



**WALLAGA UNIVERSITY
SCHOOL OF GRADUATE STUDIES**

MSc. THESIS

**ASSESSMENT OF DRINKING WATER QUALITY, CONTAMINANT
TRANSPORT, AND QUANTITATIVE HEALTH RISK MODELING
FOR AKAKI SUB-CITY RESIDENTS, ADDIS ABABA, ETHIOPIA**

**By
OBSA HAILE FANTA**

JANUARY, 2026

NEKEMTE, ETHIOPIA



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TRANSPORT, AND QUANTITATIVE HEALTH RISK MODELING
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**A THESIS SUBMITTED TO THE, COLLEGE OF NATURAL AND
COMPUTATIONAL SCIENCES, DEPARTMENT OF PHYSICS, IN
PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE
DEGREE OF MASTER OF SCIENCE IN PHYSICS
(ATMOSPHERIC PHYSICS)**

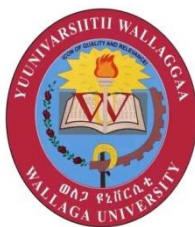
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APPROVAL SHEET FOR SUBMITTING FINAL THESIS

As member of Board of Final MSc. Thesis open defense, we certify that we have read and evaluated the thesis prepared by **Obsa Haile Fanta** under the title “**Assessment of Drinking Water Quality, Contaminant Transport, and Quantitative Health Risk Modeling for Akaki Sub-City Residents, Addis Ababa, Ethiopia**” and recommended that the thesis be accepted as fulfilling the thesis requirement for the Degree Master of Science in Biology.

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Certification of the final research

I hereby certify that all the correction and recommended suggested by the board of examiners are incorporated into the final thesis entitled “**Assessment of Drinking Water Quality, Contaminant Transport, and Quantitative Health Risk Modeling for Akaki Sub-City Residents, Addis Ababa, Ethiopia**” by Obsa Haile Fanta

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DECLARATION

This is to certify that this thesis entitled " Assessment of Drinking Water Quality, Contaminant Transport, and Quantitative Health Risk Modeling for Akaki Sub-City Residents, Addis Ababa, Ethiopia," accepted in partial fulfillment of the requirement for the award of the M.Sc. Degree in Physics, Atmospheric Physics stream, by the School of Graduate Studies, Wallaga University, through the College of Computational and Natural Sciences, done by Obsa Haile Fanta, is a genuine work carried out by him under my guidance. The matter embodied in the thesis work has not been submitted earlier for the award of any degree. The assistance and help received during the course of this investigation have been duly acknowledged. Therefore, I recommended that it can be accepted as a research thesis requirement for filling an MSc degree in physics.

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STATEMENT OF THE AUTHOR

First, I declare that this thesis is my own work and that all sources of materials used for this thesis have been duly acknowledged. This thesis has been submitted in partial fulfillment of the requirements for an MSc. degree in Physics at Wallaga University and is deposited at the university library to be made available to borrowers under the rules of the library. I solemnly declare that this thesis has not been submitted to any other institution anywhere for the award of any academic degree, diploma, or certificate. Brief quotations from this thesis are allowable without special permission provided that accurate acknowledgement of the source is made. Requests for permission for extended quotation from or reproduction of this manuscript in whole or in part may be granted by the head of the major department or the dean of the school of graduate studies; in these instances, however, permission must be obtained from the author.

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BIOGRAPHY

The author was born in 1984 E.C. in East Wollega Zone, Wayu Tuka Woreda, at Kichi Kebele. He completed his primary school at Sibu Sire Primary and secondary school at Sibu Sire. He joined higher education at Addis Ababa University and graduated with a B.Sc in Applied Physics on December 8, 2014. At present, he serves as a physics teacher at Abiyot Fana Pre, Primary, and Middle School in Finfinne town. Then he joined Wallaga University for a master's degree in physics summer program from 2011 to 2017 G.C.

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ACRONYMS AND ABBREVIATIONS

ADWQ	Assessment Of Drinking Water Quality
DW	Drinking Water
EH	Environmental Health
EPA	Environmental Protection Agency
FHA	Formative Health Assessment
GIS	Geographical Information System
GPS	Geographical Position System
H ₂ O	Chemical Formula For Water
MG/L	Milligram Per Liter
MOH	Ministry Of Health
PH	Potential Of Hydrogen
SGS	School Of Graduate Studies
TDS	Total Dissolved Solids
WHO	World Health Organization
WQ	Water Quality
ANOVA	Analysis of Variance
CCME	Canadian Council of Ministers for the Environment
CES	Compulsory Ethiopian Standards
EPA	Environmental Protection Authority
FAO	Food and Agriculture Organization of the United Nations
GPS	Global Positioning System
IARC	International Agency for Research on Cancer
IPCS	International Program on Chemical Safety
IQ	Intelligence quotient
ISO	International Standard Organization
IUPAC	International Union of Pure and Applied Chemistry
WQS	Water Quality status

TABLE OF CONTENTS

Contents	Pages
APPROVAL SHEET FOR SUBMITTING FINAL THESIS.....	i
DECLARATION.....	ii
STATEMENT OF THE AUTHOR.....	iii
BIOGRAPHY	iv
ACKNOWLEDGMENTS	v
ACRONYMS AND ABBREVIATIONS.....	vi
LIST OF TABLE	x
LIST OF FIGURE	xi
ABSTRACT	xii
1. INTRODUCTION.....	1
1.1. Background and Justification of the Study	1
1.2. Statement of the Problem	4
1.3. Research Questions.....	6
1.4. Objectives of the Research 1.4.1. General Objectives of the Thesis	6
1.4.2. Specific Study of the Objectives.....	6
1.5. The Scope and Limitation of the Study	7
1.6. Significance of the Study.....	8
2. THEORETICAL LITERATURE REVIEW.....	9
2. 1. Concepts Quality of Water	9
2.1.1. Major Drinking Water Parameters.....	9
2.1.2. Biological, Physical, and Chemical Parameters Quality of Water	10
2.1.3. Major Drinking Water Sources in Akaki Kaliti Subcity	13
2.1.4. Major Drinking Water Pollution in the Sub-City of Akaki Kaliti	13
2.1.5. Water Quality Index (WQI).....	14
2.1.6. Physics of Water Quality and Atmospheric Components	15
2.1.7 Water Quality Index (WQI) and Comparison with Quantitative Health Risk Assessment	17
Non-Carcinogenic Risk	19
The Hazard Quotient (HQ) is calculated as:.....	19
Carcinogenic Risk: For carcinogenic contaminants, the Carcinogenic Risk (CR) is calculated as:	20
2.1.8. Ethiopian and WHO Drinking Water Quality Standards	20
2.1.9. Comparison and Relevance.....	21
2.1.10. Seasonal Variation in Water Quality	22
2.1.11. Global Perspective on Drinking Quality of Water	22
2.1.12. Contemporary Challenges in Water Quality	22
2.1.13. Health Implications of Poor Water Quality.....	23
2.1.14. Impact of Contaminated Drinking Water on Health in Akaki Kaliti	24

2.1.15. Socioeconomic Factors and Water Quality.....	25
2.1.16. Water Quality in Addis Ababa, Ethiopia's Akaki Kality Sub-City	26
2.1.17. Economic Benefits of High-Quality Drinking Water.....	26
2.1.18. Environmental Impact of Water Pollution	26
2.1.19. Water Scarcity and Climate Change.....	27
2.1.20. Water Quality Monitoring Technologies	27
2.1.21. Impact of Industrialization and Urbanization on Water Quality.....	27
3. MATERIALS AND METHODS	28
3.1. Description of the Study Area.....	28
3.1.1. Location	28
3.1.2. Altitude and Distance from the Center	28
3.1.3. Climate.....	29
3.1.4. Topography	29
3.1.5. Soils	31
3.1.6. Drainage.....	31
3.1.7. Land Use Pattern	31
3.1.8. Population.....	32
3.1.9. Demographics.....	32
3.1.10. Urbanization Rate.....	32
3.1.11. Environmental Conditions	32
3.1.12. Humidity	33
3.1.13. Socio-Economic Zones	33
3.1.14. Transportation & Infrastructure	33
3.1.15. Sources of Water.....	33
3.2. Materials	34
3.2.1. Source of Data sampling	34
3.2.2. Equipment/Instruments	35
3.2.3. Experimental design	35
3.3. Methodology.....	36
3.3.1. Data collection.....	36
3.3.1.1. Sampling Site Selection and Sampling Strategies	36
3.3.1.2. Sample collection, preservation and transportation procedures.....	37
3.3.1.3. Laboratory Analysis.....	37
3.3.1.4. Health Data Collection	38
3.3.1.5. Data Analysis	38
3.4. Assessment of Water Quality Index (WQI) of Akaki River Samples.....	40
4. RESULTS AND DISCUSSION	43
4.1. Physiochemical water quality parameters.....	43
4.2. Chemical Parameters (Heavy Metals).....	43
4.3. Microbiological Water Quality	44
4.4. Quantitative Health Risk Modeling Results.	45
4.5. Seasonal Variation in Water Quality	45

4.6. Implications on Residents' Health	46
4.7. Drinking Water Quality and Its Implication on Residents' Health	48
4.8. Pearson Correlation between physical, chemical and microbiological analysis	56
5. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS	58
5.1. Summary	58
5.2. Conclusion	59
5.3. Recommendations	60
REFERENCES.....	62
APPENDIX.....	65

LIST OF TABLE

Table 1: (Source: WHO, 2022; Ethiopian Standards Agency, 2015).....	21
Table 2: Akaki Kality subcity health bureau (2025), Annual disease surveillance report, AA.....	24
Table 3: Water quality metrics, sources, relevance, and effects on human health.	39
Table 4: Category, Variable and Percentage	47
Table 5: laboratory analysis performed on water samples from Akaki groundwater physical analysis	51
Table 6: laboratory analysis done on the water samples from the Akaki ground water chemical analysis	53
Table 7: microbiological study performed in the lab on the water samples from Akaki groundwater	55
Table 8: Correlations	57

LIST OF FIGURE

Figure 1: Location map of Akaki Kality Subcity, Addis Ababa	28
Figure 2: The climate graph for Akaki Kality, Addis Ababa, Ethiopia.....	29
Figure 3: Description of the study area.....	30
Figure 4: Land Use Pattern of the Study Area.....	31
Figure 5: Dry season	49
Figure 6 : Main Rain season	50
Figure 7: physical Analysis.....	52
Figure 8 : chemical Analysis	54
Figure 9: Microbiological Analysis	56

ABSTRACT

Public health and well-being depend on having availability of clean drinking water, but many urban centers in developing countries face challenges related to water quality deterioration. Rapid population expansion, industrialization, and poor sanitation infrastructure have raised the risk of water contamination in urban areas like Addis Ababa, particularly Akaki Kality sub-city. Thirty Samples of water were gathered for this investigation from public taps, groundwater, boreholes, and spring water sources throughout the dry and wet seasons and were utilized to evaluate the chemical, physical, and microbiological characteristics of the drinking water in Akaki Kality Sub-City, Addis Ababa, Ethiopia. According to the American Public Health Association's standard procedure, the microbiological parameters that were examined were total coliform, fecal coliform, and Escherichia coli (E. coli), while the physicochemical parameters that were examined were pH, turbidity, Nitrate, electrical conductivity, and total dissolved solids concentration (APHA, 2017). The results were compared with the fourth edition of the World Health Organization's (WHO, 2022) drinking water guidelines and ES 261:2015. Seasonal variation in contaminant levels is driven by aquifer dilution capacity and kinetic transport rates surface runoff is the main advective transport vector. During the rainy and dry seasons, the chemical parameters, including pH, were 7.464 ± 0.09 and 7.455 ± 0.081 , respectively, corresponding to within the WHO-recommended acceptable range of 6.5 to 8.5. These findings highlight the critical need for better water treatment, particularly increased chlorination during the rainy season, routine chemical contaminant monitoring, community health education to lower the risk of waterborne diseases, and infrastructure upgrades that reduce the sources of contamination. High contaminant levels results from uncontrolled advective transport, showing discount between fast hydraulic transport and slower geochemical reaction. Overall, this thesis provides important insight into the dynamic nature of Akaki Kality's drinking water quality management and how it affects for public health. It also helps policymakers address drinking water safety, reduce health risks, and provide evidence-based recommendations to protect residents' health during seasonal changes.

Key Words: Drinking water quality, physicochemical parameters, microbiological contamination, waterborne diseases, Akaki Kality, Addis Ababa, Ethiopia.

1. INTRODUCTION

1.1. Background and Justification of the Study

Water is an essential source for human existence and well-being directly impacting public health, encouraging socioeconomic growth, and guaranteeing environmental sustainability. It is essential to be able to obtain safe, clean drinking water, as its quality profoundly affects human well-being and the prevalence of waterborne diseases. Globally, this resource faces immense stress: the World Health Organization (WHO, 2022) estimates that approximately 2 billion people worldwide use drinking water sources contaminated with fecal matter, posing serious health risks. Waterborne infections remain a major contributor to illness and mortality in countries with low to middle incomes, especially in children under five. Despite significant global and regional efforts, the challenge of safe water provision persists. Two billion people worldwide still lack access to safe drinking water, according to the United Nations World Water Development Report 2023, and 3.6 billion reside in water-stressed areas. Developing nations, including Ethiopia, struggle to assure consistent drinking water quality even as supply coverage improves. For instance, UNICEF estimates that by 2021, just 65% of Ethiopians have access to basic drinking water services. This problem is compounded by rapid urbanization, industrial growth, and inadequate sanitary infrastructure, all of which contribute to the deteriorating water quality in many regions (Mengesha *et al.*, 2020; CSA, 2021; AAWSA, 2022). This public health issue is particularly acute in Addis Ababa, the capital city of Ethiopia, which faces serious water supply and quality challenges due to fast population growth and urban expansion (Mengesha *et al.*, 2020).

Provision of safe and reliable drinking water is a critical prerequisite for safeguarding public health and achieving sustainable urban development. International health agencies emphasize that contaminated drinking water is a major contributor to waterborne diseases, particularly in low and middle income countries where urban growth often exceeds infrastructure capacity (WHO, 2017). In Ethiopia, rapid urbanization combined with industrial expansion has placed increasing pressure on both surface and groundwater resources, leading to widespread deterioration of drinking water quality (MoH & EPHI, 2013). Akaki Sub-City,

located in the southern part of Addis Ababa, represents one of the most environmentally stressed urban areas in the country. Drinking water quality in Akaki sub-city, Addis Ababa, faces severe contamination from industrial effluents, untreated sewage, and agricultural runoff in the Akaki Kaliti River watershed, posing significant health risks to residents. Akaki River and associated groundwater sources in Akaki sub-city exhibit high pollution levels, with wastewater from households, industries, and agriculture discharged untreated into the Little and Great Akaki Rivers. Physico-chemical parameters such as electrical conductivity, nitrates, phosphates, and heavy metals exceed WHO standards, particularly in the Little Akaki, which is more polluted due to industrial proximity. Akaki Kaliti River and associated groundwater sources in Akaki Kaliti sub-city exhibit high pollution levels, with waste water from households, industries, and agriculture discharged untreated into the Little and Great Akaki Rivers. Physico-chemical parameters such as electrical conductivity, nitrates, phosphates, and heavy metals exceed WHO standards, particularly in the Little Akaki, which is more polluted due to industrial proximity. Primary contaminants point sources (industrial effluents, sewage) and non-point sources (urban runoff, agriculture).

The Akaki catchment's volcanic aquifer receives recharge from rainfall river infiltration, and lake seepage, but steady-state MODFLOW modeling shows flow converging toward well fields, heightening vulnerability. Heavy metals like Pb and Cd bio accumulate from tannery, battery, and fertilizer wastes, transported downstream with increasing concentrations. Microbial transport follows fecal pollution from 63% pit latrine usage and illegal discharges, with *E. coli* persisting through distribution systems.

The sub-city hosts numerous industries, dense residential settlements, and informal waste disposal sites, all of which generate significant pollutant loads. Groundwater serves as an important source of drinking water for the local population; however, its quality is increasingly threatened by contaminant migration within the subsurface environment. The movement and rate of contaminants in groundwater systems are primarily governed by hydrodynamic transport processes, notably advection and hydrodynamic dispersion. Advection describes the transport of dissolved contaminants along groundwater flow paths, while dispersion causes the spreading of contaminants due to velocity variations and aquifer heterogeneity (USEPA, 2016). During high-flow (rainy) seasons, enhanced advection

accelerates the downstream movement of contaminants and increases the potential for riverbank infiltration into groundwater. Conversely, during low-flow (dry) seasons, reduced dilution and longer residence times may lead to higher contaminant concentrations in both surface water and nearby wells. Under natural conditions, these processes can contribute to dilution and attenuation of pollutants. In Akaki Sub-City, however, these hydrodynamic mechanisms have become ineffective due to excessive contaminant inputs, shallow aquifer depths, highly permeable sediments, and modified hydraulic gradients. Consequently, contaminants are transported rapidly through the aquifer system, increasing the likelihood of reaching drinking water abstraction points without sufficient natural attenuation. A key factor exacerbating groundwater contamination in the area is the physical flow of the Akaki River, which functions as the principal contaminant transport pathway.

