# Schriftenreihe Umweltingenieurwesen

Agrar- und Umweltwissenschaftliche Fakultät

Band 117

Dissertation

*Semaria Moga Lencha*

# Estimating pollutant fluxes and their impact on Lake Hawassa in Ethiopia's Rift Valley basin based on combined monitoring and modelling

PROFESSUR **Wasserwirtschaft**

Universität Rostock Traditio et Innovatio

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ISBN 978-3-86009-550-8
https://doi.org/10.18453/rosdok_id00004446

**Schriftenreihe** Bd. 117 **Umweltingenieurwesen** ▪ Wasserwirtschaft

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Dissertation Semaria Moga Lencha
Universität Rostock
Agrar- und Umweltwissenschaftliche Fakultät
Rostock, 2023

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ISBN 978-3-86009-550-8
https://doi.org/10.18453/rosdok_id00004446

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# Foreword

The chemical and environmental quality of fresh water systems is worldwide in a worrisome condition. While in the EU with the water framework directive a strategic approach has been initiated aiming at a good ecological status of all surface water bodies, the situation in other regions of the world is much worse. Namely in developing and emerging economies, a sustainable water management is missing, leading to uncontrolled pollution of rivers and lakes. Due to limited financial resources and deficient institutional capacities, a comprehensive systems analysis and derivation of strategic mitigation measures is rarely performed.

A key problem, even in developed economies, is the limited environmental data situation. To understand a complex system, monitoring data always need to be explorated/expanded by meaningful modelling, addressing the relevant drivers, states and processes. Depending on data situation, expert knowledge and economic resources, the appropriate setup of data acquisition, exploration and modeling is always case specific. Still, for comparable situation, a methodological transfer can be advisable. The thesis of Mr. Lencha is addressing this topic for the case study of Lake Hawassa, which stands characteristically for multi-source polluted surface water bodies in Ethiopia and probably comparable conditions in neighbouring countries like Uganda, Tansania, Kenia and beyond. He developed a concept, combining targeted monitoring, use oriented quality assessment and modelling and pollutant fluxes to identify the current state and the relevant drivers in order to derive/prioritise a set of pollution mitigation measures. Although, comparable approaches have been proposed elsewhere, this thesis provides a so far rare combination of a rather mesoscalic approach with foci on known high impact point sources and pollution by urban stormwater runoff. The chosen method is applicable and adaptable to other multi-source pollution situations, namely in data scarce conditions.

However, system analysis is only the first step in improving water quality. With this in mind, I hope that this work will not only inspire other scientists, but also lead to the development and implementation of concrete remedial actions.

Prof. Dr.-Ing. habil. Jens Tränckner

# Estimating pollutant fluxes and their impact on Lake Hawassa in Ethiopia's Rift Valley basin based on combined monitoring and modelling

Commulative Dissertation

For obtaining the academic degree of
Doctor of Engineering (Dr.-Ing.)

At the Faculty of Agriculture and Environmental Sciences of the University of Rostock

Submitted by

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Matriculation number: 219204982

Rostock, Germany
2023

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## Declaration of independency

I hereby declare that this dissertation was prepared and submitted independently by me without any assistance other than those cited and acknowledged in the dissertation.

Semaria Moga

Rostock, 06. 04. 2023

## Dedication

I devote the dissertation to my wife Fikrab Abreham, for her philanthropic and boundless motivation and support for its successful completion

## Acknowldgements

First, I thank God for giving me the opportunity, the knowledge, the strength and the courage to complete my dissertation. I, therefore, would like to say to the King of ages, immortal, invisible and omniscient God, be honor and glory forever and ever. Amen.

**Dear Prof. Jens Tränckner,**
I would like to express my deepest gratitude and respect for your dedicated guidance, support and timely advice to complete my thesis successfully. It would have been incredible to achieve my goal without your critical comments, reviews and consistent guidance. Your support in my research has been great.

**Dear Dr. Mihret Dananto Ulsido,**
I am indebted to your valuable comments, critical review and editing of the manuscripts and thesis.

I am grateful to the German Academic Exchange Service (DAAD) and the Ethiopian government for supporting this research through the Engineering Capacity Building Program (ECBP), which offered a three-year fellowship.

I would like also to extend my gratitude to all members of the chair of water management, the Faculty of Agriculture and Environmental Sciences of the University of Rostock particularly Dr. Ing. Christine Stapel, Axel Melzer and Silke Lorenz.
I will never forget Dr.-Ing. Zelalem Abera, Mr. Teshale Tadesse, Mr. Tesfalem Abraham and Mr. Rediet Girma’s contribution for the realization of my PhD study. All my friends in Hawassa and Rostock, you are simply the best.
I want to express my sincere gratitude for my parents' unfailing support and contribution in every area of my life.
Finally, to my wife, Fikrab Abreham, words cannot express your encouragement and support for me. You are my partner in life and I am very grateful that you were able to earn this degree with me. I would like to thank my daughter Ephrata for understanding if I was not there enough for her.

## Summary

Degradation of water quality due to anthropogenic activities is a rapidly growing threat to water security and public health in developing countries. Deterioration of water quality directly leads to environmental, social and economic problems. The majority of the degradation of surface water quality is caused by point, dispersed or diffuse emissions, with discharge of untreated or partly treated wastewater from residential, industrial, healthcare facilities and runoff from urban and agricultural activities. Also in the investigated surface system of the river Tikur-Wuha, ending in the Lake Hawassa, the coincidence of various emissions sources has lead to severe effects on water quality, aquatic life and water use.

Although there were few studies that have investigated the pollution status of LHWs by physical, chemical, bacteriological and metal concentration analyses, none of the studies has explicitly determined the contribution of single pollution source from the various land uses for different pollutants.

Thus, this thesis aims to conduct a thorough analysis of the spatial and temporal variations in water quality, dynamics and transport, estimation of trophic state and suitability for anthropogenic uses, determination of multi-sourced pollutants loads in the catchment and integration of watershed modeling to help in the resolution of complex environmental issues followed by identification of pollution mitigation strategies.

In the first part, water quality monitoring and assessment of the Lake Hawassa watershed (LHW) has been conducted by applying different water quality indices to categorize the suitability of the water quality of the LHW for anthropogenic uses and to identify the trophic status of Lake Hawassa. To evaluate the current state of the LHW, a sampling campaign of 19 monitoring sites and 21 physicochemical parameters was perfomrmed. The investigation was used to group the water quality of the LHW using the following water quality indices (WQI): a) Canadian council of ministries of the environment WQI (CCME WQI), b) Weighted arithmetic water quality indices (WA WQI), and c) Carlson’s trophic State Index (TSI). Based on the sampling location and the indices applied, the water quality is commonly categorized as unfit for drinking water puposes, aquatic life, and recreation, and good to unsuitable for irrigation. The findings of the study revealed that the WA WQI and the CCME WQI have come up with slightly differing results, with the WA WQI indicating that the upper streams of the rivers were excellent for irrigation purposes and Lake

Hawassa was good. However, the CCME WQI findings classified the rivers as good for irrigation but Lake Hawassa as being marginal. Point sources were impractical for all purposes. The mean TSI of Lake Hawassa showed that the lake was classified as eutrophic due to high phosphorous concentrations.

This study revealed that the monitored point sources in the city of Hawassa and its numerous industrial discharges are key polluters, requiring a fast and consequent set-up of an efficient wastewater treatment (due to missing centralized sewage systems preferably at the individual point sources), accompanied by a rigorous monitoring of the key emitters (e.g., industry, hospitals and hotels).

