model comprises of 3 measures of variance from specific water quality parameters (Scope; Frequency; Amplitude). In this approach, there are 3 main factors which guide the arrival to a WQI. The factor (F_1 F_2 and F_3) are evaluated using mathematical formula to answer the questions:

F_1 how many $$F_1 = (\frac{numb \quad of\ failed\ variable}{Total\ no.of\ variable}) x\ 100 \quad (2.3)$$

F_2 Number of failed test $$F_2 = \left(\frac{Number\ of\ failed\ tests}{Total\ number\ of\ tests}\right) x100 \quad (2.4)$$

F_3 How much $$F_3 = \left(\frac{Failed\ test\ value}{Objective}\right) - 1 \quad (2.5)$$

This combination will combine to produce one value between 0 and 100 that represents the overall water quality as shown in Table 2.5.

Table 2. 5: Categorization of CCME WQI Values

CCME-WQI-Value	Water Quality
95-100	Excellent
80-94	Good
60-79	Fair
45-59	Marginal
0-44	Poor

Source: (Uddin, Moniruzzaman, & Khan, 2017)

CCME-WQI is well applicable in cases of missing data, it has high suitability in analysis of data from automated sampling, it has high flexibility to different water uses and it is simple to calculate. However, CCME-WQI has its disadvantages, for instance; does not analyze biological data, it rates all variables with the same significance determination of index, has a partial description of water quality and since the variables are considered for a study, the method is not appropriate.

2.6.4 Weighted Arithmetic Water Quality Index Method

WQI under this method is given by the equation in 2.6: weighted arithmetic mean method, WQIA can be calculated using equation 2.6 (Brown et al., 1972):

$$\mathbf{WQI}_{A} = \sum_{i=1}^{n} q_i \ X \, W_i \tag{2.6}$$

$$\sum_{i=1}^{n} w_i = 1$$

Where:

W_i unit weight allocated per parameter

q_i 0–100 subindex rating for each variable and

n is the number of sub-indices aggregated.

Weighted Arithmetic method is not limited to the number of parameters, the number of parameters required are less for a specific water use, it provides information to policy makers and community and the method gives a combined influence of various parameters (Tyagi et al., 2013). The WQI values are given as shown in Rable 2.6 (Vaschenko et al., 2001).

Table 2. 6: Categorization of Arithmetic WQI values

Weighted Arithmetic WQI	Water Quality
0-25	Excellent
26-50	Good
51-75	Bad
76-100	Very Bad
100 & above	Unfit

Source: Vaschenko et al., (2001)

2.7 Groundwater vulnerability assessment

Groundwater is a reliable source of fresh water for all present-day human needs: industrial and domestic use (Machiwal, Jha, Singh, & Mohan, 2018). However, increased human population and their activities are impacting negatively on the quality of groundwater, putting this most reliable resource at high risk. Human activities, such as mechanized agriculture, wastewater handling, urbanization, land use changes, climate change and global warming are serious threat to groundwater therefore risking its existence (Chaudhari, Mithal, Polatkan, & Ramanath, 2021; Gardner & Vogel, 2005; Haritash, Mathur, Singh, & Singh, 2017; Machiwal et al., 2018; Nagkoulis & Katsifarakis, 2022; Ncibi et al., 2020).

It is important to effectively manage groundwater and free from contamination for posterity use. This makes it necessary to carry out a periodical assessment of groundwater vulnerability in order to make appropriate decisions for management of groundwater. Mapping groundwater vulnerability is actually an effective way to significantly protect groundwater from pollution (Oke 2020). Carrying out groundwater assessment to monitor contamination is an uphill task especially in extensive areas. Various researchers have developed several models to assess groundwater vulnerability in various areas (Gogu & Dassargues, 2000; M. Kumar, Chaminda, Honda, & Furumai, 2019; M. Kumar et al., 2006; Vrba & Zaporozec, 1994) these models are discussed in section 2.7.1 below.

2.7.1 SINTACS model

This model was first proposed by (Civita & De Maio, 1998) for the particularities of Mediterranean areas. SINTACS method was developed to modify DRASTIC to the distinctiveness of Mediterranean zones, such as Greece, Italy, Morocco and Algeria. The definition weights and rates of parameters in this SINTACS model is more flexible than DRASTIC, though the parameters of this model are similar to those used for DRASTIC model only that they have different rating: depth of water, infiltration, vadose zone, soil media, aquifer media, hydraulic conductivity and slope. In SINTACS model the values assigned to each parameter are different. It's important to note that assigning weights in SINTACS is inclusive, thus considering environmental conditions. SINTAX model is suitable for all hydrogeological zones (M. Kumar et al., 2019). The SINTACS indices range between 26 to 260 and is calculated as the weighted summation seven parameters as shown in equation 2.7:

$$\mathbf{SINTACS = S_r S_w + I_r I_w + N_r N_w + T_r T_w + A_r A_w + C_r C_w + S_r S_w} \tag{2.7}$$

To incorporate land use changes, SINTACS was modified to adopt the Land Use parameter (SINTACS-LU), majorly to ameliorate the accuracy in assessment of groundwater vulnerability (Jesudhas, Chinnasamy, Muniraj, & Sundaram, 2021; Tashayo, Honarbakhsh, Akbari, & Eftekhari, 2020). This model has been successfully used by (S. Kumar, Thirumalaivasan, Radhakrishnan, & Mathew, 2013) to carry out groundwater vulnerability assessment in Tamil Nadu, India. (Johnny, Sashikkumar, Anas, & Kishan, 2015) have also carried out Groundwater Vulnerability Mapping using SINTACS model interfaced in Remote Sensing and GIS Techniques. The model has been widely applied in groundwater vulnerability assessment because it is suitable and depends on available data thus making it affordable (Al-Amoush, Hammouri, Zunic, & Salameh, 2010).

2.7.2 Multi-Criteria Decision Analysis Techniques

Another model used in groundwater vulnerability model is the multi-criteria decision analysis (MCDA). This tool widely applied by researchers to deal with complicated decision problems (Kafy et al., 2021; Machiwal et al., 2018; Milan, Roozbahani, & Banihabib, 2018; Neshat, Pradhan, Pirasteh, & Shafri, 2014). It is applicable coming up with solution based on varying characteristics. The tool divides the situation into many and simpler fragments shown in Figure 2.1 the tool then does analysis separately for every part and integrates to give a solution.

The MCDA works as shown in the following steps:

i. Identification of the goal.

ii. Choice of decision benchmark

iii. Determination of relevance of each benchmark with the help of group of decision-makers with opinions.

iv. Fix the evaluation of alternatives according to these preferences and criteria values

v. Generation of outcomes associated with alternative/interest combinations.

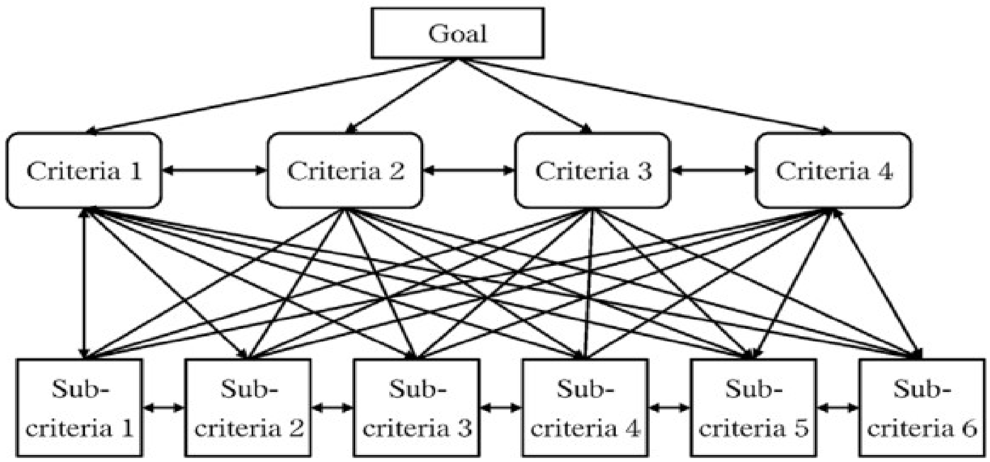

Figure 2. 1: Steps of MCDA model

Source: (Machiwal et al., 2018)

This method works in GIS interfaced application to make it suitable for groundwater analysis. The method is transparent, its steps are clearly specified and can adjust to accommodate complex scenarios. However, the method has too many paired comparisons leading to inconsistencies in classification (Machiwal et al., 2018).

2.7.3 DRASTIC model

US Environmental Protection Agency (USEPA) developed DRASTIC method to standardize and evaluate potential occurrence of groundwater contamination (Aller, Bennet, Lehr, Petty, & Hackett, 1987). It is an empirical method which helps to carry out assessment of groundwater vulnerability through numerical ranking of hydrogeological factors that influence groundwater movement through its vertical profiles. DRASTIC method is not new in groundwater vulnerability assessment.(Murmu, Kumar, Lal, Sonker, & Singh, 2019; Pacheco Castro, Pacheco Ávila, Ye, & Cabrera Sansores, 2018) Previously, researchers (Foster & Hirata, 1988; Morris & Foster, 2000) have conducted this assessment by veiling the vulnerability and hazard map (Uricchio, Giordano, & Lopez, 2004). DRASTIC model is familiar for carrying out an assessment for groundwater vulnerability. DRASTIC is an extensively renowned model for groundwater vulnerability assessment. It is the most popular, reliable and extensively applied empirical index method (Patel, Mehta, & Sharma, 2022). The total impact is based on score of the DRASTIC values based on the Equation 2.8 for vulnerability rating:

$$\boldsymbol{Vulnerability\ Index} = \sum_{i=1}^{7} \boldsymbol{W_i\ R_i} \qquad (2.8)$$

Where;

w is weight

r is rank.

(Patel et al., 2022)

2.7.4 Conceptual model – Measurement considerations

The following is a model presentation of the processes undertaken to arrive at groundwater vulnerability.

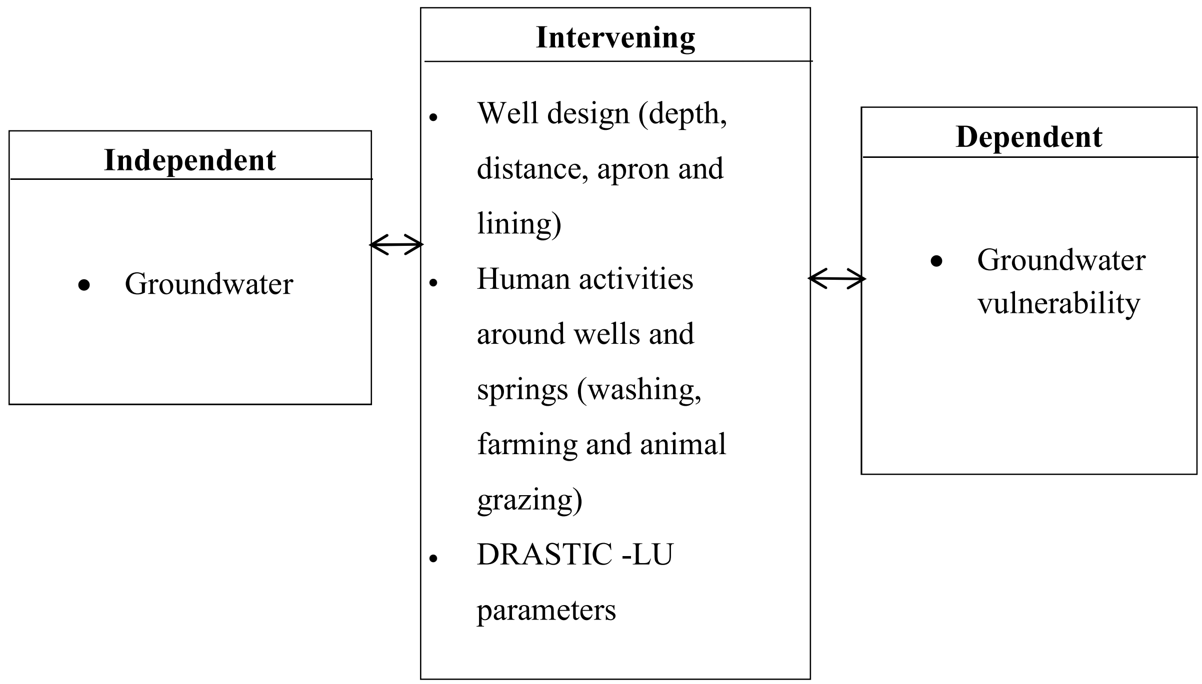

Figure 2. 2: Conceptual framework

CHAPTER THREE

MATERIALS AND METHODS

3.1 Introduction

This chapter discusses the approaches in data collection, research design and analysis to arrive at the objectives of the study.

3.2 Study area

This study was carried out in Webuye West Sub-County in Bungoma County. The area is located at latitude 00 45’0” N and 00 30’0” N of the Equator and longitude 340 40’0” E and 340 45’0” E of the Greenwich meridian. Webuye municipality totals up to 95.48 Km^2. Webuye West is made up of five sub locations namely Malaha, Maraka, Matulo,Township and Mihuu. The Sub-County is comprised of both rural and semi-urban areas, with a population of 151,654 and approximately 32,839 households in 6 sub-locations (KNBS, 2019). The Webuye Local Physical Development Plan estimations that the current population of Webuye town is about 65,000, implying that 43% of the population in the study area live in the urban areas. Increased population in Webuye has resulted in the increase in waste generation. Currently, only 15% of the total population within the study area is served by the sewerage system while 85% rely on on-site sanitation as disposal methods. Webuye town, like other urban centers in Kenya, is experiencing rapid population growth largely due to rural-urban migration and natural rate of increase.

3.2.1 Climate

Wet seasons in Webuye varies throughout the year varying 7.9 months, from March 26 to November 22, with a greater than 42% chance of a given day being a wet day. The month with the most wet days in Webuye is August, with an average of 21.9 days with at least 0.04 inches of precipitation. The drier season lasts 4.1 months, from November 22 to March 26. The month with the fewest wet days in Webuye is January, with an average of 4.4 days with at least 0.04 inches of precipitation. Rain falls throughout the year in Webuye. The month with the most rain in Webuye is April, with an average rainfall of 8.5 inches. The month with the least rain in Webuye is January, with an average rainfall of 1.2 inches.

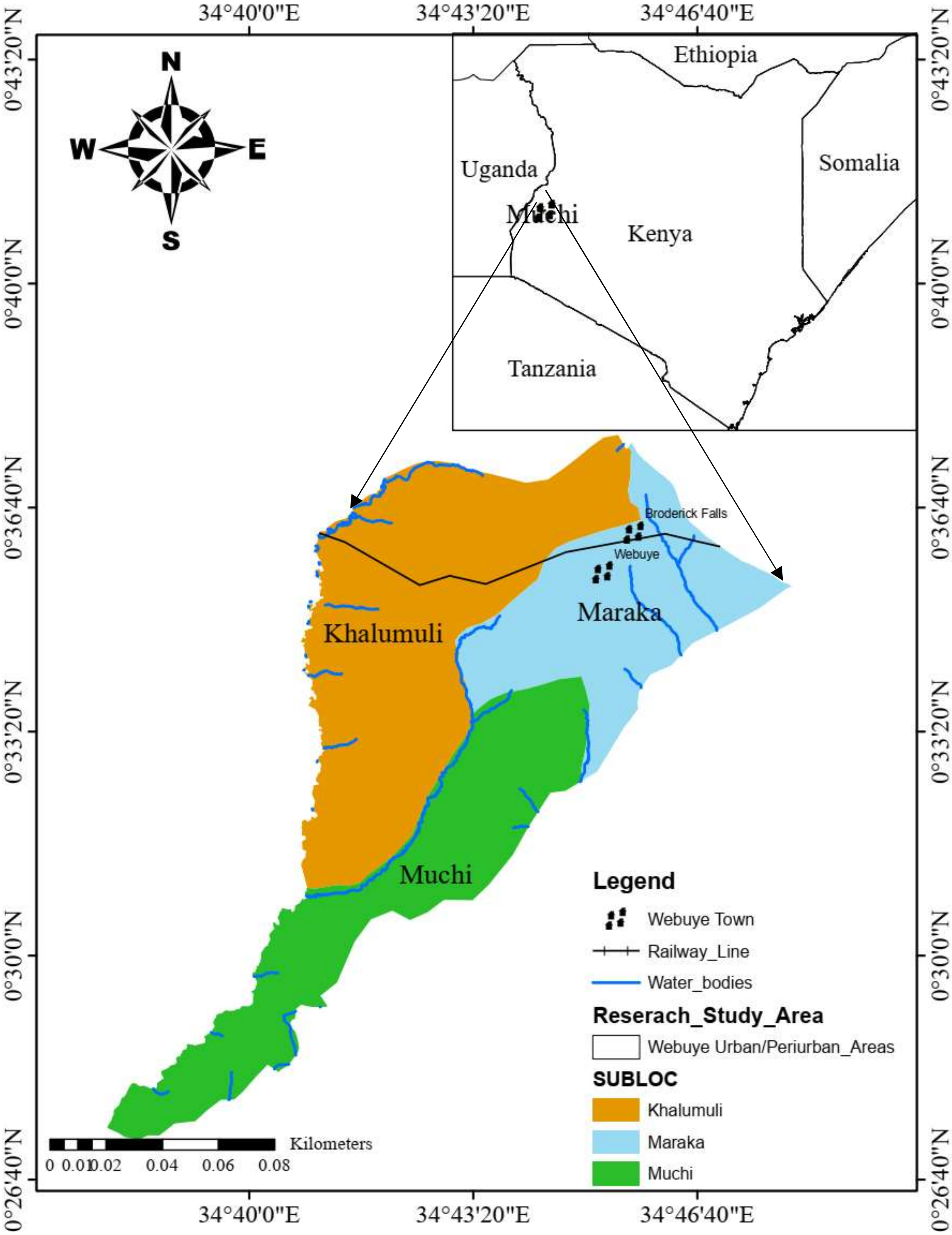

Figure 3.1: Map of the Study area

3.3 Sample size determination

According to the Water Service Provider in the region-Nzoia Water Services Company ltd., Webuye Municipality have approximately 85 shallow wells and 8 springs. In order to determine the correct sample size for this study, Slovin's formula was used. Slovin's formula is applicable in cases where a sample size is estimated from a population which one has no idea about how it behaves (Espinosa et al., 2008).

