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Review

Groundwater pollution and climate change vulnerability in Kenya: A review

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Groundwater is a significant water source for agriculture, industry, and domestic use. In Kenya, pollution and unprecedented climate change vulnerability threaten the sustainability of groundwater sources. Climate change has intensified frequent droughts, leading to water shortages and access to clean water. This research study review identifies the causes of groundwater pollution and distribution of surface water and boreholes in relation to climate change vulnerability in Kenya. It also elucidates projections and the effect of climate change vulnerabilities on aquifers. The findings show that the gradual, steady increase in groundwater pollution results from the continued use of various uncoordinated legal and policy frameworks that have yet to do much to address groundwater resource management in Kenya. This research paper recommends the creation and implementation of strong institutions with clearly defined legislation and policies governing groundwater, integration, and cooperation of groundwater resources with surface water and all key stakeholders, as well as the creation of awareness to enhance understanding of the dangers of groundwater mismanagement and its importance in climate change adaptation.

Key words: Climate change, aquifers and boreholes, groundwater, pollution and contamination, ground water vulnerability assessment.

INTRODUCTION

Groundwater abundance can be defined as a resource that remains largely undiscovered and underutilized, with its location, purpose, volume, and quality poorly understood in both human and ecological systems (Veeraswamy et al., 2024). Globally, groundwater constitutes approximately 29.9% of freshwater, with 69% locked in polar ice caps and 1.1% found in lakes, rivers, and natural springs (Swain et al., 2022). It provides 95% of the accessible freshwater globally for consumption. In Kenya, out of a population of over 46 million people, about 19 million (41%) lack access to clean water (Sarkar et al., 2022). Approximately 17 million Kenyans live in arid and semi-arid lands (ASALs) and rely on groundwater due to unpredictable rainfall patterns,

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exposing them to water scarcity (Lasagna et al., 2020).

The demand for groundwater is expected to increase gradually due to climate change impacts, population growth, and depletion of surface water resources, urbanization, industrialization, and agricultural development. Climate change increases groundwater vulnerability by raising temperatures, causing irregular rainfall and drought, leading to declining groundwater levels and storage (Veeraswamy et al., 2024). Flooding, another climate change impact exacerbates groundwater pollution by washing solid waste such as sewage into wells. These vulnerabilities and groundwater pollution have severe impacts on the health and survival of surface flora and fauna (Kumar, 2012).

A variety of activities contribute to groundwater pollution near existing aquifers in Kenya. These activities include industrialization trends, urban sprawl, and agricultural development, among other things (Oiro et al., 2020). For instance, groundwater is widely used for agriculture, industry, and domestic purposes in the Kisumu aquifer in the western region.

The sugarcane production industry has resulted in industrialization and urbanization within the Kisumu region. The water supply from Lake Victoria is limited due to the increased cost of water treatment caused by pollution and eutrophication, making the lake's pipped water unaffordable to most of the surrounding areas. Because of the low cost of hand-dug shallow well construction, most Kisumu residents prefer borehole water, which has resulted in increased pollution of the Kisumu aquifer (Kanoti et al., 2019).

Unprecedented urbanization in Kenya has piled pressure on water service provision and sanitation infrastructure endowed in the country (Oiro et al., 2020). The low capital investment ensures that sanitation infrastructure remains unchanged. As the institutions in charge of water and service provision struggle to meet ever-increasing water demands, groundwater becomes an option in urban and rural areas (Hussain et al., 2019). Poor sewerage and drainage systems significantly contribute to groundwater pollution in most urban areas, such as Nairobi. The Nairobi Aquifer System (NAS) has experienced significant water decline, deterioration, and depletion due to overexploitation to meet water demands (Oiro et al., 2020). Due to the rapid population increase, there is no corresponding investment in solid waste management infrastructure, and this is worsened by the development of informal settlements (slums) characterized by the use of pit latrines, open defecation by humans and animals, and landfills developing near groundwater resources (Kamau and Njiru, 2018).

Similarly, the other pervasive groundwater pollution is resultant from increased nitrate inorganic fertilizers to meet agricultural production demand in Kenya (Ware et al., 2024). These nitrates are transported through surface runoff and deposited during the rainy seasons. High nitrate levels in water cause environmental degradation and a heightened health problem. These consequential ramifications provide significant hazards or cancer, eutrophication, and blue baby syndrome in newborns (Senoro et al., 2023). In Kenya, the Kano region is a potential source of groundwater nitrate pollution from the increased use of inorganic fertilizers for sugarcane farming (Nyilitya et al., 2020).

The purpose of this review is to investigate the implications of groundwater pollution in relation to the impact of subterranean water sources, specifically the aquifers, in an array of prospective places in Kenya. In addition, this review paper dives into the consequences that climate change may have on groundwater zones, groundwater vulnerability assessment (GVA), and the methods that are used to monitor groundwater pollution and quality. Furthermore, we summarize our findings by providing recommendations that are geared towards ensuring the long-term viability of Kenya's ground and subsurface water sources.

STATE OF GROUNDWATER POTENTIAL IN KENYA

The following are the main aquifer distribution in Kenya recharged with freshwater rivers: Merti Aquifer recharged by river Ewaso, located in Eastern Kenya close to the Somali border which mainly provides water for socioeconomic and domestic use to the Dadaab refugee camps which is the biggest refugee camp in the world (Nyilitya et al., 2020).

Lodwar Aquifer is recharged by the Turkwel River, which usually supplies water to Lodwar municipality. Gongoni Aquifer is recharged by the Mkurumudzi River in Kilifi and Mombasa counties and is mainly used by the Base Titanium Mining Company. Kisumu aquifer recharged through rainfall infiltration from Nandi hills (Oiro et al., 2020). Baricho Aquifer is recharged by river Galena, providing fresh water to Mombasa, Malindi, and Kilifi (Nyilitya et al., 2020). Other aquifers include Nairobi, Lotikipi Mombasa Island Pleistocene, and Limestone Aquifers (Mbugua et al., 2022).

Groundwater is a critical resource, vital as a habitat for various aquatic species, and a critical component of the sustainability of hydrologic and human systems. Groundwater has astounding benefits for cities for domestic and industrialization that enhance today’s urbanization phenomena. The anticipated large-scale groundwater use is attributed to boosting Kenya’s economic prosperity through crucial water-dependent sectors like agriculture, processing, and manufacturing if only management of this groundwater is fully attended to (Oiro et al., 2020).