Therefore, a central water supply system that treats and provides water according to World Health organization (WHO) standards for the fringe inhabitants still using lake water is imperative to ensure safe drinking water. Besides, introducing riparian buffer zones of vegetation and grasses can support the direct pollution alleviation measures. Adaptation of on-site treatments like EcoSan may be viable to reduce the dispersed pollution coming from the population using latrines, to eliminate large-scale contamination of groundwater and contamination at various points in the sanitation chain. Furthermore, the integration of aeration technologies such as pumping atmospheric air into the lake's bottom using solar energy panels or diffusers, will improve the water quality of the lake. In parallel, environmental monitoring must be integrated with specific development goals in order to control the effectiveness of interventions.

In the second part, the characterization of water quality and identification of pollution source in the Lake Hawassa Watershed (LHW) was carried out in both the dry and wet seasons, where water and effluent samples were collected monthly for examination of selected physicochemical parameters at some preferred monitoring stations. This study used statistical methods to identify the potential sources of pollution and examined seasonal and spatial variabilities of the water quality in the LHW. Also, the effects of an anthropogenic intervention on the physicochemical aspects of water quality at the monitoring stations were examined using pollution index (PI) and multivariate statistical techniques (MVST) like the descriptive statistics, discriminant analysis (DA), spatial clustering using factor analysis (FA) and cluster analysis (CA). Before applying multivariate statistical analysis, the raw data was Z-standardized, outlier were corrected and normality was checked.

The study revealed that all the monitoring sites were spatially grouped into two statistically significant clusters i.e. moderately polluted (MP) and highly polluted (HP) by applying the pollution index, discriminant analysis and cluster analysis.

Accordingly, point sources (i.e. industries, hospitals, and hotels) were identified as as highly polluted (HP), while rivers and Lake Hawassa were classified as moderately polluted (MP). The contributing parameters that were extracted with the spatial variance based on discriminant analysis (DA) were electrical conductivity (EC), dissolved oxygen (DO), chemical oxygen demand (COD), total nitrogen (TN), total phosphorus (TP), sodium ion ($Na^+$), and potassium ion ($K^+$), to differentiate the pollution condition of the groups identified by CA.

According to the result of study, the possible sources of pollution for the LHW were qualitatively identified using principal component analysis (PCA). Accordingly, the various pollution sources that heavily affects the LHW include industrial discharges and diffused sources from agricultural land use and urban runoff in both dry and wet seasons.

Therefore, effective management is crucial to improve both point and non-point source pollution from residential, industrial, livestock and agricultural runoff to reduce the amount of pollutants entering the lake. In light of this, appropriate municipal and industrial wastewater treatment should be supplemented by strict management that calls for extensive implementation of technologies like buffer strips. Additionally, the adption of indigenous aeration techniques like the installation of placement of drop structures at critical locations would help to enhance the water quality in the lake watershed.

In the third part, process-based modelling was applied to quantify the LHW's point and diffuse pollution loads in the LHW and their accumulative effect, using the Pollutant Load estimator (PLOAD) model based on landuse specific export coefficients (ECs).

The definition of realistic ECs plays an important role in determining the sources of diffuse pollution fluxes. Those values are missing in many developing countries, including Ethiopia, due to the lack of monitoring data. However, EC values from other watersheds with similar characteristics of landuse, soil type, slope and climate were used to generate local EC values to estimate the non-point load of the study area. Based on the estimated EC values and the measured water quality data, the PLOAD model was calibrated and used to estimate the nonpoint sources pollutant load of the watershed was made with it.

Besides, the SCS-CN method of calculating runoff volume and peak flows was used in this study. For this purpose, the spatial data are linked with hydrological modelling using geographic information systems (HEC-GeoHMS) to produce a CN that is used to estimate the runoff depth at monitoring stations in Hawassa City. Runoff depth, monitored water quality data and catchment area will then be combined to determine stormwater pollutant fluxes from the main catchments in Hawassa City.

The findings revealed that the contribution of organic and nutrient pollutants from the point and nonpoint sources due to agricultural activities and dispersed faecal pollution by the rural population are prevailing in the study area. However, it is difficult to distinguish between pollution from agricultural activities and dispersed faecal pollution from the rural population where the maximum pollutant loads were observed in the Tikur-Wuha sub-catchments. This station was located downstream of the twopoint sources and received flow from the upper streams where the agricultural landuse predominants. Besides, Hawassa city has been identified as a key pollutant load driver, owing to increased impacts from clearly identified point sources and stormwater pollutant fluxes from major outfalls. Cultivated land, on the other hand, covers a large portion of the catchment and contributes significantly to the total load reaching the lake. It is therefore recommended that to both, urban and cultivated land and prioritize pollution mitigation measures that are focused on reducing the flow of pollutants from point and non-point sources into Lake Hawassa.

In summary, the high pollution load of LHW augmented with a subpar water quality management strategy led to an unsustainable water quality management system for Lake Hawassa and Tikur-Wuha river. Due to Lake Hawassa's and the Tikur-Wuha River's positive social and economic effects, it is now crucial to carefully consider the best options for integrated water resource management-based pollution management and control.

If appropriate water quality management options and the pollution reduction mechanisms presented in this study are implemented, restoration of the water quality in the Tikur-Wuha River and Lake Hawassa will be achieved, creating a favourable environment for aquatic life. In addition, with the improvement of water quality, the natural ecology of Lake Hawassa and Tikur-Wuha River will be restored and the economy of the community living on the vicinity of Lake Hawassa can be secured.

Key recommendations from the overall study are setting discharge limits and treatment requirements for a few of large point sources, followed by implementation of sustainable sanitation technologies like centralized, decentralized and on-site wastewater management systems where applicable. Centralized treatment systems for densely populated areas, while decentralized systems like EcoSAN for small towns and rural communities, where the collected urine and faecses can be valorized in agriculture. Meanwhile centralized and decentralized stormwater treatment systems could be developed and the authorities could demand a sustainable stormwater management where new areas are sealed.

Moreover, environmental pollution policy can be enforced by implementation of legal remedies such as restriction order and compounding offenses. The enactment of economic instruments such as emissions taxes, tradable emission allowances and tax differentiation may help reduce industrial emissions in all sectors that generate wastewater. However, these require a resolute commitment, continued evaluation and stricter enforcement of guidelines by their respective environmental authorities. On the other hand, pollution control from nonpoint sources in lake catchment requires land use planning and integrated watershed management with strict environmental restrictions.

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## List of Abbreviations

| | |
|---|---|
| AAS | Atomic Absorption Spectrophotometer |
| AnnGNPS | Annualized Agricultural Non-point Source Pollution Model |
| APHA | American Public Health Association |
| BMP | Best Management Practices |
| BOD | Biochemical Oxygen Demand |
| CA | Cluster Analysis |
| CCME WQI | Canadian Council of Ministries of the Environment |
| CM | Confusion Matrixes |
| CN | Curve Number |
| COD | Chemical Oxygen Demand |
| CSA | Central Statistical Agency |
| CV | Coefficient of Variation |
| CW | Constructed Wetland |
| DA | Discriminant analysis |
| DAAD | Deutscher Akademischer Austauschdienst |
| DEM | Digital Elevation Model |
| DFA | discriminant function analysis |
| DO | Dissolved Oxygen |
| EC | Electrical Conductivity |
| ECs | Export Coefficients |
| ECBP | Engineering Capacity Building Program |
| EcoSan | Ecological Sanitation |
| EEPA | Ethiopian Environmental Protection Authority |
| EPA | Environmental Protection Agency |
| FA | Factor Analysis |
| FAO | Food for Agricultural organization |
| GIS | Geographical Information System |
| GNSS | Global navigation satellite system |
| GWLFE | Generalized Watershed Loading Function |