The Slovin's equation is shown in Equation 3.1

$$\mathbf{n} = \frac{N}{1+Ne^2} \tag{3.1}$$

N = population size

e = margin of error

N = population size

Information on exactly how many shallow wells exist in Webuye Municipality is scanty, the figures provided were approximated. In such cases, when there is no enough information on the population targeted, Slovin's formulae is applicable. In sample size determination, a 4% margin of error was applied.

$$n = \frac{N}{1+Ne^2}$$

$$= \frac{85}{1+(85\ x\ 0.04^2)}$$

$$= 74$$

The sample size for the Well was 74, which were simple randomly sampled across the study area. However, total number of springs were 8 and were all sampled for the study. The collected samples are spatially mapped in Figure 3.2 below.

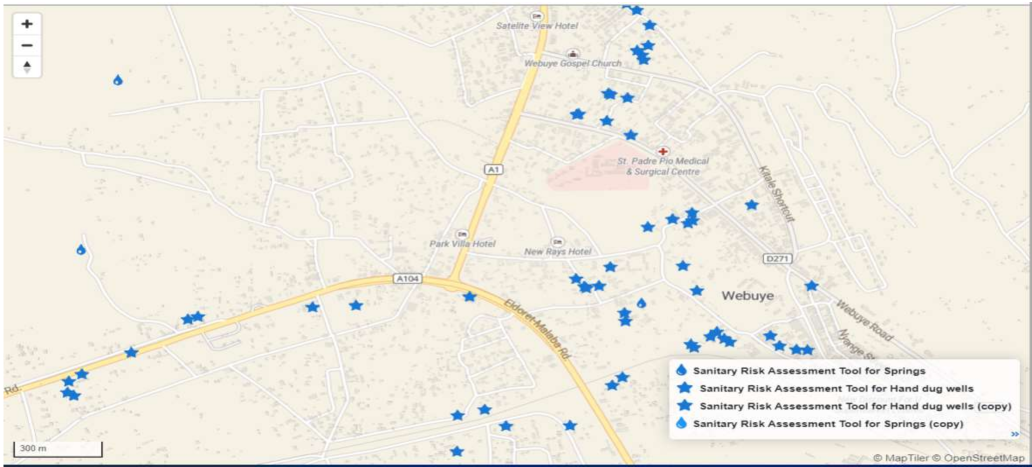

Figure 3. 2: Distribution of Shallow wells and Spring in Webuye

3.4 Research Design

This study used both experimental and correlational research designs. The research design used for each objective is shown in the Table 3.1 below.

Table 3. 1: Research Design

No	Specific objective	Measurable variable/ indicator	Research Design
1	To determine pollution risk factors on groundwater quality in Webuye Municipality	Design, construction factors: status of well covers, water depth, distance, availability of cut-off drains. Location of onsite sanitation systems; Waste generation, transport and discharge and soil geological characteristics	Experimental
2	To determine chemical, physical, and biological water quality parameters of ground water sources in Webuye Municipality	chloride, phosphates, Electrical Conductivity (EC), Total Dissolved Solids (TDS), nitrates, salinity, pH, turbidity, Total Suspended Solids (TSS), sulphates, and Total coliforms and Fecal coliforms	Experimental
3	To develop and map water quality index of Urban and urban parts of Webuye Municipality	Physical Water Quality Index: Electrical Conductivity (EC), Total Dissolved Solids (TDS), salinity, pH, turbidity, Total Suspended Solids (TSS), chloride and Bacteriological Water Quality Index: Total coliforms and Fecal coliforms	Experimental, ArcGIS
4	To assess groundwater vulnerability to pollution in Webuye Municipality	Depth to groundwater (D), Recharge (R), Aquifer type (A) Soil properties (S), Topography (T), Impact of the vadose zone (I), Hydraulic conductivity (C) and LU	Modelling

3.5 Data Collection

This part explains how the data for this research was collected in the study area including technology and devices used for the exercise.

3.5.1 Pollution factors

The pollution risk factors were collected from field observation, field measurements, well design, construction and operation. This data was collected from water wells where water sample were drawn. The wells were simple randomly sampled where water samples were take, observations were made, field measurements were taken in order to fill the sanitary risk assessment tool. The data collected in this category was: measurement of well distance form pollution sources, measurement of well width and the cover radius, measurement of well depth, abstraction methods, protection, human activities and drainage. The data was collected using sanitary risk assessment tool (as shown in Appendix 1 and 2) which was uploaded on the M-water application, installed on smart phones.

3.5.2 GPS Coordinates

Geographical points of groundwater, onsite sanitation systems and solid wastes disposal sites were collected during field data and water samples collection. This data was collected using M-water application which was installed on a mobile phone. The app was able to collect GPS points using the mobile phone's location. This enabled faster data collection, real time submission and easy precise data analysis.

3.5.3 Groundwater sample collection

The study area was categorized in three regions depending on the settlement's arrangements;

i. Webuye peri-urban site and

ii. Webuye town

Water points were collected from shallow wells and springs were randomly sampled. According to the sample size total of 74 water well and 8 spring samples were to be collected in both rainy and dry periods. However, the first data set was collected in February during dry periods and it was observed that 28 Hund dug wells and one spring had no water, they had dried up. The water samples were then collected from 46 water wells and 7 springs making it a total of 53 water samples that were collected in dry season and also another set of 53 in wet season for comparison. Water samples was collected from groundwater sources such as public drinking places, private residence and springs from contributing area. The 100ml sample bottles were carefully washed and rinsed in distilled water before sampling. The samples were categorized according to their sampling sources; as either spring or well.

3.5.4 DRASTIC-LU model data input

This section describes how the parameters DRASTIC-LU of the model were calculated and classified.

3.5.4.1 Depth of water

Depth-to-water level was measured using Solinst Model 102M P4 Probe Water Level Meter, manufactured in Canada by Solinst Canada Ltd. The water level was determined by reading directly from the flushing with the well surface. The tip of the cable has probe which send a signal once it gets in contact with water, the signal is made through a light and an audible buzzer. For accurate water level depth, the measurement was conducted very early in the morning before water is drawn from the wells. Water depths in wells was measured in meters (m). Water level of all wells was collected except for the wells that had no water.

3.5.4.2 Net recharge

The Webuye net recharge was generated from Webuye rainfall data sourced from regional the meteorological department in Kakamega. The data was overlaid on land use map which was downloaded from Diva GIS, for allocation of values based on the anthropogenic activities and natural occurrence in reference to percolation. The net recharge was allocated weight of 4 and classified in 5 classes >200, 150- 200, 100- 150, 50- 100 and 0- 50 mm/yr. this implied that the higher the rate of net recharge, the higher the chances of groundwater pollution.

3.5.4.3 Aquifer media

The aquifer information was taken from the geological maps obtained from Earthwise (https://earthwise.bgs.ac.uk/index.php/Hydrogeology_of_Kenya#Soil), and geophysical reports of boreholes done in the study area. The main lithological formation of the aquifer in Webuye, the aquifer is majorly comprised of assorted formation of sand, gravel and clay, the rating value of this media is 3. The aquifer was classified in two classes Sandy and Clayey. The formation was converted to raster, and reclassified under spatial analysis in ArcGIS.

3.5.4.4 Soil

The soil media is rated to reflect the potential of water and contaminants to infiltrate water. Soil data was derived from the soil maps obtained from ICPAC geoportal, was overlaid on the study area to be able to identify the soil category. The soil composition in Webuye is: Clay soils, Loam Clay and Nitisols. Soil data was collected from the soil maps downloaded from the ICPAC geoportal (https://geoportal.icpac.net/layers/geonode%3Asoils) and overlaid into ArcGIS 10.7, clipped into the study area to classify soil layers. Through this data it was possible to get the:

i. Type of the soil
ii. Soil classifications

iii. Hydraulic conductivity

iv. Soil depth and permeability

These soil attributes affect the rates of attenuation and through infiltration and contaminant transport.

3.5.4.5 Topography (slope)

The slope of Webuye municipality was sourced from the Digital Elevation Model (DEM). Slope values (%) were calculated from the DEM which was overlaid on the map of the study area in ArcGIS 10.7, then spatial analysis technique used to categorize and interpolate. The slope values were rated on the basis of principles of DRASTIC model. The slope was divided into four classes ranging from 0-2, 2-6, 6-18 and >18. The slope was rate 1-10 with 10 representing the highest slope and 1 representing lowest slope.

3.5.4.6 Impact of vadose zone (I)

The information about the aquifer was found from geological map and geophysical reports in Webuye Municipality. The aquifer in Webuye Municipality area is semi-confined. The confined area spreads to approximately 72% of Webuye municipality. Therefore, the vadose zone of the confined and unconfined parts is rated 1, 6 and 8 in classes of; clay, medium and fine sand. Impact of vadose was allocated weight of 5.

3.5.4.7 Hydraulic conductivity (C)

The data on conductivity was derived from standard conductivity provided for the type of soil composing the subsurface aquifer system. The values for hydraulic conductivity used in the study were 15.21 and 0.11 for clayey and sandy aquifer respectively. Hydraulic conductivity was rated 3 and 1, and it was weighted 3.

Table 3. 2: Standard hydraulic conductivity ranges for various soil type

S/No	Soil Texture	Hydraulic Conductivity (m/s)
1	Sand	1.7×10^{-4}
2	Loamy	1.56×10^{-4}
3	Sand loam	1.13×10^{-5}
4	Silt loam	7.19×10^{-6}
5	Loamy	6.94×10^{-6}
6	Sandy clayey loam	6.31×10^{-6}
7	Silty clayey loam	1.70×10^{-6}
8	Clay loam	2.45×10^{-6}
9	Sandy clayey loam	2.17×10^{-6}
10	Silty clay	1.02×10^{-6}
11	Clay	1.2×10^{-6}

Source: (Novák, Kňava, & Šimůnek, 2011)

3.5.4.8 Land Use

The landsat map was prepared using landsat image of Webuye for the year 2021 downloaded from earth explorer. Land use is important in DRASTIC modelling as it's the source of primary information and also helps in understanding the behaviour of a parameters like net recharge.

3.5.5 Sanitation flow analysis

Sanitation data was analyzed and input in the SFD for sanitation service chain analysis of Webuye municipality. The data included the population, type and the percentage of on/off site sanitation system used in the area, emptying and transport, the transport system: number and volumes of trucks, quality assessment, functionality and standard operation procedures of performance in wastewater treatment plants, end-use/disposal or reuse. Sanitation data was used to prepare a Shit Flow Diagram to explain the sanitation chain of Webuye municipality.

3.6 Data analysis

This section illustrates the methods used in data analysis and presentation.

3.6.1 Risk assessment methods

This was basically an assessment of a groundwater sources and the likelihood of the surrounding environment to contaminate the water source. Factors considered in this analysis were: existence of onsite sanitation facilities, dumpsites, their proximity to the groundwater source, geological properties, environmental conditions faults design and construction designs; well depth, upstream or downstream of the well or springs, human activities around wells and springs and water source protection. These factors were organized in two categories; Level I and Level II categories (Hazards and Risks) as shown in the Table 3.3 below.

In this study, DRASTIC indexing method was applied as used in (Baalousha 2006), where pollution factors were divided into 2 level categories: level 1 were the hazards and level II were the risks. Risks were allocated, weights ranging from 0-1 with 0 being less chances of pollution while 1 representing highest chances to cause pollution. The pollution risk factors weights were then multiplied across the level II category to get risk factors (RF), which were the categorized into desirable risk index (RI). The risk indices (RI) were classified into Risk classes (1,2,3) which were presented as Risk level (high, moderate or Low) and then coded with color (Red to mean high risk, Orange to mean moderate while Green mean low risk, (Viban et al., 2021).

DRASTIC indexing method was used to come up with rates and weights for the seven indicators. The product of rating values and weights of each parameter produced an index value for each parameter. The summation of the indices gave pollution index, called DRASTIC INDEX, which is measure extend of aquifer hydrogeologic vulnerability. The Drastic Index range from minimum value to maximum. higher index represents high vulnerability to contaminants while lower indices represent lower vulnerability. This can also be referred to as degree of vulnerability.

3.7 Generation of a Shit Flow Diagram (SFD)

The following stages were followed in generation of a Shit Flow Diagram:

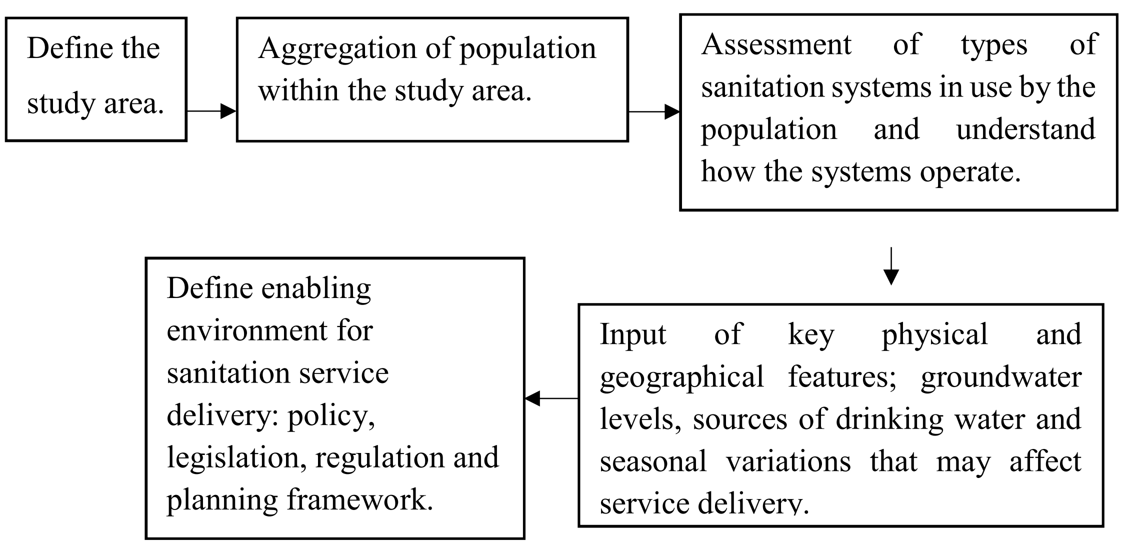

Figure 3. 3: SFD preparation

The results of the SFD were based on the percentage of either "safe" or "unsafe". "Safety" was a measure of likelihood of hazard to intrude into the environment.

3.8 Water quality analysis

The samples were analyzed in at Matisi Water Laboratory operated by Nzoia Water Services Company Ltd. Physical and chemical laboratory analysis was carried out both in-situ and ex-situ. The main parameters analyzed were: Turbidity, PH, Total Suspended Solids, Total Dissolved Solids, Electrical Conductivity, Salinity, Sulphates, Phosphate and Nitrates. Bacteriological tests were also carried to test for Total Coliforms and Faecal Coliforms. All samples collected in two seasons were exposed to same standard procedures for chemical and biological tests as shown in the Table 3.4 below and assessed against the drinking water standards in Kenya.

Table 3. 3: Sampling and analytical methods

No.	Parameters	Sample Container	Preservation	Volume (mL)	Analytical methods/Instrument
1	pH	Plastic	≤ 4 °C	25	Electrometric: pH Meter
2	Turbidity	Plastic	≤ 4 °C	100	Nephelometry
3	TSS	Plastic	≤ 4 °C	1000ml	Filtration, constant weight at 103°-105°C
4	Electrical Conductivity	Plastic	≤ 4 °C	1000ml	Electromagnetic induction method
5	Salinity	Plastic	≤ 4 °C	1000ml	Electrical conductivity meter
6	Sulphates	Plastic	≤ 4 °C	1000ml	Spectrophotometer
7	Phosphate	Plastic	≤ 4 °C	1000ml	Spectrophotometer
8	Nitrates	Plastic	≤ 4 °C	1000ml	Spectrophotometer
9	TDS	Plastic	≤ 4 °C	1000ml	Gravimetric, Dried at 180 degrees C
10	Total Coliform	Plastic	< 10 °C, Dark	100	MPN technique
11	E. Coli	Plastic	< 10 °C, Dark	100	MPN technique

3.9 Water Quality Index (WQI) Calculation

Weighted arithmetic was used to calculate the water quality index for Webuye municipality using Equation 2.6. The equation has been applied in several studies (Chauhan & Singh, 2010; Chowdhury, Muntasir, & Hossain, 2012; Olowe, Oluyege, & Famurewa, 2016; Tyagi et al., 2013) on the common measured water quality parameters.