The river receives untreated and partially treated industrial effluents, domestic wastewater, urban runoff, and solid waste from upstream and adjacent areas. Studies have shown that polluted rivers can act as continuous sources of groundwater contamination where strong hydraulic connectivity exists between surface water and aquifers (USEPA, 2016). In Akaki Sub-City, the river flows through alluvial formations with high permeability, facilitating infiltration of contaminated river water into the groundwater system. This interaction enhances advective transport of pollutants, while hydrodynamic dispersion promotes their spatial distribution within the aquifer. As a result, drinking water sources in Akaki Sub-City are increasingly exposed to physical, chemical, and microbiological contaminants, including pathogens, nutrients, and potentially toxic metals. Many of these contaminants have been reported at concentrations exceeding recommended guideline values set by the World Health Organization and national regulatory bodies (WHO, 2017; MoH & EPHI, 2013).

The Ethiopian Drinking Water Quality Standards specify maximum permissible limits for key water quality parameters to protect human health; however, compliance remains a significant challenge in urban settings influenced by polluted surface waters. Although several investigations have documented water pollution in the Akaki River basin, most have focused on surface water quality or limited physicochemical analysis. This sub-city is characterized by a dense population, a developing industrial base, and a reliance on diverse and vulnerable drinking water sources. The main sources include piped water supply from

the Water and Sewerage Authority of Addis Ababa (AAWSA), private groundwater wells, springs and protected sources, and water vendors. Unfortunately, these sources are highly susceptible to recontamination from industrial discharges, improper waste disposal, sewage, agricultural runoff, and inadequate sanitation infrastructure, leading to severe quality deterioration (Mengesha *et al.*, 2004; Mekonen, A., & Asefa, Y., 2020; Weldegiorgis, F., & Dejene, H., 2019).

The deterioration of water quality in Akaki Kality has created a serious public health crisis. Assessments of the water quality, typically following WHO guidelines and Ethiopian national standards focus on critical physical, chemical, and microbiological parameters (Wondimu & Mulugeta, 2024; Kumar & Singh, 2021; Biruk & Melaku, 2023). However, Akaki Kality's position as an industrial zone means its water bodies, particularly the Akaki River, are heavily contaminated with untreated industrial and household effluents, including heavy metals, chemicals, and infections (Abate, A., Dibaba, M., 2022; Tesfaye & Yared, 2023). This contaminated water is directly linked to an increased incidence various water-borne illnesses such diarrheal infections, typhoid and cholera as well as long-term health concerns, including dental and skeletal fluorosis from high fluoride levels. These issues underscore the urgency of rigorous water quality monitoring and intervention in this rapidly developing urban environment. The findings are expected to provide scientific evidence to support improved water resource management and public health protection in line with national and international drinking water standards.

1.2. Statement of the Problem

Public health depends on having access to potable water, which is a fundamental human right. But in many cities, especially in countries that are developing, this right can be compromised by inadequate water quality. Contamination of urban drinking water sources continues to pose a significant challenge to environmental sustainability and public health, particularly in rapidly growing cities such as Addis Ababa. According to the Addis Ababa City Administration (AACA, 2022), daily garbage output in the city is anticipated to be between 0.3 and 0.4 kilograms per capita per day. Around 75% of municipal garbage is collected, with the remainder generally disposed of inappropriately. In Akaki Sub-City,

intensified industrial operations, inadequate wastewater management, and strong hydrological interaction between surface water and groundwater systems have contributed to declining drinking water quality. Drinking water contamination is a major public health concern in Akaki Kality main rivers. Microbial and chemical pollutants from industrial discharge, sewage, and runoff from urban jeopardize water quality.

The absence of adequate treatment and monitoring raises major concerns regarding drinking water quality. Contaminated water can cause a variety of health problems, including waterborne infections, water-based diseases, water-related diseases, heavy metal toxicity, and long-term chronic disorders (Abate & Dibaba, 2022). Previous investigations in the area have reported the presence of various physical, chemical, and microbiological contaminants in drinking water sources, especially those influenced by the Akaki River. Despite these findings, existing studies in Akaki Sub-City have predominantly focused on measuring contaminant concentrations and comparing them with national and international drinking water standards. While such approaches are useful for regulatory compliance assessment, they do not provide sufficient information on the magnitude of health risks experienced by exposed populations.

The most critical research gap is the lack of Quantitative Health Risk Assessment (QHRA) capable of converting water quality data into quantitative estimates of human health risk. This study is needed to integrate contaminant transport modeling with Quantitative Health Risk Assessment (QHRA) in Akaki Kality Sub-City, enabling the calculation of exposure doses, Hazard Index (HI), and Carcinogenic Risk (CR) to provide physics-based predictive outcomes for proactive water quality management and public health protection. Moreover, the interaction between contaminated river water and groundwater, governed by advection and hydrodynamic dispersion processes, results in variable exposure conditions that cannot be adequately addressed through qualitative evaluations alone. Without quantitative risk modeling, it remains difficult to assess cumulative exposure, distinguish between non-carcinogenic and carcinogenic effects, or support predictive decision-making for water safety management. The study is needed to model the exposure dose and derive the Hazard Index (HI) and Carcinogenic Risk (CR), which provide the physics-based predictive outcomes.”

1.3. Research Questions

1. What is the current status of the physical, chemical, and microbiological quality of drinking water in Akaki Kaliti Sub-City and how does it vary seasonally?
2. How do contaminant transport processes (advection and hydrodynamic dispersion) influence the movement of pollutants between the Akaki River and groundwater drinking water sources?
3. To what extent does the standard of drinking Water comply with the WHO and Ethiopian drinking water standards?
4. What are the exposure doses of contaminants resulting from the interaction between contaminated river water and groundwater through advection and hydrodynamic dispersion processes?
5. What measures can be taken to improve Water quality and protect public health?
6. How can the integration of contaminant transport modeling with Quantitative Health Risk Assessment (QHRA) support risk-based drinking water management and public health protection in the study area?

1.4. Objectives of the Research

1.4.1. General Objectives of the Thesis

The overall objective of this study was to evaluate the quality of the drinking water in Akaki Kaliti sub-city and evaluate its health implications for residents.

1.4.2. Specific Study of the Objectives

The specific objectives of this thesis were:

- ❖ To analyze the microbiological, chemical, and physical characteristics of the quality of drinking water sources in selected sites across Akaki Kaliti Sub-City during dry and rainy seasons.
- ❖ To quantify the contaminant transport processes (advection and hydrodynamic dispersion) influence the movement of pollutants between the Akaki River and groundwater drinking water sources?

- ❖ To evaluate the physical, chemical, and microbiological quality of drinking water sources in Akaki Sub-City in relation to national and international drinking water standards.
- ❖ To analyze the spatial and seasonal variation of key contaminants in drinking water sources influenced by the Akaki River and groundwater flow processes.
- ❖ To quantify non-carcinogenic health risks by calculating the Hazard Quotient (HQ) and Hazard Index (HI) for selected contaminants.
- ❖ To apply the exposure dose model as a physical modeling exercise, using measured contaminant concentrations as input parameters to quantitatively estimate human exposure levels.
- ❖ Estimate carcinogenic health risks by determining the Carcinogenic Risk (CR) associated with long-term ingestion of contaminated drinking water.

1.5. The Scope and Limitation of the Study

The capital of Ethiopia, Addis Ababa, has eleven sub-cities, including Akaki Kality Sub-City. Akaki Kality is situated between 2200 and 2400 meters above sea level. Its coordinates are 8° 53' 44.9916" N and 38° 47' 20.9832" E, around 20-25 kilometers south of Addis Ababa's city center (CSA, 2021). The sub-city shares boundaries Addis Ababa is surrounded by the Oromia Special Zone, which is an important industrial and residential district in the capital. Approximately half of Addis Ababa's industries are concentrated in Akaki-Kality, a 125-square-kilometer region with approximately 250,000 persons. Water samples were collected from Saris Abo Area, Tullu Dimtu, Akaki Fanta Spring, Kality Condominium, Kality Industrial Zone, Old Stadium Area, Akaki Kality Bus Terminal, Kality Sub-City Administration, Hana Mariam Area, Akaki Market, Beside Akaki River Channel, Near Kality Industrial Park, Kality Housing Estate, Industrial Worker Camp, Akaki Health Centre area, Private borehole (residential), Near Akaki River Crossing, Upper Akaki Hill Spring, and sources including piped water supply.

1.6. Significance of the Study

The study of drinking water quality was necessary for ensuring environmental sustainability, public health, and economic growth. Assessing the quality of water for drinking in Akaki Kality Sub-City is critical to ensuring the availability of clean, safe water for households. The purpose of the study was to determine the quality of drinking water and its impact on resident human health at the Akaki River in Addis Ababa City, as well as the suitability of this river water for drinking, domestic use, irrigation, cooking, food preparation, bathing, cleaning, washing, personal hygiene, garden watering, livestock sanitation, and other purposes. Generally, the significances of the current study were:

- Provide accurate information on drinking water quality in the Akaki River to protect the health of those who use it.
- Assist Woreda's water, irrigation, and energy office with baseline information on river water quality for irrigation purposes.
- This study is scientifically significant because it integrates contaminant transport modeling with Quantitative Health Risk Assessment (QHRA) to transform drinking water quality data into quantitative health risk indicators
- From a public health and water management perspective, the study provides clear quantification of both non-carcinogenic and carcinogenic risks associated with drinking water consumption in Akaki Kality Sub-City.
- The study aims to help industries and authorities design preventive measures to improve river water quality.
- Incorporating advection and hydrodynamic dispersion processes improves understanding of contaminant migration between river water and groundwater, thereby supporting proactive, risk-based decision-making for water safety management and source protection.
- Provide baseline data for environmental analysts to conduct additional investigations.
- Understanding industrial contamination can help control and manage waste more effectively.

2. THEORETICAL LITERATURE REVIEW

2. 1. Concepts Quality of Water

Water is the most essential natural resource of the ecosystem, serving both the drinking and commercial sectors. Surface and groundwater availability and quality have altered during the previous century, owing mostly to urbanization, industrialization, and other factors. Globally, Access to safe drinking Water is a critical issue The WHO/UNICEF Joint Monitoring Programme (JMP, 2021) estimates that 2 billion people, or 26% of the world's population, lack access to clean drinking water. In developing countries in general, sub-Saharan Africa in particular, water quality degradation is influenced by urbanization, industrialization, poor sanitation, and environmental pollution (Kassahun *et al.*, 2020). The physical, chemical, and biological characteristics of water are referred to as their qualities that affect its acceptability for diverse applications such as industrial processes, drinking, and irrigation, and recreation (WHO, 2020). Safe drinking water must meet specific standards to protect human health, emphasizing parameters such as physical turbidity, microbial content, and the presence of contaminants and chemicals (Wondimu & Mulugeta, 2024).

2.1.1. Major Drinking Water Parameters

"The technical term "water quality" describes the characteristics of water with regard to recommended values for human consumption and all other household uses, including personal hygiene. Physical, chemical, and biological elements comprise water quality parameters. Chemical parameters factors of drinking water quality indicate the water's suitability for human consumption, which might encompass home, agricultural, and industrial uses. Water quality assessments must take into account key chemical criteria such as source protection, treatment efficiency, and distribution network dependability (WHO, 2017). These refer to the presence and concentration of chemicals in water, which can occur naturally or as a result of pollution. Chemical parameters include pH, nitrates, nitrites, total iron, phosphate, sulfate, ammonia, magnesium hardness, calcium hardness, carbonate alkalinity, chlorides, fluoride, metals that are heavy (such as lead, arsenic, and mercury), pesticides and herbicides. Physical Parameters are water properties that may be recognized or

quantified using basic devices. Physical parameters include temperature, turbidity, taste, and electrical conductivity. Microbiological Parameters describe the presence of microorganisms in water, particularly those that might cause disease. Total coliforms, fecal coliforms (like *E. coli*), and other microbiological parameters, bacteria, viruses, protozoa (giardia), and parasites (EPA, 2022). Chemical testing is less common than microbiological analysis because changes in water chemistry usually take longer to appear. Water quality evaluates a water source's capacity to fulfill chemical, biological, and physical criteria for specific applications.

2.1.2. Biological, Physical, and Chemical Parameters Quality of Water

Acceptable quality of drinking water is determined by the limitations on microbiological and physicochemical criteria. Chemical testing is less common than microbiological analysis because changes in water chemistry are often more long-term. However, the following list includes some of the physical, chemical, and microbiological traits utilized in water quality studies.

Turbidity: This is Water's optical characteristic that makes light appear absorbed and diffused rather than passing through the sample in straight lines. Turbidity occurs when light is blocked by silt, microbes, wood ashes, sawdust, plant fibers, chemicals, or coal dust. Turbidity in lakes and rivers is often produced by plankton and soil erosion brought on by mining, logging, and dredging activities. An electronic turbid meter, which measures the amount of light scattered by suspended particles in a water sample, is the most precise method of detecting turbidity. The WHO advises that turbidity be kept below 5 NTU (Nephelometric Turbidity Units) for safe drinking water. Low turbidity means that the water is cleaner and clearer. High turbidity can host disease-causing organisms and limit the efficiency of disinfectants. High turbidity levels are frequently related to increased microbial contamination, which leads to diarrheal illnesses.

Temperature: Both chemical and biological processes are impacted by temperature. Temperature affects solubility, reaction rates, and chemical equilibrium constants. High levels of water temperatures promote microorganism development and may exacerbate issues

with the color, taste, and odor of drinking water. Temperature also impacts dissolved oxygen concentrations as well as the action of microorganisms in bodies of water.

Nitrate: Nitrates reach rivers through a variety of sources, including runoff from lawn fertilizers, leaking cesspools and septic tanks, farm animal waste, and automobile exhaust emissions. Many newborns have been poisoned due to high amounts of nitrate nitrogen. **pH:** Water's acidity or basicity depends on the amount of positive hydrogen ions (H^+) there are compared to negative hydroxide OH^- ions. Pure water has an exact pH of 7 because the amounts of negative hydroxide ions and positive hydrogen ions are identical. The WHO suggests that drinking water have a pH between 6.5 and 8.5. Low pH (<6.5) water can leach metals like copper and lead and damage pipes. A pH of more than 8.5 can have an unpleasant taste and interfere with disinfection efficiency (e.g., chlorine). Extreme pH values may indicate harmful chemical or industrial contamination and cause gastrointestinal irritation.

Total Dissolved Solids (≤ 1000 mg/L): TDS refers to every organic and inorganic material dissolved in water, including metals, salts, and minerals. TDS values less than 1000 mg/L are considered acceptable and safe for eating. Water with a high TDS level may taste salty or metallic and can degrade pipes.

Fluoride (≤ 1.5 mg/L): This naturally occurring substance mineral that may be found in groundwater; amounts (0.5-1 mg/L) are helpful to tooth health. Levels higher than 1.5 mg/L can result in dental fluorosis (discoloration) and, over time, fluorosis of the skeleton. **Hardness:** Caused by calcium and magnesium salts. While not hazardous, it reduces soap efficiency and causes pipe scaling. **Nitrates and Nitrites:** Common in agricultural runoff and sewage. High nitrate levels (>50 mg/L) can result in methemoglobinemia ("blue baby syndrome") (MoH). (2011). **Heavy Metals (e.g., lead, arsenic, cadmium):** Even trace amounts can be harmful and are frequently associated with industrial pollutants or damaged pipes. **Chlorine Residuals:** Added for disinfection; however, excessive chlorine can have a disagreeable flavor and long-term consequences.

EC, or electrical conductivity, is an indirect measurement of water's ionic content that indicates salinity. WHO guidelines: There is no health-based limit; however, readings above

1500 $\mu\text{S}/\text{cm}$ suggest pollution. Higher EC values were found in regions near industrial parks and waterways, such as Little Akaki.

Ammonia (NH_3): Pure ammonia is a colorless gas with a strong odor. It is composed of nitrogen and either from coal gas or hydrogen. In the natural world, bacteria operate on proteins and urea to produce ammonia. When ammonia and water are combined, they form a potent cleaning agent. As a result, it is among the most widely used industrial and home chemicals. Ammonia has the formula NH_3 , which implies it consists of three hydrogen atoms and one nitrogen atom. Ammonia is an excellent fertilizer since it contains a lot of nitrogen. In actuality, a major source of nitrogen in fertilizers is ammonium salts. The presence of Ammonia in water indicates recent fecal contamination or organic decomposition. WHO limit: There is no health-based recommendation; however, readings more than 0.5 mg/L are problematic.

Iron (Fe) and Manganese (Mn): These occur naturally in geological formations but can also leach from aging pipelines and industrial effluents. High amounts can affect taste, staining, and, in severe cases, neurological function (Mn). WHO guidelines Manganese (0.1 mg/L) and Iron (0.3 mg/L). Untreated borehole water frequently contains more than 0.5 mg/L of iron.

Sulfate (SO_4^{2-}): Although naturally occurring, industrial and mining operations may cause a rise. High doses (>250 mg/L) may have a laxative effect. Moderate sulfate levels, particularly around industrial zones.