In Kenya, groundwater is the primary water source in most metropolitan regions, including Mombasa, Nairobi, Kisumu, and, most crucially, ASAL regions (Sarkar et al., 2022). In addition, these ASAL areas make up 80% of the land and are home to 34% of the country's inhabitants and 50% of the cattle population. It is estimated that only

0.18 billion Cubic Meters (BCM) of Kenya's 1.04 BCM of renewable groundwater are utilized annually (Sishu et al., 2022). The degradation of the water catchment areas and reduced investment in water development has led to reduction of per-capital volume of water in the groundwater level (Ciampi et al., 2022).

Many commercial, residential, and industrial water users in the coastal region rely on groundwater in Mombasa, the North Coast, and the South Coast to supply their needs (Kilifi and Malindi) (Makokha, 2019).

The use is constrained by overexploitation, salt intrusion along the coast, and inadequate understanding of the resource’s presence (Ferrer Ramos et al., 2020).

In rural areas, groundwater resources are extensively used for domestic and irrigation purposes. Private irrigation systems covering 78,500 ha primarily rely on boreholes, particularly in the Lake Naivasha and northwest Mt. Kenya regions. Smallholder irrigation schemes (86,500 ha) and public irrigation schemes (18,900 ha) typically source their water from surface streams (Blandenier et al., 2016). In some parts of northeastern Kenya, less than 5% of the irrigation water comes from groundwater, though this may be underestimated given the reliance on groundwater by private sector irrigators in the Central, Rift Valley, and Eastern regions (Sishu et al., 2022). The irrigation master plan anticipates future growth in groundwater-based irrigation driven by the private sector due to the high capital costs associated with surface water storage (Oiro and Comte, 2019). According to the findings, approximately 0.2 billion cubic meters per year of groundwater could potentially be conserved for irrigation purposes (Rashid et al., 2023).

Groundwater-dependent ecosystems (GDEs) are ecosystems that wholly rely on groundwater (Eamus et al., 2016). They include karst, deep-rooted plants, seeps, springs, and, to a greater extent, rivers, wetlands, and lakes are part and parcel. There are many ecological uses for GDEs. However, these uses need to be better utilized. For example, the proposed National Wetlands Policy 2015 specifically recognizes wetlands' significance for groundwater recharge and outflow (Foster and Chilton, 2021). The geomorphological conditions of GDEs make classification the most straightforward. Examples of this classification in Kenya include brackish coastal lagoons fed by natural discharge, wetlands created by discharge from shallow aquifers in depressions, extensive aquifers that provide dry-weather flow in the upper reaches of river systems, and terrestrial ecosystems devoid of open water (Oiro and Comte, 2019).

Although groundwater is a potential mitigation and adaptability mechanism for the current climate change crisis, most of the country's aquifers are degrading and depleting (Ayobami et al., 2023). Thus, there is a need to protect and conserve disappearing streams, rivers, and wetlands.

CLASSIFICATION AND CATEGORIZATION OF GROUND WATER QUALITY

Groundwater quality can be classified into two main categories:

1. Naturally occurring high arsenic levels.
2. Human-induced degradation of groundwater resources.

Naturally occurring arsenic levels refer to the natural occurrence of the arsenic element that combines with other organic and inorganic substances to form compounds in soil or groundwater. For example, Southeast Asia is thought to be afflicted by arsenicosis symptoms caused by directly or indirectly consuming agricultural food produced from contaminated irrigation water (Katuva et al., 2020). What makes it difficult is that, while the water is contaminated, mitigation measures are available, but they are prohibitively expensive for locals (Postma et al., 2016). The natural contamination of aquifers from hard-rock aquifers (Arsenic compound) is directly linked to overexploitation. For example, the Nairobi Vulcanic Aquifer (NVA) is contaminated with fluoride in the Embakasi region, caused by overexploitation. Consumption of such water leads to chronic diseases, for example, skeletal, dental, and non-skeletal fluorosis (Kumar et al., 2019).

Human-caused degradation and salinization refer to the anthropogenic activities that reduce groundwater quality. These activities include the farming system, land management, and use, which account for the biggest threat to the aquifer’s sustainability (Sarkar et al., 2022). The potential of groundwater resource depletion brought on by increased abstraction to enable increased irrigation leads to salt accumulation in the upper soil profile, which is caused by excessive irrigated water application, rising water table, and naturally occurring salts drawn upwards towards the soil surface via capillary (Kanoti et al., 2019). This results in a dire remedy of reduced productivity and utility of soil and water. The other cause is climate change, which leads to temperature increases, enhancing high evaporation rates and leaving naturally occurring salt in applied water on the soil surface (Gevera et al., 2020).

Aquifer recharges pollutants and point sources

The recharge of the aquifer depends on the hydrologic system. It is through this process that contamination of groundwater occurs. Groundwater contamination can be caused by bacteria, viruses, chemicals, fuel, medications, and fertilizers (Tudi et al., 2021). Groundwater pollution differs from surface water in that groundwater is invisible, and its recovery is challenging and expensive since it is on the subsurface geological strata. These pollutants come from natural and mainly anthropogenic sources.

There are three types of groundwater pollution: chemical, biological, and radioactive contaminants (Uddin et al., 2024).

Chemical pollutants are inorganic compounds that dissolve in groundwater, such as nitrogen contaminants (Abascal et al., 2022). Nitrates, nitrites, and ammonia are prevalent inorganic sources predominantly from anthropogenic activities, such as agriculture. Other inorganic contaminants include the anions and cations that are primarily found in their natural environment, but they dissolve in the water through seepage and infiltration. Heavy metal pollutants are a risk factor for human health and the natural environment. The metals and metalloids widely detected in groundwater include mercury (Hg), lead (Pb), cadmium, and arsenic (As) (Fatoki and Badmus, 2022). Though exposure to these elements at lower doses is essential to our health, exposure at higher concentrations can lead to poisoning, and most of them are carcinogenic, with arsenic ranked as Group 1 human carcinogenic by the US Environment Protection Agency (EPA) and the International Agency for Research on Cancer (IARC) (Jiang et al., 2022). Other sources include hydrocarbons and pharmaceutical products. For example, halogen compounds (chlorinated, brominated, fluorinated) are stable in the environment, but once they have accumulated in higher trophic levels (human beings), they have a harmful effect (Uddin et al., 2024). Chemical pollutants tend to persist for an extended period, which gives enough time for contamination of deeper aquifers (Mitra et al., 2022).