Shown below are the steps followed in the calculation of urban and peri-urban areas of Webuye as guided in Brown et al (1972). The WQI was calculated using physical and chemical parameters; Turbidity, PH, Total Suspended Solids, Total Dissolved Solids, Electrical Conductivity, Salinity, Sulphates, Phosphate and Nitrates as shown in Table 3.4. The results of WQI were presented in five categories depending on the scores of each water source as shown in Table 3.5.

Table 3. 4: Water quality rating as per weight Arithmetic WQI Method

WQI Value	Rating of Water	Quality Grading
0-25	Excellent	A
26-50	Good	B
51-75	Bad	C
76-100	Very Bad	D
>100	Unfit	E

Source: (Tyagi et al., 2013)

Fecal coliform results were not considered for the WQI because the ratio of fecal coliforms to coliphage is influenced by prior contamination, presence of sediment, chlorination, and temperature but not when a fecal pollution event occurred.

3.9.1 Calculation of Unit Weight (W_n)

This step involves calculation of unit weight (W_n) for each parameter using the following approach;

$$\boldsymbol{W_n = \frac{K}{S_n}} \qquad 3.2$$

Where;

$$\boldsymbol{K = \frac{1}{\frac{1}{S1}+\frac{1}{S2}+\frac{1}{S3}+\cdots\frac{1}{Sn}} = \frac{1}{\sum\frac{1}{S_n}}}$$

S_n = Standard desirable value of the nth parameters

The allocated unit weight of all selected parameters sums to 1 W_n=1 (unity)

3.9.2 Calculation of sub-index of quality rating (Q_n)

Here, the calculation is based on equation 3.3;

$$\boldsymbol{QpH = \left(\frac{V_{pH}-7}{8.5-7}\right)100} \qquad 3.3$$

Let;

(*n*) there be the water quality parameters

(q_n) sub-index corresponding to nth parameter

The Q_n value of is calculated using equation 3.4.

$$q_n = \left(\frac{V_n - V_0}{S_n - V_0}\right) 100$$

Where:

Q_n = quality rating for the nth water quality parameter;

V_n = estimated value of the nth parameter at a given sampling station;

S_n = standard permissible value of the nth parameter;

V_0 = actual value of n^{th} parameter in pure water

Note: All actual (V_0) values are taken as zero (0) for pure water for all other parameters except the parameter pH, where it is 7.0 (Chowdhury et al., 2012) .

3.10 Groundwater Vulnerability - DRASTIC model

This section explains how DRASTIC-LU model was used; sources of data for the model and data input.

3.10.1 Model preparation

DRASTIC consisted of seven mappable hydrogeological parameters:

i. D- **D**epth to water,

ii. R- **R**echarge,

iii. A- **A**quifer media,

iv. S- Soil media,

v. T- **T**opography,

vi. I- **I**mpact of the vadose zone,

vii. C- Hydraulic **C**onductivity.

3.10.2 DRASTIC-LU Model preparation

To apply this model numerical ranking coupled with DRASTIC component, are used to assess the groundwater pollution potential for each hydrogeological variable. The model contains three parts:

1) Weights

2) Ranges and

3) Ratings.

Every DRASTIC parameter was allocated weight ranging between 1 to 5. In this order, 5 being considered highest contamination probability and 1 being considered least significant. Each DRASTIC parameter was also assigned a rating ranging between 1 to 10 based on the influence of each parameter to pollution concentration, as shown in the Table 3.6 below. In this study, Land use pattern in Webuye municipality was in the groundwater vulnerability assessment. Land use activities are very key in determining groundwater quality due to agricultural, sewerage, land use and industrial activities. Land use pattern was included in the vulnerability mapping. This section represents the DRASTIC-LU parameters, the ranges, rating and weight allocated to each parameter.

Table 3. 5: Rating and weight values of DRASTIC-LU models for Webuye

Parameters	RANGE	RATING	WEIGHT
D (Groundwater Depth (M))	>21	1	5
	10–20	3	
	5–10	8	
	<5	10	
	>200	9	
	150- 200	7	4
R (Net Recharge (Mm/Yr)	100- 150	5	
	50- 100	3	
	0- 50	1	
	Sandy	9	3
A (Aquifer Media)	Clayey	1	
	Clay soils	1	
	Loam Clay	3	2
S (Soil Group)	Nitisols	5	
	0-2	10	1
T Topography (Slope %)	2-6	9	
	6-18	3	
	>18	1	
I (Impact Of Vadose Zone)	Medium sand	8	5
	Clay	1	
	Fine sand	6	
C (Hydraulic Conductivity (M/D)	>16	10	3
	5-15	3	
	0-5	1	
Land-Use	Agricultural area	9	4
	Built-up area	8	
	Water body	3	
	Tree-clad area	1	

3.10.3 DRASTIC-LU index

The DRASTIC-LU index, was applied in this study to measure the probability of pollution. The parameters were then assigned weights depending on the hydrogeological conditions of Webuye urban and peri-urban areas. Weight factors of the DRASTIC-LU parameters ranged between 1 and 5 represent the relative importance of those parameters. The linear equation of the total impact score is the vulnerability rating or the DRASTIC index based on equation 3.5:

$$\boldsymbol{Vulnerability\ Index = \sum_{i=1}^{8} W_i\ R_i} \qquad 3.5$$

Where;

w is weight

r is rank.

Literally, these formulae can be interpreted in the simplified equation 3.6:

$$\mathbf{DRASTIC - LU\ ind} = \boldsymbol{D_r D_w + R_r R_w + A_r A_w + S_r S_w + T_r T_w + I_r I_w + C_r C_w + LU_r LU_w} \qquad \mathbf{3.6}$$

Where:

$\mathbf{D_r}$=ratings to the depth to water table,

$\mathbf{D_w}$= weights assigned to the depth to water table,

$\mathbf{R_r}$=ratings for ranges of aquifer recharge,

$\mathbf{R_w}$= weights for the aquifer recharge,

$\mathbf{A_r}$=ratings assigned to aquifer media,

A_w=weights assigned to aquifer media,

S_r=ratings for the soil media,

S_w= weights for soil media,

T_i=ratings for topography,

T_w= weight for topography,

I_r=ratings assigned to the vadose zone,

Iw= weights assigned to the vadose zone,

C_r=ratings assigned of hydraulic conductivity,

C_w= weights given to hydraulic conductivity,

L_r=ratings assigned of land use, and

L_w=weights assigned of land use.

In this study, the model was interfaced with ArcGIS 10.3 to carry out spatial interpolation of DRASTIC-LU values, from points using an inverse distance weighted (IDW) technique, which is based on assumption that things that are close to one another are more alike than those that are farther apart. To predict a value for any unmeasured location, IDW uses the measured values of parameters surrounding the predicted location. The IDW methos is also referred to as "Shepard's method" (Shepard 1968). Equation 3.7 is as follows:

$$\boldsymbol{F(x,y)=\sum_{i=2}^{n} w_i f_i} \qquad 3.7$$

Where:

n< is the number of scatter points in the set,

f_i are the prescribed function values at the scatter points (e.g., the dataset values)

w_i are the weight functions assigned to each scatter point.

3.11 Data Validity and Reliability

The following section presents how validity and reliability of data collection instruments was carried out in this study.

3.11.1 Pilot Test

The results of the pilot test were assessed by the researcher and the supervisors for clarity of the questions. Omissions and modifications were made on the questions as suggested by the supervisors in the Department of Civil and structural engineering of Masinde Muliro University of Science and Technology. The data was pretested to determine the validity and reliability. A pilot test was carried out on 11 wells sampled randomly in Lugulu area which is outside the study area. The data collection tools; interview schedule and the checklist were used to collect data. This exercise helped to evaluate for relevance, comprehension, meaning and clarity.

3.11.2 Validity

Validity is the level which tested items measure to what they purport to do and reliability as the consistence of a score from one occasion to the next (Auka et al., 2012). To determine whether the tool was able to answer the objectives of this study, content validity was used during by pilot test. Advice was sought from the supervisors from the Department of Civil and structural engineering of Masinde Muliro University of Science and Technology for instrument validation. Their corrections and suggestions were used to reproduce the final questionnaire. The content validity measures contained all variables used to measure every objective. The results in the spearman correlation gave a coefficient of 0.65, implying that the measure was acceptable.

3.11.3 Reliability

The definition by Mugenda & Mugenda (1999), gives reliability as a degree to which a research instrument is acceptable. Reliability is therefore, basically a measurement of the degree to which a procedure yields same outcome over repeated trials. Reliability was attained during pilot study where the interview schedule was administered to the same group or more than one times through test-retest method. Alpha (Cronbach) technique was used in reliability measurements, where a score obtained in one item was matched up with scores obtained from other items. Cronbach's Alpha is a general form of the Kunder-Richardson (K-R) 20 formula, whose application in assessment of consistency of instruments was on the basis of split – half reliabilities of data from possible halves of the instrument. Application of K-R 20 to compute a reliability as compared to other methods is time saving.

The K-R formula is as follows:

KR20= (K) (s2-∑s2) 3.8

(S2) (K-1)

Where:

KR20= Reliability Coefficient of internal consistency

K= Number of items used to measure the concept

S2= Variance of all scores

s2= Variance of individual items

High coefficients show that there is high correlation of items thus showing consistency among the items under the test. A model of intra consistency on the basis of average inter-item correlation is measured by Alpha (Cronbach) model. The instrument used in this study was divided in two parts based on even and odd numbers. High value of alpha (preferably greater than 0.6) implies higher consistence of the instruments. Respondents commented on the clarity and duration taken to answer an instrument. The value of internal consistency co-efficient was reached at 0.86, showing a high level of instrument reliability. Finally, the questionnaire was modified with considerations of the findings of the pilot test.

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 Pollution Risk Factors

This section identifies natural and manmade factors which pose contamination threat to groundwater sources in Webuye municipality. The factors are based on solid waste dumping, human waste disposal, transport and sources of water for Webuye by referring to both secondary and primary data. In this section, analysis of the risk levels of pollution risk factors on the groundwater sources will be carried out.

4.1.1 Sources of water

The sources of water for the Webuye municipality residents were sought. This was to profile the residents against their sources of water, to find out the commonly used water source in the study area. The results were analyzed and presented in the Table 4.1 below.

Table 4. 1: Sources of water for Webuye residents

No.	Sources of water	Population	Percentage (%)
1	Dam/pond	132	0.9%
2	Stream/River	788	2.0%
3	Protected Spring	19306	58.1%
4	Unprotected Spring	1281	4.0%
5	Protected Well	3185	10.0%
6	Unprotected Well	427	1.0%
7	Borehole/Tube well	1642	5.0%
8	Piped water	5549	17.0%
9	Rain/ Harvested water	196	1.0%
10	Water Vendor	328	1.0%
		32834	**100%**

Source: KNBS 2019

Table 4.1 above shows that 63% draw water from springs, 17% have access to piped water, 11% from Wells, 2% get water from rivers/streams, 1% from water vendors while 1% get water from rain harvesting. This data reveals that 74% of the population in Webuye municipality rely on groundwater sources. The natural water cycle s interfered with by human activities and affect the water quality status regardless of the water source. Human population has increased expectations on the nature to meet its needs to improve its living standard results into increased exploitation of existing resources and water suffers the most from both exploitation and the impact of other activities on its sources (Banu, Chowdhury, Hossain, & Nakagami, 2013). Surface and groundwater sources are recipient for rain water from surrounding catchment areas but also of wastewater and effluents both from surface runoff and infiltration (recharge) respectively. Getting rid of groundwater pollutants is almost impossible and expensive; we would rather prevent such pollution (Sasakova et al., 2018).

4.1.2 Pollution risk factors

The pollution risk factors in this study range from environmental, human and well design factors that contribute to groundwater pollution as described in the subsequent sections below.

4.1.3 Human waste disposal

Waste disposal is a pivotal factor which determines the safety of groundwater quality. The Table 4.2 shows various modes of human waste disposal as found in Webuye.

Table 4. 2: Human waste disposal in Webuye

No.	Human Waste Disposal	Frequency	Percentage (%)
1.	No sanitary facility	2	3%
2.	Pit latrine	38	51%
3.	Both Pit latrine and Septic Tank	13	18%
4.	Pour flush connected to pit	6	8%
5.	Septic Tank	7	9%
6.	Sewer line	8	11%
		74	**100%**

The study reveals that 51% residents use pit latrines as their main sanitation facility while 18% use both pit latrine and septic tanks. The results also show that 9% of the residents use septic tanks while 8% have their pour flush systems connected to pits. The results show that 3% respondents did not have toilets in their areas of residence.

These results agree with the findings of Kenya National Bureau of Statistics (KNBS) which conducted a sanitation census in Webuye Municipality in 2019 and found that 74% of the residents use covered pit latrines, 9% use VIP latrines, 8% use uncovered pit latrines, 4% use septic tanks, 2% connected to sewer and 5% had no sanitation facilities (KNBS 2019). The observation in the study area confirms the use of onsite sanitation systems in Webuye Municipality. Onsite sanitation systems have can have negative impact on groundwater with an aid of environmental factors. Several studies found that human and environmental factors are the roots of nitrate and bacterial contamination from onsite sanitation facilities, and the greatest concentrations in water wells are majorly found downstream of areas with high use of onsite sanitation systems (Chidavaenzi, Bradley, Jere, & Nhandara, 2000; Vinger, Hlophe, & Selvaratnam, 2012).

4.1.4 Solid waste disposal practices

Solid waste disposal is an important factor when assessing the quality of water in a given area. The study sought to find various ways used in solid waste disposal in the study area.

Table 4. 3: Means of solid waste disposal

No.	Human Waste Disposal	Frequency	Percentage (%)
1	Composite pit on compound	49	66%
2	Designated dumpsite outside the compound	11	15%
3	Garbage collectors	7	9%
4	No designated dumping point	7	9%
		74	**100%**

Table 4.3 shows that majority (66%) of the respondents use composite pits on their compounds, 15% had designated dumping sites outside their compounds, 9% was collected by garbage collectors while 9% had no designated dumping points in their residential areas. The results agree with the findings of (KNBS, 2019) which reported that 62% of residents in Webuye Municipality dump waste in composite pits, 12% dumped on the compound, 11% burnt in the open, 6% burnt in a pit while 2% is dumped on street, Vacant plot, Drain or Waterways. Solid waste dumping is a human factor which can have adverse effects on groundwater quality. The study reveals that most residents have composite pits around their compound. The observation shows most residents live on very small land areas where they some onsite sanitation facilities majorly pit latrines and groundwater sources thus leading to potentially compromising the hygienic status of the environment.

Dumpsite influences the environment and ecosystem of an area, and due to their openness, they attract flies, insects and other insects that would carry germs or public health hazards to water and people living around such areas (Nai et al., 2021). Dumpsites can also pollute groundwater directly through organic or inorganic leachates compounds from biodegradation of solid wastes flowing out from the refuse dumps, saturated with rainwater flowing through them (Nai et al., 2021).

4.1.5 Well design and human practices

This section discusses well design factors and human operational risk factors around the groundwater sources. The pollution factors ranged from human activities around the well, well design factors and type of sanitation facilities used as presented in the Table 4.4 below.

Table 4. 4: Pollution risk factors for wells

Depth		Types of toilet facility		Floor apron sloping		Location of the toilet		Human activities <2 m	
Depth	%	Facility	%	Sloping	%	Location	%	Human activity	**%**
0-5	49%	flush to septic	47%	Towards the well	44%	Higher ground	8%	Grazing	21%
5.1- 7	28%	flush to pit	16%	Away	29%	Level ground	5%	Cloth washing	41%
7.1 - 10	19%	pit latrine	23%	Flat	3%	Lower ground	11%	well area is kept	11%
10.1 - 20	3%	no toiles	3%					Waste dumping	8%
20.1 over	1%							Farming around	12%

The study reveals that 49% water wells have water depth between 0-5m, 28% have depth ranging between 5.1-7 m while 23% are water wells that have depth above 7.1 m. The study show that 47% residents use septic tanks, 39% of the residents use unlined pits while 3% had no toilet facility within their compounds. It was also observed that 44% floor apron slope towards the well while 8% toilets were located on higher grounds than wells and springs. The observation showed that there were human activities around hand dug wells and springs. The human activities include: Grazing, cloth washing, well area is kept, Waste dumping and farming around the groundwater sources. The results further show that 55% of the wells are less than 6m away from pollution sources, 28% are more than 21m away while 17% are between 7-20m away as shown in the Figure 4.2 below.