Chloride (Cl^-): This indicates contamination from human or animal waste or incursion from salty sources. WHO recommends up to 250 mg/L for palatability. Lead: neurological and developmental consequences,

Chromium VI: carcinogenic, and Cadmium: Limits set by WHO for kidney damage: Cadmium: 0.003 mg/L, Lead: 0.01 mg/L, and Chromium: 0.05 mg/L (Gebremedhin & Egziabher, 2020).

2.1.3. Major Drinking Water Sources in Akaki Kality Subcity

The principal drinking water sources in Akaki Kality Sub-City include piped water supply, private groundwater wells and boreholes, springs and protected sources, water vendors, and tanker water bodies. Drinking water contamination is becoming a serious issue as the world's industrialization and population increase accelerate. Because of the weathering of rocks and soils, heavy metals are naturally found in trace amounts in the aquatic environment (Kassegne *et al.*, 2019). Due to population growth, urbanization, and other human activities, high concentrations of heavy metals and other emerging contaminants have been found in water, soil, aquatic life, vegetables, fruits, and other food crops (Aschale *et al.*, 2016; Ebrahimi & Barbieri, 2019; Rajasulochana & Preethy, 2016). Heavy metals can have serious health consequences, causing a variety of disorders by ingestion, cutaneous contact, and inhalation. Even low levels of heavy metals in drinking water may have an impact on people (Egbueri & Unigwe, 2020). Because of its toxicity, bioaccumulation, and environmental durability, heavy metal poisoning in drinking water poses a threat to human health (Rasool *et al.*, 2016). Heavy metals can accumulate in many organs, posing major health risks. Arsenic has been found in the copper in the liver, brain, and kidneys (Treddenick, 1981), nickel in the kidneys, skin, and lungs (Denkhaus & Salnikow, 2002), manganese in the brain, gastrointestinal tract, lungs, bone, liver, pancreas, and kidneys (Avila *et al.*, 2014; Chen *et al.*, 2016; O'Neal *et al.*, 2014).

2.1.4. Major Drinking Water Pollution in the Sub-City of Akaki Kality

Akaki Kality, one of Addis Ababa's industrial zones, has serious water pollution brought caused by industrial waste and sewage discharge (Abate & Dibaba, 2022). The Akaki River is polluted with heavy metals, chemicals, and infections from companies, hospitals, and homes. Poor waste disposal procedures cause plastic and organic debris to accumulate in water bodies, further lowering water quality. Leakage and pollution in the water distribution system raise the possibility of microbiological diseases. Intermittent water delivery compels households to store water in dangerous settings, resulting in secondary pollution (Tadesse & Beshah, 2021). Climate Change, Water Scarcity Addis Abeba and its neighboring areas face seasonal water shortages, particularly during extended dry spells (Gebremedhin & Kassa,

2024). Deforestation and land degradation diminish groundwater recharge, worsening water shortages. Flooding during the rainy season frequently contaminates drinking water supplies, raising the possibility of disease epidemics (Tesfaye & Yared, 2023). Socioeconomic Inequalities in Water Access Poor households sometimes pay extra for water from private sellers owing to unstable public supplies. Many informal settlements and slums lack piped water connections, requiring inhabitants to rely on potentially dangerous sources (Abebe & Desta, 2023; Hailu & Alemayehu, 2025).

2.1.5. Water Quality Index (WQI)

The WQI, or Water Quality Index, is a simple approach to be representing the water's quality resources for consumption, leveraging data that can be used to adjust regulations. Several national and international organizations have developed water quality indices over the years to assess water quality in certain circumstances (Paiu & Breaban, 2014). The WQI evaluates water quality by determining surface water's physicochemical properties, which serve as an indication of water contamination caused by both natural and anthropogenic activities. It is one of the most efficient instruments for monitoring surface and groundwater contamination and may greatly help with the execution of water quality improvement initiatives (Alam, 2010).

The WQI is a practical and effective tool for determining the quality of drinking water. It's converts enormous volumes of water quality data into a single cumulatively determined value, facilitating communication with policymakers and interested parties about overall water quality (Shweta *et al.*, 2013; Elisabet Yilkal *et al.*, 2019; Rakotondrabe *et al.*, 2018). The WQI indicates the combined effect of several water quality characteristics and is determined based on the appropriateness of surface and groundwater for human consumption (Elisabet Yilkal *et al.*, 2019; Toma *et al.*, 2013). An index is most beneficial for comparison reasons and broad queries, but it is less appropriate for specialized issues. Site-specific judgments should be based on a review of the original water quality data. The WQI is a useful tool for informing the public and legislators about water quality decision-makers, but it is not a sophisticated prediction model for technical and scientific applications (Paiu & Breaban, 2014). Using the most frequently observed water quality indicators, the weighted

arithmetic water quality index technique evaluates water quality based on purity (Shweta *et al.*, 2013). The WHO's guidelines for drinking water quality were used to create the Water Quality Index (WQI) and the method of Weighted Arithmetic Index.

2.1.6. Physics of Water Quality and Atmospheric Components

The physical, chemical, and biological characteristics of water are measured to determine its quality that is necessary to determine its fitness for diverse applications such as drinking, industrial activities, and ecological support (EPA-2024). Water quality in surface and groundwater systems is fundamentally controlled by physical transport mechanisms that govern the movement, spreading, and attenuation of contaminants. Regardless of their chemical or biological nature, pollutants behave according to the laws of mass conservation and fluid flow. Consequently, observed water quality conditions are best understood through the physics of contaminant transport. Advection refers to the transport of dissolved contaminants by the bulk motion of flowing water. In groundwater systems, advective transport follows hydraulic gradients, while in surface waters it is driven by stream velocity. Advection determines the primary direction and rate of contaminant migration from source areas to points of exposure. Mathematically; advective transport is represented by the advective flux term:

$$J_{adv}=v.C$$

Where J_{adv} =advective mass flux (M/L^2T)

v = average linear groundwater or flow velocity (L /T)

C = contaminant concentration (M /L^3).

Dispersion: Hydrodynamic dispersion describes the spreading of contaminants caused by velocity variations at the pore scale and molecular diffusion. Dispersion results in both longitudinal and transverse spreading of contaminant plumes, influencing concentration gradients and the spatial extent of contamination.

The dispersive flux is expressed as:

$$J_{\text{disp}} = -D \cdot \nabla C$$

Where:

J_{disp} = dispersive mass flux ($M L^{-2} T^{-1}$)

D = hydrodynamic dispersion coefficient ($L^2 T^{-1}$)

∇C = concentration gradient ($M L^{-4}$).

Advection–Dispersion Equation (ADE): The combined effects of advection and dispersion are described by the Advection–Dispersion Equation (ADE), which governs contaminant transport in porous media and flowing water systems. In one-dimensional form, assuming constant flow velocity and dispersion, the ADE is written as:

$$\frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial x^2} - v \frac{\partial C}{\partial x}$$

Where:

- $\frac{\partial C}{\partial t}$ = change in concentration with time,
- D = dispersion coefficient,
- v = advective velocity,
- x = spatial coordinate along the flow direction,
- t = time.

This equation forms the physical basis for predicting contaminant migration in both groundwater and surface water systems.

Dilution is a physical process whereby contaminant concentrations decrease due to mixing with cleaner water, without altering the total contaminant mass. In river systems, dilution is strongly influenced by discharge variability, while in aquifers it depends on recharge rates and mixing volumes. Dilution modifies concentration levels but does not eliminate contaminants, making it a critical factor in interpreting observed water quality data. All chemical and microbiological findings reported in water quality studies are manifestations of these physical transport processes. Spatial variability, seasonal concentration changes, and exceedances of guideline values are controlled by the interaction of advection, dispersion, and dilution within the hydrological system. Therefore, chemical analyses cannot be meaningfully interpreted in isolation from the governing transport physics. In urban catchments such as Akaki Sub-City, strong surface water groundwater interaction

particularly along the Akaki River enhances advective transport of contaminants into adjacent aquifers, while dispersion and dilution control their spatial distribution and concentration. The Advection Dispersion Equation thus provides the theoretical foundation for understanding contaminant behavior and supports subsequent exposure modeling and quantitative health risk assessment

2.1.7 Water Quality Index (WQI) and Comparison with Quantitative Health Risk Assessment

The most convenient way to express the quality of water resources for consumption is the Water Quality Index (WQI), using the water quality data being very useful for the modification of the policies. The Water Quality Index (WQI) is a widely applied tool for summarizing complex water quality data into a single numerical value that reflects the overall status of a water source. One of the key limitations of WQI is that it does not account for the pathways of human exposure or the dose of contaminants actually received by individuals. While WQI indicates whether water quality is generally “good” or “poor,” it does not quantify the magnitude of health risk associated with consuming contaminated water, nor does it distinguish between contaminants with different toxicological effects. In contrast, Quantitative Health Risk Assessment (QHRA) provides a more robust and predictive framework for evaluating drinking water safety. QHRA is grounded in physical and toxicological principles and explicitly models human exposure dose by incorporating contaminant concentration, water ingestion rate, exposure frequency, exposure duration, body weight, and averaging time. Through this approach, QHRA converts measured contaminant concentrations into quantitative estimates of health risk. Unlike WQI; QHRA enables the calculation of non-carcinogenic risk indicators, such as the Hazard Quotient (HQ) and Hazard Index (HI), as well as carcinogenic risk (CR) for substances with cancer-causing potential.

Water Quality Index (WQI) and QHRA Equation-Based Comparison

(a) Water Quality Index (WQI)

The Water Quality Index aggregates multiple water quality parameters into a single numerical value using weighting and normalization techniques. A commonly applied weighted arithmetic WQI model is expressed as:

$$WQI = \sum (W_i \times Q_i) / \sum W_i$$

The water quality index (WQI) was determined using the standard technique of drinking water quality recommendations established by the WHO using the weighted arithmetic index method. In these procedures, individual water quality components are multiplied by a weighting factor and then aggregated using the basic arithmetic mean for a single parameter of water quality at a sample site. The quality rating scale (Q_i) for each parameter was derived using the equation below.

$$\text{Quality rating, } Q_i = 100 \left[\frac{(V_n - V_i)}{(V_s - V_i)} \right] = (V_i / S_i) \times 100 \text{----- (1)}$$

Where V_n is the actual quantity of the n th parameter, V_i is the ideal value of this parameter, except for pH and DO, where V_i is 7.0 for pH and 14.6 mg/L for DO, and V_s is the suggested WHO standard for the corresponding parameter.

The relative weight (W_i) was determined as a value inversely proportional to the suggested standard (S_i) for the associated parameter, as shown below.

$$W_i = \frac{1}{S_i} \text{----- (2)}$$

W_i is a scale of 1 to 5 or 1 to 4 (where 1 is the least significant and 5 is the most significant).

WQI are often considered for a specific and intended use of drinking water. The entire WQI was determined using the equation:

$$\text{WaterQualityIndex}(WQI) = \frac{\sum(Q_i)W_i}{\sum W_i} \text{----- (3)}$$

$$WQI = \sum W_i / \sum W_i \times \left(\frac{V_i}{S_i} \right) \times 100 \text{----- (4)}$$

Where: W_i is the parameter's weight, and V_i is the measured value (mean).

S_i is the standard permitted value (WHO/CES). - Q_i represents the quality ranking.

The calculated WQI values are divided into five categories: excellent, good, bad, extremely poor, and unstable water quality (Elisabet Yilkalet *et al.*, 2019).

WQI Range	Water quality status (WQS)	Category.
0-25	Excellent water quality.	Suitable for drinking.
26-50	Good water quality.	Minor treatment needed.
51-75	Good water quality	Extensive treatments are needed.
76-100	Poor water quality.	Not suited for drinking.
>100	Not appropriate for drinking	Highly polluted.

Source: Priya and Vidya, 2019; Elisabet Yilkalet *et al.*, 2019.

(b) Quantitative Health Risk Assessment (QHRA): In contrast, QHRA explicitly models human exposure dose, making it a physics-based and predictive approach. The chronic daily intake (CDI) through drinking water ingestion is calculated as:

$$CDI = (C \times IR \times EF \times ED) / (BW \times AT)$$

Where:

- C = contaminant concentration in drinking water (mg L^{-1}),
- IR = ingestion rate of drinking water (L day^{-1}),
- EF = exposure frequency (days year^{-1}),
- ED = exposure duration (years),
- BW= body weight (kg),
- AT = averaging time (days).

Non-Carcinogenic Risk

The Hazard Quotient (HQ) is calculated as:

$$HQ = CDI / \text{RfD}$$

Where:

- RFD = reference dose ($\text{mg kg}^{-1} \text{ day}^{-1}$).

For multiple contaminants, the Hazard Index (HI) is defined as:

$$HI = \sum HQ$$

An HI value greater than 1 indicates potential non-carcinogenic health risk.

Carcinogenic Risk: For carcinogenic contaminants, the Carcinogenic Risk (CR) is calculated as:

$$CR = CDI \times SF$$

Where:

- SF = cancer slope factor ($\text{mg kg}^{-1} \text{ day}^{-1}$)⁻¹.

CR values represent the probability of an individual developing cancer over a lifetime due to exposure.

2.1.8. Ethiopian and WHO Drinking Water Quality Standards

Water is necessary for sustaining life, as well as providing safe, accessible, and sufficient supplies for everybody individuals is fundamental for public health. Improving access to clean drinking water can significantly decrease the incidence of waterborne illness and enhance overall well-being. According to recent studies, ensuring drinking water safety throughout an individual's life is crucial, as it minimizes health risks across different age groups, including children and the elderly (WHO, 2023). However, drinking water standards are not uniform globally; they vary depending on local environmental conditions, infrastructure, and cultural factors. Developing effective water quality regulations requires careful consideration of these local contexts, alongside existing legislation related to health and water management, to ensure that standards are both appropriate and enforceable (UNICEF, 2022).

The WHO, or World Health Organization, has established comprehensive standards for the quality of drinking water, serving as a benchmark for national standards worldwide to protect public health from contaminants (WHO, 2023). In Ethiopia, the national standards set by the Ethiopian Standards Agency (ESA) align with these international guidelines and include specific characteristics including turbidity and pH, which are essential markers of water

safety (ESA, 2021). Since these standards specify acceptable values for the physical, chemical, and microbiological characteristics of drinking water, adherence to them is crucial for protecting health. In order to guarantee safe drinking water for all populations, international organizations such as the United States Environmental Protection Agency (USEPA) and the World Health Organization (WHO) continue to update these guidelines to reflect new scientific findings, stressing the significance of strict water quality monitoring and regulation (WHO, 2023).

Table 1: (Source: WHO, 2022; Ethiopian Standards Agency, 2015)

Parameter	ES 261:20015)	WHO Guideline (2022)	Health/Aesthetic Significance
PH	6.5 – 8.5	6.5 – 8.5	Impacts corrosion, flavor, and treatment efficiency
Turbidity	≤ 5	< 5	interferes with disinfection; aesthetic concerns
TDS	≤ 1000 mg/L	<1000 mg/L	Affects taste and consumer acceptance
Fluoride	≤ 1.5 mg/L	≤ 1.5 mg/L	Prevents fluorosis at safe levels
Nitrate	≤ 50 mg/L	≤ 50 mg/L	High levels cause methemoglobinemia.
Manganese	≤ 0.1 mg/L	≤ 0.1 mg/L	
Fecal Coliforms	0 CFU/100 mL	0 CFU/100 mL	Potential neurotoxic effects at high levels
Total Coliforms	0 CFU/100 mL	0 CFU/100 mL	Indicates fecal contamination; risk of disease

2.1.9. Comparison and Relevance

Microbial pollutants (e.g., *E. coli*, total coliforms) are subject to zero tolerance under both national and WHO criteria due to their acute health concerns. While national standards are generally consistent with WHO guidelines, specific thresholds, particularly for emerging toxins or aesthetic characteristics (e.g., taste, color), may differ significantly. 0CFU/100ml indicates that no bacteria colonies should be present in 100 milliliters of water (ES 261:2013).

2.1.10. Seasonal Variation in Water Quality

Seasonal variations have a substantial impact on water quality, especially in tropical and subtropical climates like Ethiopia's. Rainy Season: Heavy rainfall increases surface runoff, which carries sediments, organic debris, and toxins into bodies of water. Microbiological pollution frequently increases presently as a result of sewage systems and latrines flooding (Tekle-Haimanot *et al.*, 2012). Dry Season, reduced dilution can result in higher concentrations of certain chemical parameters (for example, fluoride and nitrate). If surface runoff is modest, microbial contamination may be reduced.

2.1.11. Global Perspective on Drinking Quality of Water

Public health, economic stability, and environmental sustainability are all impacted by the fundamental human right to clean and safe drinking water (Smith *et al.*, 2025). However, by 2025, the global were confront considerable hurdles in providing widespread availability of potable water as a result of a complex interaction of factors like population increase, industrialization, changes in the climate, and socioeconomic inequality (Johnson & Lee, 2025). This report gives a complete overview of worldwide drinking water quality, including historical background, current concerns, health consequences, socioeconomic considerations, regulatory frameworks, community participation, and specific issues in locations such as Akaki Kality, Ethiopia. Globally, the issue of drinking water quality remains a major concern. The World Health Organization (WHO) estimates that more than 2 billion people lack access to clean drinking water services globally (WHO, 2025). This alarming estimate corresponds to roughly 485,000 fatalities from diarrhea each year, predominantly affecting children under the age of five (Miller *et al.*, 2024). Pathogens, chemical compounds, and physical impurities are examples of pollutants present in drinking water, each of which poses a different level of health risk (Harper & Smith, 2025).