The biological organic pollutants are naturally produced from carbohydrates, proteins, oils, and fats and can be converted to inorganic substances by microorganisms (Genchi et al., 2020). They have been widely detected in drinking.

They have no direct toxic effects on living organisms but can reduce oxygen dissolved in groundwater. They include algae and microbial organisms (bacteria, viruses, and protozoa). Drinking contaminated water causes many human diseases, including typhoid and cholera (Ayaz et al., 2023). The biological pollutants primarily come from human, animal, or agricultural runoff (Ifeanyi Maxwell Ezenwa et al., 2023). The biological pollutants only persist for a short period and thus threaten shallow groundwater (Jyothi, 2020).

Radioactive contaminants originate from geological deposits of radionuclides and anthropogenic improper disposal of medical radioisotopes and wastes from nuclear power plants and testing grounds (Akshitha et al., 2022). These contaminants get into our bodies through drinking contaminated water, although cases of groundwater contamination with radioactive contaminants have been rarely detected (Chen et al., 2022).

There has been a growing importance of groundwater as an alternative water source due to the impacts of climate change. In Kenya, groundwater has been utilized in various ways to enhance human survival. These include industries for cooling machines, agriculture through irrigation, and domestic use (Ferrer et al., 2019). However, with the ever-rising groundwater contamination, the viability of Kenya’s aquifer to continue supporting ecological services is being threatened (Owuor et al., 2016).

Prospects impacts of climate change on groundwater zones

Climate change is an ongoing, inevitable phenomenon projected to pose varied environmental issues, including but not limited to hydrological cycle alterations (Jerome et al., 2023). These anticipated detrimental impacts are attributed to anthropogenic effects through modelled climate data and scenarios (Adeola et al., 2024; Ngare et al., 2022). For example, groundwater will be an outstanding vital resource to alleviate drought scenarios (Zewde Alemayehu Tilahun et al., 2023). Climate change poses various impacts on aquifers, some of which are:

i) Changes in the precipitation patterns: climate change alters the amount, frequency, and distribution of precipitation, reducing rechange rates for aquifers in some regions and increasing recharge in others.
ii) Sea level rise: Rising sea levels result from climate change, leading to saltwater intrusion into coastal aquifers, making the groundwater unfit for human consumption or irrigation.
iii) Increased evapotranspiration: Higher temperatures associated with climate change may cause increased evapotranspiration rates, reducing the amount of groundwater available.
iv) Changes in soil moisture: Climate change can lead to changes in soil moisture content, which can affect the recharge rates of aquifers.
v) Changes in groundwater quality: Climate change can affect the chemical composition of groundwater by altering the temperature and precipitation patterns, leading to changes in the concentration of dissolved solids, nutrients, and contaminants.
vi) Changes in groundwater availability: Climate change can impact the availability of groundwater resources, with some regions experiencing water scarcity due to reduced precipitation, while others may experience more frequent and severe flooding, affecting water quality.

Overall, the impacts of climate change on aquifers are complex and vary depending on the region, hydrogeological conditions, and the severity of climate change (Chen et al., 2023). The climate has undergone changes in the past and is presently experiencing, and will continue to experience, changes in the future, which can vary in scale from decades, centuries, to millennia. It is now undeniable that there is a planet-wide observation of a current warming trend, which is no longer a mere hypothesis (Mumma et al., 2011). The Intergovernmental Panel on Climate Change (IPCC) has projected that the rising temperatures will continue to increase over centuries, regardless of the actions taken, with impacts extending beyond the present time (Mas-Pla and Menció, 2019). The acceleration of this warming trend is attributed to anthropogenic activities that release greenhouse gases into the atmosphere. Furthermore, data indicates that climatic variations alter hydrological processes (Wetts, 2020).

The relationship and importance of climate change and groundwater cannot be overstated (Pletterbauer et al., 2018). Aquifers or groundwater mitigate drought because of their high storage capacity and are less sensitive to climate change, unlike ground surface water bodies (Ebi et al., 2017). Investing in geology, hydrology, and hydrogeology studies is essential to provide the necessary platform for investigating the impacts of climate change on groundwater, and these studies hold concrete prospects (Mirón et al., 2023). To evaluate and validate knowledge gained through experimental work for present and future situations, there is a need to establish a continued evolution of data collection networks (Comte et al., 2016).

Aquifers provide excellent opportunities for climate change adaptation through groundwater resources during dry periods in anticipation of wet season recharge, utilizing aquifers' natural buffering capacity, and managing aquifer recharge (Qureshi, 2020).

Conducting dedicated monitoring is necessary for numerous parameters (Ph, temperature, Oxidation-Reduction Potential, turbidity, nitrate) to assess the impact of climate change on a specific groundwater system (Becker et al., 2022). Depending on the subsurface features, process representation, and boundary conditions, many modeling programs can account for flow in both the saturated and unsaturated zones and other water quality and quantity challenges (Odeloui et al., 2022).

Variations in temperature and precipitation caused by climate change affect evapotranspiration, affecting groundwater recharge (Comte et al., 2016). In general, groundwater recharge will increase in areas with increasing precipitation and decrease in irregular or scant precipitation areas. Groundwater is a site-specific quantity, complicating questions about its regional implications. Groundwater recharge is influenced by climatic conditions, land use, geology, and topography (Barthel et al., 2021).

This suggests that the groundwater recharge impacts the groundwater flow network and the aquifer discharge, for example, unexpectedly turning losing streams into gaining streams (Szabó et al., 2022). Climate has an impact on these factors, as does groundwater flow direction. Numerical models with calibrations confirm the placement of numerical models at different stages to trace or quantify the potential climatic fluctuations to springs (Chepkemoi et al., 2023). It is crucial to artificially improve recharge in Kenya's northeastern region, which frequently experiences drought due to climate change, and the technology for reusing aquifers with low-quality recycled water (Karuku, 2018).