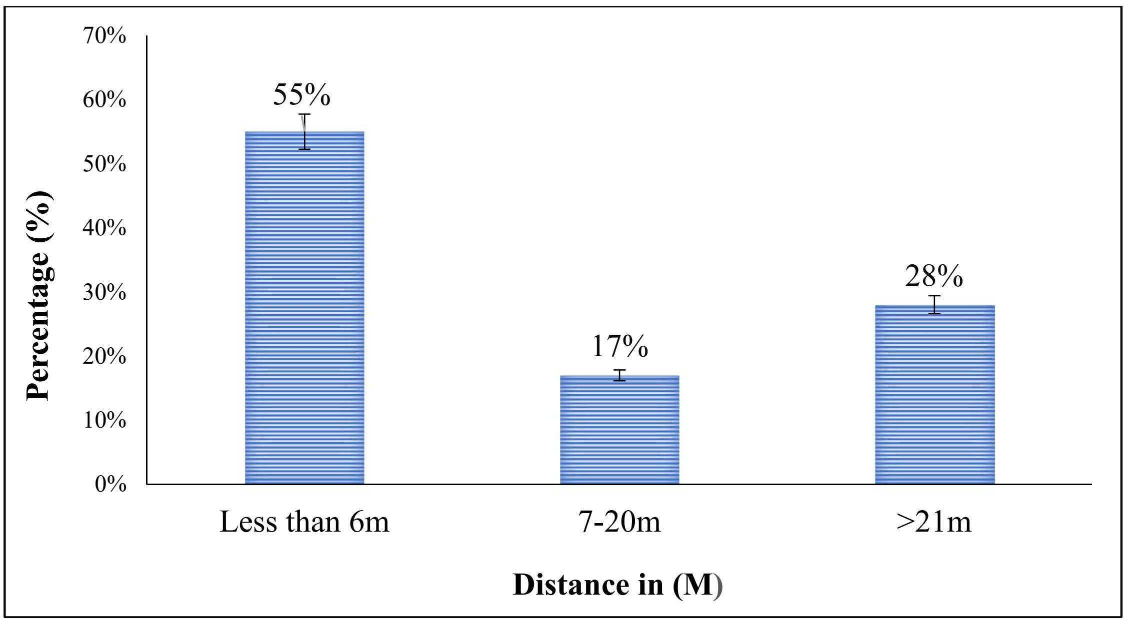

Figure 4. 1: The distance between groundwater sources and point pollution

In agreement with the findings, research on groundwater has drawn attention on onsite sanitation systems in urban and peri-urban communities, and most importantly; their distance to groundwater abstraction points (Palamuleni & Akoth, 2015), the fact that these are not lined or semi-lined systems, soaring chances of polluting groundwater through leakages to the aquifer (Shivendra & Ramaraju, 2015). Unlined and semi-lined systems are commonly used in the third world, and are not watertight. As a result, wastewater leaches to the ground and move long distances within the movement of groundwater. There are limited spaces in urban dwellings but residents try as much as possible to have water points and onsite sanitation systems in areas not served by sewer lines. In such arrangements, Pit latrines are commonly located closer to groundwater (Deepnarain et al., 2020).

There are private exhauster operators in Webuye Municipality who offer emptying and transport services. As seen from the most parts of the country the applicable tariff for this service is not affordable to all residents especially in low-income areas (Peletz et al. 2020). Some residents claimed that these trucks are expensive and therefore they can manage hire them, resorting to manual emptying where they empty one pit and fill another and cover. In the interview with the company, it was realized that some exhausters avoid paying dumping fee, and dump in the unregulated environment thus endangering the community.

4.1.6 Pollution risk assessment

This section shows the analysis of pollution risk factors which were observed in the field, analyzed and ranked according to their potential to cause harm. These factors were allocated weight, which was then multiplied by their impact. The scores were used to categorize the risk levels as shown in the following sections.

4.1.7 Risk assessment for springs

Pollution risk factors analyzed for springs in this section are: distance of spring from dumpsites, pit latrines, location relative to sources of contamination (upstream or downstream of the well or springs, human activities around wells and springs and water source protection. The risk profile prepared for spring is presented in the Table 4.5 below.

Table 4. 5: DRASTIC method for pollution assessment in springs

Source	Risk Index	Risk Factor (RF)	Risk Class	Percentage %	Risk Level	Color
SP 1	>8	10.29	3	44%	High Risk	
SP 9	>8	9.36				
SP 5	>8	8.43				
SP 7	>8	8.43				
SP 2	5-7.9	7.50	2	44%	Moderate Risk	
SP 3	5-7.9	7.50				
SP 8	5-7.9	7.50				
SP 6	5-7.9	6.57				
SP 4	<5	3.79	1	12%	Low Risk	

*1 low risk *2 Moderate risk *3 High risk

The results of risks assessment for springs in town and peri-urban areas of Webuye Municipality. The likelihood of a risk occurrence was achieved by the totals of all the weights allocated on each factor, to form risk factors. The results show that 44% springs are in high-risk environments, risk factor between 8.43 – 10.29. This represents the springs where animals access for grazing and watering, spring that are downstream of farming areas, cloth washing, short distances between the spring and pit latrines, open defection and dumpsites. In risk level two, the 44% of springs are in moderate environments; risk factors between 5.1 – 7.9 where hazards are moderate, and chances of pollution majorly depends on triggering these factors. They are represented in orange color code. Finally, there results show that 12% of the springs are in risk index (<5) the spring had a risk factor 3.79 representing the least chances of pollution. This is a spring that is fenced, restricted access to animals, no farming activities upstream, vegetated and minimized human activities. Findings by(Schneiderman et al., 2007), Mohapatraet al., (2011) show that spring water quality is a function of a number of factors and the nature of the geological formation, water–rock interactions, topography, and the nature of anthropogenic activities. Sewer lines, as much as they form the best part of offsite sanitation network, but wastewater can pollute drinking water in different patterns originating from cesspits, partially treated wastewater and sludge mismanagement infiltrating into the ground and polluting nearby groundwater sources (Gothwal & Shashidhar, 2015).

4.1.8 Risk assessment for wells

Assessment of risk factors causing pollution in Wells in Webuye urban and peri-urban areas took into consideration of; depth of the Wells, distance from pollution source, Protective cover, well lining, Unlined Pit latrine, toilet, pit and human activities around the well. The results are as shown in the Table 4.6 below.

Table 4. 6: DRASTIC approach for pollution risk assessment in wells

Source	Risk Index	Risk Factor (RF)	Risk Class	%	Risk Level	Color Designation
Wells	1.69-2.5	1.86	3	32%	High Risk	10.28571 9.357143 8.428571
	1.28-1.69	1.02	2	39%	Moderate Risk	7.5 7.5 7.5 7.5
	0.88-1.28	0.64	1	29%	Low Risk	3.785714 3.785714

***1 low risk** ***2 Moderate risk** ***3 High risk**

The pollution risk factors; depth of the Wells, distance from pollution source, Protective cover, well lining, Unlined Pit latrine, toilet, pit and human activities were assigned values depending on their likelihood to cause pollution. The results show that the average number of wells in 1.69-2.5, with an average risk factor of 1.86, were 32% representing wells in conditions with the highest potential to cause water pollution, represented by red color code. The next category of wells 39% lie in the risk category of 1.28-1.69 with an average risk factor of 1.02. This category represents water well which are in moderate environments. This implies that the environment around the wells have moderate risk chances of causing pollution and is represented in yellow color code. The last category lies in 0.88-1.28 with an average of 0.64 risk factor. The environment within this class is safe and chances of ground water pollution are minimized, these wells are presented in green color code.

Groundwater contamination occurrence is not well understood but its linkage to on-site sanitation facilities as the main sources of pollution grows has grown with more research conducted to link the relationship (Galadima, Garba, Leke, Almustapha, & Adam, 2011; Hunter, MacDonald, & Carter, 2010). Groundwater sources of pollution are categorized into; human factors such as chemical discharges, insecticides and herbicides, petroleum hydrocarbons, the release of effluents from human waste, pesticides, fertilizers, radioactive wastewater, dyes, detergents (Galadima et al., 2011) and community market waste which lead to excessive pollutants loading in groundwater, and natural. Polluted water sources is endanders human health, economic development, and social prosperity (Galadima et al., 2011).

4.1.9 SFD model analysis of human waste chain

The Figure 4.3 below is an output of SFD model showing human waste chain from generation, transport and disposal. The model helps to identify the gaps that need to be sealed in the study area.

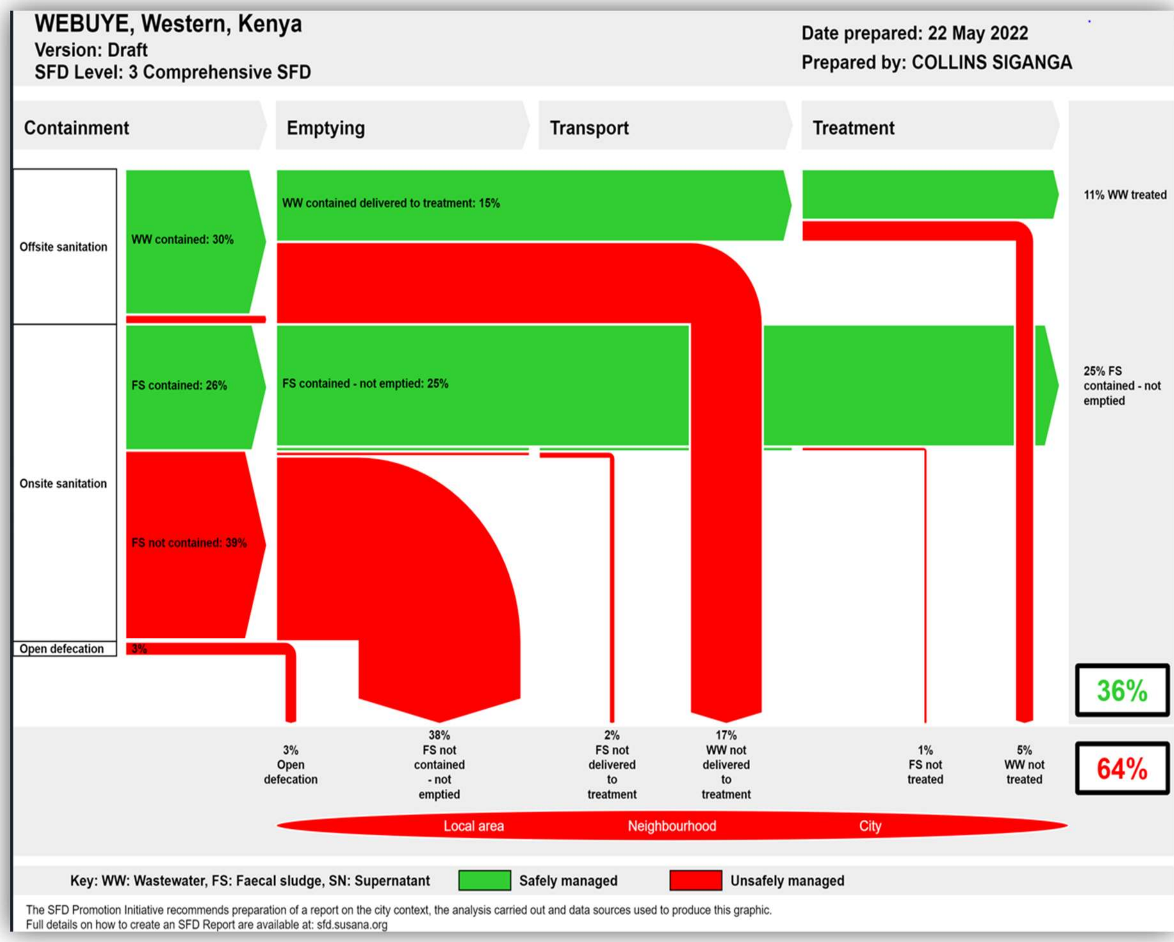

Figure 4. 2: SFD graphical model output of Webuye municipality sanitation chain

The results indicate that 30% of the study population use offsite sanitation systems implying that they are connected to the sewer network, 67% use onsite sanitation systems while 3% practice open defecation. The general results show that 36% of the waste generated in Webuye urban and peri-urban areas were safely managed while 64% were unsafely managed. The results further show that the waste that is safely managed is largely contributed by 26% of the population whose waste is contained, and not emptied. This includes sanitation systems which ensure protection from excreta. Pathogen dissemination to the public is limited and managed through lined pits and septic tanks with no outlets or overflows, in areas where water table is low.

The population using offsite sanitation contribute 15% to the safely managed waste which is contained and delivered for treatment in wastewater treatment plant. It's important to note that the results also show that 17% of the waste generated by the off-site sanitation users is not delivered for treatment, this is as a result of lack or avoidance to payment of dumping fees to the point of discharge, lack NEMA transport license and hence avoiding road transport and manual emptiers who dig pits for dumping and cover them. The assumption of this study is that the 64% waste not properly managed represents as ground water pollution risk if assisted by other instrumental factors such as water table, distance of water source from pollution source, geological formation, hydraulic loading of the soil and depth of water.

Research conducted by Sreekanth, Moore, and Wolf (2016), in Love Canal on groundwater pollution, indicated that bacteria in human or animal waste can pollute groundwater when they find their way to the water, thus making it unsafe. Contaminated groundwater if consumed, can lead to serious fecal-oral disease channeling for instance: cholera and diarrhoea. Therefore, pit latrines and dumpsites can result into serious health risks through groundwater contamination, especially when the surrounding hydrogeological conditions vary within a radius of a few square kilometers are ignored.

4.2 Groundwater Quality

The study sampled 46 wells out of 74 which is 61% of the intended samples. This is because during dry period, 28 shallow wells and 2 springs had dried up.

4.2.1 Water quality analysis

The Figure 4.3 presents seasonal average water quality results for Turbidity, PH, Total Suspended Solids, Total Dissolved Solids, Electrical Conductivity, Salinity, Sulphates, Phosphate, Nitrates and Bacteriological tests of water samples in shallow Wells taken in Muji, Maraka and Khamululi areas, in two rainfall seasons.

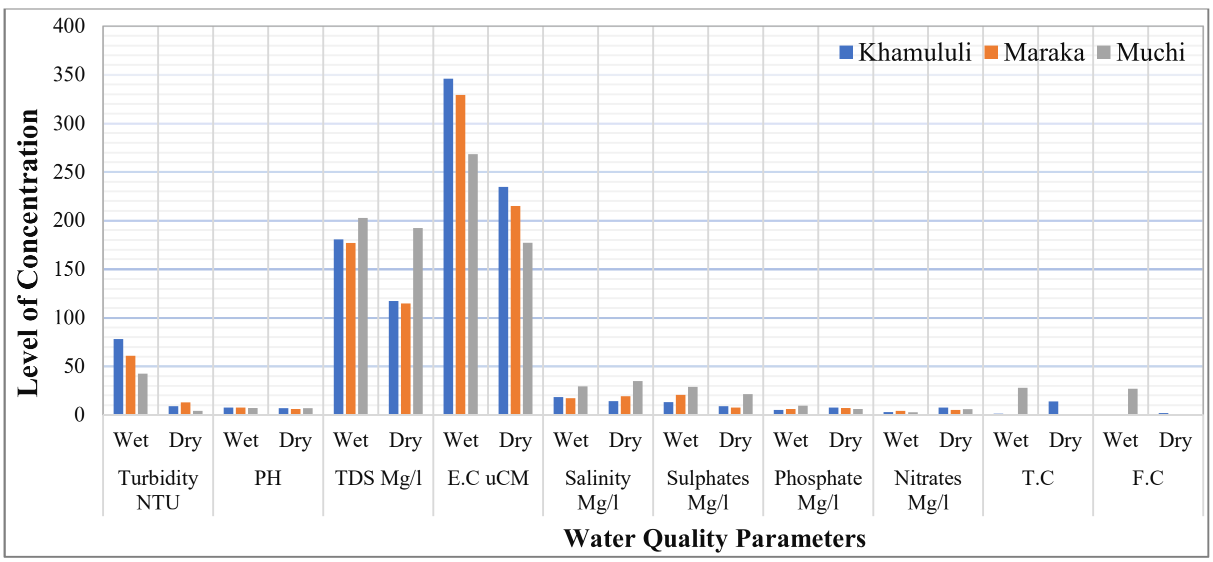

Figure 4. 3 Seasonal variation in concentration of water quality parameters

The results show that average Turbidity ranged between 48-72 NTU in wet season and 4-7 NTU during dry season against the KEBS water quality standards of 5 NTU. This shows that turbidity was high during rainy seasons as compared to during dry season. The samples with high levels of turbidity were majorly concentrated at Khamululi area in the study area. Turbidity in poorly designed or dilapidated wells and springs can be as a result of surface water inflow, mostly in rainy seasons. Turbidity in groundwater is caused by geological factors. According to Manitoba Water Stewardship and (Hans, Goertzen, Krieg, & Leslie, 2011), turbidity reduces that aesthetic value of water and shields bacteria from disinfection. The organic and inorganic factors also mix with chlorine to form harmful by-products, such as trihalomethanes (THMs). According to Informational Resources and Services, Environment Canada, (2005), bacterial contamination in water is closely associated with increased in turbidity.

Increased pH is an indicator for a polluted aquifer system. Pure water has a neutral pH between the ranges of pH 6.6-8.4. (Ram et al., 2021). The average results from Maraka, Khamululi and Muchi show that pH ranged averagely between 6.6-8.4 in wet season and was within the KEBS water quality standards, however, in dry season pH ranged between 4.5 to 9.4 showing that pH range was beyond KEBS standards of 6.5-8.5. Total Dissolved Solids in samples collected during dry season ranged between 53-244mg/L and was within the KEBS water quality standards of 700 Mg/l. The samples collected in wet season show that TDS raged between 61mg/L to 945 mg/L which went beyond the KEBS water quality standards.

The highest value of TDS was recorded in Muchi during wet season, the lowest TDS was 114 mg/L in Maraka area during dry season. These results agree with the results by Adeolu et al. (2011) who carried out a similar study on the impact of dumpsites on the quality of soil and groundwater in satellite towns of Abuja, Nigeria. Electrical conductivity (EC) values ranged from 53 to 942 µs/cm in dry season and from 10 to 434 µs/cm during wet season. The EC values in both seasons were within the KEBS water quality standard of 1500 µs/cm.