| | |
|---|---|
| HCA | Hierarchical Cluster Analysis |
| HEPA | Hawassa City Environmental Protection Authority |
| HIP | Hawassa Industrial Park |
| HP | Highly polluted |
| HSPF | Hydrological Simulation Program—FORTRAN |
| IPDC | Industrial Park Development Corporation |
| KMO | Kaiser-Meyer-Olkin |
| KR | Kelly’s ratio |
| LHW | Lake Hawassa Watersheds |
| LID | Low Impact Development |
| LULC | Land Use Land Cover |
| MAPE | Mean Absolute Percentage Error |
| MAR | Magnesium Adsorption ratio |
| MCMC | Markov Chain Monte Carlo |
| MP | moderately polluted |
| MPCA | Minnesota Pollution Control Agency |
| MPE | Mean Percentage Error |
| MS | Monitoring Stations |
| MVST | Multivariate Statistical Techniques |
| $NH_3$-N | Ammonia Nitrogen |
| $NO_2$-N | Nitrite Nitrogen |
| $NO_3$-N | Nitrate Nitrogen |
| NPS | Nonpoint Sources |
| NSE | Nash-Sutcliff |
| NSF WQI | National Sanitation Foundation Water Quality Index |
| NTU | Nephlometric Turbidity Unit |
| PBIAS | Percent Bias |
| PCA | Principal Components Analysis |
| PI | Pollution Index |
| PLOAD | Pollutant Loading Estimator model |
| $PO_4$-P | Phosphate Phosphorus |

| | |
|---|---|
| RVLB | Rift Valley Lake Basin |
| SAR | Sodium Adsorption Ratio |
| SCS-CN | Soil Conservation Service-Curve Number |
| SD | Secchi depth |
| SPSS | Statistical Package for the Social Sciences Software |
| SRP | Soluble Reactive Phosphorous |
| SRSEPA | Sidama Regional State Environmental Protection Authority |
| SSP | Soluble sodium percentage |
| SUDS | Sustainable Urban Drainage Systems |
| SWAT | Soil and Water Assessment Tool |
| SWMM | Storm Water Management Model |
| TAN | Total Ammonium Nitrogen |
| TDS | Total Dissolved Solids |
| TN | Total Nitrogen |
| TP | Total Phosphorus |
| TSI | Trophic State Index |
| TSS | Total Suspended Solids |
| USEPA | United States Environmental Protection Authority |
| WA WQI | Weighted Average Water quality Index |
| WASP | Water Quality Analysis Simulation Program |
| WHO | World Health Organization |
| WQI | Water quality Index |
| WWTPs | Wastewater Treatment Plants |
| ZLD | Zero Liquid Discharge |

# 1. Introduction

## 1.1. Background

Water, an elixir of life, is considered as most delicate part of the environment and essential for human and industrial development. Its scarcity currently affects one-fifth of the world's population while a quarter of the world's population facing a technological shortage in retrieving freshwater from rivers and ponds [1]. Water resources have a versatile use globally, but they are the most threatened natural resource largely due to the human interventions [2]. According to recent estimates, the amount of available water in Africa, the Middle East and south Asia is rapidly declining, while the quality of water is gradually deteriorating due to growing population, increasing urbanization and climate change [3].

The total amount of water necessary for adequate municipal service increases as cities grow in population and economic development [4]. The urban expansion affects the water quality as it alters the biophysical processes and fluxes of water, sediment, chemicals and microorganisms [5]. Consequently, the environmental impact on local lakes and rivers appears to be growing, especially the city does not adequately treat solid waste, industrial wastewater and sewage [6]. Additionally, the release of untreated municipal and industrial wastes into bodies of water, which resulted in greater pollutant concentrations in rivers and lakes, has been related to serious water quality degradation in developing countries, where solid waste can accumulate along river channels [7].

In developing countries, pollution has posed a big challenge by bringing shortage of freshwater due to manmade problems. In addition, in these countries, expansion is rapid and uncontrolled, as a result surface water quality continues to deteriorate. Furthermore, rapid urbanization and high population influx are affecting basins with large cities and rural areas. Pollution of surface water bodies comes from industrial waste, agricultural runoff and untreated municipal sewage (Figure 1.1**)** [8]. Besides, there are inadequate wastewater treatment facilities to deal with the increase in pollution [9]. Also, enforcement of pollution control laws has been flimsy in many cases [10].

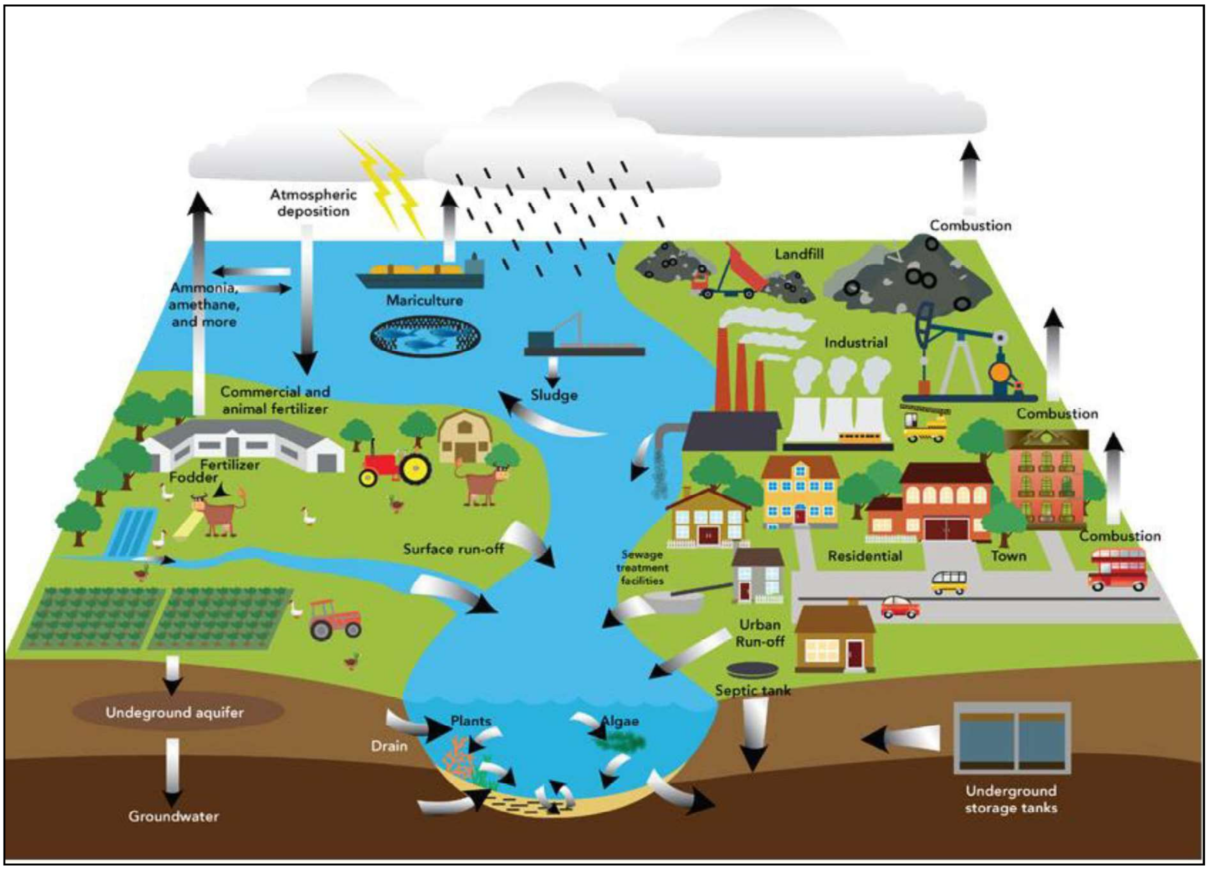

Figure 1.1. Pollutants pathways into surface water (https://www.waterpollution/filterwater.com.et)

Water pollution is a significant barrier to sustainable development in Sub-Saharan African countries posing a challenge for long-term development. The main sources of pollution in surface water have been human-caused and this trend is continuing [11]. Many lakes and reservoirs receive a significant amount of metals, organics and nutrients from their watersheds and tributaries.