Another crucial part of the water cycle is groundwater discharge, which increases the amount of water lost from aquifers to the earth's surface through wells, lakes, rivers, and streams and through abstraction for human uses.

Measuring base flows to rivers, lakes, wetlands, and seas again influences and evaluates the impact of climate change and entails researching the role of plants in transpiration (Burnside et al., 2019). The contribution of subsurface discharge to the oceans has helped to materialize the freshwater discharge to the ocean due to climate change over the past ten years (Hounsinou, 2020). This shows that coastal areas frequently employ the technique for quantifying undersea groundwater outflow mechanisms (Alfarrah and Walraevens, 2018).

Desertification and global warming result from climate change; therefore, adequate vegetation cover improves water infiltration through the soil profile (Haile, 2005). Because of direct and indirect effects on recharge and dependence on vegetation and groundwater, vegetation is essential and plays a significant role in the interactions between groundwater and surface water systems (Bwiza et al., 2024). By altering one of the components of the hydrological cycle, evapotranspiration, the shift in vegetation cover and structure from low vegetation, such as grassland to tall vegetation, such as forest, can substantially affect groundwater recharge. About half of the most significant changes in the water balance are caused by the transpiration (Ochungo et al., 2019).

Floods caused by climate change may pave the way for natural hazards such as landslides. Variations in groundwater level precisely focus on the geomorphological effects (Sousa et al., 2018). Flooding has a significant impact on slope stability, decreased suction, rising groundwater water table and subsequent increasing porewater pressure, groundwater exfiltration from bedrock, seepage erosion hydraulic uplift pressure from below the landslide, and the influence of water on the plasticity of the landslide (McInnis et al., 2013).

Groundwater vulnerability assessment (GVA)

For decades, there has been an increase in awareness of the risk of groundwater contamination (Hanasaki et al., 2008). There is a dire need to protect groundwater quality through the regeneration of polluted groundwater, which seems costly (Vasanthavigar et al., 2010). The groundwater vulnerability assessment (GVA) concept emerged due to the need to protect groundwater bodies against contamination (Rendilicha, 2018). This first emerged in the 1970s in France to address the problems associated with groundwater pollution due to human-induced anthropogenic activities (Jürgen Mahlknecht et al., 2017). Scientists have a consensus to study groundwater vulnerability to have a common understanding of the concept and approaches that will enable them to address the issue of groundwater pollution (Makanda et al., 2022).

The GVA recognizes zones where groundwater is susceptible to contamination due to anthropogenic activities and translates them into a groundwater vulnerability map that is utilized to direct monitoring, educational, policy, and regulatory development efforts to mitigate the harmful impacts on groundwater quality (KC et al., 2022). The extent of groundwater pollution in a given zone is determined by the natural impoverishment between the pollution point source and the aquifer (Haque et al., 2020). Areas, where soil, subsoils, and bedrock do not provide adequate attenuation, have higher chances of pollutants reaching the groundwater (Egbueri, 2023). Therefore, GVA assists in pointing out regions that are more vulnerable to pollution in relation to surface and underground characteristics and the availability of polluting sources (Teklu et al., 2022).

Three methods have been developed to assess groundwater vulnerability to human-induced contamination: statistical influence, overlay and index, and process-based mathematical methods (Zohud et al., 2023). The statistical approach examines contaminant occurrence in a specific area across different scales, correlating it with intrinsic aquifer properties to assess contamination levels. An example includes principal component analysis (Bharti et al., 2024). The overlay and index methods integrate thematic maps of physical parameters known to influence groundwater dynamics and contaminant transport (Wekesa and Otieno, 2022). These parameters are assigned relative scores based on their impact on groundwater vulnerability within the regions, exemplified by the DRASTIC index (Gad et al., 2022). The process-based mathematical approach predicts contaminant transport from a localized source with high accuracy, utilizing fundamental principles governing water flow in porous media and the behavior of chemical constituents carried by water. This approach includes models for behavior assessment, such as those discussed by Mbaka et al. (2017).

Aquifers nexus and attributed impacts in Kenya

Kenya is predominantly rich in the aquifer and its underground water sources; however some of them are vulnerable to degradation and depletion. For example, the Baricho aquifer is potentially one of the most vulnerable aquifers, but it is protected because the area surrounding the waterworks is sparsely populated and government-owned (Rendilicha, 2018). The Sabaki River's polluted surface water is most likely the most severe threat to the aquifer. The susceptibility of this aquifer to contamination by trace contaminants, such as pesticides, is unknown because no analyses of trace contaminants, such as pesticides, have been performed (Sharma et al., 2019). The Baricho aquifer is used solely by the Coast Water Service Board (CWSB) to supply the public with water (Nyanchaga, 2016). The abstraction details should be easy to prepare. However, the Water Resource Management Authority (WRMA) only has access to the abstraction details because no water usage charges or licenses for the Baricho aquifer have been issued or paid (Howland, 2023).

The Merti aquifer is about to become exposed to contamination (Oiro and Comte, 2019). Despite the possibility of slightly high amounts of metal traces, their existence is almost certainly normal (Comte et al., 2016). Some of the aquifers are not significantly stressed by depletion despite the scant amount of data that is currently accessible (Michael van der Laan et al., 2021). There is some proof that long-term abstraction at Habaswein, as well as other boreholes from the middle of the 1970s, may have contributed to some salinization of the groundwater there (McInnis et al., 2013). At Dadaab, depletion has happened and is still happening, albeit slowly, and the water quality has been worse over time (electrical conductivities have approximately doubled since the early 1970s (Blandenier et al., 2016).

Compared to other aquifers, the NAS aquifer is sensitive to contamination (Oiro et al., 2020). This generalization needs to be used carefully because not much research has been done on the (north) western recharge zones (Fankhauser et al., 2022). Concerns regarding the sustainability of the existing levels of abstraction have been mounting, as NAS is the most heavily exploited aquifer in Kenya (Chepyegon and Kamiya, 2018). The Nairobi Groundwater Conservation Area was established during colonial times as the first attempt to control extraction from the NAS (Wekesa and Otieno, 2022). However, the Nairobi Groundwater Conservation Area (GCA) agenda failed to manage abstraction because of the increased demand due to population increase (Danert and Healy, 2021). The boreholes increased tremendously from 10 in 1940 to 2,000 in 2002. There are a lot of boreholes that have contributed to its depletion (Ochungo et al., 2019).