Salinity is the total concentration of all dissolved salts in water. The results show that salinity in water samples collected in dry season was 0.4 to 52 in mg/L and 0.3 to 234 mg/L in wet season. The level of salinity in drinking water as stipulated by KEBS standards for drinking water is 200mg/L. this implies that results in both dry and wet seasons were found to be within the KEBS standards expect for in all parts of the study area. Muchi had the highest value of salinity 35mg/L in wet season while Maraka had the lowest value 17mg/L. It is important to note that this well was located in Sango area which is an industrial side of the study area. (Gong et al., 2020) found that groundwater salinization not only exists in coastal areas, but also dwells in inland rural areas due to industrial effluent, natural dissolution farming and other human activities where levels of salinity may exceed level as compared to coastal areas. The results show that sulphates in water samples presented ranged between 1 to 289 mg/L in dry season and 1-47mg/L during rainy season. The KEBS standard for Sulphate is 400 mg/L, implying that sulphate concentration was within water quality standards for drinking water.

The water quality results further show that Phosphate concentration in wells was 1.22 to 61.8 mg/L dry season while in wet season the concentration ranged between 0.39 to 20.4 mg/L in wet season. Phosphate concentration in drinking water as stipulated by KEBS water quality standards should be 2.2 mg/L. The results show that phosphate concentration exceeded the 2.2mg/L KEBS standards. The results were contrary to the findings by Holman et al. (2008), who found that dissolved phosphorus (DP) is low in groundwater because it is not transported, but sorbs to soil and aquifer sediments. The chief contributor of phosphates in groundwater are land use practices in the drainage area which are predominantly agriculture especially around water wells. Most wells with high levels of phosphates are around agricultural areas. Most residents were found to have small plots where they have kept animals, practice farming and still have a water well on the same compound, where the animal wastes are lumped for decomposition to be used as manure on the farm.

Plate 4. 1: Animal waste decomposition next to a garden for manure

Source: Researcher, 2023

The results further show that Nitrate concentration ranged between 0.1-11.8 mg/L in dry season and in wet season it ranged between 2.4 to 29.7 mg/L, showing a high concentration of Nitrates during wet seasons. As determined by the KEBS standards for water quality, Nitrate concentration in drinking water is 10 mg/L. Nitrates exist in groundwater, however, concentrations above 3 mg/L show contamination (Madison & Brunett, 1985). Recent studies show that concentrations above 1 mg/L in nitrate indicate human activity (Dubrovsky et al., 2010). Nitrates can infiltrate in groundwater through point and non-point sources. Runoff from fertilized agricultural land is the most common source of nitrates. Nitrates can be deposited in groundwater sources as a result of poor waste disposal, use of pit latrines and leachates.

Plate 4. 2: Pit latrine and hand dug well in less than 10m a part in Webuye Town

Source: Researcher, 2023

Bacteriological tests show that wet season had more contaminated shallow wells especially in Much area. This implies that there was a high level of positive cases of fecal coliform in wet season as compared to dry season. The results show the likelihood of coliform contribution to Wells especially during wet seasons as a result of onsite sanitation systems and sewer drains. The presence of coliforms especially during wet seasons could be attributed to infiltration of Leachate from the cracked or unlined septic tank, pits and dumpsite. Solid wastes in dumpsites with no base lining release leachate to the groundwater. Infiltration and leachates from landfills and onsite sanitation systems in residential areas have been reported;(Ekwere & Edet, 2015; Eni, Ubi, & Digha, 2014). Contamination of groundwater is increased in areas where there is a high number of waste dumping and improperly constructed and sited onsite sanitation systems as opposed to areas where there is a low usage (Ekwere & Edet, 2015; Eni et al., 2014).

4.2.2 Springs water quality results

Water quality results for springs in Webuye municipality are presented in the Table 4.7 below.

Table 4. 7: Water quality parameters for springs

Parameter	Season	Sp 1	Sp 2	Sp3	Sp 4	Sp 5	Sp 6	Sp 7	KEBS Requirement
Turbidity (NTU)	Wet	14	6	8	3	23	8	7	
	Dry	4.28	2.21	3.6	2.23	6.43	6.1	2	5
PH	Wet	7.9	7.6	7.3	7.4	7.2	6.9	6.8	
	Dry	7.5	7.2	7.42	7.24	7.21	7	7	6.5-8.56
Total Suspended Solids (Mg/l)	Wet	10	5	7	2	8	5	5	
	Dry	0	0	0	0	2	1	1	30
Total Dissolved Solids (Mg/l)	Wet	81	52	53	141	33	30	27	
	Dry	90	72	86	73	63	61	40	700
Electrical Conductivity (µS/cm)	Wet	159	104	128	285	67	53	54	
	Dry	181	145	172	146	126	173	90	1500
Salinity (Mg/l)	Wet	22	15	37	12	0.6	7	24	
	Dry	8.1	3.4	3.1	2.6	1.8	2.9	7.8	200
Sulphates (Mg/l)	Wet	4	9	6	4	1	2	4	
	Dry	4	7	6	14	10	9	6	400
Phosphate (Mg/l)	Wet	4.93	8.17	1.67	1.87	2.73	1.27	1.22	2.2
	Dry	0.78	1.52	3.99	2.71	2.5	2.87	3	
Nitrates (Mg/l)	Wet	2	5	2.2	5	10	2	4	
	Dry	3	2.4	4	3.4	3.2	3	2.2	10
T.C (Cfu/100ml)	Wet	1	3	1	Nil	Nil	Nil	Nil	
	Dry	8	Nil	7	3	Nil	Nil	Nil	Nil
F.C (Cfu/100ml)	Wet	Nil	1	Nil	Nil	Nil	Nil	Nil	
	Dry	5	Nil	3	1	Nil	Nil	Nil	Nil

The results in Table 4.7 show that Turbidity was high above 5 NTU KEBS water quality standards in wet season except in spring 4 where turbidity was 3 NTU within the standard. During field data collection, it was observed that spring 4 was located in a natural protected environment. The spring has minimal human activities due to the fence surrounding its catchment.

pH was found to be within the KEBS water quality standard scale of 6.5-8.5 in both wet a dry season. It is however noted that pH was high in dry seasons as compared to wet seasons. Total Suspended Solids in all samples in both seasons were compliant to KEBS standards of 30 mg/L. In wet season, springs had higher TSS compared to dry seasons were springs 1,2,3,4 and 5 had 0 TSS values. Total Dissolved Solids in all springs in both seasons were within the KEBS standards of 700 mg/L. However, there was some variation where, dry season showed higher concentration as compared to dry season than wet season. Electrical Conductivity (µS/cm) in springs complied to KEBS water quality standards of 1500 µS/cm in all 7 springs in both rainfall seasons. The conformity of electrical conductivity in spring samples can be linked to less concentration of ions in the surrounding environments, due to reduced human activities.

Salinity (Mg/l) in samples taken from springs complied with the KEBS water quality standards of 200mg/L. However, there was variation in seasonal concentration of salinity, where wet season was higher than dry season. It is commonly expected that salinity would reduce in spring water during rainy season as seen in the samples from Wells. The presence of salinity can also be attributed to the aquifer composition in which groundwater flow.

The results further show that Sulphates were within the required water quality standards by KEBS 400 mg/L. There was high level of sulphate concentration during dry season as compared to wet seasons. It was also observed that spring samples show phosphates levels exceeding the water quality standards set by KEBS 2.2 mg/L. Samples from springs 1, 2 and 3 show high level of phosphate concentration 4.93, 8.17 and 2.73 respectively in wet season. Springs 4, 5, 6 and 7 show high levels of phosphates 3.99, 2.71, 2.5, 2.87 and 3 respectively in dry seasons. This generally implies that phosphates concentration was higher in dry season and compared to wet season. The concentration salinity, sulphates and nitrates in dry season is generally due to reduced water levels. The levels tend to reduce in wet seasons due to increased water levels which help in dilution. This agrees with findings of (Adeyemo, Adedokun, Yusuf, & Abeleye, 2008) which reported that salts and nutrients accumulate in dry season. During wet seasons, increased rainfall lead to high dilution thus reduced concentration of salts and nutrients in water. Samples also show that nitrates in all samples in both seasons were within the required water quality standards 10 mg/l by KEBS. It can however be noted that nitrates in rainy seasons was higher as compared to wet season. The findings agree with the findings of (Bolge, Doan, Kannan, & Baran, 2009). Nitrate is loosely bound to soils, and its mostly found in runoff and hence its concentration. As a result, nitrates concentration increases during wet seasons.

High nitrate levels is mostly caused by nitrogen fertilizers leachates used in agricultural production, sewage effluents, dumpsites and animal wastes (Efe, Ogban, Horsfall, & Akporhonor, 2005). High Nitrate concentration is can harm pregnant women and infants (Falzon et al., 2011). Bacteriological tests show that there was presence of Total Coliforms in the in springs 1, 2 and 3 during wet seasons while during dry season, springs 1, 7 and 3 had total coliforms. Samples from springs showed that there were no faecal coliforms in springs except for spring 2 in wet season. The results also so there was increased number of springs with faecal coliform in dry season where spring 1, 3 and 4 showed faecal coliform contamination.

4.3 Water Quality Index of Webuye

4.3.1 Introduction

The water quality parameters discussed in Chapter Five were used to develop the Water Quality Index for urban and peri-urban areas of Webuye Municipality.

4.3.2 Spatial distribution of parameters

Water quality results were mapped across the study area to show their concentration in their location. The GPS position of the groundwater sources were interpolated with their water quality results in ArcGIS 10.7, for each parameter. The results are as shown the set of spatial distribution maps below.