2.1.12. Contemporary Challenges in Water Quality

Despite technical developments, there are still problems with preserving and increasing water quality. Climate change, rising populations, and increased industrial activity continue to put pressure on water supplies and complicate water management (Nguyen *et al.*, 2025). Climate

change, in particular, has an impact on water supply and quality because It increases the frequency of extreme weather occurrences, modifies precipitation patterns, and raises temperatures. These environmental changes can raise pollution concentrations and promote the growth of hazardous microbes in water sources (Jones, 2025).

2.1.13. Health Implications of Poor Water Quality

Water is an essential need for for life. Unfortunately, not all water is beneficial humans live Water from contaminated sources results in a variety of ailments and premature deaths. Because humans require water and cannot survive without it, they must it from any source, clean or contaminated (Zeyede and Tesfaye, 2004).Waterborne, water-washed, water-based, and water-related diseases may arise from the use of deteriorated water quality. The term "water-associated disease" describes any illness that has water-borne causal agents. A condition that impacts sanitation and water supply is known as water-associated illness. According to Salvato (2003), there are four types, which are as follows:

1. Water-borne illness: Several infections Human enteric, or intestinal, infections are spread by fecal matter pollution of water. Pathogens discharged in water by an infected individual are classified into four types: bacteria, viruses, parasitic worms, and protozoa. Water acts as a passive carrier of the infectious agent in this category. Examples of waterborne illnesses and the microbes that cause them include cholera, typhoid, amebiasis, and giardiasis.

2. Water-washed disease: These illnesses are associated with a lack of water for personal hygiene. Trachoma and scabies are shown as examples of water-washed diseases.

3. Water-related illnesses: These are illnesses spread by insects that reside near water. Schistosomiasis and Guinea worms are given as examples of water-based diseases.

4. Water-related diseases: Insects that live close to water can spread these infections. Examples include mosquitoes (malaria), tsetse flies (sleeping sickness), and flies. The health consequences of drinking low-quality water are numerous and far-reaching. Waterborne infections, including cholera, giardiasis, dysentery, and typhoid, are common in places without proper water treatment facilities (Williams & Carter, 2025). Long-term exposure to

some chemicals in drinking water can result in long-term health issues such developmental difficulties, neurological system or reproductive issues, kidney and liver damage, and carcinogenic consequences (Taylor *et al.*, 2024). The presence of contaminants such as lead, arsenic, and nitrates has been related to serious health consequences, stressing the importance of rigorous water quality monitoring and treatment (Fisher & Kumar, 2025).

2.1.14. Impact of Contaminated Drinking Water on Health in Akaki Kality

Toxic chemicals in drinking water can have both immediate and long-term health impacts. An acute impact generally develops relatively immediately, and it is simple to determine the source as well as the potential cure. Table 2 shows the top ten illnesses that occurred in the Akaki Kality subcity of Addis Abeba, Ethiopia, during the 2025 working calendar.

Table 2: Akaki Kality subcity health bureau (2025), Annual disease surveillance report, AA

Number	Month	Disease	Number of peoples			
			M	F	T	%
1	February	Acute Watery Diarrhea	124	132	256	20%
2	March	Typhoid Fever	89	101	190	15%
3	April	Cholera	64	58	122	10%
4	May	Hepatitis A	43	57	100	8%
5	June	Giardiasis	51	49	100	8%
6	July	Amoebiasis	72	83	155	12%
7	August	Schistosomiasis	37	39	76	6%
8	September	Cryptosporidiosis	25	31	56	4%
9	October	Dysentery	48	44	92	7%
10	November	Skin diseases (rashes)	58	64	122	10%

The table shows the top ten diseases reported in Akaki Kality sub-city in 2025, which are directly or indirectly associated with polluted drinking water. The data is disaggregated by month, illness kind, and gender (male and female), providing information about gender susceptibility and seasonal trends of waterborne disease prevalence.

1. High Incidence Diseases: Acute Watery Diarrhea (20% of cases) was the most often reported ailment, particularly in February, perhaps due to increased bacterial contamination during the rainy season.

Typhoid fever occurred in 15% of patients, indicating ongoing fecal contamination and inadequate hygiene. Amoebiasis (12% of cases) and cholera (10% of cases) were prevalent, highlighting issues with unsafe drinking water, poor sanitation, and inadequate water treatment systems.

2. Gender Analysis: In most situations, females had significantly more cases than males: female total = 658 and male total = 611. This shows that women, particularly those in charge of water handling and caring at home, may be more vulnerable or impacted.

3. Seasonal Trends: Waterborne illness reports were greater in months such as February, March, and July, which are commonly linked with seasonal rains or water shortages. Diseases like cryptosporidiosis and giardiasis existed throughout the year, demonstrating that contamination persisted regardless of season.

4. Implications: The findings indicate a substantial correlation between water pollution and public health in Akaki Kality. Inadequate water treatment, sewage overflow, and proximity to industrial discharges in the sub-city may all contribute to the problem. Vulnerable populations, particularly women and children, are at greater danger as a result of their regular water usage.

2.1.15. Socioeconomic Factors and Water Quality

Socioeconomic considerations are essential in determining access to clean water. Communities with few resources frequently experience higher difficulty in obtaining clean drinking water owing to inadequate infrastructure for the supply and purification of water (Martinez *et al.*, 2024). Inadequate sanitation and hygiene standards raise the risk of waterborne illnesses in a variety of developing countries (Nguyen *et al.*, 2025). To address these gaps, focused interventions must take into account each community's distinct social, economic, and cultural settings (Roberts, 2024).

2.1.16. Water Quality in Addis Ababa, Ethiopia's Akaki Kality Sub-City

Water quality issues are especially significant in certain areas, such as the Akaki Kality sub-city of Addis Ababa, Ethiopia. Residents' health is intimately tied to the quality of their drinking water, with data revealing a greater frequency of waterborne infections and health disorders caused by low water quality (Kassa *et al.*, 2024). The sub-city confronts particular issues due to urbanization, industry, and insufficient water supply infrastructure, resulting in pollution from industrial waste, home sewage, and agricultural runoff (Zewdie & Bekele, 2025). Water source protection, treatment process control, transmission and distribution system management, and domestic water handling may all be used to regulate the quality of drinking water.

2.1.17. Economic Benefits of High-Quality Drinking Water

Ensuring high-quality drinking water has enormous economic benefits. Poor water quality can lead to higher medical bills, decreased productivity, and lower economic output owing to disease (Brown & Johnson, 2025). Investments in clean water infrastructure and sanitation facilities benefit both public health and economic growth by generating job opportunities and increasing agricultural output (Smith *et al.*, 2025). Addressing the global water issue is critical to attaining sustainable development and ending the cycle of poverty in vulnerable areas (Nguyen *et al.*, 2025).

2.1.18. Environmental Impact of Water Pollution

The investigation of drinking water quality is critical not only for human health but also for environmental preservation. Polluted water sources can degrade ecosystems, threatening aquatic life and biodiversity (Taylor *et al.*, 2024). Preserving clean water sources is critical for preserving balanced ecosystems and guaranteeing the availability of clean drinking water for future generations (Fisher & Kumar, 2025). Sustainable water management strategies are required to reduce the environmental effect of Water pollution and safeguard aquatic habitats (Harper & Smith, 2025).

2.1.19. Water Scarcity and Climate Change

Climate change is intensifying water shortages, increasing competition for water supplies, and increasing the likelihood of water-related calamities (Adams & Brown, 2024). Rising temperatures, changing patterns of precipitation and severe weather make access to clean drinking water more challenging, particularly for the most vulnerable communities (Jones, 2025). Addressing climate change and implementing sustainable water management techniques are critical for maintaining water security in the face of these issues (Nguyen *et al.*, 2025).

2.1.20. Water Quality Monitoring Technologies

Advances in water quality testing technologies provide creative alternatives for protecting water resources. Remote sensing technology, portable testing kits, and real-time water quality monitoring sensors enable for the effective and ongoing evaluation of water conditions (Zewdie *et al.*, 2025). Utilizing data and the Internet of Things (IoT) analytics in water testing enables real-time insights into water quality, enabling fast decision-making and quick reaction to pollution incidents (Kassa *et al.*, 2024).

2.1.21. Impact of Industrialization and Urbanization on Water Quality

Industrialization and urbanization have a significant influence on water quality. Industrial discharges, untreated sewage, and polluted urban runoff can severely pollute surface water bodies, leaving them unsafe for use (Thompson & Patel, 2024). Urbanization increases impermeable surfaces, altering the natural water cycle and causing more stormwater runoff, which transports contaminants into rivers (Garcia, 2023). Proper industrial waste management and the construction of green infrastructure are critical for reducing the impact of urbanization on water quality (Zewdie & Bekele, 2025).

3. MATERIALS AND METHODS

3.1. Description of the Study Area

3.1.1. Location

The study was carried out at Akaki Kality Sub-City, one of the eleven sub-cities of Ethiopia's capital, Addis Ababa. The sub-city has boundaries that connect with Oromia Special Zone to the south, Nifas Silk Lafto Sub-City to the west, and Bole Sub-City to the northeast. It is a densely populated and industrialized area with increasing population expansion and water-related concerns.

3.1.2. Altitude and Distance from the Center

Akaki Kality is situated between 2200 and 2400 meters above sea level. Its coordinates are 8° 53' 44.9916" N and 38° 47' 20.9832" E, approximately 20-25 kilometers south of Addis Ababa's city center (CSA, 2021).

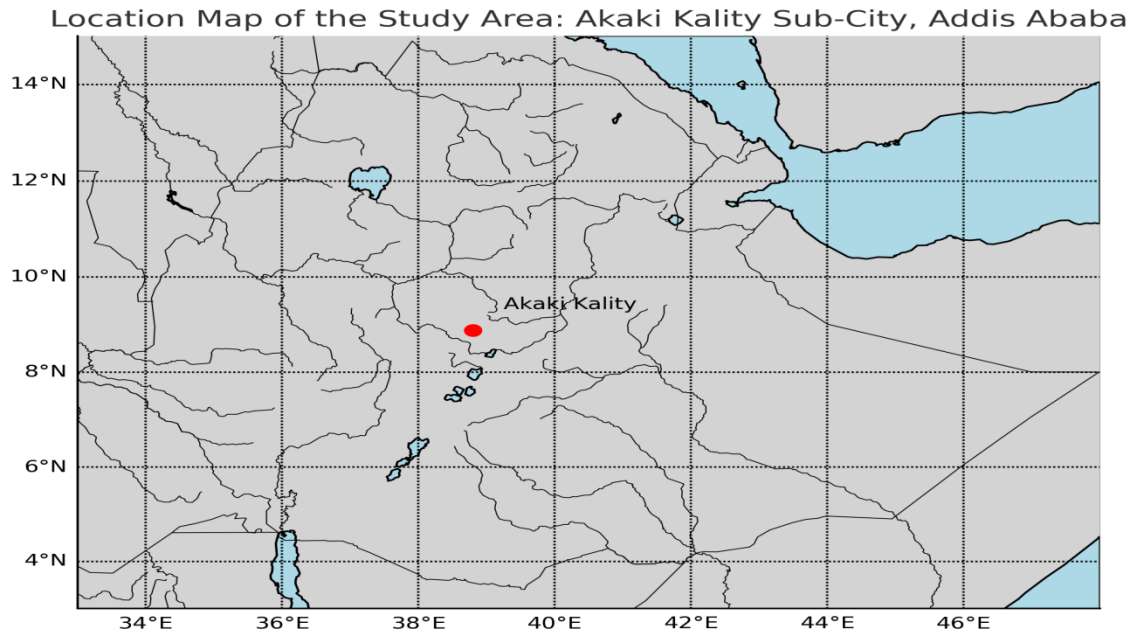


Figure 1: Location map of Akaki Kality Subcity, Addis Ababa

3.1.3. Climate

The sub-city of Akaki Kality is situated in the southernmost portion of Addis Ababa, has a Köppen-Geiger climate classification of subtropical highland (Gebremedhin, T., Kassa, A. (2024)). This climatic type is characterized by moderate temperatures all year round, with distinct dry and wet seasons. The average annual temperature in the sub-city ranges between 12°C and 26°C, with the hottest months being February to May and the coldest being July to September. Rainfall in Akaki Kality is very seasonal, with the main rainy season lasting from June to September, when the area receives the majority of its yearly precipitation. The annual rainfall ranges from 800 mm to 1200 mm, which contributes to surface runoff and may have an impact on the quality of shallow groundwater sources. . These seasonal variations strongly influence surface water flow, groundwater recharge, and potential contamination pathways of drinking water sources in the area

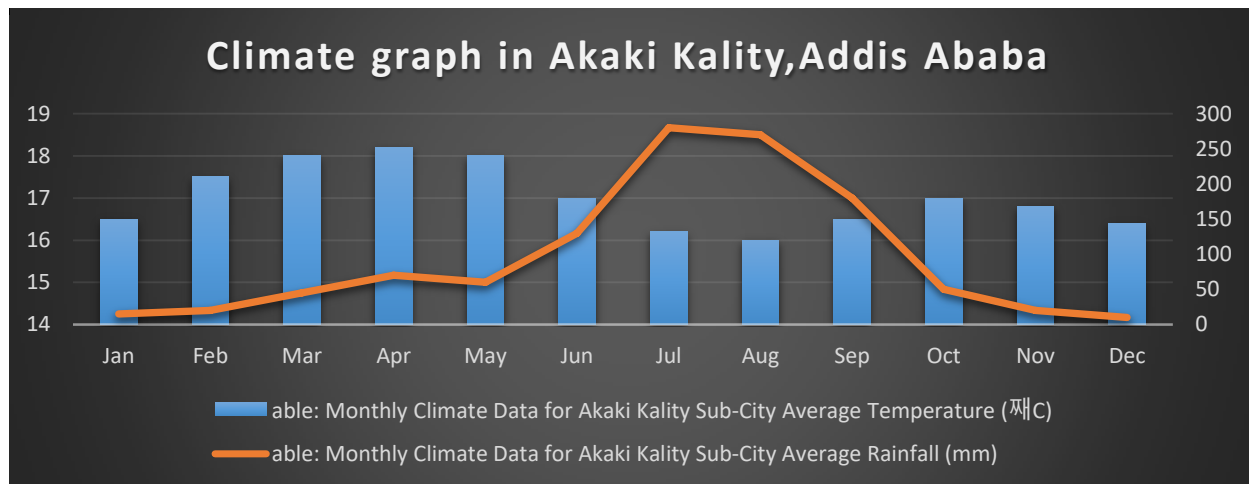


Figure 2: The climate graph for Akaki Kality, Addis Ababa, Ethiopia

3.1.4. Topography

Akaki Kality has a diverse terrain that includes both hills and lowland areas, as typical of Addis Ababa's southern and southeastern regions. Akaki Kality is situated at an elevation of around 2300 meters above sea level, which contributes to its cooler temperature. The topography of the Akaki sub-city is gently sloping, with elevations gradually decreasing from the higher upstream areas towards the Akaki River. This topographical gradient establishes

the hydraulic gradient, which serves as the primary physical driving force for groundwater flow.

Rainfall patterns in the area are seasonal, with a distinct rainy season from June to September and a dry season from October to May. Rainfall not only contributes to aquifer recharge but also influences the dilution capacity of the groundwater system. During periods of high precipitation, increased infiltration enhances the volume of water in the aquifer, which can reduce contaminant concentrations through dilution. Conversely, low rainfall periods may reduce dilution and increase contaminant concentrations in wells and other water abstraction points. The combination of topography driven hydraulic gradient and rainfall dependent dilution defines both the direction and rate of contaminant transport as well as the aquifer's capacity to naturally attenuate pollutants.



Figure 3: Description of the study area

3.1.5. Soils

The soils in the area range from clay-loam to sandy-clay in texture, influencing in filtration rates contaminant mobility. The most common soil types are Vertisols (dark, clay-rich soils) and Andosols (volcanic soils with low bulk density and strong water retention), which are clay-rich and have moderate to poor natural drainage capabilities (Tadesse, 2020).

3.1.6. Drainage

The natural drainage is frequently disrupted by industrialization, causing low-lying areas to flood, especially during the rainy season.

3.1.7. Land Use Pattern

Akaki Kaliti Sub-City, located on the southern periphery of Addis Ababa, has a diversified land use pattern that represents both urban growth and peri-urban development. The area has a mix of residential, industrial, agricultural, and open or undeveloped sites, all of which have important consequences for water quality and public health. Residential areas dominate much of the northern and central parts of the sub-city, ranging from high density informal settlements to more formally built housing complexes. The industrial zones, particularly in the sub-city's eastern and southeastern parts, are distinguished by medium to large scale manufacturing, which includes tanneries, textile manufacturers, metal workshops, and beverage industries.