The Tiwi Aquifer is a modest but substantial groundwater source near the South Mombasa Coast (Ojwang et al., 2017). The Tiwi Aquifer is not in danger because the land is primarily used for agriculture, and abstraction is far lower than the mean annual recharge. This aquifer could be endangered by urban development without sewers and sand mining. If unrestrained sand harvesting sufficiently removes the surrounding unsaturated material, there is an increased risk of pollution from directly recharging dirty water (Nlend et al., 2018).

Any urban growth that uses onsite sanitation techniques like pit latrines or septic tanks puts this aquifer at risk (Maria Rosaria Alfio et al., 2023). The Tiwi well field's individual borehole wellhead protection is insufficient (Comte et al., 2016).

Although Tiwi borehole compounds are guarded and protected, leaving a borehole open is not a good idea. Boreholes should have steel caps, and holes punched through them to accommodate the rising main, power cable, and dipper tube (Kuria, 2013).

POLICY RESPONSES ON GROUNDWATER

Most water managers have been accused of suffering from hydro-schizophrenia, which is the inability to differentiate the interconnectedness between surface and groundwater and the creation of separate surface and groundwater governance, bureaucracies, and policies (Messabia et al., 2022). One of the critical challenges facing groundwater resources is management. This paper presumes if no actions are taken on the following policies, there will be higher chances of groundwater vulnerability to pollution and depletion. They include:

i) Water allocation
ii) Identification and creation of groundwater conservation zones
iii) Establishment of a national standing committee
iv) Groundwater Conservation Act 2016
v) Proposal for a Policy for Protection of Groundwater (PPPG) resource conservation.

Merti, Lodwar, Gongoni, and other aquifers in Kenya are not actually "managed" because new water allocations are made without following a methodical appraisal technique or water allocation plan (Foster et al., 2022). Water allocation is, at best, a shaky process due to the low level of compliance by water users with regard to water permits and the payment of water use fees (Foster, 2020). The Nairobi aquifer system (NAS) was supposed to be protected by a groundwater conservation area (GCA), but it still yet to do so (Chávez García Silva et al., 2020). The lack of coherent land use planning makes it difficult to limit abstraction, and efforts have been seriously hampered by a building boom, commercial interests, and indifference (Foster and Chilton, 2021).

The country's water resources are at risk due to increased human activity since groundwater supplies are susceptible to land use and human activity. The policy highlights the requirement for identifying and creating groundwater conservation zones (Waheed et al., 2021). Except for the area around Nairobi that existed before this policy statement, Groundwater Conservation Areas (GCAs) have yet to be created (Foster and Chilton, 2021). An effort has been made to create a groundwater conservation zone near Lake Naivasha, although it has not yet been gazetted (La Vigna, 2022).

Regarding IWRM, the policy suggests the establishment of a National Standing Committee with representation from all significant players in the water and allied sectors to address cross-sectoral concerns (Rendilicha, 2018). Such a committee has not been established. Several sectors (land, water, and forests) are still developing policies without the required connections with several other sectors (Mumma et al., 2011).

The Water Resources Management Authority created a Proposal for a Policy for Protection of Groundwater (PPPG) Paper in 2006 to explore groundwater resource conservation by balancing sustainable use and national development and groundwater quality protection by lowering the hazards caused by pollution (Jyothi, 2020). This significant conversation was never taken further than the proposal stage (Nyanchaga, 2016).

The institutional framework has several issues, including overly centralized decision-making processes, ineffective monitoring networks and databases, discontinuous assessments, uncoordinated source development, inoperative water rights, and a lack of specialized courts to resolve disputes over water use (Foster et al., 2022). This situation still exists today despite the passage of the 2016 Water Act. This demonstrates how the lack of policy is not the issue; rather, the lack of willingness to put the ideas into practice (Rendilicha, 2018).

Due to ineffective monitoring mechanisms and a poor user database, information flow is characterized by data gaps (Vasanthavigar et al., 2010). At all levels, this needs to be addressed. There currently needs to be a database for groundwater data for Nairobi's groundwater extraction survey by WARMA (Oiro et al., 2020).

Low water tariffs, a small revenue base, and inefficient revenue collection methods have all contributed to insufficient water income. Despite the fact that the Act and regulations impose water use fees for the abstraction of raw water, the amount of money collected from groundwater has been insufficient until now (Mumma et al., 2011). The government will support private sector-led drilling efforts through competitive contracting to improve groundwater management capability. This policy regulating the numerous, frequently careless boreholes dug by private drilling contractors has become a significant problem (Howland, 2023).

The Environmental Management Policy (EMP) of 1999c had neglected groundwater resources while protecting water catchment regions, wetlands, and rangeland resource management. To accomplish holistic environmental management, these policies had to have considered groundwater management (Chepyegon and Kamiya, 2018).

The critical legal provisions for groundwater conservation, such as the Groundwater Conservation Act (GCA) Underwater Act 2016, have yet to be implemented (Rendilicha, 2018). This Act mandates the mapping and gazetting aquifer protection zones and groundwater recharge regions to safeguard them against pollution.

Additionally, many groundwater abstractors operate without permits, and many with licenses frequently fail to reimburse customers for the water they use to extract groundwater (Mumma et al., 2011). The lack of a framework for methodically establishing and enforcing the necessity for paying user fees exacerbates this. Given that the implementing agency, WRMA, depends on water use charges to carry out its purpose, this has prevented it from accessing crucial financial resources (Foster and Chilton, 2021).

Groundwater resource management is still addressed by various fragmented legal and policy frameworks that have done nothing to solve the myriad problems that affect land use management in Kenya (Katuva et al., 2020). Moreover, there is a lack of cross-sector collaboration and coordination among organizations responsible for managing groundwater resources (Qureshi, 2020). The management choices in physical planning, land use planning, and agricultural operations are made without considering the effects on groundwater resources. In addition, Kenyan planners are unaware that aquifer use patterns, as well as aquifer recharge and discharge characteristics, are impacted by land use plans (Foster, 2020). The Nairobi Aquifer System (NAS) is a classic Kenya case in which planning permission is granted for development in areas where municipal water supplies are insufficient or unavailable, leaving groundwater as the only available water resource.