Primarily, the wastewater released into water bodies from various sources such as industries, residential areas, institutions, agricultural and urban landuses has augmented the pollution load in the rivers, which heavily degrades the aquatic environment [12]. The effects of untreated wastewater discharge has been analyzed in many studies [13] and identified as the most hazardous to aquatic ecosystems due to the large amounts of nutrients and organic contents [14]. Moreover, the release of nutrients from agricultural land to the surface water resources promotes eutrophication, which ultimately depletes the dissolved oxygen concentration [15].

In addition, stormwater is a major cause of urban river water pollution in both developed and developing countries [16]. During the runoff process, stormwater picks up contaminants that have accumulated on the various surfaces in the antecedent dry period and carries the pollutant load to the river. Existing stormwater management systems are fragmented and mainly serve major roads, with rivers as the final receiving system [17]. Stormwater generation increases with the growing area of impervious surfaces as the city expands and densifies [6].

Agricultural runoff also has a complex contaminant composition including nitrates, ammonium, phosphorus compounds, heavy metals and persistent organic pollutants. In addition, N and P, the main limiting nutrients in eutrophication, are important for aquatic plant growth [18]. Pollution from agricultural nonpoint sources has long been recognized as an important factor influencing the degree of eutrophication [19] and it is thought to affect the health and safety of the world's aquatic ecosystems [20]. Moreover, agricultural chemicals and fertilizers overwhelmed the carrying capacity of water bodies, leadng to deterioration of surface water quality [21].

Industrial wastewater pollution poses a serious threat to human and environmental health, especially in developing countries and Egun [22] identified industrial wastewater as a major source of water pollution. According to Reza and Singh [23], the major anthropogenic sources of metal, nutrient, and organic waste pollution are untreated and partially treated wastewater discharges into water bodies from various industries. In developing countries, industries generate substantial wastes into surrounding water bodies, 70% of which is discharged untreated [24]. In Uganda, most industries lack functional effluent treatment plants [25], while in Ethiopia most industries and municipalities lack wastewater treatment facilities and instead release their effluents directly into surface water. These industries in the major cities of Ethiopia usually located near to rivers or Lakes are the sources of water pollution [26]. Rivers or Lakes that crosses urban centers, densely populated areas and close to industrial establishments are the most affected [27].

The recent decline in water quality and increased sedimentation in Ethiopia's Lakes and rivers are largely due to land-use changes, which has a negative impact on the environment. This is mainly due to increased pollution from agricultural intensification and the concomitant use of agrochemicals [28].

Nowadays, pollution from the aforementioned sources have posed a major threat to the land and water quality in many of Ethiopia's river or lake basins, owing to natural and anthropogenic sources [29]. Thus, water quality is becoming a major issue in Ethiopia's Rift Valley Lakes basin and its contributing rivers, which are used for irrigation, domestic use, fish farming and recreation [30]. In this basin,the majority of water quality degradation in rivers or lakes is attributed to the dumping of domestic and industrial wastes, as well as wastes from agriculture and health institutions [31,32].

The Lake Hawassa watershed is located in the Sidama and Oromiya Regional state in the Rift Valley lakes basin of Ethiopia's (Figure 1.2). The Lake watershed is a closed basin system, receiving water only from the Tikurwuha River (the only river in the Lake Hawassa watershed that has been gauged) and runoff from the surrounding area. This river is used for a number of purposes, including drinking, industrial and irrigation. It also functions as an open dumping ground for wastes generated by industries and other sources in Hawassa and the surrounding area[33]. Furthermore, there is a fast expansion of urban, industrial and agricultural activities in the watershed. Hence, the issue of water quality has become one of the major concerns in water resource management and calls for integrated water quality monitoring and assessment [34].

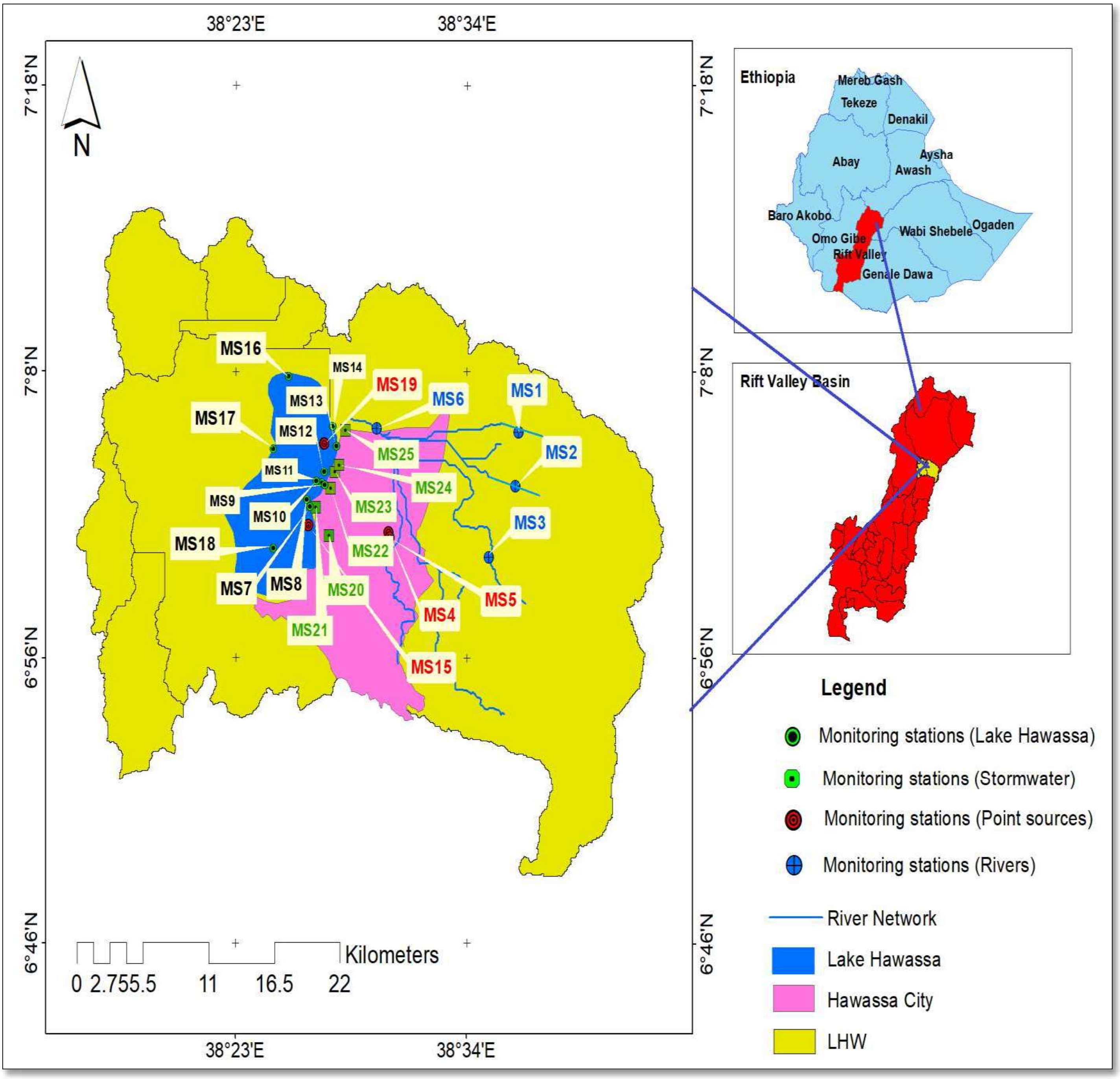

Figure 1.2. Study area map and monitoring stations' (Lake Hawassa, Point sources, Rivers and Stormwater)

Consequently, the Ethiopian government is currently taking positive steps to enhance the state of the waterbodies, particularly in the areas of water resource management, environmental pollution control, and industrial pollution prevention. The detailed proclamation and regulation statements are listed in Table 1.1.