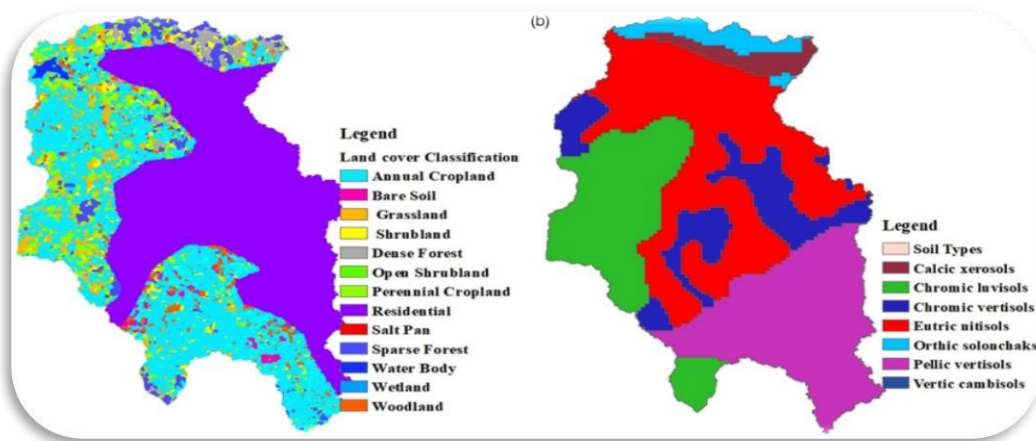


Figure 4: Land Use Pattern of the Study Area

3.1. 8. Population

Akaki Kaliti is one of Addis Ababa's most densely populated sub-cities, with an estimated population of more than 250,000 people (Tadesse, 2020). The population is made up of residents, workers, and small holder farmers from surrounding rural areas, and it is fast rising as a result of urbanization and migration from rural areas in pursuit of economic opportunities, notably in the industrial sector (Gizaw, 2019). The area is also a popular destination for migrant workers because of the concentration of industrial parks and manufacturers, which puts additional strain on water delivery infrastructure (CSA, 2021). This influx of people has resulted in higher demand for housing, services, and infrastructure, putting extra strain on local resources.

3.1.9. Demographics

The population is made up of various Ethiopian ethnic populations, with a dominant presence of Amhara, Oromo, Tigre, and other minor ethnic communities. The subcity also has a combination of low-income residential districts and higher-income industrial estates, resulting in a mixed socioeconomic demographic.

3.1.10. Urbanization Rate

The population density is rising as more people migrate to the area to work in the industries and tanneries, which are a key source of employment.

3.1.11. Environmental Conditions

Environmental deterioration is a major concern in Akaki Kaliti. The release of untreated industrial effluents, poor domestic disposal of waste and inadequate infrastructure for sanitation contribute to river and groundwater contamination. Studies have shown significant amounts of heavy metals and microbiological pollution in the Akaki River, raising major concerns for human well-being and environmental safety (Kebede *et al.*, 2022).

3.1.12. Humidity

The area has moderate humidity levels, which range between 50% and 60%. Akaki Kality's relatively moderate climate makes it excellent for both industrial and agricultural enterprises.

3.1.13. Socio-Economic Zones

Akaki Kality Sub-City is home to some of Addis Ababa's greatest industrial zones, making it an important hub for industry and production. The primary sources of livelihood include industrial jobs, small-scale trading, and informal sector activities. The area's major businesses include metals, textiles, food processing, and chemical manufacturing, exhibiting Akaki Kality's diversified industrial capabilities (Gizaw, 2019). Furthermore, the Kality Industrial Zone is a designated area that focuses on the metal, textile, and chemical sectors, boosting operational efficiency by grouping related companies (Abebe, 2020).

3.1.14. Transportation & Infrastructure

Akaki Kality Sub-City has a well-developed transportation network that includes key routes like the Addis-Adama Expressway and Debre Zeit Road. These thoroughfares improve industrial transit by allowing products and services to and from the sub-city to flow more efficiently (Tadesse, 2020). Buses and minibuses serve as the primary mode of public transit in the region, connecting inhabitants to other sections of the city. The main transport networks of Akaki Kality Sub-City include a well-connected transportation network that comprises key commercial and industrial routes. The Addis-Adama Expressway is a key economic route that connects Addis Abeba to Oromia and then to Djibouti, allowing for the efficient transit of commodities between regions (Tadesse, 2020).

3.1.15. Sources of Water

The sources of potable water quality in the Akaki Kality sub-city include piped water supply, private groundwater wells and boreholes, and springs, as well as both protected and unprotected sources. These sources are distributed across various land use zones, including residential, industrial, and agricultural areas.

3.2. Materials

3.2.1. Source of Data sampling

Checklists, laboratory results, and field observations were used to gather primary data. Stratified dual-season sampling (n=45, sites=30): wet (June-Sep2025, peak dilution/recharge) and dry (Oct-May2025, max concentration/transport). Dual-season sampling was necessary to capture extremes in dilution (wet EC 164.2→749.3 $\mu\text{S}/\text{cm}$ dry) and transport kinetics, or the rate of pollutant movement (advection velocity $v=0.1\text{-}1$ m/d wet vs. $0.05\text{-}0.5$ m/d dry; Peclet $Pe>10$ wet advection-dominant, $Pe<1$ dry dispersive). Materials: sterile 500ml (10% HNO_3 rinsed), Hach HQ40d (pH/EC/turbidity $\pm 0.01/\pm 1$ $\mu\text{S}/\pm 0.1$ NTU), coolers (4°C , <4hr AAU labs), GPS Garmin eTrex, ICP-MS certified standards.

The test analysis of the water sample was obtained from Saris Abo Area, Tulu Dimtu, Akaki Fanta Spring, Kaliti Condominium, Kaliti Industrial Zone, Old Stadium Area, Akaki Kaliti Bus Terminal, Kaliti Sub-City Administration, Hana Mariam Area, Akaki Market, Beside Akaki River Channel, Near Kaliti Industrial Park, Kaliti Housing Estate, Industrial Worker Camp, Akaki Health Centre Area, Private Borehole (Residential), Near Akaki River Crossing, and Upper Akaki Hill Spring at selected sampling points for Water quality is determined by microbiological parameters (E. coli and total coliform), physical parameters (pH, turbidity, conductivity, and TDS), and chemical parameters (selected ions, Ca, Mg, hardness, and alkalinity). Sample water were collected and examined for various criteria at the Addis Ababa State Water and Sewage Authority's central laboratory at Akaki Kaliti. After examining criteria that reflect the drinking water's quality and its effects, the results were in contrast to the WHO and Ethiopian guidelines standard 4th edition results. Data were gathered from both published and unpublished literature, as well as Akaki Kaliti sub-city reports, and health data on waterborne illnesses, including diarrhea, typhoid, and cholera, were obtained from local health clinics for triangulation purposes.

3.2.2. Equipment/Instruments

Analysis of the chemical and aesthetic content was done in the AAWSA laboratory, while chemical water quality was assessed using pH meters, comparator or colorimeter methods, and quantitative spectrophotometer procedures. Using an authorized multiple-tube fermentation method, microbiological examination was also carried out in the same lab. The primary method involved incubating sample water in media (70% ethanol, lactose broth, brilliant green bile broth, Escherichia coli media, and distilled water) that specifically encourage the growth of total coliform bacteria, fecal coliform, and Escherichia coli, a well-known pathogenic contamination indicator. Sampling bottles (pipettes 1 ml, 5 ml, and 10 ml), tasting tubes, sterile diurnal tubes, a knife/spoon, and distilled water. Incubator ($36\pm 2^{\circ}\text{C}$), sterilization machine, refrigerator ($5\pm 3^{\circ}\text{C}$), and waste container. Chemical analysis was also carried out in the same facility, employing a verified multiple tube spectrometer, pH meter, spectrophotometer (Model DR5000, Japan), fast column extractor, and jar test device. Beakers (500 mL, 1000 mL), Syringe, Volumetric flask (100 mL), Conical (Erlenmeyer) flask (125 mL), pipettes (1 mL, 5 mL, 10 mL, or 25 mL), graduated cylinders (50 mL, 500 mL, 1000 mL, and 250 mL), Glove, Plastic Beaker (250 mL, 400 mL), Glass bottles (2000 mL), Polyethylene bottle (PEB), Timer Icon, Ice-packed cooler, Refrigerator, and sample temperature between 15 and 25°C . Physical analysis was performed in the same lab utilizing a multiple tube validation spectrometer, turbidity meter (20 ± 1 NTU between 19 and 21 NTU, 200 ± 10 NTU between 190 and 210 NTU), pH meter (HI9124), reagents, media, and solutions (pH buffer 4→pink, pH 7→yellow, pH 10→blue, pH storage buffer, dissolved 1 tablet of the needed pH buffer in 20 ml distilled water), and gloves.

3.2.3. Experimental design

The study employed both descriptive and experimental study designs to comprehensively evaluate various aspects of the Akaki Kaliti region. The descriptive research approach aimed to investigate the sanitary conditions of the area and assess the local population's knowledge, attitudes, and practices (KAP) regarding water quality and sanitation. The study employed a cross-sectional observational methodology to evaluate the standard of drinking water sources and their potential influence on people's health in Akaki Kaliti Sub-City. The design also

included household surveys and health data gathering to investigate possible links between water quality measures and common waterborne illnesses in the community. In contrast, the experimental study design centered on determining drinking water's physical, chemical, and microbial characteristics quality at both source locations and consumer taps. This comprehensive investigation sought to uncover any disparities in quality of drinking water across the system of distribution, as well as to establish the safety of human drinking water. The research was conducted out at Akaki Kaliti from September 2024 to August 2025, with an extension until September 2025. This time span enabled a detailed evaluation of seasonal fluctuations and their impacts on water quality and public health. By integrating these two study approaches, the researchers want to give a comprehensive knowledge of water quality concerns and their consequences for community health in Akaki Kaliti.

3.3. Methodology

3.3.1. Data collection

3.3.1.1. Sampling Site Selection and Sampling Strategies

After a preliminary survey along the river course, 30 sampling sites were selected based on accessibility, ease to identify, proximity to point, and non-point sources of pollution. The water samples were collected between June–Sept wet season and Oct–May 2025 which is typically the dry season to investigate the pollution status of the river during the dry period when downstream communities are largely using the river water for different purposes; the river is accessible and water scarcity becomes critical in the area. Analysis for physico-chemical parameters were done immediately after transporting to the laboratory, while the samples for heavy metal analysis were preserved with 10mL HNO₃ and kept in a refrigerator at 4 °C until they were further processed and analyzed. Water samples were collected from multiple sources, including groundwater wells, boreholes and surface water points along the Akaki River, using standard sampling containers and preservation reagents in accordance with WHO and Ethiopian drinking water guidelines. Laboratory equipment for analyzing physicochemical parameters (pH, EC, turbidity, major ions, and heavy metals) and microbiological indicators (E. coli, total coliforms) was employed to ensure accurate characterization of water quality. Thirty water samples in all were collected from the Saris

Abo area (Kality well, W-6), Tulu Dimtu, Akaki Fanta Spring, Kality condominium, Kality industrial zone, Old stadium area, Akaki Kality bus terminal, Akaki Kality sub-city administration, Akaki Alem bank, Akaki health center, near Akaki crossing road, Tulu Mebrat area, Kality housing state, and Hana Mariam area, Akaki market water sources in different Akaki Kality sub-cities, including piped water supply, private groundwater wells and boreholes, springs, and protected sources, across various land use zones. Sites were purposively selected based on population density, industrial activities, and potential health concerns.

3.3.1.2. Sample collection, preservation and transportation procedures

Water samples were taken from Akaki Kality ground, public taps, boreholes, and spring water in sterilized 1 polyethylene bottles, stored in iceboxes at 4°C using the Addis Ababa Water and Sewerage Authority (AAWSA) Central Laboratory for examination. The samples were collected during the major rain season (June-Sept), the shorter rain season (March-May), and the dry season (October-February) to analyze seasonal variance. Samples were collected using 1000 ml polyethylene bottles with big lids for easy filling and removal, as well as a composite random sampling approach. To remove any pollutants, the bottles were cleaned and immersed overnight in a 5% HNO₃ solution (Rao & Mamatha, 2004). To avoid contamination during sampling, precautions were collected, and the bottles were repeatedly cleaned using the collected water.

3.3.1.3. Laboratory Analysis

Physicochemical parameters such as pH, temperature, turbidity, total dissolved solids, electrical conductivity, hardness, nitrate, chloride, fluoride, and heavy metals (lead and arsenic), along with microbiological indicators like total and fecal coliforms, were analyzed in Akaki ground and spring water samples following standard protocols (APHA, 1998) between September 2024 and August 2025 at the AAWSA Laboratory. The assessments employed current laboratory procedures and the Hach DR-5000 Spectrophotometer for precise chemical measurements, with microbiological analyses using reagents including ethanol, lactose broth, BGB media, sterile tubes, Durham tubes, an incubator at 36±2°C, and sterile techniques to detect coliforms and E. coli. Heavy metal determinations also adhered to

established methods, utilizing high-purity reagents and spectrophotometry to ensure accurate results.

3.3.1.4. Health Data Collection

Akaki Kality Sub-city health centers and clinics provided secondary health statistics. Water pollution and public health were linked by reviewing disease data pertaining to intestinal parasites, cholera, typhoid, and diarrhea.

3.3.1.5. Data Analysis

The gathered water samples were physicochemical analysis characteristics and heavy metals using SPSS (version 26), with results compared to CES 2020 and WHO 2022 drinking water standards to assess their suitability for human consumption. Instrument detection limits and spectrophotometric procedures were meticulously followed to ensure accuracy and precision. For all descriptive statistics, the mean, median, standard deviation, minimum, and maximum were calculated all water quality indicators, and findings were interpreted in relation to health outcomes. The data analysis framework employed in this study integrates water quality measurements with a Quantitative Health Risk Assessment (QHRA) model to estimate potential non-carcinogenic and carcinogenic health risks associated with long-term consumption of contaminated drinking water in Akaki Sub-City. Inferential statistics, including the use of a one-way Hach DR-5000 Spectrophotometer, assessed differences across various water sources and land use zones. Pearson's correlation coefficient determined relationships between physicochemical and microbiological parameters, while logistic regression analyzed associations between water quality indicators and waterborne illnesses. A 95% confidence interval and $p < 0.05$ were used to determine statistical significance. Additionally, Water Quality Index (WQI) was used to assess the water quality based on the collected data to comprehensively assess the quality of Akaki groundwater, public tap, borehole, and spring water (Smith *et al.*, 2024).

Table 3: Water quality metrics, sources, relevance, and effects on human health.

N	Parameters	Sources	Significance	Effect on human health
1	Turbidity	Soil erosion, runoff, algal blooms	Sediment, microorganisms	Indicates suspended solids, microbial risks
2	PH	Natural minerals, industrial discharge	Indicates suspended solids, microbial risks	High turbidity can harbor pathogens, increasing the risk of gastroenteritis and other infections.
3	Electrical conductivity	Salts, minerals, industrial effluent	Affects solubility, toxicity, and taste	Extreme pH can irritate skin and eyes, affect digestion, and increase heavy metal solubility.
4	TDS	Minerals, salts, organic matter, pollutants	Indicates dissolved ions and pollution	High EC may signal harmful ions (heavy metals, nitrates), linked to kidney and cardiovascular issues.
5	Total Alkaline(Ca CO ₃)	Carbonates, bicarbonates, hydroxides	Reflects total dissolved solids	High TDS can cause kidney stones, digestive issues, and cardiovascular problems
6	Bicarbonate alkalinit	Dissolution of carbonate rocks, soil	Buffers pH, protects aquatic life	Generally safe; extreme alkalinity can cause digestive discomfort.
7	Calcium hardness	Limestone, gypsum, industrial sources	Buffers pH, stabilizes water chemistry	Generally safe; essential for pH stability.
8	Magnesium hardness	Dolomite, industrial sources	Indicates water hardness	Essential for health; excess may cause scaling; low levels may increase cardiovascular risk ⁶ .
9	Ammonia	Decomposition, sewage, agriculture	Indicates water hardness	Essential for health; excess may cause laxative effect; low levels linked to cardiovascular risk ⁶ .
10	Nitrite	Fertilizers, sewage, industrial waste	Toxic to aquatic life, indicates pollution	High levels can cause irritation, respiratory issues, and methemoglobinemia in infants.

11	Nitrate	Fertilizers, sewage, industrial waste	Indicates pollution, toxic to fish	Causes methemoglobinemia ("blue baby syndrome") in infants.
12	Sulphate	Natural minerals, industrial discharge	Indicates pollution, toxic at high levels	Causes methemoglobinemia in infants; potential carcinogen at high doses.
13	Phosphate	Detergents, fertilizers, sewage	Affects taste, laxative effect	High levels can cause diarrhea and gastrointestinal distress.
14	Fluoride	Geological formations, industrial discharge	Causes eutrophication, algal blooms	Generally safe at low levels; high levels can indirectly affect health via algal toxins.
15	Iron	Natural minerals, industrial discharge	Prevents tooth decay, toxic at high levels	Low levels prevent cavities; high levels cause dental/skeletal fluorosis.
16	Manganese		Affects taste, stains plumbing	High levels cause metallic taste, constipation, and liver issues in extreme cases.
17	Chloride	Saltwater intrusion, industrial waste, sewage	Indicates salinity, affects taste	Corrosive, salty taste, harmful to plants at high levels
18	Silica	Salts, sewage, industrial discharge	Affects taste, stains plumbing	High levels may cause neurological symptoms, but evidence is limited.