As of 2006, Kenyan law and regulation (Legal Notice No. 170 The water resources regulation) call for identifying and mapping groundwater protection and vulnerability zones (Mumma et al., 2011). To date, nothing has been done to achieve this. The National Water Policy acknowledges that Kenya has shared groundwater resources, but the policy objectives make no explicit recommendations for their management. The ministry created a draft policy paper on shared water resources in 2009. However, shared groundwater resources were given little attention.

Groundwater management is generally poor and ineffective, with little resources and a lack of strategic focus. The belief that groundwater is an endless supply is to blame for this since this view is brought on by a lack of understanding of groundwater resources, general institutional weakness, limited technical capability that is not exploited effectively, insufficient finance, and a lack of political commitment at the highest levels of policymaking (Chris De Bont and Lowe Börjeson, 2024). As a result, poor management and excessive abstraction have persisted. It is underappreciated in Kenya that better groundwater management and utilization will significantly influence measures for coping with climate change to support socio-economic development (Velis et al., 2017). However, there is also a disconnect between groundwater, climate change knowledge, Sustainable Development Goals (SDGs), and benefits accruing from groundwater management (Cling and Delecourt, 2022).

Most of the literature and technical reports show groundwater is generally being polluted, especially from the agricultural practices and onsite sanitation systems, for example, soak pits, septic tanks, and pit latrines, the case in Mombasa and Kisumu (Kanoti et al., 2019).

No particular long-term measures have been put in place to contain and curb the increasing groundwater contamination, especially from anthropogenic activities Akhtar et al. (2021).

GROUNDWATER POLLUTION AND QUALITY MONITORING APPROACHES

Due to poor hydrogeological data, lack of specialists with the necessary skills, the inapplicability of the majority of vulnerability methodologies, inadequate funding particularly in Sub-Saharan African (SSA) countries, make it difficult to carry out quality monitoring process of groundwater (Chris De Bont and Lowe Börjeson, 2024). Some research on the hydrogeology of SSA nations is highlighted in the African Climate Policy Centre's (ACPC) Working Paper 6 of the United Nations Economic Commission for Africa (Foster and Chilton, 2021).

Natural population growth and climate change impacts create a high-water demand (Mas-Pla and Menció, 2019). There are inadequacies in water and waste management infrastructure and public services for much of the population growth, especially in urban areas like Mombasa, Kisumu, and Nairobi (Foster et al., 2022). For instance, unplanned high-density settlements and slums account for the underserved areas in Mombasa, particularly in Kisauni. The lack of pure drinking water makes this apparent, leaving the residents with no choice but to supplement their supply with groundwater (Ferrer et al., 2019).

The DRASTIC model used to examine the intrinsic aquifer's susceptibility to groundwater pollution's results indicate that Kisauni and Mombasa's northern and southern regions are most at risk[1]. Particularly in the Kisauni area, the high population has increased the concentration of nitrates, which is linked to groundwater contamination through on-site waste disposal systems that open up a pathway for leachate seepage in groundwater or through erosion that drains the leachate to the wells and contaminates groundwater (Akhtar et al., 2021). Aquifers and recharge water may both be contaminated by some of these land uses. These can either be diffuse sources, like fertilizers (nitrates, phosphates), or point sources, such as industrial releasing garbage that mixes with recharge water (toxins) (Mitra et al., 2022). This only applies to the coastal aquifers' pH, colour, TDS, chloride, salinity, alkalinity, hardness, magnesium, and calcium (Ifeanyi Maxwell Ezenwa et al., 2023). Nitrate and total phosphorus should be included in the studied parameters since they serve as indirect pollution indicators. Iron and manganese levels in Baricho should be monitored and regular tests for

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[1] https://iwaponline.com/ws/article/22/5/5190/87592/A-review-on-the-application-of-the-DRASTIC-method

Figure 1. Camel taking water from a water pan in Wajir county Kenya (photo credit: ILRI/George Wamwere-Njoroge).

pesticide metabolites and various trace elements should also be conducted (Tudi et al., 2021).

Despite prior UNICEF recommendations, a repeat test for a few heavy metals has yet to be performed (Mumma et al., 2011). Groundwater samples from the Nairobi aquifers are occasionally tested for health-related factors, and fluoride is suspected to be present in samples from boreholes used by the Nairobi City Water and Sewerage Company Limited (NCWSC) (Oiro et al., 2020). Groundwater resources have not been routinely monitored or have only been monitored occasionally until recent years (Sousa et al., 2018). Most significant Kenyan aquifers are currently the focus of WRMA's monitoring program (Nyanchaga, 2016). The main drawback of the existing monitoring network is the use of production boreholes, the bulk of which require water levels to be restored to static levels before readings (Becker et al., 2022).

As an acceptable compromise for a developing country, WRMA makes an effort to manually gather water level and quality trends every quarter. Water level measurements, however, are made every month for intensively utilized aquifers like the NAS (Oiro et al., 2020). 20 monitored boreholes, or one well per 273 km^2, are present in the NAS. CARE Kenya takes weekly to monthly water level readings in the Dadaab Merti (Blandenier et al., 2016). The most extended continuous groundwater level data set in the nation comes from these boreholes, which have been continuously monitored since 1992. At Tiwi and Baricho, a restricted water level monitoring program is about to begin.

Figure 1 shows a herdsman fetching water for the camel and goats. Water pan is a groundwater resource, and from the image, it is clear that it is vulnerable to pollution from the excreta of human and animal waste (Diriba Tulu et al., 2023).

Although there is monitoring, there is no collaboration and coordination of multisectoral bodies to manage the pollution of groundwater resources (Egbueri, 2023). If the same applies to most pans and boreholes in Wajir and across the northeastern part of Kenya, groundwater pollution will increase swiftly (An et al., 2021).