Table 1.1: The governance instruments related to environmental pollution and control and key issues addressed

| Governance instrument | Key issues addressed |
|---|---|
| Water resources management regulation [35]. | • States that those who use water for industrial or other purposes that may cause pollution should:<br>• install and use waste treatment method;<br>• discharge only the type and volume of treated waste permitted;<br>• allow the supervising body to take the treated waste discharge sample at any time; |
| Environnemental pollution control [36]. | • Provides the basis for the development of relevant environmental standards and violations of these standards are punishable according to the polluter pays principle.<br>• The regulation affords a five-year gestation period for existing industries and reduces the strength of their effluents to within the industrial standards |
| Prevention of Industrial Pollution [37]. | • Factories should ensure that liquid waste meets environmental standards, obtain permits before discharging liquids and monitor waste composition, keep records and periodically report to the Environmental Protection Agency |

To fill the gaps, however, there are still many things that need to be improved, as the real situation in the country is hostile and poor wastewater management remains the main factor contributing to surface water pollution in the country. In addition, a strategic plan for the Ethiopian Rift Valley Lakes Basin was developed with a number of key objectives, including safeguarding the basin's water resources and the environment and the development of implementation plans for the efficient management of water resources and the prevention of environmental pollution. It provided some technical approaches to reducing water losses, improving water quality and watershed management. It also incorporated communicative participation of stakeholders, political commitment of government officials, capacity building, awareness raising and experience sharing among the participants. Despite, the establishment of the strategic plan, a detailed study of the pollutant dynamics and pollution load in the study basin is not thoroughly examined . Pollution of rivers and lakes is considered to receive little attention, and the lack of national regulations has slowed its implementation. Therefore, attempts to control water quality were unsuccessful. Thus, water quality monitoring and modelling LHW can help make informed decisions to minimize pollution levels and adverse impacts.

## 1.2. Water quality monitoring and modelling

Water quality assessment aims to evaluate the physical, chemical and biological characteristics of water bodies in terms of their natural quality, intended uses and human impacts [38]. Moreover, the quality of water sources depends on the various chemical constituents and the variation in concentrations mostly caused by natural and anthropogenic activities [39]. On the other hand, the physicochemical analysis of water quality is expensive, difficult, requires qualified personnel and appropriate laboratory setting. In developing countries like Ethiopia, limited technical and financial resources are not available to implement a national water qualitymonitoring program for all water sources [40]. As a result, the monitoring approach is not regularly implemented mainly due to budgetary constraints. This situation limits the decision-making and implementation capabilities of regulatory authorities in environmental agencies.

Integrated watershed management plans should also consider the total pollutant load entering a water body from point source discharges, diffuse or non-point source contributions and runoff water from the watershed. However, the impact of diffuse source pollution on the water quality deterioration is not sufficiently examined. It is challenging to allocate and quantify the numerous dispersed sources that add tothe load [41]. Thus, it is evident that monitoring and regulating merely point sources is insufficient to meet the objectives of water quality management plans [42]. Thus, in-depth knowledge of the watershed, population (urban vs. rural), wastewater and industrial effluent discharges, land use types and climate is often required to conduct a thorough assessment of a surface water pollution loads.

In the absence of better mitigation and remediation in the management strategy, most river water quality management and pollution control measures in developing countries has been futile, mainly due to the direct adaptation of management strategies from developed countries without acclimatization to local conditions [43]. To improve this situation, these countries can develop future conditions for the use of modelling tools in the environmental decision-making process [44].

The researchers recommend that sustainable management of river and lake pollution should include practical remediation approaches. In this context, water quality models are gaining greater significance in simulating and predicting the levels, distributions and risks of chemical pollutants in a given water body and are therefore used in decision making and implementation of remedial measures [45].

Water quality models are used to determine the pollution of water bodies and the fate and behavior of pollutants in the aquatic environment and help to reduce the labor and material costs of a large number of chemical experiments [46]. Additionally, the role of water quality assessment models in environmental decision-making is considered essential because the models enable a knowledge based and cost-effective watershed management through their predictive capability [47]. These models make use of accurate and extensive historical databases maintained by scientific institutions and government agencies [48]. Therefore, environmental agencies in developing countries need to begin modeling exercises as part of their watershed and water quality management programs [44].

On the other hand, modelling requires reliable input data, skilled personnel and sophisticated management culture, which are often lacking in developing countries [49]. As a result, the use of water quality models in these countries for environmental policy decisions is not common as their intended application is hampered by the limited input data interms of quantity and quality and by a lack of experience with model-based water quality decisions [50].

Nowadays, many models were used to explore surface runoff, sediment, nutrient and pollutant transmission from point and nonpoint pollution by taking organics and nutrients into account [51]. However, models that estimate organics and nutrient loadings are often data intensive and costly. Sometimes lack of access to proprietary software and decision support systems due to lack of funding significantly impedes the use of appropriate models [39,52]. As a result, the local governments are unable to estimate pollutant loads or measure their levels in rivers. Thus, appropriate models that are suitable for data-poor environments and provide reliable information for the area in question are needed to compensate for data deficiencies and costs [53].

To date, several water quality models have been developed with different focus and capabilities to solve complex environmental and pollution management problems. They can be broadly categorized based on the types of approaches (physically based, conceptual and empirical), the pollutants simulated (nutrients, sediments, and salinity), the scale (catchments, groundwater, rivers or streams, lakes and coastal waters), the nature of models (deterministic or stochastic), state analyzed (steady state or dynamic simulation), spatial analysis (lumped or distributed) and dimensionality (1-D, 2-D, or 3-D) and data requirements (extensive minimal or minimal data requirements) [54,55].

Thus, to select a suitable modelling tool, the different water quality models are reviewed. Table 1.2 shows the summary of reviewed models based on application domain of the model, accessibility of the software, input data requirements and spatial and temporal discretization.

Table 1.2: Some selected modelling tools and their selection criteria evaluation

| Name of the Model and References | Characteristics | Application Domain of the Model | Accessibility of the Software | Input Data Requirement | Spatial and temporal discretization |
|---|---|---|---|---|---|
| AGNPS [56] | A distributed model that evaluates the agricultural NPS pollution and simulates the transport of sediments and chemicals | Catchment | Public domain | Data-intensive | Spatial: Flexible,<br>Temporal: a daily time step |
| GWLF [57] | A semi-distributed/lumped model that estimates runoff, sediment and nutrient loadings | Catchment | Public domain | Moderate | Spatial: Flexible,<br>Temporal: flexible or user-defined time step |
| MONERIS [58] | A conceptual model, which allows the quantification of nutrients emissions via various point and diffuse pathways into river systems | river | Public domain | Data-intensive | Spatial: Flexible,<br>Temporal: yearly or monthly time step |
| MIKE 11 [59] | A distributed hydrodynamic model of flow and water quality in streams and simulates solute transport and transformation in complex river systems | River | Proprietary | Data-intensive | Spatial: Flexible,<br>Temporal: flexible or user-defined time step |
| QUAL2E [60] | A one dimensional and steady-state model typically used for water quality modelling of pollutants in rivers, streams and well-mixed lakes | River/Lake | Public domain | Minimum | Spatial: Flexible,<br>Temporal: user-defined |
| SPARROW [61] | Semi distributed statistical regression model that is designed to account for the spatial variability in contaminant flux in stream water quality to impose the mass balance | Catchment/River | Proprietary | Data-intensive | Spatial: Flexible,<br>Temporal: user-defined |
| HSPF [62] | An analytical tool designed to simulate catchment hydrology and water quality for conventional and toxic organic pollutants | Catchment/River | Public domain | Data-intensive | Spatial: Flexible,<br>Temporal: Flexible or user-defined time step |
| PLOAD in BASINS 4.5 System [63] | A Simple or an export coefficient based method that is used to estimate NPS contribution from each land use by incorporating point source and GIS-based land-use data | Catchment level | Public domain | Minimum | Spatial: Flexible,<br>Temporal: flexible or user-defined time step |
| SWMM [64] | A distributed physically based, dynamic, continuous urban stormwater runoff quantity and quality model | Urban catchment | Public domain | Data-intensive | Spatial: Flexible,<br>Temporal: Event-based and continuous |