3.4. Assessment of Water Quality Index (WQI) of Akaki River Samples

The weighted arithmetic index approach was used to calculate the water quality index (WQI) in accordance with the WHO's standard drinking water quality criteria. These methods include multiplying each component of water quality by a weighting factor before aggregating the results using the simple arithmetic mean for a single parameter of water quality at a sample site. The following equation was used to get the quality rating scale (Qi) for each parameter.

$$\text{Quality rating, } Q_i = 100 \left[\frac{(V_n - V_i)}{(V_s - V_i)} \right] = (V_i/S_i) \times 100 \text{-----(1)}$$

With the exception of pH and DO, where V_i is 7.0 for pH and 14.6 mg/L for DO, and V_s is the recommended WHO standard for the corresponding parameter, V_n is the actual quantity of the n th parameter, and V_i is the ideal value of this parameter. As indicated below, the relative weight (W_i) was calculated as a number inversely proportional to the recommended standard (S_i) for the corresponding parameter.

$$W_i = \frac{1}{S_i} \text{-----} (2)$$

W_i is a scale of 1 to 5 or 1 to 4 (where 1 is the least significant and 5 is the most significant). WQI are often considered for a particular and intended application of drinking water. The following equation was used to calculate the total WQI:

$$\text{WaterQualityIndex}(WQI) = \frac{\sum(Q_i)W_i}{\sum W_i} \text{-----} (3)$$

$$WQI = \sum W_i / \sum W_i \times \left(\frac{V_i}{S_i}\right) \times 100 \text{-----} (4)$$

Where: W_i is the parameter's weight, and V_i is the measured value (mean). S_i is the standard permitted value (WHO/CES). - Q_i represents the quality ranking. The calculated WQI values are divided into five categories: excellent, good, bad, extremely poor, and unstable water quality (Elisabet Yilkalet *et al.*, 2019).

Range of WQI	Water quality status (WQS)	Category.
0-25	Excellent water quality.	Suitable for drinking.
26-50	Good water quality.	Minor treatment needed.
51-75	Good water quality	Extensive treatments are needed.
76-100	Poor water quality.	Not suited for drinking.
>100	Not appropriate for drinking	Highly polluted.

Source: Priya and Vidya, 2019; Elisabet Yilkalet *et al.*, 2019.

Excellent (0-25): Water is safe for consumption, irrigation, and industrial use without any treatment.

Good (26-50): Water is typically safe but may need moderate treatment for residential, irrigation, and industrial usage.

Poor (51-75): Water requires significant treatment before drinking and is utilized for agriculture and industrial purposes. Water quality is quite bad (76-100), making it dangerous for drinking and irrigation.

Unsuitable (>100): Water is filthy and unfit for drinking or residential use. It is also prohibited for irrigation.

4. RESULTS AND DISCUSSION

4.1. Physicochemical water quality parameters

The physicochemical characterization of drinking water sources revealed variations in parameters such as Total Dissolved Solids (TDS) and electrical conductivity (EC) generally meet WHO and Ethiopian standards, seasonal fluctuations especially during the rainy season pose risks to water quality due to increased turbidity, potential microbial contamination, and dilution of disinfectants like chlorine. These parameters serve as reliable indicators of the ionic strength of the water, which directly influences the mobility and transport behavior of heavy metals. Elevated TDS and conductivity levels suggest a higher concentration of dissolved ions, which can enhance the solubility and migration rates of metals through the aquifer. Physicochemical analysis of dual-season samples (n=30) revealed elevated Total Dissolved Solids (TDS 82-371 mg/L, mean $1260.373,650 \pm 450$) and electrical conductivity (EC 164-749.3 $\mu\text{S}/\text{cm}$, mean 521.023 ± 101.4471), exceeding WHO limits ($>1,000$ mg/L TDS, $>1,000$ $\mu\text{S}/\text{cm}$ EC) downstream, serving as indicators of ionic strength that influence the mobility and transport rates of heavy metals.

4.2. Chemical Parameters (Heavy Metals)

Analysis of chemical parameters indicated that certain heavy metals, particularly Lead (Pb), were present at concentrations exceeding guideline values. For determination of the heavy metal concentrations, the water samples were digested following standard procedures ([APHA, 1999](#)). The preserved water samples were well mixed and then 100 ml of samples were digested using 5 ml of conc. HNO_3 . The samples were gradually heated to boil and evaporate using a hot plate in the hood to achieve the lowest volume of the digest and removed before drying occurs. Again, 5 mL conc. HNO_3 and 2 mL H_2O_2 were added and reheated again until the digest become a light-colored and clear solution. After cooling the digest, the volumetric flask wall was rinsed with deionized water and the digests were filtered using What-main filter paper and the filtrate was transferred to a pre-cleaned glass cup and made 50 ml with deionized water, sealed, and kept at 4 °C in the refrigerator until analysis. Such high concentrations are indicative of significant advective transport of

pollutant plumes, where in contaminants are carried by the bulk movement of groundwater. In these cases, the natural dispersion and dilution capacity of the aquifer is insufficient to attenuate the pollutants, allowing the plume to reach drinking water points with minimal reduction in concentration. These findings underscore the critical role of hydraulic gradient and aquifer heterogeneity in controlling contaminant distribution and highlight areas of elevated exposure risk.

4.3. Microbiological Water Quality

Microbiological indicators are among the most important factors influencing drinking water safety since they immediately represent the presence of disease-causing organisms. The Akaki Kaliti Sub-City research evaluated microbiological quality by testing for total coliforms and fecal coliforms (*E. coli*), both of which are globally regarded as significant markers of water pollution.

Total Coliforms: Total coliforms are a diverse collection of bacteria found in soil, water, and plants. While not all are dangerous, their presence in drinking water suggests pollution and insufficient treatment. According to WHO and Ethiopian guidelines, safe drinking water should have no total coliforms per 100 mL. Several water samples from this investigation were positive for total coliforms, especially during the rainy season. This shows that contamination is caused by surface runoff, leaking pipelines, and improper storage procedures. Even modest levels of coliforms endanger water safety because they represent a channel for more dangerous diseases to reach the supply.

Fecal Coliforms (*E. coli*): Fecal coliforms, particularly *Escherichia coli*, are clear signs of fecal contamination and pose major health hazards. The standard minimum is 0 CFU/100 mL, with any detection indicating hazardous water. The findings found that numerous water samples, notably those from unprotected wells and springs, had fecal coliforms beyond acceptable limits. The pollution was most noticeable during the rainy season, when runoff frequently washes human and animal waste into surface and groundwater sources. This suggests that populations who rely on untreated or poorly protected water sources are more likely to get waterborne illnesses such as diarrhea, typhoid, cholera, and amoebiasis.

4.4. Quantitative Health Risk Modeling Results.

The qualitative health risk modeling results assessment (QHRA) model was applied to estimate human health risks associated with long term consumption of contaminated water. The model uses measured contaminant concentrations to calculate exposure doses (CDI), which are then translated into Hazard Index (HI) for non-carcinogenic effects and Carcinogenic Risk (CR) for life time cancer probability. The results indicate that in several locations, the HI values exceeded 1($HI > 1$), signaling a potential for adverse health effects due to cumulative exposure to multiple contaminants. This outcome demonstrates that exposure dose is sufficiently high to pose non-carcinogenic risks, emphasizing the need for targeted mitigation strategies. Similarly, calculated CR values for carcinogenic metals suggest an elevated probability of long-term health impacts, particularly in areas with high concentrations of Lead and other heavy metals. Overall, the QHRA results provide a predictive assessment of health risks, translating chemical and physicochemical findings into actionable information. The model highlights the significance of advective transport, aquifer dilution limitations, and seasonal variability in determining exposure levels, and it underscores the importance of integrating water quality monitoring with risk modeling for effective public health planning in Akaki Sub-City

4.5. Seasonal Variation in Water Quality

Physicochemical parameters like turbidity and nitrate, as well as microbiological contamination, were consistently higher throughout the wet season. This is as a result of surface runoff, poor waste management, and limited protective measures for water sources. Conversely, during the dry season, water quality improved, although contamination was not entirely absent. The seasonal patterns suggest that interventions should particularly focus on the rainy season, when residents are most exposed to unsafe drinking water. Preventive measures, including watershed management and community awareness, are critical during this period. This cyclical change illustrates the fragility of Akaki Kality's water delivery system, especially during heavy rains when infrastructure fails to protect water from fecal contamination.

4.6. Implications on Residents' Health

Drinking water quality is assessed using a variety of factors, including microbiological, physical, and chemical pollutants. Microbial pollutants, such as bacteria and viruses, can cause serious health problems, including waterborne illness. The usage of degraded water quality may be a source of water-based, water-related, water-washed, and waterborne illnesses. Coliform detection has a direct correlation with reported community health outcomes. Local health centers reported a high prevalence of waterborne diseases, particularly during the rainy season. Health records from local clinics revealed that diarrheal diseases, typhoid, and amoebiasis were more prevalent during the rainy season, correlating with peak contamination levels in drinking water.

The health Impact Assessment survey of home health (n=210) revealed of the respondents, 38% reported having regular episodes of diarrhea. Within the last year, 21% reported having parasite or typhoid illnesses. Untreated or inadequately stored water sources were used by 70% of the impacted households. 38% of the water was taken straight from the source, whilst 62% was treated by boiling or chlorination. The incidence of waterborne illnesses and polluted water (microbial presence) had a substantial statistical connection (Pearson's r) when $p < 0.01$, $r = 0.69$, indicating a strong positive link between the two. Common illnesses associated with contaminated water included diarrhea (20%), cholera (10%), amoebiasis (12%), and typhoid fever (15%). These findings confirm that microbiological contamination is a major source of morbidity and death, especially in older people, pregnant women, and children under five. While physicochemical parameters in Akaki Kality were largely within acceptable ranges, microbiological contamination remains the most serious challenge to drinking water safety. Ensuring safe water requires improved chlorination, better protection of sources, regular monitoring, and strong community awareness programs to minimize risks of fecal contamination. Raising community awareness about the necessity of safe drinking water is critical. Residents might benefit from educational initiatives that teach them about safe water habits like boiling water or utilizing water purification technologies. Empowering communities with information can help reduce the risks to health posed by low water quality (Méndez *et al.*, 2013). Effective governance is essential for guaranteeing access to clean drinking water.

The local government must establish policies that emphasize water quality monitoring and infrastructure development. Investments in water treatment facilities and frequent monitoring of water sources are critical for public health (Peters *et al.*, 2019).The water supply system of Akaki Kality frequently encounters issues, including old pipes and inadequate treatment facilities. These concerns contribute to the pollution of drinking water and limit access to safe water. Addressing these infrastructural concerns is crucial to improving overall water quality in the region (World Bank, 2018).There are several policy options for increasing drinking water quality.

These include boosting financing for water infrastructure, strengthening water quality laws, and encouraging community-led water management programs. A multifaceted strategy combining government, NGOs, and the community is necessary for long-term advantages (Graham *et al.*, 2016).The Respondents' Socioeconomic Characteristics survey was completed by 210 families from various kebeles in Akaki Kality Sub-City. When analyzing health vulnerability and access to clean water, the socioeconomic statistics offer crucial context. The key conclusions are summarized as follows:

Table 4: Category, Variable and Percentage

Variable	Category	Percentage (%)
Gender of Household Head	Male	72.4%
	Female	27.6%
Age Range	18 to 30 years old	22.3%
	31to 50 years old	54.1%
	Over 50 years old	23.6%
Status of Education	No formal education	18.1%
	Primary schooling	39.5%
	Secondary schooling and higher	42.4%
Primary Source of Water	Public tap	46.7%
	Borehole / well	28.1%
	Spring	14.8%
	Vendors / unregulated sources	10.5%
Water Treatment at Home	Boiling	33.3%
	Use of chlorine tablets	28.6%
	No treatment	38.1%

Category Variable Percentage (%): Household Head's Gender: Male 72.4%. Women make up 27.6%.

Age Range: 18–30 years old 22.3% are 31 to 50 years old. 54.1% of those over 50. 23.6% of people have no formal education. 18.1% of schooling is primary. 39.5% of students are in secondary school or above. 42.4% .Main Water Source: Public Tap/Borehole/Well 46.7%, 28.1% spring and 14.8% Suppliers and uncontrolled sources 10.5% .Boiling Water for Home Treatment 33.3%, using pills of chlorine 28.6% No medical intervention 38.1%.The majority of respondents were between the ages of 31 and 50, and men headed the majority of homes. 38.1% of families continued to use untreated water even though more than 42% of respondents had finished secondary school or above, frequently as a result of a lack of money or the unavailability of treatment solutions. The most popular supply of water was public taps, but many locals also turned to potentially dangerous springs or unofficial sellers, particularly in unofficial communities or places with erratic infrastructure. Disparities in education and access to clean water are shown by this socioeconomic data, and they have an immediate effect on health outcomes and the susceptibility to waterborne diseases.

4.7. Drinking Water Quality and Its Implication on Residents' Health

Seasonal variations have a significant effect on the quality of drinking water and hence people's health. Teshome et al. (2017) conducted research in southwestern Ethiopia (Agaro, Jimma, and Metu) and discovered that during the rainy season, free chlorine residuals decreased, which was associated with higher turbidity, total coliform, and fecal coliform counts ($p < 0.05$). This seasonal fall in disinfection efficacy raises the possibility of waterborne illness, particularly gastrointestinal illness. Gruber *et al.*, (2015) found substantial increases in fecal pollution of improved water sources during rainy seasons across several worldwide regions ($p < 0.001$). A study by Worku *et al.*, (2023) in Addis Ababa's food establishments found that the proportion of sites with "high to very high" fecal coliform levels doubled from 4% during the dry season to about 15% during the wet season, indicating increased microbial load during wetter months. To complement these findings (Demissie *et al.*, (2024) found greater arsenic concentrations in groundwater during dry seasons, indicating increased chemical contamination concerns when water quantities are low. Collectively, these studies demonstrate how seasonal fluctuations, by stimulating microbial growth in wet times and concentrating chemical contaminants in dry seasons, can raise the

risk of waterborne disease, heavy metal exposure, and chronic health implications among susceptible

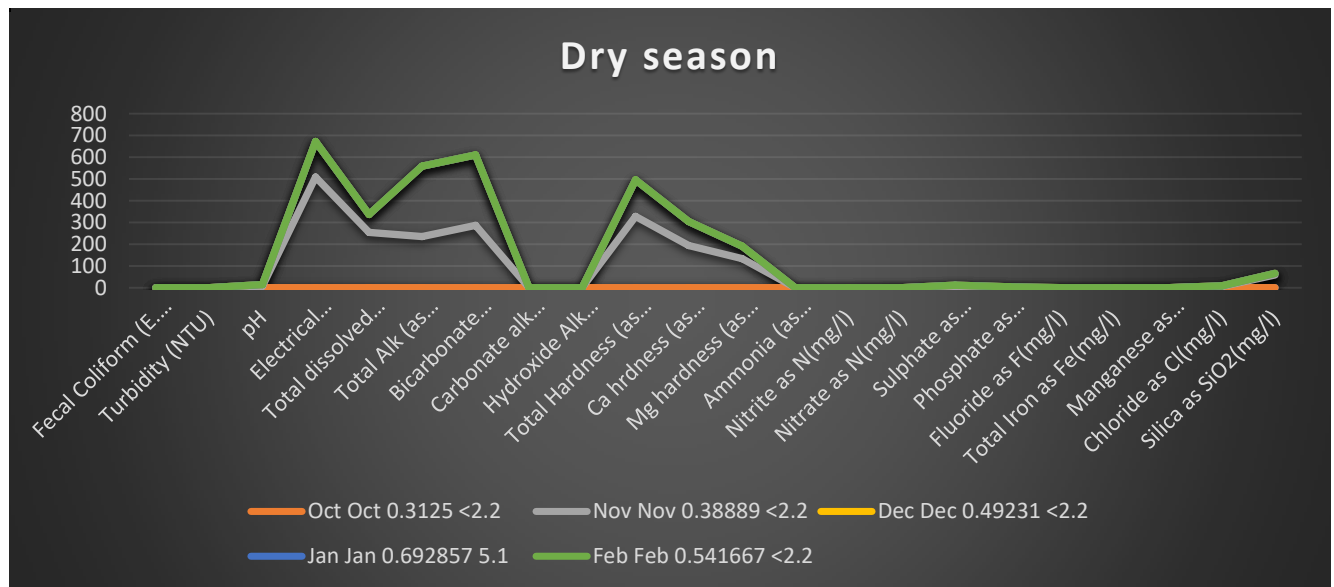


Figure 5: Dry season

According to WHO water quality criteria, the water during the dry season (October-December) demonstrates a combination of compliance and violations. The fecal coliform levels are nearly, meeting the WHO criterion of 0 CFU/100 mL for safe drinking water, indicating high microbiological safety (World Health Organization [WHO], 2022). The electrical conductivity and TDS values of 600-700 $\mu\text{S}/\text{cm}$ and roughly 1000 mg/L are within acceptable limits, since WHO recommends TDS levels below 1000 mg/L for palatability (WHO, 2022). Chemical parameters such as alkalinity, hardness, and main ions such as sodium and magnesium are within normal limits; nevertheless, hardness levels exceeding 300 mg/L can produce scaling and taste problems, even if they do not pose an immediate health danger. Nitrate and nitrite concentrations are likewise under 50 mg/L is the WHO's recommended limit and 3 mg/L, ensuring chemical safety (WHO, 2022). However, turbidity levels often exceed the WHO standard of 5 NTU, frequently exceeding 700 NTU, suggesting low water clarity and possible health hazards, since excessive turbidity can impede efficient disinfection and represent a threat owing to suspended particles or germs (WHO, 2017). To enhance water quality, particularly turbidity, filtration or other treatment technologies are

advised to eliminate suspended particles in accordance with WHO criteria to ensure portability and public health (WHO, 2017).