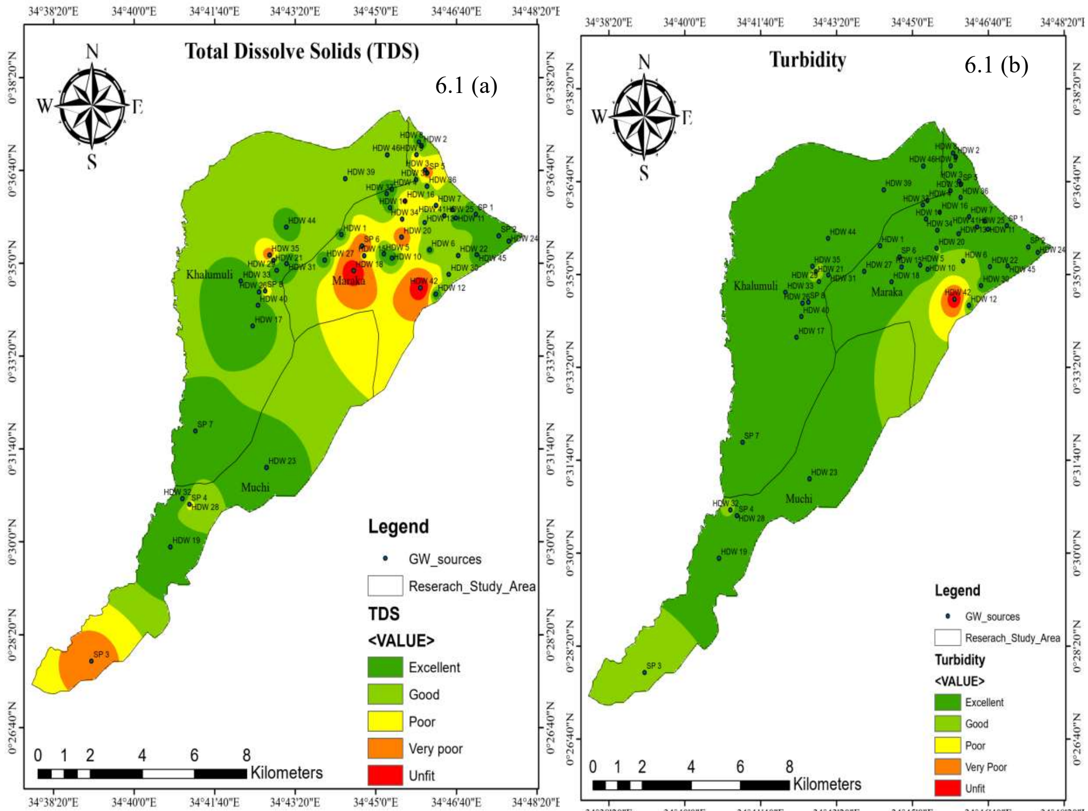

Figure 4. 4: Spatial distribution maps for TSS and Turbidity

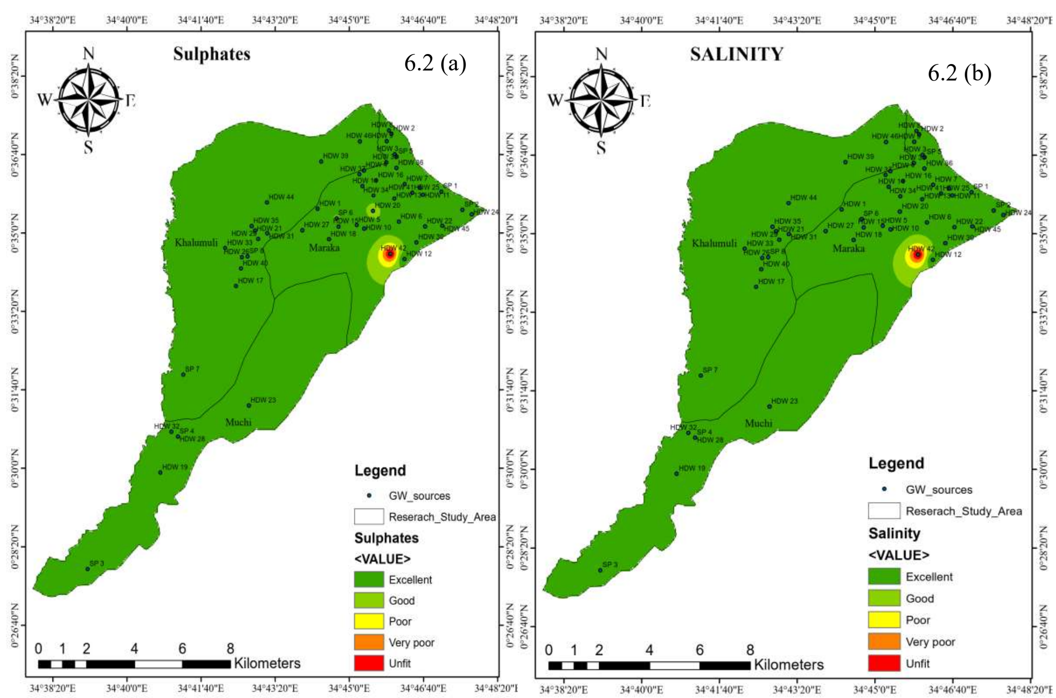

Figure 4. 5: Spatial distribution maps for Sulphates and salinity

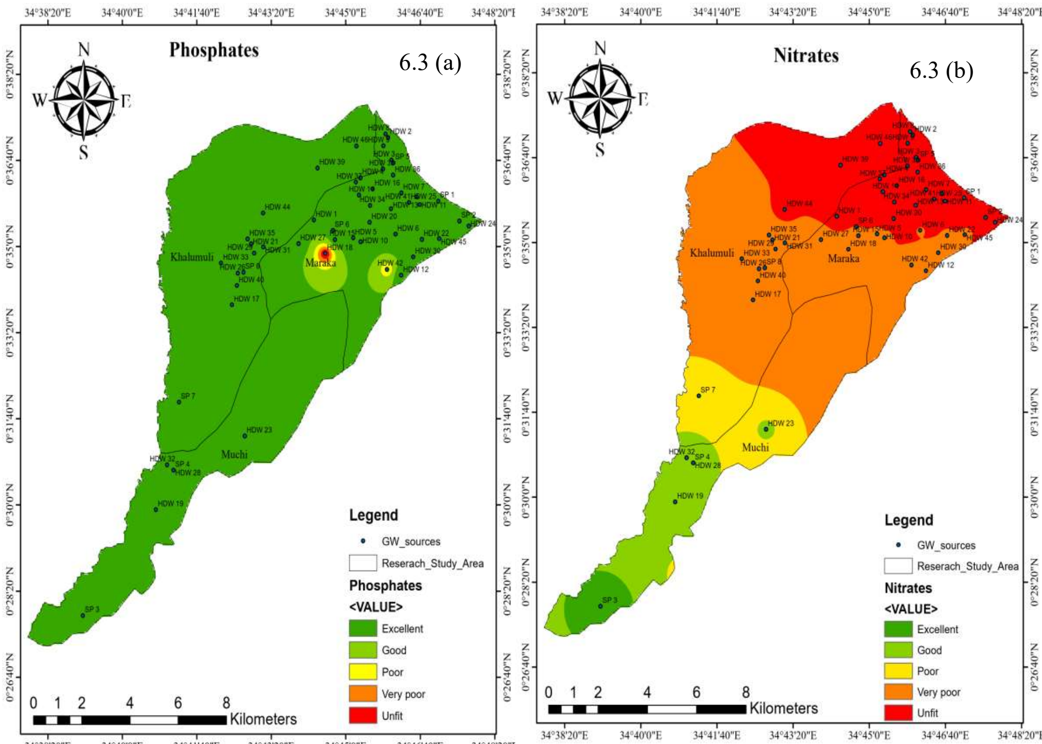

Figure 4. 6: Spatial distribution maps for Phosphates and Nitrates

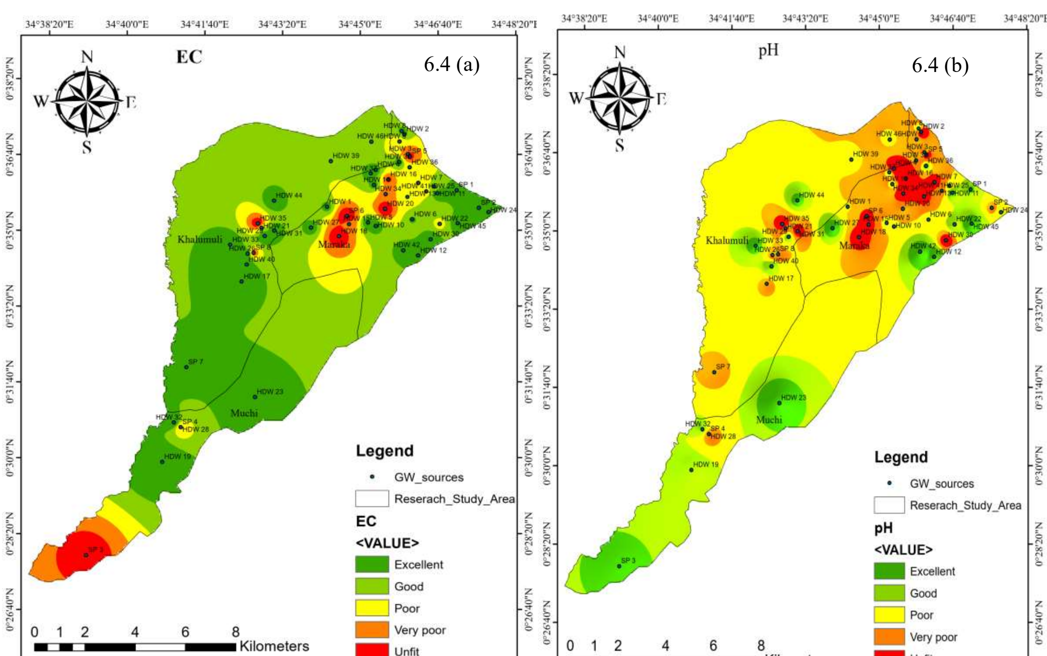

Figure 4. 7: Spatial distribution maps for EC and pH

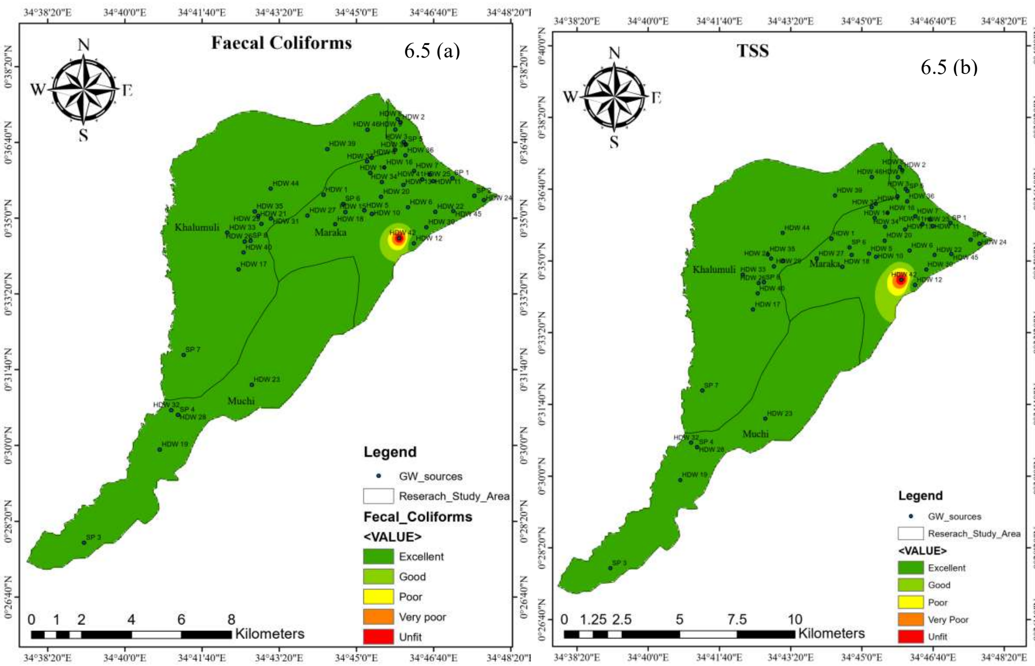

Figure 4. 8: Spatial distribution maps for Fecal coliforms and TSS

The spatial distribution of water quality parameter maps in this study, provide an assessment of the distribution of groundwater quality in order to check for relationship within the parameters. Electrical conductivity, pH, Nitrates and Total Dissolved parameters largely affect water quality in study area. These parameters affect water quality in both urban and peri-urban areas of Webuye. The spatial map show that the urban areas of Webuye town are majorly affected by high concentration of water contaminants. Areas like Khalumuli and Muji which are peri-urban/rural areas are not affected by other parameters except for Electrical conductivity, pH, Nitrates and Total Dissolved Solids most probably because of their geographical location. These areas are located on the lower sides of the town thus receiving wastes from the larger urban area, especially during rain seasons. Bacteriological pollution is majorly observed in urban areas of the study area. Concentration of pH and nitrates largely distributed in industrial areas of the study area.

4.3.3 Calculation of WQI

Water quality standards and the unit weights allocated to parameters are shown in the Table 4.8.

Table 4. 8: Drinking water quality standards and the unit weights

Parameter	Sn	$1/S_n$	$\sum 1/S_n$	K	W_n	V_n/S_n	Q_n	W_nQ_n
Turbidity	5	0.2000	0.9151	1.0928	0.2186	4.1174	411.7358	88.06
PH	8.5	0.1176	0.9151	1.0928	0.1286	0.4670	46.7000	5.88
TSS	30	0.0333	0.9151	1.0928	0.0364	0.6654	66.5409	2.37
TDS	700	0.0014	0.9151	1.0928	0.0016	0.2659	26.5876	0.04
EC	1500	0.0007	0.9151	1.0928	0.0007	0.2086	20.8579	0.01
Salinity	200	0.0050	0.9151	1.0928	0.0055	0.1015	10.1519	0.05
Sulphates	400	0.0025	0.9151	1.0928	0.0027	0.0507	5.0660	0.01
Phosphate	2.2	0.4545	0.9151	1.0928	0.4967	3.2312	323.1218	157.06
Nitrates	10	0.1000	0.9151	1.0928	0.1093	0.3800	37.9962	4.06
		0.9151			1			257.56

Values are in mg/L, except for pH, EC (µS/cm) and turbidity (NTU).

4.3.4 Water quality index results

Water quality index of urban and peri-urban parts of Webuye were determined by calculating the for all the water sources sampled for this study. The values ranged from 55.29 - 3119.34 as shown in the Figure 4.9 below.

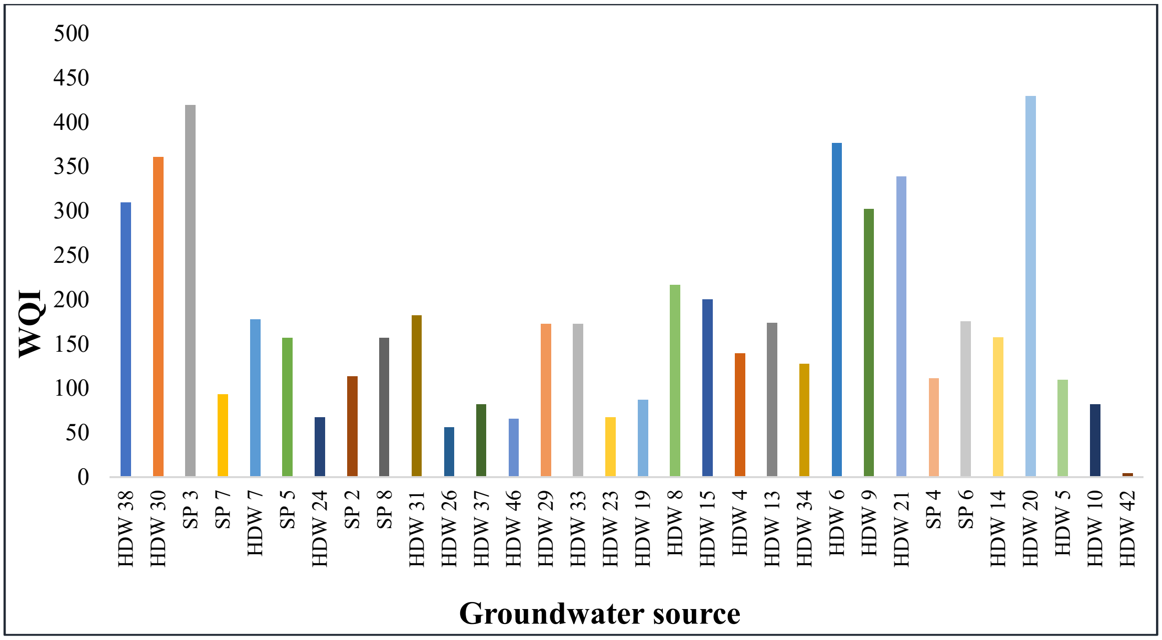

Figure 4.9: WQI results

The values Figure 6.6 Shows how water sources scored on rating, the general finding was that the water in Webuye Municipality is poor in quality. The water quality index shows that water well 20 had the highest water quality index value of 429 which is > 100 category which is unfit for consumption. Well number 42 has the lowest water quality index of 4 which falls in the excellent water quality category. The results show that 69% of ground water samples were Unfit for consumption >100, 16% were very poor 76-100, 11% of the samples was poor 50-75, good water quality was 3% 26-50 while excellent 0-25 was 1%. According to the classification as guided by (Brown et al., 1972; Yogendra & Puttaiah, 2008), the results of Webuye urban and peri-urban results show that water quality index was poor (51-75), very poor (76-100) and unfit for consumption (>100) as shown in the Table 4.9 below.

Table 4. 9:WQI categories of Webuye municipality

Range	Score	Percentage (%)	Water quality status	Rating
0–25	1	1%	Excellent	
26–50	2	3%	Good	
51–75	56 -71	11%	Poor	
76–100	80 - 100	16%	Very Poor	
Above 100	> 100	69%	Unfit for Consumption	

The results show that 69% of water samples from the study area majorly fell in class >100 (Unfit for consumption), class 76-100 (Very poor) were 16%, class 51-75 (poor) were 11%, WQI class 26-50 (Good) 2% and WQI class 0-25 (Excellent). This generally implies that groundwater quality in Webuye urban and peri-urban areas of Webuye is fit for irrigation and Industrial use due to the observed high water quality index. However, this water requires treatment before being used for domestic and drinking purposes. The results on pollution risk factors indicated that majority (66%) of solid waste disposal was composite pits, 42% use unlined pits for human waste disposal, it was also found that 49% of the wells were developed in high water table areas with a depth of less than 5 meters. The results also report numerous human activities around groundwater sources in Webuye Municipality. These factors create a potential environment for the transfer of contaminants from sources to the near groundwater sources. The SFD also indicate that 64% of human waste generated in Webuye Municipality is unsafely managed. This puts groundwater sources at a great risk of pollution. These results agree with (Kanda et al., 2023) who established a significant relationship between use of pit latrines, their proximity to groundwater sources, and the quality of water in wells. The distribution of various WQI classes for the study area shows the spatial distribution of water quality indices of sampled wells in Webuye Municipality.

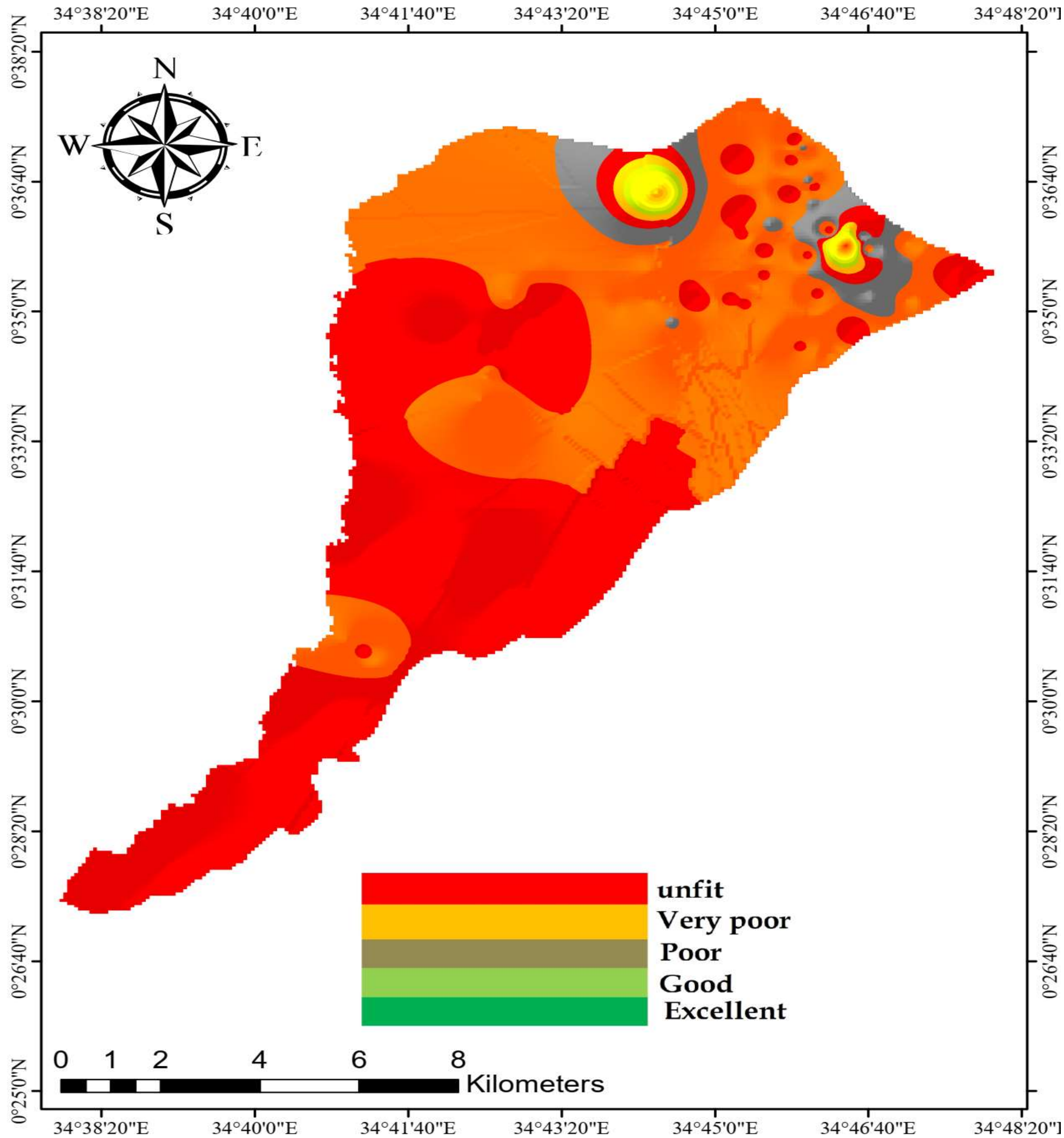

Figure 4. 10: WQI spatial distribution for Webuye Urban and Peri-Urban areas

The results show that major parts of the study area have high water quality index score >100 representing water that is unfit for consumption. These areas are represented in a red color and it shows that such areas have water that is not fit for consumption. Orange color in the map represents WQI 76-100 class where water is of very poor quality.

It can also be observed that high risk areas majorly are in low areas of the study area, implying that that the urban area contribute highly to the pollution in peri-urban areas. High WQI is majorly contributed to by human activities and behaviors such as inflow of sewer overflows in the urban set up and lack of or inadequate sanitation system especially in areas of unplanned settlements. Urban agricultural activities were also observed around water points to improve food production especially for vegetables, fruits and to some extend maize and beans with fertilizer application practiced this can be a great contributor of Phosphates and Nitrates as a result of observed agricultural run-off to unprotected water points. Sulphate, pH, Turbidity and Electrical conductivity was also high in these areas.

Groundwater pollution in the study area is attributed to waste handling practices, farming, human waste disposal and groundwater sources design factors. The reduced water quality in these areas can be related to groundwater pollution risk factors in the study are. Use of fertilizers in groundwater abstraction areas, and it is attributed to effluents from the wastewater treatment plant. Open defecation and regular sewer overflows Webuye municipality areas contribute to increased fecal contamination in unprotected groundwater sources. Unregulated solid waste dumping leads to leaching of contaminants especially in the areas with high water table.

4.3.5 Pollution risk factors and water quality

A relationship between the distance between the well and the onsite sanitation systems in Webuye municipality was assessed. The assessment was carried out using biologically related water quality parameters, nitrates and fecal coliforms. This assessment was carried out to find out if the existence of toilet pit latrines closer to groundwater sources affects the water quality.