|  |  |  |  |  |  |
|---|---|---|---|---|---|
| WASP [65] | A surface water quality modelling tool used to analyse a variety of water quality problems in water bodies such as ponds, rivers/streams, lakes/ reservoirs, estuaries and coastal waters | River/Lake | Public domain | Data-intensive | Spatial: Flexible<br>Temporal: User-defined time step or flexible |
| SWAT [66] | A semi-distributed model that is used for the prediction of the effects of alternative land use management practice on water, sediment, crop growth, nutrient cycling, and pesticide in watersheds with varying soils, land use and management conditions. | Catchment level | Public domain | Data-intensive | Spatial: Flexible,<br>Temporal: sub-daily to yearly time step |
| AGWA [67] | A distributed multipurpose hydrologic analysis system that integrated several sub-models to predict runoff and erosion rates | Catchment level | Public domain | minimum | Spatial: Flexible,<br>Temporal: Event-based and continuous |
| MIKE SHE [68] | The key purpose of the MIKE SHE model is the integrated modelling of evapotranspiration, groundwater, surface water, and groundwater recharge. | Catchment level | Proprietary | Data-intensive | Spatial: Flexible,<br>Temporal: Event-based and continuous |
| SWIM [69] | The SWIM model was established to examine the impacts of climate and land-use changes at the regional level. | Catchment level | Public domain | Data-intensive | Spatial: Flexible,<br>Temporal: Daily |

Despite the development of various water quality models that have wider application in environmental management, most of them are still complex and require a large data set, which is a tailback especially in developing countries where hydro-meteorological and water quality data are scarce. Mechanistic watershed models can provide more accurate results on pollutant losses, but such models need a huge amount of input data. These intensive input data requirements make such a modelling a highly challenging task, which hinders its use [70]. Therefore, the use of a less complex but relatively accurate water quality model would be a viable technique for pollution management in developing countries [47].

Various researchers have integrated different water quality models to solve environmental problems and found that the integrated models can simulate water quality constituents very well [71,72].

The majority of researchers recommended the use of the PLOAD model to simulate the effect of non-point source pollution load in catchments with limited data because of its adaptability and capability to operate in different watersheds [53,73]. Furthermore, the model can also be used in conjunction with other water quality models and it has been successfully used to develop water quality management plans in various watersheds across the world and in the study area.

### 1.3. Rationale of the study

Ethiopia is endowed with a vast potential of surface and groundwater resources with 12 river basins with a total annual volume of 124.4 BMC from rivers, 70 BMC from lakes and 30 BMC from groundwater. Despite the enormous potential of the country's water resources, the water quality of many of them has remained in its incipient juncture [74]. According to Haile et al. [75], previous studies in Ethiopia have mostly concentrated on water quantity, particularly water scarcity, while ignoring the problem of water quality. The source of the main pollutants affecting lakes and rivers in Ethiopia appear to be sediment transport and siltation, industrial effluents from emerging factories and mining operations, from agricultural runoff and domestic sewage [76].

Ethiopia has a number of lakes that are of scientific and economic importance. These include Lake Hawassa, which has attracted considerable research interest because of its diversity of aquatic life, high fisheries productivity and environmental friendliness. Due to increasing anthropogenic impacts, especially industrialization and population growth, lake water quality and the safety of aquatic communities are at risk [77]. Besides, the few water quality studies that are now available have not been able to adequately address the issue due to the difficulty of monitoring water quality and the lack of sufficient research [78]. Studies have shown that the ecology and water quality of the lake Hawassa was highly impaired, because of industrial effluents and other non-point source pollution. Pollution mainly comes from point and nonpoint sources caused by urban, agricultural and industrial effluents [79]. The main factories in the study area are a ceramics factory, a flour mill, a cement products factory, a soft drink factory in Moha, a BGI (St. George's Brewery), an Etabs soap factory, Hawassa industrial park and other small-scale industries. They are virtually all concentrated along the main road, which is close to the small marshy land and discharge their effluents into the lake via streams [76]. This is a danger to people who depend on rivers, streams, and lakes for domestic and other uses and to the existence of marine life [80].

Consequently, water quality of the Lake Hawassa watershed has been the subject of several investigations. A number of studies conducted on the pollution problem and the ongoing efforts to enforce the existing environmental regulations. Teshome [78] investigated the seasonal variations in water quality and its suitability for designated uses in the eastern part of the catchment. Amare [81] investigated the major sources of nonpoint source pollution and their proportional contributions in the western part of the lake basin. In addition, Kebede et al. [33] investigated the effects of changes in land cover on water quality and streamflow in the lake's eastern watershed. Zemede et al. [82] examined the water quality parameters to determine the suitability of water for the intended use and the trophic status classification of Lake Hawassa were some of the studies to mention a few.

However, little effort has been made to investigate the pollution status of LHW's through physical, chemical, bacteriological and metal concentration analyses and none of the studies has explicitly determined the contribution of each source's of individual pollutants from the respective land uses. Besides, little information is documented on water quality studies that link agricultural and urban land use to identify pollution sources. Previous studies relied primarily on haphazard monitoring and literature data and they targeted on a few water quality parameters that do not accurately reflect the overall water quality of the watersheds. Furthermore, some earlier investigations yielded contradicting findings.

Accordingly, decisions regarding water quality management and pollution control in lake basins are often based on these short-term monitoring campaigns that lead to rather limited causality in pollution control.

Urbanization, industrialization, economic activity and population growth, on the other hand, are all fast expanding, which could lead to an increase in wastewater generation. Likewise, the impacts of polluted water resources on the welfare of individuals and aquatic species as well as the socioeconomic impacts on the watercourses and the population downstream in the Lake basin did not received much courtesy.

Following this, the EPA of Hawassa City Administration in 2016 suggested and established a buffer zone regulation to be implemented in its designated areas around Lake Hawassa with regard to the management, control and mitigation of lake pollution. Succeeding the implementation of this governance tool, efforts to safeguard and enhance the buffer zone have been noted. However, the buffer zones (deltas) are not performing their duties as intended. To improve the situation, the determination of pollutant loads from point and non-point sources ought to be estimated by integrating watershed and hydrological models including event-based pollutant concentrations on top of regular monitoring of pollutants from point and non-point sources. However, this remains the major gap in the study area and is the main reason for the infeasibility of improving water quality management and pollution control.

Hence, an alternative decision-making process that can actually work in such scenarios needs to be implemented to mitigate the pollution problem. Essentially, there is no standard ‘one size fits all’ blueprint or protocol that could solve the complex water quality issues to obtain the most appropriate results. Furthermore, a systematic investigation of the pollutant dynamics and the pollution load carried by the LHW is an essential consideration of the pollution reduction efforts, on top of characterizing the constituents of the Lake watershed water quality for the water quality management decision-making process to be viable and identifying pollution hotspots to deliver the best mitigation strategies.

Thus, this study is aimed at conducting a thorough analysis of the spatial and temporal variations in water quality, dynamics and transport, estimation of trophic state and suitability for anthropogenic uses, determination of multi-sourced pollutants loads in the catchment and integration of watershed modeling to help in the resolution of complex environmental issues despite suggesting better mitigation strategies.