Before the construction of infrastructure, the hydrological, social, and financial hazards of groundwater investments should be considered (Ifeanyi Maxwell Ezenwa et al., 2023). A risk study for proposed pipped water in Wajir, Kenya, indicated significant salinization risks, sociopolitical problems, and ignorance as investment deterrents (Haile, 2005). In the proposed Habaswein-Wajir Water Supply Project in Northern Kenya, water will be piped to the city of Wajir from a significant aquifer close to Habaswein (Jürgen Mahlknecht et al., 2017). Eight specialists created an Applied Information Economics model that considered all costs, advantages, and risks crucial to project success. They described their level of uncertainty for the model's around 100 variables using probability distributions (Kuria, 2013). Monte Carlo simulation and partial least squares (PLS) regression were used to project choice outcomes (Ojwang et al., 2017). Most stakeholders regarded the project as dangerous, primarily because of the possibility of political influence brought on by concerns over Habaswein's water supply and the industry's dubious profitability (Ferrer et al., 2019). It was also crucial to be uncertain how to value declining infant mortality and the prevalence of water-borne diseases. Seawater infiltration into the aquifer posed the most hydrological concern (Swain et al., 2022). Figure 2

Figure 2. Polluted shallow groundwater in Kisumu (photo curtesy of Dan Lap worth).

shows polluted shallow groundwater in Kisumu (photo curtesy of Dan Lap worth).

The Unplanned informal communities frequently lack basic amenities like a piped water supply or have sporadic and erratic piped water supply surrounding the metropolis (Kamau and Njiru, 2018). Locals frequently turn to other water sources, like shallow hand-dug wells, to meet their demands. As shown by the image above, urban groundwater safety in Kisumu's informal settlements is being impacted by fecal contamination (Kanoti et al., 2019). The usage of shallow groundwater in squatter urban settlements is projected to be significantly impacted by climate change demands and future urban population growth (Chepkemoi et al., 2023). A study of the water quality in two informal settlements (Manyatta A and Migosi) reveals that the risk of water pollution has grown over time as a result of an increase in dangers, including neighboring pit latrines and garbage dumps. Out of the 46 wells tested, 44 of them were deemed to be unfit for drinking (Oiro et al., 2020). However, 87% of those who used well water, did so for purposes other than drinking, such as washing clothing and maintaining personal hygiene (Hutton and Chase, 2017). Most residents are more likely to utilize other sources, such as piped or rainwater, when choosing the water to consume since water quality and safety are vital priorities (Zohud et al., 2023). Residents of these unofficial towns receive essential water via shallow wells that draw water from the ground. Most people are aware that the quality of water comes from varied sources. The future pressures from urban population growth and climate change are anticipated to have significant adverse effects on the usage of shallow groundwater in these towns.

Salinity intrusion affects water quality from wells and boreholes in Kenya's coastal regions (Kilifi County). Compared to deeper small-diameter boreholes, shallow large-diameter wells exhibit less saltwater intrusion (Katuva et al., 2020). A triple isotope method revealed that animal manure application from farming or free-range livestock keeping in the rural areas is mostly to blame for the nitrate contamination of groundwater in Kisumu city and its environs. However, concomitant denitrification and dilution of in situ nitrates help to reduce the nitrate burden (Egbueri, 2023). On the other hand, the accumulation of nitrate in the groundwater system is probably the result of incomplete nitrification. However, more process-based study is required to thoroughly understand the local groundwater nitrate destiny. To prevent further deterioration of groundwater sources, it is urgently necessary to expand and enhance waste-

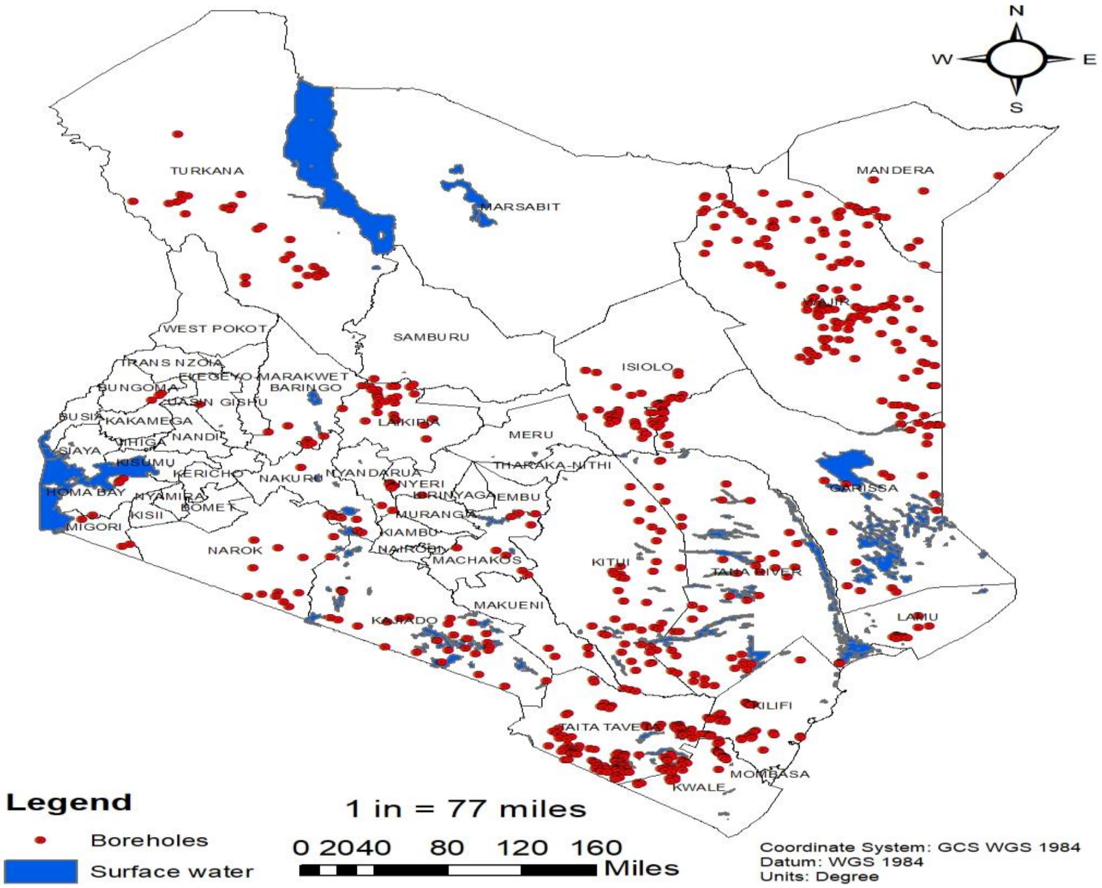

Figure 3. The distribution of surface water and boreholes distribution in Kenya.
Source; Developed using ArcMap software with datasets from sources such as USGS, OSM and Earth observation application (Google Earth Pro).

water sanitation in the area (Hutton and Chase, 2017).