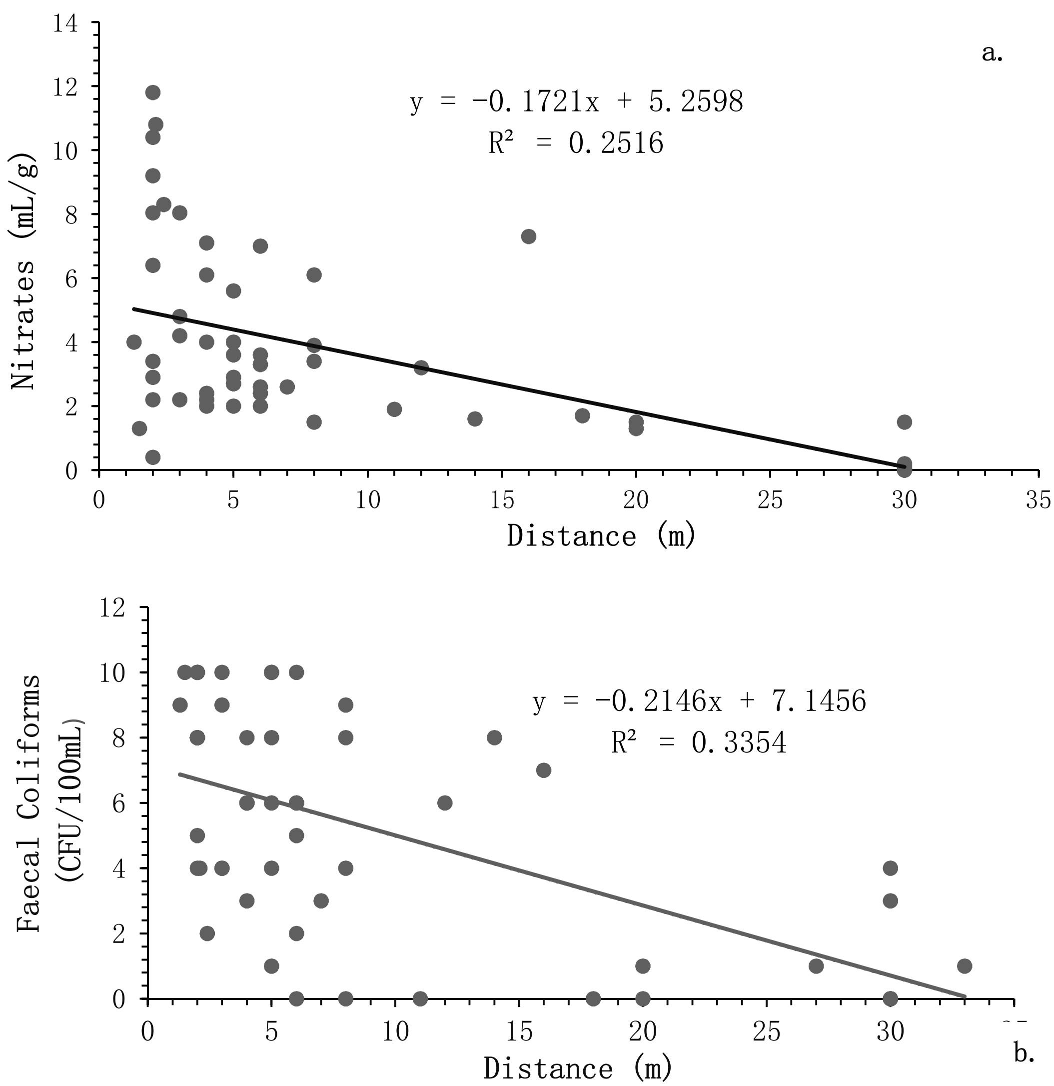

Figure 4. 11: Bivariate analysis for Nitrates and Fecal Coliform and distance

The results in Figure 6.8 (a)Shows that there was a significant relationship between Nitrates in groundwater samples and the distance between onsite sanitation systems. The relationship shows that groundwater sources are safe from contamination if located at a minimum distance of 30 m away from onsite sanitation facilities. This can be seen from the scatter plot where there is concentration of nitrate in sources that are located in less than 30 m. The bivariate analysis in the scatter plot in Figure 6.8 (b) also established a significant relationship between the distance of the well and the location of onsite sanitation systems by showing positive fecal contamination. This relationship establishes that its is safe to develop groundwater sources at a minimum distance of 33 m away from the unlined sanitation facilities, to protect sources from fecal contamination.

Studies carried out to establish a minimum distance between pit latrines and well location. (Kanda et al., 2023) established a minimum distance of 30 m in Vihiga County, (Kiptum & Ndambuki, 2012) found a minimum distance of 48m in Langas Eldoret while (Mzuga, Tole, & Ucakuwun, 2001) established a safe distance of 150m. The WASREB's Guidelines for Inclusive Urban Sanitation Service Provision (2020) it recommends horizontal distance of 30 m between wells and onsite sanitation facilities in Kenya. However, it is seen that each study area has a different recommendation of the safe distance based on the hydrogeological conditions, such as the type of soil, the slope and the hydraulic conditions of the soil. There is need therefore to carry out regional assessment to establish safe distances based on the hydrological conditions. This is because more populations are moving to urban area and spaces are becoming limited, to provide housing, farming areas, OSS and groundwater sources.

4.4 Groundwater Vulnerability Assessment

4.4.1 Spatial distribution of DRASTIC-LU parameters

The results were are presented in a sum of 8, where 7 maps representing the DRASTIC-LU risk factors as stated in Equation (I) above and an additional map of land use changes.

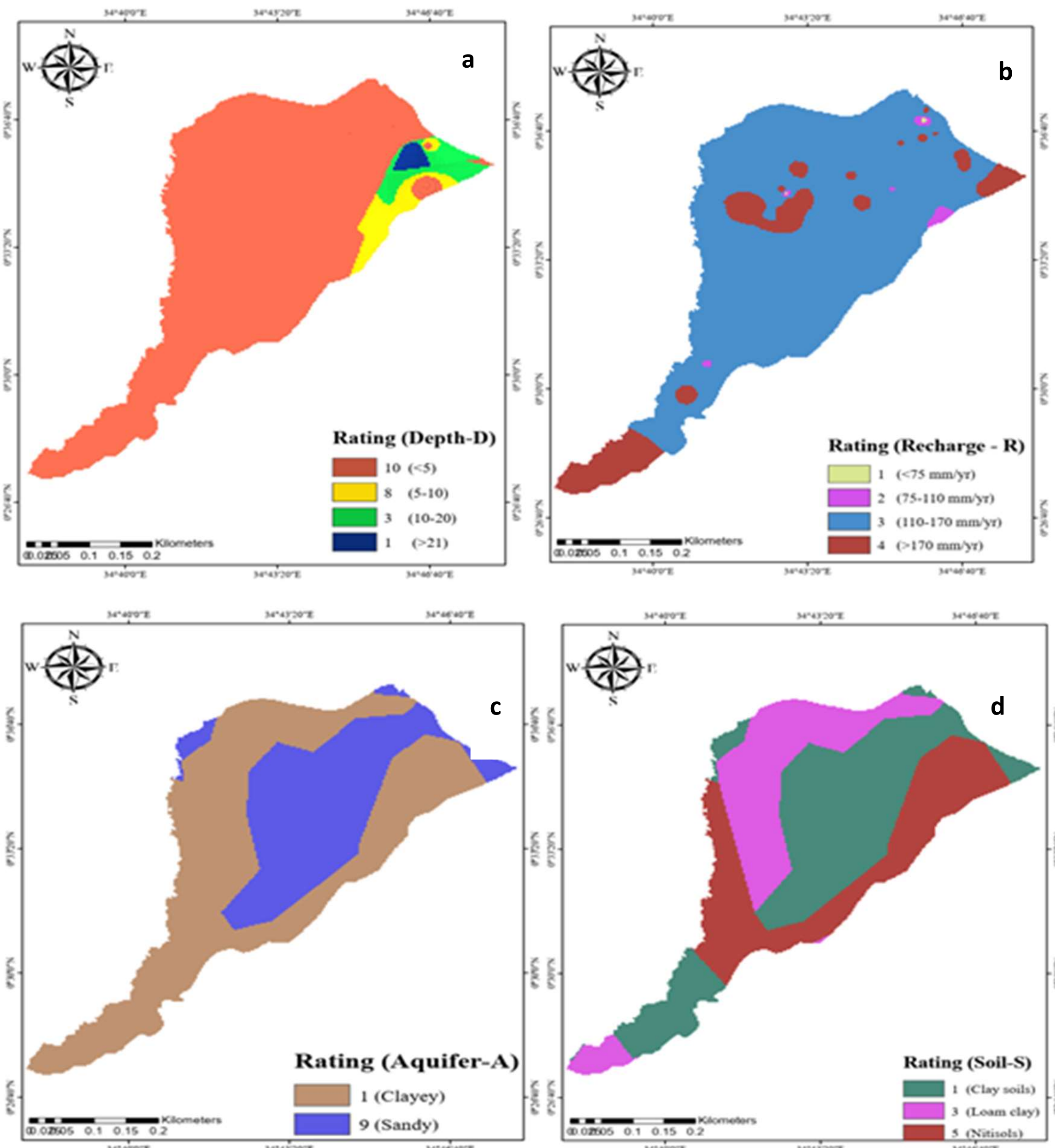

Figure 4. 12:Spatial distribution of: (a) Depth (b.) Recharge (c) Aquifer (d)Soil media

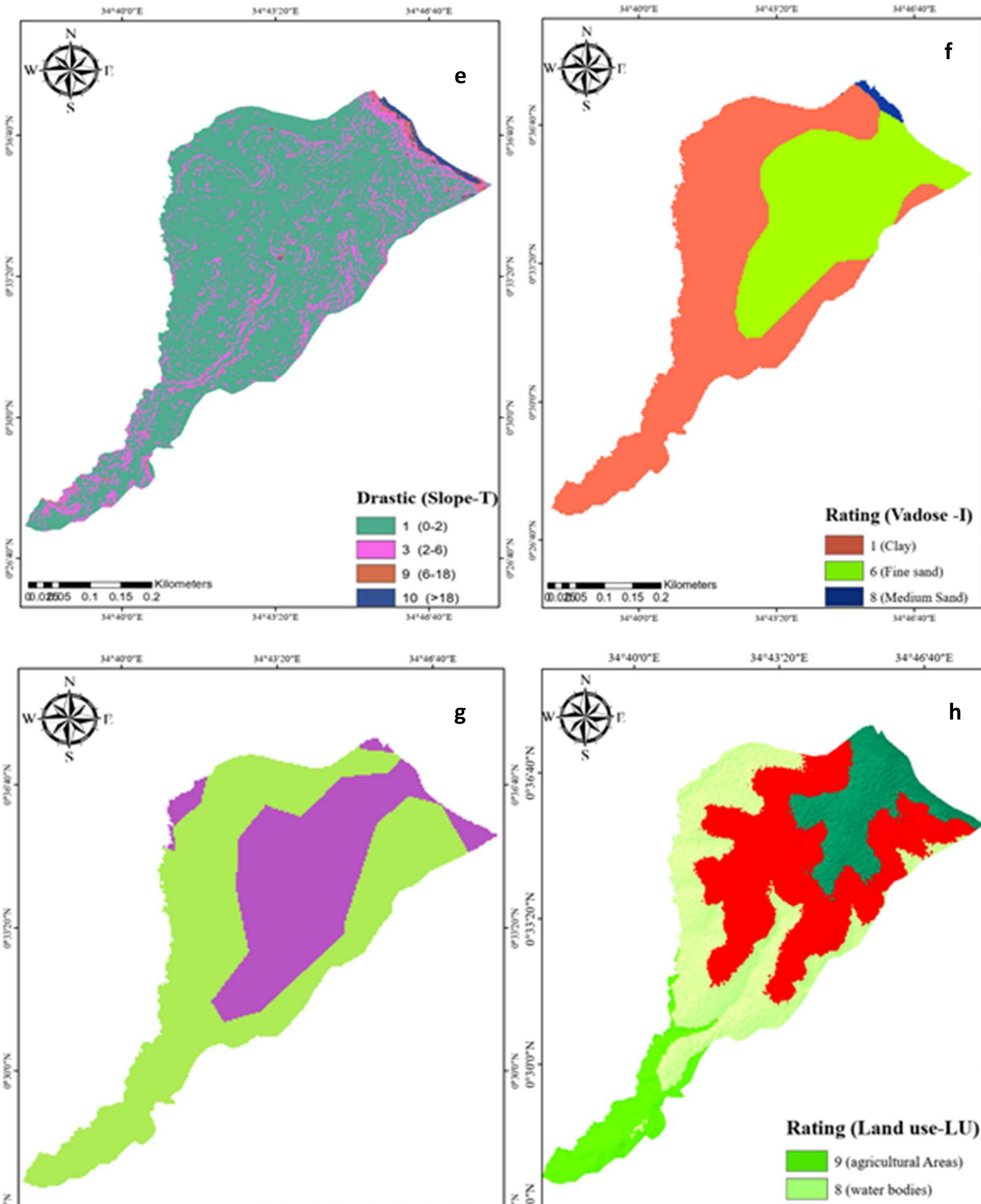

Figure 4. 13: Spatial distribution (e) Slope (f) impact of vadose (g) hydraulic conductivity and (h) Land Use

4.4.2 Discussion of results

4.4.2.1 Depth of water in wells (D)

The study indicates that 77% of the water wells measured a groundwater depth less than 5m. It is of importance to note that 86% of the study area has shallow wells >5m in depth. Water wells in Muchi and Khamululi areas are mainly below 5m, Maraka area which is the North east areas of the study area has wells within 5-10m, 10-20m and >21m in depth which represents 14% coverage however, the wells below 5m deep were still predominant as shown in Figure 4.12 (a). above. The findings show that Webuye urban and peri-urban area has a high-water table and this could be the reason why many residents construct their wells with shallow depths. Areas around the town and peri-urban areas in the study area are likely to have contaminated water wells because of the shallow depth. Wells with shallow depth are prone to contamination from especially from the surface of the earth, because of the reduced media through which contaminants infiltrates. Well depth of water is used to refer to the distance pollutants are transported through the soil media. Well depth is an important parameter as it measures the stretch water infiltrates (Ullah, Malik, & Qadir, 2009). It's important to note that the shallow water table zone, the higher the chances of vulnerability to pollutants.

4.4.2.2 Net recharge (R)

The net recharge was allocated weight of 4 and classified in 5 classes >200, 150-200, 100-150, 50-100 and 0-50 mm/yr. The classification was arranged from the highest recharge to the lowest (200mm/yr – 0mm/yr), based on the fact that high net recharge, leads to high probability of groundwater pollution. The results depict areas with the highest rate of recharge are Muchi and some parts of Khalumuli which recharge more 170 mm/yr. Other areas in the study area have an average groundwater recharge ranging between 75mm/year to 110 mm/year. Areas with the lowest recharge are majorly in town areas where most surfaces are lined; buildings, roads, pavements and roofs. This prevents infiltration thus affecting groundwater recharge. Groundwater recharge plays a big role in contaminant movement. Webuye town is located along River Nzoia, which is the main supply for raw water for treatment and also source of industrial water. The river is the main aquifer recharge in the area. Net recharge highly influences dilution and dispersal of pollutants. Net recharge from polluted potential urban recharge (onsite sanitation systems, sewer mains leakage, urban drainage and wastewater disposal) can be so instrumental in migrating pollutants to spread in the water table. The results are shown in Figure 4.12 (b).

4.4.2.3 Aquifer media (A)

The aquifer was classified in two classes Sandy and Clayey. The formation was converted to raster, and reclassified under spatial analysis in ArcGIS. The results indicate that the study area has just town main types of aquifer formation. The Webuye municipality central, especially the town areas have sandy aquifer. Clayey aquifer occupies areas such as Muchi and some parts of Khalumuli. The geological formation of the aquifer determines the flow rate and the content of contaminants in the aquifer. The aquifer containing high void ratio and larger grain size have higher permeability. This leads to reduced pollutant attenuation which may lead to greater contamination potential (S. H. I. A. Shah et al., 2021). The main lithological formation of the aquifer in Webuye, the aquifer is majorly comprised of assorted gravel and sand with clay, aquifer media was assigned a rate of 3. The results are as shown in Figure 4.12 (c).

4.4.2.4 Soil

The results in the Figure 4.12 (d) show that there are three categories of soil in the study area; Loam, Clay and nitisols. Clay soil is fairly distributed in Khamululi, Muchi and Maraka areas covering 48% of the study area. Loam soils are majorly concentrated in Muchi and Khamululi areas of the study area covering 21% of the study area, while nitisols are covering 31%. Soil is the geological formation of top weathered portion over the vadose zone. Soil is a defining attribute on recharge and transportation of pathogens into the groundwater. Silt and clay soils have low permeability, therefore reduced contaminant transport (Salomó-Coll et al., 2021). Soil data was derived from the soil maps which was overlaid on the study area to be able to identify the soil category.

4.4.2.5 Topography (slope)

The slope was divided into four classes ranging from 0-2, 2-6, 6-18 and >18. The slope was rate 0-18 with 18 representing the highest slope and 1 representing lowest slope. The slope was allocated the weight of 1. The results in Figure 4.13(e). show that the study area is largely comprised of fair slopes between 0 to 6, this is in all parts of the study area; Muchi, Khamululi and Maraka. Water on steeply slope surface of earth creates surface runoff and infiltrates less than water falling on flat land surface. This implies that Muchi, Khamululi and Maraka have high vulnerability of groundwater to contamination due to level ground surfaces which increase the rate of infiltration. The far north eastern parts of the study area the boundary of maraka area which is around the foot of Chetambe hills have steep slopes (>18) meaning that there is low vulnerability of the groundwater to contamination beause of steep slopes which do not allow enough time for maximum infiltration. The results give an implication that the northern and eastern parts of the study area have reduced chances of contamination because of reduced rates of infiltration. The topography of an area is a determinant of contaminant movement. Areas with gentle slopes have reduced surface runoff rates, implying that there will be increased infiltration which will likely increase the aquifer vulnerability because of increased infiltration. Studies have been carried out to link slope to contamination of groundwater. A study carried out by (Mao et al., 2021) revealed that the runoff on uneven topography increases the rate of infiltration. The study is confirmed by the experimental findings of (Cui et al., 2020) who reported that velocity of water, runoff rate and erosion were greater in less slopes than on three steep slopes especially those that are conically shaped.