## 1.4. Objectives of the study

### 1.4.1. Main Objective

The main objective of the research is estimating pollutants flux contributed by various land uses that are entering into Lake Hawassa from point and nonpoint sources based on water quality monitoring and modelling for Lake Hawassa Watershed.

### 1.4.2. Specific objectives

- To assess the water quality of Lake Hawassa watershed, identify the trophic state and suitability for anthropogenic uses by applying common water quality indices.

- To evaluate seasonal and spatial variations in water quality and identification of potential sources of pollution using multivariate statistical techniques
- To estimate point and nonpoint source pollutant flux by combining various models for Lake Hawassa watershed.
- To derive and prioritise effective pollution mitigation measures

### 1.5. Structure of the Thesis

Five chapters make up this cumulative thesis as shown in Figure 1.3. The state-of-the-art and the general overview of the pollution of the Lake Hawassa watershed caused by physicochemical water quality parameters are elaborated and the appraisal of major issues related to pollution management and modelling approaches are presented in Chapter 1. This is followed by the rationale of the study and the objectives of the study. Thus, chapters 2, 3 and 4 are the results of the research conducted to achieve of the first three of the stated goals and are based on three articles that were published in peer reviewed international journals, indexed by Scopus and Web of Science.

Chapter 2 explains the first research objective by assessing the water quality of Lake Hawassa via applying common water quality indices and evaluating the trophic state and suitability for anthropogenic uses in the Lake Hawassa watershed. The available monitoring data and analysis of the physicochemical characteristics of water quality parameters from streams or rivers and industrial effluents that are discharged into the Lake Hawassa directly or indirectly and evaluating the compliance of domestic, irrigation, aquatic and recreational water use with the guideline values. To do so, the water quality indices were used to associate the water quality of different sources and monitoring sites to integrate and deliver the water quality information to experts and the wider community. This chapter also aims at identifying gaps in water quality monitoring, assessment and industrial pollution management and control measures. The chapter is based on the following publication;

**Lencha, S.M., Ulsido, M.D., and Tränckner, J. (2021).** Assessing the Water Quality of Lake Hawassa Ethiopia—Trophic State and Suitability for Anthropogenic Uses—Applying Common Water Quality Indices. Int. J. Environ. Res. Public Health 2021, 18, 8904. https://doi.org/10.3390/ijerph18178904.

Chapter 3 contributes to achieve the second objective of the research. This chapter explains the main findings of the evaluation of the seasonal and spatial variations in water quality in the Lake Watershed based on statistical interpretation. This chapter also makes an identification of potential sources of pollution using multivariate statistical techniques for Lake Hawassa watersheds. Further, the identification of pollution sources and composition of individual constituents by incorporating the multivariate statistical techniques based on predefined pollution sources was discussed in detail. Moreover, spatial clustering, discriminant analysis, factor analysis and pollution hotspots identification in the study area are also discussed in detail. The chapter is based on the following publication;

**Lencha, S.M., Ulsido, M.D., and Muluneh, A. (2021).** Evaluation of Seasonal and Spatial Variations in Water Quality and Identification of Potential Sources of Pollution Using Multivariate Statistical Techniques for Lake Hawassa Watershed, Ethiopia. Appl. Sci. 2021, 11, 8991.
https:// doi.org/10.3390/app11198991.

Chapter 4 is devoted to the third objective and the estimation of point and nonpoint source pollutant fluxes by integrating various models. It mainly investigates and quantifies the diffuse sources load contributed by various land uses and the point sources loads from industrial plants. Moreover, the local pollutants export coefficient was developed for selected water quality parameters in the study area. It also integrates the PLOAD, SWAT, FLUX32, HEC-GeoHMS and SCS-CN with monitoring data to determine the pollutant fluxes from point and non-point sources (i.e. PLOAD at the catchment outlets for nonpoint sources, HEC-GeoHMS and SCS-CN were integrated to determine stormwater flux and FLUX32 for point source loads) in Hawassa City. This chapter consists of the following publication;

**Lencha, S.M., Ulsido, M.D., and Tränckner, J.** (2022). Estimating Point and Nonpoint Source Pollutant Flux by Integrating Various Models, a Case Study of the Lake Hawassa Watershed in Ethiopia's Rift Valley Basin. Water 2022, 14, 1569.
https://doi.org/10.3390/w14101569.

Chapter 5 discusses about the general synthesis of the study. Based on the major findings it derives recommendations for an effective pollution control and proposesfuture research directions.

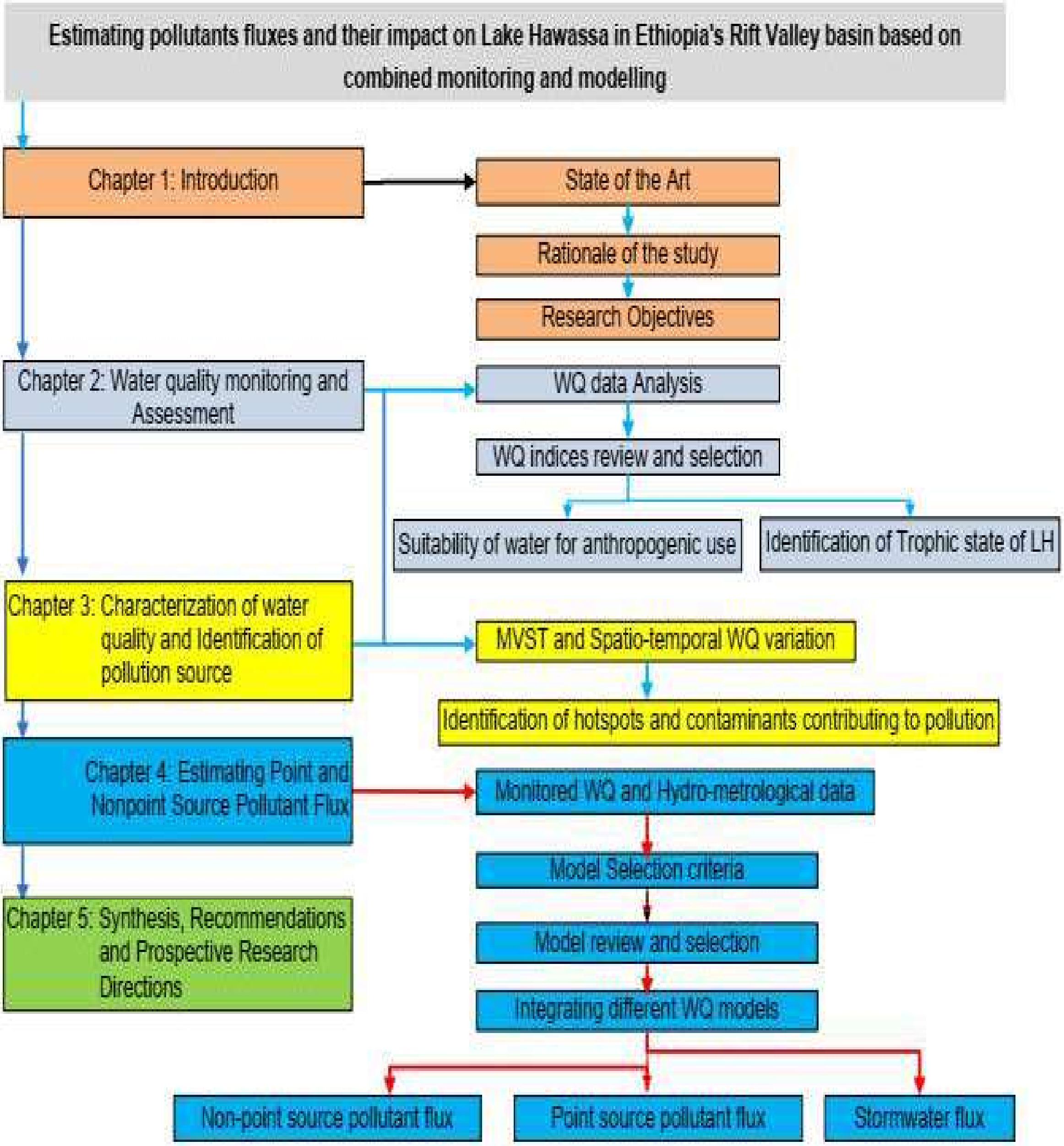

Figure 1.3. Structure of the thesis and work flow diagram

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# 2. Water qualiy Monitong and Assessment