DISTRIBUTION OF SURFACE WATER AND BOREHOLES IN KENYA

The distribution of surface water and boreholes in Kenya varies depending on several factors, including rainfall patterns, surface geology, and groundwater aquifers. However, the United States Geological Survey (USGS) does maintain a database of surface water and borehole locations in Kenya (Kuria, 2013). The USGS database includes information on over 1,400 surface water bodies and nearly 4,000 boreholes in Kenya. The data is organized by county, so it is possible to understand the distribution of surface water and boreholes across the country. For example, in the county of Nairobi, there are approximately 350 surface water bodies and 1,150 boreholes (Oiro et al., 2020).

In comparison, in the county of Turkana, there are only around 50 surface water bodies and 150 boreholes. It should be noted that the USGS database only includes information on surface water and boreholes cataloged by the USGS. This means there may be other surface water bodies and boreholes in Kenya that are not included in the database. This data can be accessed online through the USGS website[2].

Figure 3 illustrates the uneven distribution of surface water, necessitating alternative water sources such as boreholes where surface water is lacking. Climate change impacts have exacerbated this uneven distribution by causing rivers, especially those originating from Mt. Kenya's water tower, to dry up, affecting livestock, human populations, and wildlife (Chepyegon and Kamiya, 2018). For instance, the Rupingazi River in Kirinyaga County, crucial for irrigation in the Mwea Trust Land, is at risk of drying up, potentially causing significant crop losses worth millions of shillings. Wajir County, historically lacking regular clean water supply, relies heavily on boreholes, often poorly developed shallow wells exposing communities to various hazards (Sarkar et al., 2022; Sousa et al., 2018). Contamination from human and livestock waste significantly compromises the

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[2] https://www.usgs.gov/

biological quality of these wells, impacting the Merti aquifer (Blandenier et al., 2016). A government and ORIO-led initiative aimed at improving water access faced local opposition due to lack of community awareness and concerns over water salinity (Mumma et al., 2011). To address the recurrent drought impacts affecting dry regions, local leadership involvement is crucial for community ownership and successful project implementation.

Kenya's existing strategy for managing groundwater fails to meet the needs of the general public in the short term and also jeopardizes the value of the groundwater over an extended period (Foster, 2020). Because experts in the relevant industries have a minimal awareness of the relationship between the land surface and groundwater, there is little strategic understanding of the need to conserve groundwater resources. Surprisingly, little is known about groundwater and its importance to the general public, and efforts to educate the public have, at best, been ineffectual (Nyanchaga, 2016). The WRMA needs more financial and moral assistance, but its technical capacity also needs to be increased.

Even though management and protection are desperately needed, the institutional and legal framework required to support effective aquifer management already exists, even if some cross-sector streamlining would improve management processes (Foster, 2020). The only significant barriers to developing a national groundwater management strategy and implementing local aquifer management plans are a lack of political knowledge and support for such efforts and a lack of funding from the parent ministry WRMA, the competent agency (Foster et al., 2022). Many types of water resources and allocation data are purportedly available for purchase in Kenya at the prices specified in the Rules. Despite the fact that some of these data are held by the Ministry of Water, Sanitation and Irrigation (MoWSI), the Water Resources Management Authority (WRMA), the Water Service Regulatory Board (WSRB), and the Water Service Provider (WSP), they are usually inaccessible (Mumma et al., 2011).

There is no central repository for data, and no single source provides a comprehensive list detailing which agency holds what data and at what cost. Consequently, decisions regarding water distribution may be based on incomplete or unavailable data (Arshad et al., 2022). While fees for data are reasonable provided stakeholders understand the costs associated with data collection and maintenance, the MoWSI must take proactive steps to organize the proper archiving, upkeep, and sale of groundwater data, as the current situation is chaotic. This responsibility is mandated by Kenyan law and falls under the WRMA's jurisdiction (Rendilicha, 2018), which requires access to groundwater data for archival purposes and operational needs. While essential for fulfilling its duties, groundwater data may require processing before being used by the ministry, which is responsible for legislation, policy formulation, sector coordination, and monitoring and evaluation (Alahacoon et al., 2021).

CONCLUSION

Climate change is expected to exacerbate the issue of water stress in Kenya, a country already grappling with water scarcity. Groundwater resources in Kenya are already experiencing strain as a result of various factors such as over-abstraction, wastewater discharge, and pollution. The impact of climate change will lead to more frequent and intense weather conditions, causing shifts in precipitation patterns and further exacerbating water stress. The ramifications of this will be significant, including potential impacts on water availability for domestic, agricultural, and industrial purposes and the possibility of escalating conflicts over water resources. Notably, the most vulnerable communities will grapple with water scarcity and lack access to safe water. To mitigate this situation, there is an urgent need to improve water management and governance in Kenya and invest in climate-resilient infrastructure. This will be essential to safeguarding Kenya's water resources and ensuring water security for all. As a water-stressed country, Kenya must prioritize these actions to effectively address the challenges posed by climate change and secure a sustainable future for its citizens.

RECOMMENDATIONS

Groundwater pollution is enhanced in the wake of the day. To ensure availability and sustainable management of water and sanitation for all (SDG 6) is attained, the following should be adhered to:

1) Protect and preserve groundwater resources through better management and regulation to prevent pollution.
2) Increase awareness and understanding of the importance of groundwater resources and pollution risks to encourage sustainable use.
3) Implement proper wastewater treatment and disposal practices to reduce the risk of groundwater pollution.
4) Improve monitoring and response systems to quickly identify and address pollution issues and prepare for climate change impacts on groundwater resources.
5) Collaborate with other countries in the region and other stakeholders to share knowledge and best practices on groundwater management and climate change.

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CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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