4.4.2.6 Impact of vadose zone

The results in Figure 4.13 (f). show that the study area is mainly composed of clay soil in the vadose zone found which covers 59% of the study area in Muchi and khamululi, fine sand is mainly concentrated in Maraka area and occupies 44% of the study area while medium sand composition of the vadose zone is mainly found in the northern part of the study area, specifically in the upper parts of Khamululi. Therefore, the vadose zone is rated 1, 6 and 8 in classes of; clay, medium and fine sand weighted 5. Vadose Zone plays a key role in groundwater protection, and it is therefore, important to combine the pollution and vadose zone characteristics in assessment of groundwater pollution intensity (J. Li et al., 2016). Vadose zone is basically (Likens, 2009) a natural filter in adsorbing the contaminants in water before it reaches the water table. Therefore, the media characteristics of the vadose zones are important in controlling the level of pollution through the vadose zone to the water table. (Singh, Saggar, & Bolan, 2009) found a physical relationship between fertilizers and soil is predominant in granular soils where high-permeable media can facilitate the vertical transport. The soil permeability can decrease as a result of reduced porosity (J.-s. Li, Xue, Wang, & Liu, 2013) .

4.4.2.7 Hydraulic conductivity

The results in Figure 4.13 (g) show that 61% of the study area has $0.11 m^3/d$ distributed in whole of urban and peri urban areas of Webuye, while 39% is $15.21\ m^3/d$ which is mainly concentrated in Maraka in Khamululi areas. Maraka and Khamululi areas have high hydraulic conductivity values implying that vulnerability of aquifers in these areas are high. It is also important to note that the areas are highly concentrated in loam and nitisols soils which have high hydraulic gradient as compared to Muchi area which has mainly clay soils. Hydraulic conductivity is important soil property which defines the drainage functions of a soil (Meena et al., 2016; Xiong, Zhuo, Zhang, & Yao, 2013) . Soil properties such as; soil type, void ratio, pore size distribution, grain size distribution, viscosity of a fluid, and degree of saturation determine the hydraulic conductivity of soil (Meena et al., 2016; Xiong et al., 2013).

4.4.2.8 Land Use

The results show that the study area has been affected by human activities through agricultural activities which occupy 44%, 41% is occupied by built up areas, water bodies occupy 9% of the study area while 6% of the area is occupied by trees. Land use activities inform spatially about nitrate and phosphates generation in the study area. Land use plays a role in determining the generation and transport of nitrate pollution, caused by anthropogenic activities (Jha, Chowdhury, Chowdary, & Peiffer, 2007; Salomó-Coll et al., 2021). Land use is important in DRSTIC modelling as it's the source of primary information and also helps in understanding the behavior of a parameters like net recharge. The land sat map was prepared using land sat image of Webeye for the year 2021 as shown in the Figure 4.13 (h).

4.4.3 Groundwater Vulnerability Map

The DRASTIC-LU index map was classified in to four general classes as Shown in the Figure 7.9 below. The map is categorized into general four classes based on DRASTIC-LU values which were further categorized into; very low, low, high and very high, to describe the vulnerability of groundwater to pollution. This therefore implies that areas that scored low DRASTIC-LU values have low vulnerability and those that scored high values have highest chances of ground water vulnerability, as shown in Figure 4.14 below.

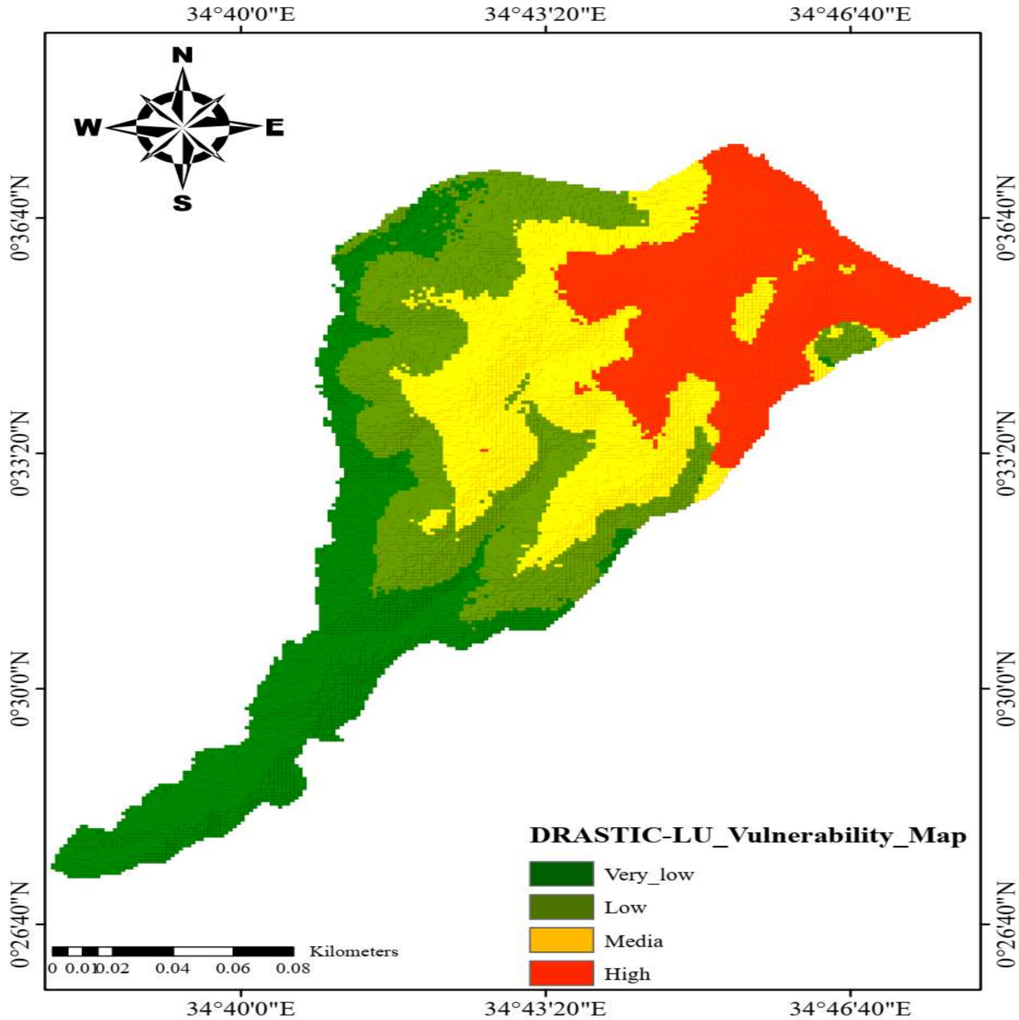

Figure 4. 14: DRASTIC-LU vulnerability map of the study area

The results show that the North Eastern areas of Webuye have high scored the highest DRASTIC-LU values and therefore have the highest chances of groundwater vulnerability to contamination. The North eastern areas are comprised of Webuye Municipality. The area is characterized by dense population, reduced distances between the Onsite sanitation facilities and groundwater sources, use of hand dug wells with shallow depths. These characteristics end up setting a vulnerable environment to groundwater in North Easter parts of Webuye. The North eastern part of Webuye municipality also shows prevalence in

DRASTIC-LU parameters such as the highest recharge in the area above 110mm/yr as seen in Figure 4.12 (b). the area has also is partly composed of sandy aquifers as seen in Figure 4.12 (c) which are porous and permeable making it easy for transmission of water and contaminants. Figure 4.12 (d) also shows the area is partly composed of nitisols which are weathered soil material and well drained. Such soils can fairly support contaminant movement from the surface to groundwater zones (RagaPriya, Janaki, & Arulmozhiselvan, 2020).

Further to these findings, Figure 4.13 (e) shows that the north east part of Webuye has the steepest slopes >18 as compared to all other zones in the study area, sandy soils in vadose zone as seen in Figure 7.2 (f) and hydraulic conductivity in Figure 4.13 (g) have collective contribution to contaminant infiltration and movement. Findings by (Savariya & Bhatt, 2014) show that when slope is combined with soils of higher infiltration capacity greatly reduces runoff than soils having lower infiltration therefore, steeper slopes contribute to greater pollutant transport and less time for infiltration. Hydraulic conductivity ranges between 0.11 and 15.21 m^3/d with the highest levels in north east parts of the study area. Higher conductivity values contribute to more vulnerability of groundwater sources. Findings by (Savariya & Bhatt, 2014) depict hydraulic conductivity results in a spread cone of depression and therefore extended contamination. The north east part has some areas of good tree cover, but its majorly composed of built-up areas of Webuye town. Finding by (Barron, Barr, & Donn, 2013) show that urbanization an instrumental role in change of groundwater quality, by altering the natural surface state and thus the groundwater and the convectional groundwater movement system interfering with dilution and groundwater movement.

CHAPTER FIVE

SUMMARY, CONCLUSION AND RECOMMENDATIONS

5.1 Summary of the study

This study found that the pollution risk factors on groundwater pollution in the study area are nature of waste disposal, well design factors such as depth, nature of apron, well lining and distance from the source of pollution. The Shit Flow Diagram was used to assess the sanitation value chain in the study area. The safely manged waste is much lower than the unsafely managed wastes. Groundwater sources; shallow wells and springs have higher chances of pollution in wet seasons as compared to dry seasons. The results show high concentration of both bacteriological and physical parameters in wet season as compared to dry season.

The spatial distribution of water quality parameters show that the study area was highly concentrated in TSS, nitrates, electrical conductivity and pH were evenly distributed in the study area. Faecal coliforms were concentrated in urban areas of Webuye. Groundwater vulnerability was high in Muchi and Maraka area of the study. The vulnerability map indicates that the areas scored high DRASTIC values thus representing high vulnerability of aquifer to contamination.

5.2 Conclusions

The observation shows that 85% of the residents in Webuye rely on groundwater municipality. Even those served by the water service provider, still have groundwater sources to supplement the supply. The study identified that leachates from onsite sanitation systems, open solid waste dumping, farming activities, well design and operational errors as the main risk factors that affect groundwater quality. Risk assessment for springs show that 44% are at high risk, 44% moderate while 12% are at low risk of contamination, while 32% of wells are at high risks, 39% at moderate risks while 29% are at low risk. The SFD analysis shows that 64% of the wastes human waste in Webuye is unsafely managed while 36% is safely managed.

The water quality results shows that salinity, phosphates, sulphates and turbidity were beyond the KEBS requirements. The results also show that there was high concentration of these parameters during rainy season to an extend that some samples tested positive for fecal coliforms. The results show a correlation between pollution risk factors and water quality. The distance between the well and groundwater sources affect the water quality in wells. Other factors such as depth, use of unlined pit latrines and well design factors have a significance impact on water quality.

The results on Water Quality Index show that 69% of water samples from the study area majorly fell in class >100 (Unfit for consumption), class 76-100 (Very poor) were 16%, class 51-75 (poor) were 11%, WQI class 26-50 (Good) 2% and WQI class 0-25 (Excellent). The water quality index revealed a strong significance relationship between the well and pollution risk factors. Farming activities, open defecation, sewer overflows and use of unlined pit latrines are attribute to undesirable water quality in Webuye municipality. The vulnerability results of groundwater in urban and peri-urban areas of Webuye town show that North Eastern areas of Webuye municipality scored the highest DRASTIC-LU values and therefore have the highest chances of groundwater vulnerability to contamination. The

North eastern areas are comprised of the urban and peri-urban areas of Webuye. The shallow water table, groundwater recharge, the type of soil, slope and the land use activities in the study area resulted into increased vulnerability of groundwater in Webuye municipality.

5.3 Recommendations

The recommendation of this study is key to leaders, planners, policy and decision makers in Webuye municipality as a decision support tool. The recommendations are given in the subsection below.

5.3.1 Recommendation from the study

The study recommends that:

i. The study recommends that a proper establishment of policies in fecal management, waste water management, land use and plot level sanitation in urban Webuye wastewater management policies. The local Water Services Provider should develop programs to ensure that all urban and peri-urban dwellers have access to clean piped water and offsite sanitation services to minimize effects of operating onsite sanitation systems on groundwater.

ii. The municipality administration should come up and enforce well designs which can be resistant to leachate and inflows of contaminated surface water from farming areas and pit latrines.

iii. The water quality indices for key parameters in Webuye should be calculated and comprehensively mapped and results simplified so as to inform the general public on groundwater exploration for a given use.

iv. Policies and guidelines should we developed and enforced on standard practices on solid waste disposal, safe distance between groundwater source and pit latrines, lining of onsite sanitation system and regulation of development of hand dug wells especially on small pieces of lands in town.

5.3.2 Recommendation for further research

This study recommends that a further study should be carried on groundwater vulnerability in rural area of Webuye with focus on establishing safe distance between well and pit latrines for a fair comparison.

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APPEDNICES

APPENDIX 1: Sanitary Risk Assessment Tool for Hand dug wells

Demographic Information

1. Household no of people in a household
2. Do you have history of water borne related diseases?
3. If YES, how often?
    a. Frequently
    b. Occasionally
    c. Rarely
4. Where do you get your water from?
    a. Well
    b. Tap
    c. Spring
5. What is the depth of Water well in m?

6. How do you dispose you waste from the house?
    a. Garbage collectors
    b. Composite pit on compound
    c. No designated dumping point on the compound
    d. Designated dumpsite outside the compound
    e. Approved dumpsites by the authorities
7. What types of toilet do you use?
    a. Pour flush connected to municipal sewer line
    b. Pour flush connected to septic tank
    c. Pour flush connected pit
    d. Pit latrine
    e. Open defecation
8. Is the toilet a shared facility? Y

Well protection

9. Does the well has a cover? Ye N
10. If Yes, please describe the cover;

a. The joint between the well cover and apron surround are sealed well to prevent water from entering the well
b. The joint between the well cover and apron surround are NOT sealed well to prevent water from entering the well
c. The cover has deep cracks that needs to be repaired
d. Only part of the well is fully covered
e. The well is wholly covered

11. Is the concrete floor <1.5 m wide around the well?

12. How is the concrete floor apron sloping?
    a. away from the well
    b. away towards the well
    c. the concreate floor is flat

13. Is there a latrine <10 m radius of the well?
14. If YES how far in Meters
    a. Less than 2m
    b. 3-5 m
    c. 6-10m
15. What is the location of the toilet?
    a. higher ground than the well
    b. lower ground than the well
    c. level ground with the well
16. What possible sources of pollution <10 m of the well
    a. Dumpsites
    b. Poorly maintained drainage from animal shades
    c. Broken/overflow sewer lines
    d. Poor drainage
    e. Open defecation
    f. Storm runoff
17. How far is the pollution source in m to the well?
    a. Less than 2m
    b 3-6 m
    c 7-10m
    d. Above 11 m
18. Is there stagnant water <2 m of the well?

19. Are the walls of the well-sealed at any point for 3 m below ground?

a. The well is adequately sealed
b. The well is inadequately sealed
c. The well is not sealed at all

20. How is water abstracted?
a. By use of a pump to abstract water
b. Rope and bucket

21. If a, are the pumps well /firmly secured on the well apron

If b, are the rope and bucket left in such a position that they may become contaminated?

Yes ☐ No ☐

22. What are some of human activities <2 m around the well at the time of visit?

a. Cloth washing
b. Animal grazing

23. How is the Environment area around the well (> 2m)?
    a. the area around the well is dusty/muddy
    b. there are water diversion ditches around the well
24. Are there wastewater drain ditch around the well area? ☐ ☐

If YES, what is the status of the drains?

a. The drain walls are cracked leaking
b. The drain walls are cracked but not leaking
c. The drains are not lined

APPENDIX 2: Sanitary Risk Assessment Tool for Springs

SN	Item	Question	YES	NO
1	Unprotected	Is the spring source unprotected by masonry or concrete wall or spring box and therefore open to surface contamination?		
2	Masonry faulty	Is the masonry protecting the spring source faulty?		
3	Unfenced	Is the area around the spring unfenced?		
4	Animals access	Can animals have access to within 10 m radius of the spring source?		
5	Lack diversion ditch	Does the spring lack a surface water diversion ditch above it, or (if present) is it nonfunctional?		
6	Immediate latrine uphill	Are there any latrines uphill of the spring?		
7	Nearest visible latrine higher	Is the nearest latrine on higher ground than the spring?		
8	Pollution	Are there any other source of pollution (e.g., animal excreta, dump sites, rubbish) within 10 m upstream of the Spring?		
9	Animals grazing	Are animals grazing <2 m around the spring?		
10	Clothes washing	Are people washing clothes <2 m uphill of the spring?		
11	Open defecation	Is there open defecation uphill the site?		
12	Human activity	Are children playing around the spring?		
13	Ponding	Is the spring collection area not developed to minimize ponding of surface water?		
14	Vegetation	Is the spring a collection area with deep-rooted vegetation?		
15	Farming activities	Is there application of fertilizers, chemicals upstream of the spring?		

APPENDIX 3: Sanitary Risk Assessment Tool for Rivers

SN	Item	Yes	No
1	Is there any human habitation upstream, polluting the source?		
2	Are there any farm animals upstream, polluting the source?		
3	Is there any crop production or industrial pollution upstream?		
4	Is there a risk of landslide or mudflow (caused by deforestation) in the catchment area?		
5	Is the intake installation unfenced?		
6	Are there any water abstraction for domestic use?		
8	Does the system require a sand or gravel filter because the water is silt-laden and can affect water treatment?		
9	If there is a filter, is it functioning badly?		
10	Is the flow uncontrolled?		

APPENDIX 4: Research Photos

Data collection and sampling of groundwater

Depth measurement in water wells during data collection

APPENDIX 5: Research License

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