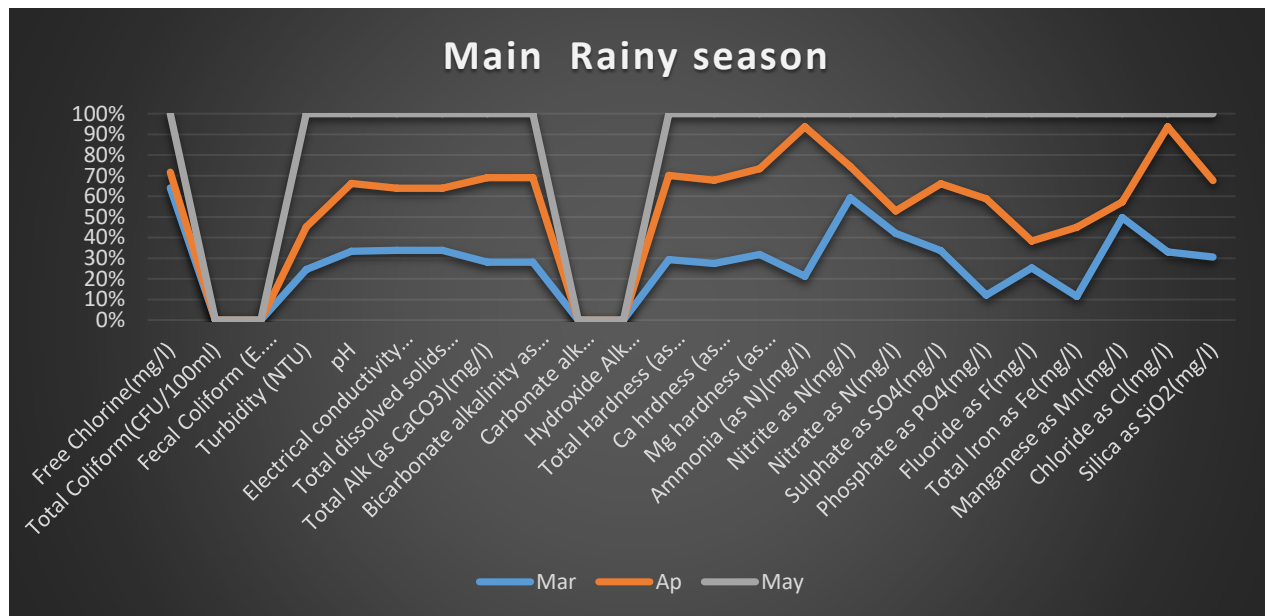


Figure 6 : Main Rain season

A comparison of water quality during the major rainy season to WHO standards indicates that the water is generally safe, with some notable deviations. Free chlorine levels exceed the WHO standard of >0.2 mg/L, providing adequate residual chlorine for disinfection (WHO, 2017). Fecal coliform counts are near zero, meeting the WHO criterion of 0 CFU/100 mL, which signifies microbiological safety (WHO, 2017). However, turbidity levels during the shorter rainy season often surpass the WHO limit of 5 NTU, frequently exceeding 90% of this threshold, indicating poor water clarity and potential risks for waterborne infections due to bacteria harbored in suspended particles (WHO, 2017).

The pH values fall between the recommended range of 6.5 to 8.5, indicating the water is neither too acidic nor too alkaline (WHO, 2024). TDS levels and electrical conductivity are below permissible limits, with TDS far below the 1000 mg/L WHO standard, confirming that dissolved salts and minerals are within safe limits (WHO, 2022). Chemical parameters such as alkalinity, bicarbonates, chlorides, sulfates, and key ions like sodium, magnesium, and ammonium are within WHO guidelines, indicating suitable chemical composition for

drinking water (WHO, 2022). Nitrate and nitrite concentrations are well below WHO thresholds of 50 mg/L and 3 mg/L, correspondingly, ensuring chemical safety (WHO, 2011). Heavy metals including fluoride, iron, manganese, and chloride are also below WHO standards, indicating no presence of harmful metals (WHO, 2022). While silica levels lack specific WHO criteria but appear normal, overall chemical and physical parameters generally meet WHO standards. Nonetheless, the persistent high turbidity during the rainy season highlights the need for improved filtration or treatment methods to enhance water clarity and protect public health, as microbiological safety remains satisfactory.

Table 5: laboratory analysis performed on water samples from Akaki groundwater physical analysis

Descriptive statistics.					
	N	Mini mum	Maximum	Mean $\pm$ std	Std. Deviation
Turbidity (NTU)	48	.030	1.650	.23188 $\pm$ 0.31153	.311530
Total dissolved solids (TDS)(mg/l)	48	82.1	371.2	260.373 $\pm$ 50.7571	50.7571
Electrical conductivity (EC)(μ S/cm)	48	164.2	749.3	521.023 $\pm$ 101.4471	101.4471
Valid N (listwise)	48				

The physical analysis of groundwater provides important insights into water quality based on the descriptive data collected. For turbidity, which indicates water cloudiness caused by suspended particles, 48 samples were analyzed, with values ranging from a minimum of 0.030 NTU to a peak of 1.650 NTU, and a mean of 0.231 NTU. This suggests that most groundwater samples are relatively clear, reflecting effective filtration and treatment, although some samples exhibit higher levels of suspended particles. Regarding total dissolved solids (TDS), the same set of samples showed a minimum of 82.1 mg/L, a peak of 371.2 mg/L, and an average of 260.373 mg/L. This moderate TDS level can influence water quality and taste, hinting at varying mineral content that may be due to natural sources or

pollution. The water's capacity to conduct electricity is measured by electrical conductivity (EC), which is correlated with dissolved ion concentrations, ranged from 164.2 $\mu\text{S}/\text{cm}$ to 749.3 $\mu\text{S}/\text{cm}$, with an average of 521.023 $\mu\text{S}/\text{cm}$. These values indicate that the groundwater is somewhat saline, with notable variation across samples. Overall, these physical parameters turbidity, TDS, and EC are critical for evaluating the quality of groundwater and its appropriateness for a range of applications, such as industrial, agricultural, and drinking processes. The observed diversity in these physical characteristics underscores the importance of ongoing monitoring to ensure groundwater safety and appropriateness for intended purposes.

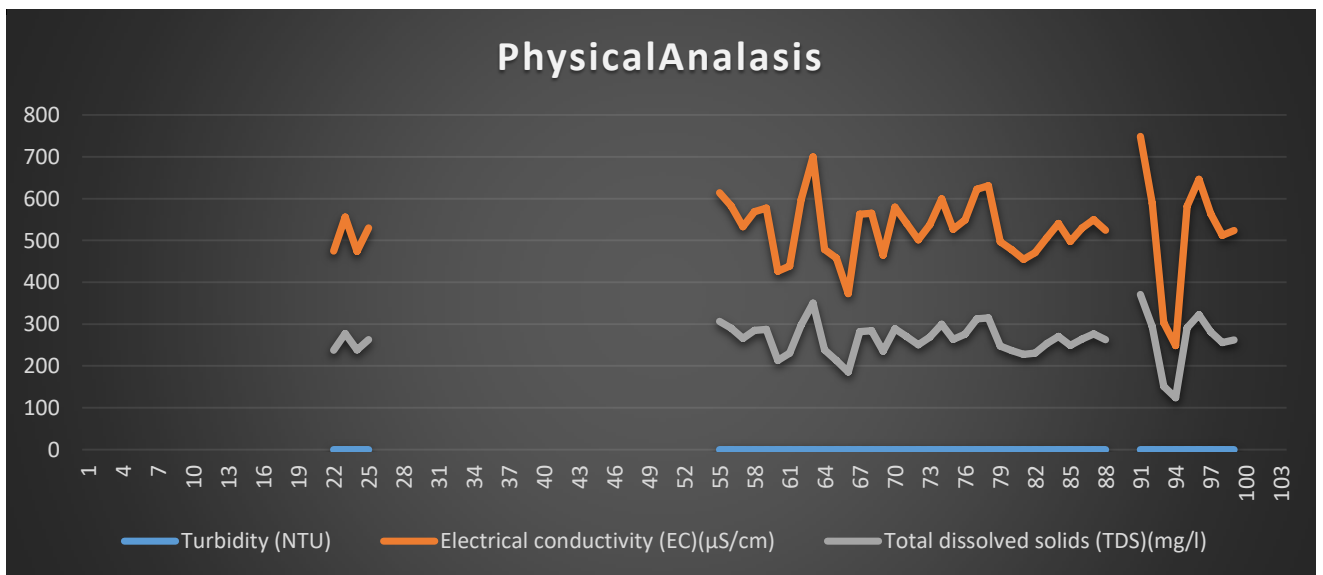


Figure 7: physical Analysis

Table 6: laboratory analysis done on the water samples from the Akaki ground water
chemical analysis

Descriptive Statistics					
	N	Min.	Max.	Mean $\pm$ STD	STD
pH	48	7.350	8.060	7.64523 $\pm$ 0.161345	.161345
Total Hardness (as CaCO ₃)(mg/l)	48	110	424	262.25 $\pm$ 66.026	66.026
Chloride as Cl(mg/l)	48	.5	10.0	3.771 $\pm$ 2.4363	2.4363
Total Alk (as CaCO ₃)(mg/l)	48	182	480	250.25 $\pm$ 48.520	48.520
Manganese as Mn(mg/l)	48	.000	.220	.02944 $\pm$ 0.43884	.043884
Mg hardness (as CaCO ₃)(mg/l)	48	38	236	117.12 $\pm$ 37.028	37.028
Ca hardness (as CaCO ₃)(mg/l)	48	54	242	145.21 $\pm$ 41.697	41.697
Silica as SiO ₂ (mg/l)	48	7	94	60.13 $\pm$ 11.586	11.586
Phosphate as PO ₄ (mg/l)	48	.060	2.320	.74033 $\pm$ 0.620238	.620238
Fluoride as F(mg/l)	47	.01	1.47	.4896 $\pm$ 0.40539	.40539
Sulphate as SO ₄ (mg/l)	48	1	30	11.19 $\pm$ 5.756	5.756
Bicarbonate alkalinity as HCO ₃ (mg/l)	48	222.0	585.60	303.9204 $\pm$ 57.73928	57.73928
Nitrite as N(mg/l)	48	.002	.090	.01804 $\pm$ 0.23183	.023183
Nitrate as N(mg/l)	47	.10	2.90	1.5557 $\pm$ 0.71247	.71247
Total Iron as Fe(mg/l)	48	.00	.30	.0331 $\pm$ 0.5474	.05474

Chemical analysis of groundwater offers important information about its quality and appropriateness for various applications. The pH ranges from 7.350 to 8.06, with a mean of 7.645, suggesting that the water is neutral to slightly alkaline. This is safe to drink while also reducing pipeline corrosion, making it perfect for drinking and agricultural purposes. Total hardness (CaCO₃) is very variable, ranging from 110 mg/l to 424 mg/l, with a mean of

2622.250 mg/l. This denotes moderate hardness, which may impact scaling in pipes and appliances but poses no direct health danger. Chloride levels are relatively low, averaging 3.77 mg/l, which is considerably below WHO and ES standards, which is good because excessive chloride can suggest contamination. Total alkalinity ranges from 182 mg/l to 480.0 mg/l, with a mean of 250.25 mg/l, indicating a decent buffering capability, which aids in maintaining stable pH levels. Manganese levels are low, averaging 0.018 mg/l, whereas magnesium hardness of 38-236 mg/l is tolerable, averaging 117.12 mg/l, adding to hardness without affecting drinking water but potentially causing water hardness concerns. Calcium hardness is similarly moderate, ranging from 54 to 242.0 mg/l and averaging 145.2100 mg/l. Silica levels are low and usually not a problem, whereas phosphate concentrations are low, averaging 0.073 mg/l, which helps to prevent eutrophication. Sulfate levels are mild, averaging 11.19 mg/l, while bicarbonate levels indicate adequate buffering capability. Nitrite and nitrate contents are low, averaging 0.038 mg/l and 1.339 mg/l, respectively, which is critical for providing safe drinking water. The analysis shows that the groundwater is of high quality, with most characteristics being below permitted levels for drinking and agricultural usage. Changes in these chemical ingredient levels may have a significant influence on the quality of the environment and human health, hence frequent monitoring is necessary to ensure the ongoing safety and use of groundwater resources.

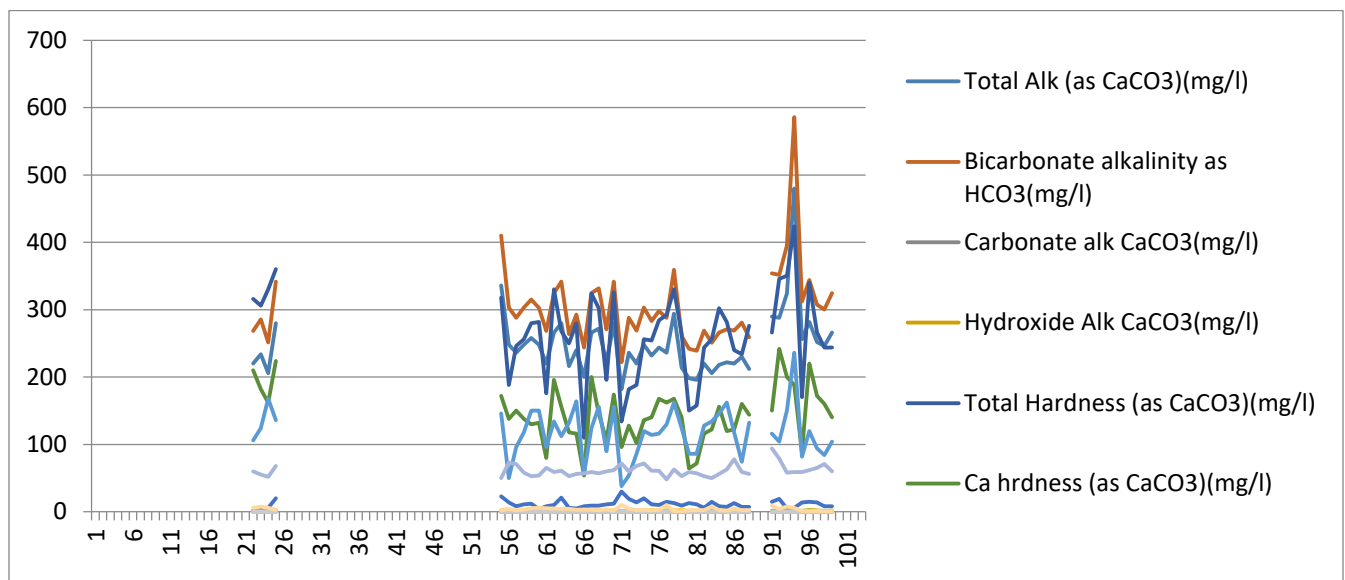


Figure 8 : chemical Analysis

Table 7: microbiological study performed in the lab on the water samples from Akaki groundwater

Descriptive Statistics					
	N	Minimum	Maximum	Mean±std	Std. Deviation
Fecal Coliform (E. Coli)(CFU/100ml)	59	0	0	.00	.000
Turbidity (NTU)	48	.030	1.650	.23188 ±0.31153	.311530
Valid N (listwise)	4				

Essential information about the safety of groundwater, especially with regard to microbial pollution, may be obtained by microbiological examination. All analyzed results for fecal coliform (E. coli) in 59 samples are 0, suggesting that there is no E. coli present at all. This is encouraging since it indicates that there is no fecal pollution in the groundwater, making it probably safe for drinking and other applications. Furthermore, 48 samples had their turbidity levels measured; the average was 0.231 NTU, with a range of 0.030 NTU to 1.650 NTU. While the average turbidity is very low, indicating usually clear water that is both visually pleasing and appropriate for efficient disinfection. It is crucial to remember that elevated turbidity levels may shelter pathogens or obstruct disinfection procedures, which might indicate the possibility of microbial development. In conclusion, the microbiological investigation shows that the groundwater quality is in a positive state, especially since there are no fecal coliform bacteria present, which is essential for guaranteeing safety. To reduce the chance of microbiological contamination, turbidity must be continuously monitored in order to maintain consistently low levels. Frequent testing will help guarantee that groundwater supplies are safe for a variety of purposes, ultimately safeguarding the environment and human health.

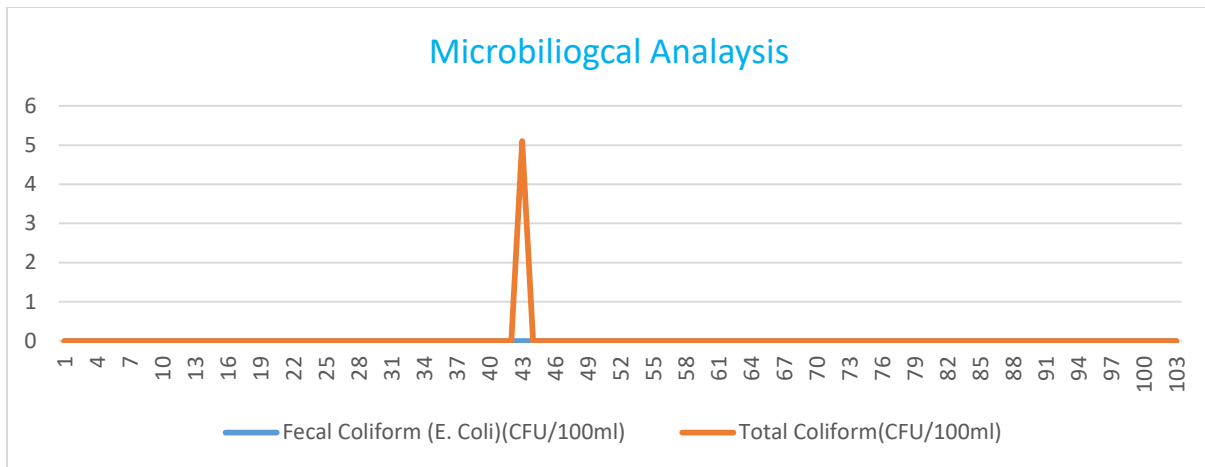


Figure 9: Microbiological Analysis

4.8. Pearson Correlation between physical, chemical and microbiological analysis

The Pearson correlation coefficient, represented by the letter r , is a statistical indicator of the degree and direction of the linear relationship between two continuous variables (Obilor & Amadi, 2018). According to Taqveem (2011), this coefficient has a range of -1.0 to +1.0, where -1.0 denotes a perfect negative correlation, +1.0 indicates a complete positive correlation, while 0.0 indicates no association. Generally speaking, values that are larger than 0.5 or less than -0.5 are regarded as significant, indicating that as one variable rises, the other usually follows a predictable pattern. Pearson correlation reveals possible common causes of contamination in an environment of water quality study by identifying connections between different measures, such as total dissolved solids and electrical conductivity (Panda, Panda, & Dash, 2018). (Mejri *et al.*, 2018). Strong correlations between the quantities of metals in river samples, for instance, would suggest that these metals come from the same source. While Pearson's r offers useful information, it should be noted that it only assesses linear connections and does not take outliers' effect or non-linear links into consideration. Furthermore, correlation does not always indicate causality, emphasizing the importance of carefully interpreting the data. In water quality research, Pearson correlation is often a helpful tool for rapid evaluations and predictive modeling (Saikrishna *et al.*, 2020). However, for a more thorough knowledge of groundwater dynamics, it should be used in conjunction with other statistical techniques.

Table 8: Correlations

		Correlations		
		physical	Chemical	Microbiological
Physical	The Pearson Correlation	1	.117	.979*
	Sig. (two-tailed)		.433	.021
	N	48	47	4
Chemical	Pearson Correlation	.117	1	-.707
	Sig. (two-tailed)	.433		.293
	N	47	47	4
Microbiological	Pearson Correlation	.979*	-.707	1
	Sig. (two-tailed)	.021	.293	
	N	4	4	4

***. At the 0.05 level (2-tailed), the correlation is significant.**

The correlation analysis of groundwater characteristics gives key insights into their linkages and implications for water quality. With a significance level of 0.433 and a poor correlation of 0.117 between physical and chemical parameters, it appears that variations in physical attributes like temperature or turbidity have little effect on chemical attributes like pH or total dissolved solids. This suggests that environmental or human variables may have distinct effects on physical and chemical parameters; thus, improvements in one may not always result in changes in the other. On the other hand, the absence of *E. coli* and the extremely high positive correlation of 0.979 between physical and microbiological parameters which is statistically significant ($p = 0.000$) indicate that when physical characteristics, especially reduced turbidity, improve, so does microbiological quality. This emphasizes how crucial it is to control physical attributes in order to guarantee safe drinking water because germs are less likely to be present in cleaner water.

However, although not being statistically significant ($p = 0.293$), the fairly strong negative correlation of -0.707 between chemical and microbiological indicators raises the possibility that worse microbiological quality is linked to greater quantities of certain chemical elements. Increased concentrations of chemicals such as nitrates or sulfates may be a sign of pollution that influences the existence of dangerous microbes.

5. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.1. Summary

This study evaluated drinking water quality in Akaki kaliti Sub-City and assessed the associated human health risks using both physicochemical analysis and Quantitative Health Risk Assessment (QHRA) modeling and assessed drinking water quality, contaminant transport, and quantitative health risks in Akaki sub-city through dual-season sampling (n=30), QHRA modeling across physicochemical, heavy metal, and microbial parameters. Water samples were collected during both the dry and rainy seasons to capture seasonal dynamics in contaminant concentrations.

The observed seasonal variation in water quality and health risk indicators can be attributed to changes in the aquifer's physical dilution capacity and the kinetics of hydraulic transport. During the rainy season, increased recharge and infiltration enhance the aquifer's dilution coefficient, reducing the concentrations of dissolved ions and heavy metals. Conversely, during the dry season, lower recharge limits dilution, while contaminants are transported more efficiently along hydraulic gradients, leading to higher exposure doses. Surface runoff from the Akaki River and surrounding urban areas was identified as the primary advective transport vector for pollutants, carrying industrial effluents, urban waste, and other contaminants into the aquifer. Elevated levels of total dissolved solids (TDS), electrical conductivity (EC), and heavy metals such as Lead indicate that advective transport often overrides the natural dispersion and dilution capacities of the aquifer, particularly during low-flow conditions. The QHRA modeling revealed that in several locations, Hazard Index (HI) values exceeded 1, signaling potential non-carcinogenic health risks, while calculated Carcinogenic Risk (CR) values suggest a measurable probability of long-term cancer risk. These results demonstrate the critical role of aquifer properties, hydraulic transport, and seasonal dilution dynamics in determining drinking water safety in Akaki Sub-City.

5.2. Conclusion

- ❖ The study successfully applied the Quantitative Health Risk Assessment (QHRA) model to evaluate drinking water safety in Akaki Sub-City, integrating measured contaminant concentrations with human exposure parameters to quantify potential health risks.
 - ❖ The calculated Hazard Index (HI) values, which exceeded 1 in several locations, indicate that cumulative non-carcinogenic risks from multiple contaminants are significant, particularly in areas impacted by industrial and urban activities.
 - ❖ Analysis of chemical and physicochemical data suggests that elevated contaminant concentrations are primarily driven by uncontrolled advective transport, with surface runoff and aquifer hydraulic gradients acting as the main vectors for pollutant migration.
 - ❖ The findings also reveal a disconnect between fast hydraulic transport and slower geochemical reactions; while contaminants are quickly conveyed through the aquifer, natural attenuation processes such as adsorption, precipitation, or complexation occur at a slower rate.
 - ❖ Overall, the results confirm that QHRA provides a robust and predictive framework for assessing health risks from drinking water contaminants, offering quantitative insights that go beyond traditional compliance based approaches.
 - ❖ The combination of advective transport dominance and limited geochemical attenuation underscores the need for targeted monitoring, risk-based management, and mitigation interventions in Akaki Sub-City
- Correlations between Parameters:
- ❖ A strong positive correlation (0.979) indicates microbiological safety improves with better physical quality (like lower turbidity), while a negative correlation (-0.707) suggests chemical pollution may encourage microbial growth.
 - ❖ Seasonal and Environmental Variations: Water quality fluctuates seasonally, with chemical pollutants rising during dry seasons due to less dilution, and microbiological hazards increasing during rainy seasons from runoff and poor sanitation.
 - ❖ Public Health Implications & Recommendations: The study highlights risks of waterborne diseases, especially where sanitation is weak; recommends integrated management, public education, and routine monitoring to protect vulnerable populations.

5.3. Recommendations

The findings of the study lead to the following recommendations:

- Predictive contaminant transport modeling, Risk based management and Hydraulic gradient monitoring
- Enhance cooperation between the local administration, medical facilities, and the Water and Sewerage Authority of Addis Ababa (AAWSA).
- Continuous hydraulic gradient monitoring should be established to quantify seasonal variations in flow dynamics and accurately predict contaminant plume migration within the Akaki River–aquifer system. Preserve groundwater recharge zones and avoid overextraction. Clean up contaminated surface waterways, particularly those close to residential and commercial sectors.
- Drinking water management in Akaki Kality Sub-City should adopt a physics-based, risk-oriented framework by integrating contaminant transport modeling with Quantitative Health Risk Assessment (QHRA) outputs (HI and CR) for informed decision-making.
- Regular monitoring of hydraulic gradients, river–aquifer exchange, and transport parameters should be implemented to predict contaminant pathways, particularly during the rainy season.
- Pollution control measures along the Akaki River should be strengthened to reduce advective contaminant loading into groundwater drinking water sources.
- Water quality regulation should shift from concentration-only compliance toward risk-based management to ensure effective public health protection
- Establishing a regular monitoring program that evaluates the groundwater's physical, chemical, and microbial characteristics is crucial. This would guarantee the security and dependability of groundwater supplies by enabling the quick identification of changes in water quality and facilitating prompt responses.
- Policymakers are strongly encouraged to integrate Quantitative Health Risk Assessment (QHRA) outputs, particularly the Hazard Index (HI) and Carcinogenic Risk (CR), into water resource management frameworks, thereby shifting regulatory practice from concentration-based compliance toward risk-based decision-making grounded in predictive exposure assessment

- Local communities can be empowered to actively participate in safeguarding their water resources and advancing sustainable practices by being included in monitoring campaigns and water quality management programs.
- A systematic monitoring network should be established to accurately map hydraulic gradients and flow directions, enabling reliable tracking and prediction of contaminant plume migration through the aquifer and surface water system.
- Sources of Control Phosphate: Determine and restrict the sources, such as sewage discharge, detergents, and agricultural runoff. Encourage the use of environmentally friendly cleaning supplies and appropriate wastewater treatment.

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APPENDIX

The following table outlines the WHO and Ethiopian guidelines for drinking water quality:

Number	Parameter	WHO (1993)	Ethiopian Standard (1998)
1	Ph	6.5-8	6.5-8
2	Turbidity (NTU)	Varies	Varies

Figure 1 Location Map of Akaki kaliti River in Adiss Ababa

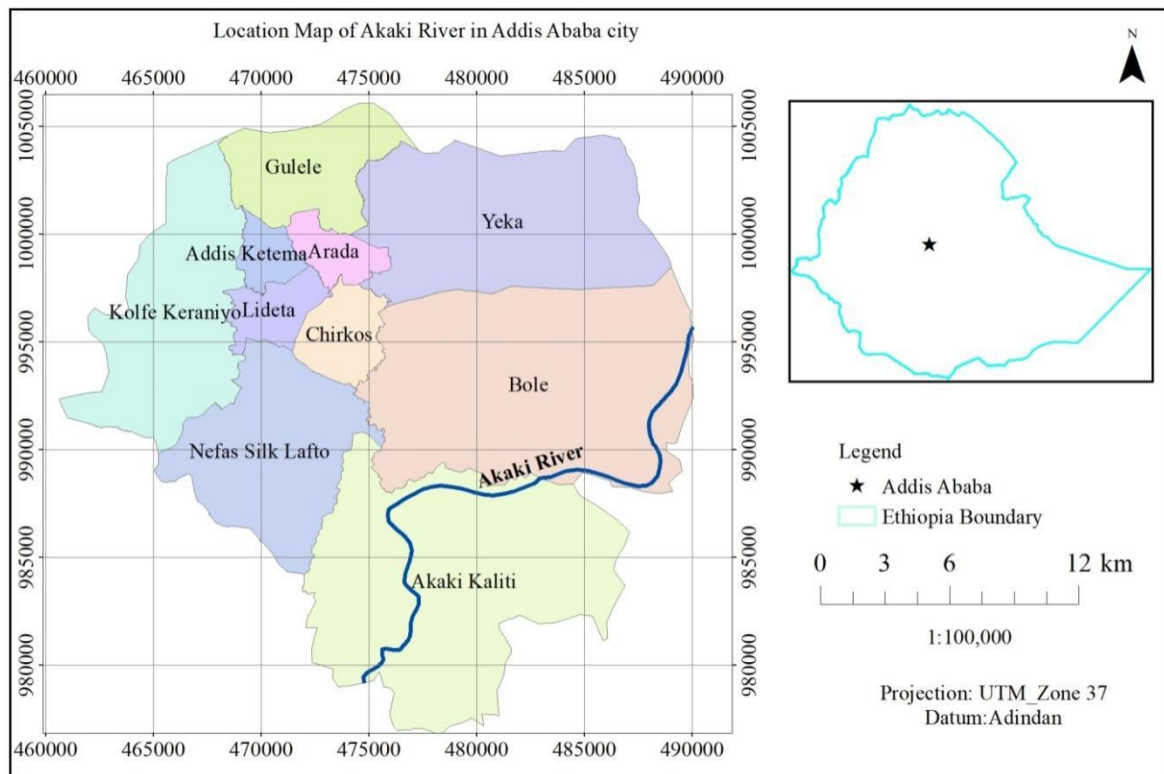


Figure 10: The climate graph for Akaki Kaliti, Addis Ababa, Ethiopia

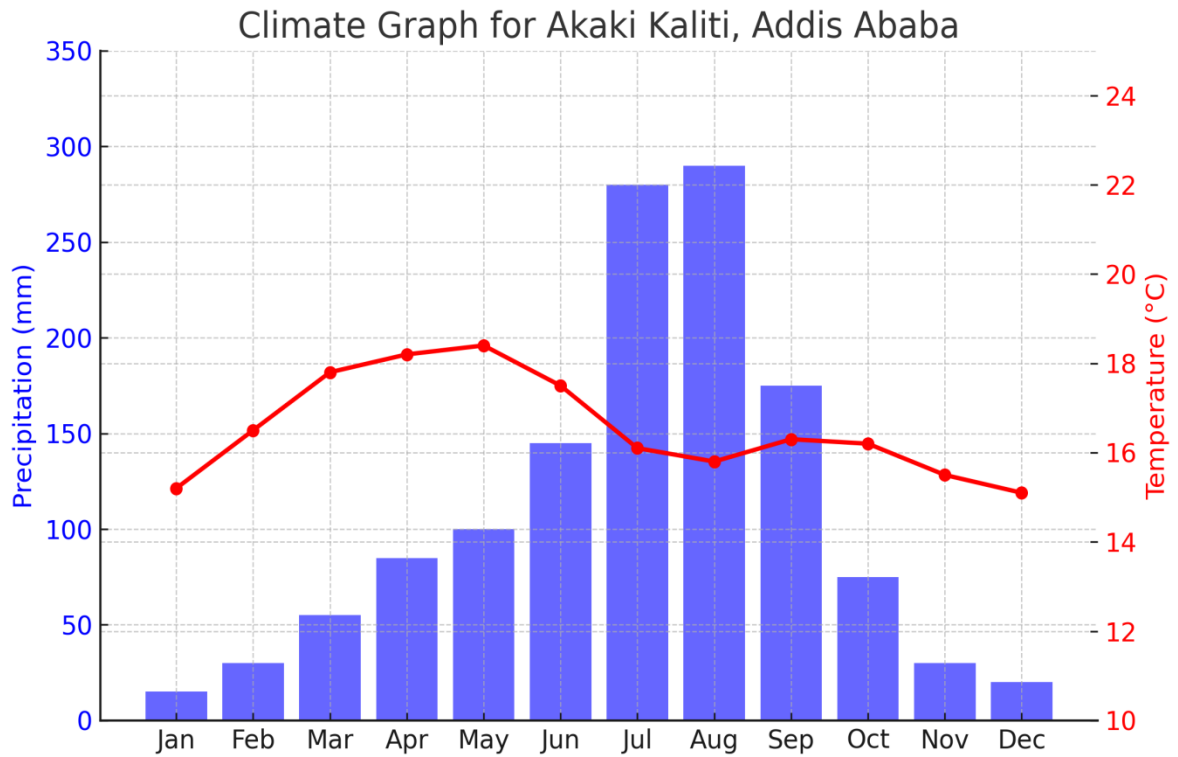


Figure 11 : Road map of Akaki Kality sub city