**Abstract:** The rapid growth of urbanization, industrialization and poor wastewater management practices have led to an intense water quality impediment in Lake Hawassa Watershed. This study has intended to engage the different water quality indices to categorize the suitability of the water quality of Lake Hawassa Watershed for anthropogenic uses and identify the trophic state of Lake Hawassa. Analysis of physicochemical water quality parameters at selected sites and periods was conducted throughout May 2020 to January 2021 to assess the present status of the Lake Watershed. In total, 19 monitoring sites and 21 physicochemical parameters were selected and analyzed in a laboratory. The Canadian council of ministries of the environment (CCME WQI) and weighted arithmetic (WA WQI) water quality indices have been used to cluster the water quality of Lake Hawassa Watershed and the Carlson trophic state index (TSI) has been employed to identify the trophic state of Lake Hawassa. The water quality is generally categorized as unsuitable for drinking, aquatic life and recreational purposes and it is excellent to unsuitable for irrigation depending on the sampling location and the applied indices. Specifically, in WA WQI, rivers were excellent for agricultural uses and Lake Hawassa was good for agricultural uses. However, the CCME WQI findings showed rivers were good for irrigation but lake Hawassa was marginal for agricultural use. Point sources were impaired for all envisioned purposes. The overall category of Lake Hawassa falls under a eutrophic state since the average TSI was 65.4 and the lake is phosphorous-deficient, having TN:TP of 31.1. The monitored point sources indicate that the city of Hawassa and its numerous industrial discharges are key polluters, requiring a fast and consequent set-up of an efficient wastewater infrastructure, accompanied by a rigorous monitoring of large point sources (e.g., industry, hospitals and hotels). In spite of the various efforts, the recovery of Lake Hawassa may take a long time as it is hydrologically closed. Therefore, to ensure safe drinking water supply, a central supply system according to World Health organization (WHO) standards also for the fringe inhabitants still using lake water is imperative. Introducing riparian buffer zones of vegetation and grasses can support the direct pollution alleviation measures and is helpful to reduce the dispersed pollution coming from the population using latrines. Additionally, integrating aeration systems like pumping atmospheric air into the bottom of the lake using solar energy panels or diffusers are effective mitigation measures that will improve the water quality of the lake. In parallel, the implementation and efficiency control of measures requires coordinated environmental monitoring with dedicated development targets.

**Keywords:** water quality index; eutrophication; Lake Hawassa water quality; point sources; contaminants; monitoring and assessment

## 2.1. Introduction

Surface waters play the lion's share in transportation and assimilation of municipal and industrial effluents and agricultural runoff; consequently, they are most prone to pollutants [1]. Industrialization on top of rapid population growth triggers land development along a river basin, exerting greater pressure on water bodies by giving rise to water pollution and ecological impediment [2].

Surface water pollution with chemical, physical and biological contaminants by anthropogenic activities from the point and non-point sources is of great environmental consideration all over the world [3].

In Ethiopia, due to lack of access to improved water supply and sanitation, people are suffering from water communicable diseases that are associated with unsafe and inadequate water supply. Additionally, water quality problems are booming in water sources of the country that demand effective monitoring and evaluation for the proper protection of water sources from contamination [4]. A study conducted by Angello et al. [5] revealed that increased urbanization has prompted the opening of medium- to large-scale industries resulting in pollution of most surface water resources by the wastewater released from different sources. Wastewater from residential areas, runoff from urban and agricultural activities near surface waters contribute a significant quantity of contaminants. Additionally, industrial effluents that are released directly with little or no treatment into surface water bodies were one of the major pollution sources in Akaki river. Lake Hawassa is one of the major Ethiopian Rift Valley Lakes basins (RVLB) and it is used for manifold purposes like irrigation, human consumption by some city and rural inhabitants close to the city, recreation, livestock, watering and fish farming [9].

Studies showed a high amount of pesticides in water, sediments and fish species in Lake Hawassa due to its exposure to effluents from factories, urban and agricultural runoff. As a result, the lake is contaminated and affects the biodiversity of the aquatic ecosystem including fish [7]. The growth and death of floating aquatic plants are supplementing the algal growth and sediments that accumulates at the bottom of the lake and yield cultural eutrophication [8].

The impact on the lake is mainly due to anthropogenic activities in its catchment. Sanitation is a great concern. Most of the population, even in the inner part of the city of Hawassa are using latrines. Larger buildings provide conventional flushing systems but without any wastewater treatment. Furthermore, industrial and commercial pollution sources (i.e., BGI, Moha soft drinks, flour factory and ceramic factory) are known to release effluents into streams or rivers that end up in the small marshy land after which Tikur-Wuha river got its name and fed Lake

Hawassa. In addition, Hawassa Industrial park and the Referral hospital are releasing their effluents directly to the lake. This is a danger to the people that depend on rivers, streams and lake for domestic and other uses and to the existence of marine species [9].

The study conducted by Zemede et al. [10] made use of different water quality indices and discovered that the status of water quality of Lake Hawassa was under the hypertrophic condition and generally unsuitable for all uses.

Evaluating the status of water quality from analytically determined data of parameters with the international and national permissible values does not guarantee the whole visualization of the water quality situation. Therefore, developing a sole value of WQI that can convey information more easily in a way that can be more rapidly understood than a list of large parameter values is vital [11].

The water quality index (WQI) is a very effective tool to integrate and deliver information regarding water quality to experts and the wider community [12] and is also used to associate the water quality of different sources and monitoring sites [13]. By addressing usage criteria, the negative impact of environmental pollution becomes tangible. It is a unit-less number that combines information from manifold analytical data into a sole aggregate through a method that portrays the situation of water quality well for the public and experts [14].

Numerous indices had been established so far in various parts of the world to estimate water quality status and pollution extents of the water bodies. Just to mention a few, the National Sanitation Foundation (NSF) water quality index (NSF WQI) [15], Canadian Council of Ministries of the Environment Water Quality Index (CCME WQI) [16], Oregon Water quality index (Oregon WQI )[13], Bascarón index [17], Fuzzy index [18], Boyacioglu's index [19], Weighted Arithmetic water quality index (WA WQI) [20] and many more. NSF WQI, CCME WQI, Oregon WQI and WA WQI are the most widely used techniques around the globe [20].

To conduct all-inclusive water quality valuation for lakes besides the water quality indices approach, implementing the trophic state index approach to identify the productivity of the lake is mandatory. The Organization for Economic Cooperation and Development provides specific criteria for temperate lakes in terms of the average annual values of total phosphorus, chlorophyll a and Secchi depth [21]. The limitations of these criteria were that the same lake could be assigned in one or another trophic class based on the applied parameters. Studies showed the computation of trophic state ranking of lakes or reservoirs from variables like Total nitrogen (TN), Total phosphorous (TP) and phytoplankton mass that are responsible for eutrophication of lakes. Kratzer and Brezonik [22] established an index for eutrophication based on TN from the Carlson index; whereas Boyle et al. [23] established a pH and dissolved oxygen-based index. Additionally, Hailin and Baoyin [23] also formulated an index that depends on Biochemical demand (BOD) by formulating statistical association between chlorophyll a (Chl-a), TP and TN. Köklüa and Alkış [25] also established a new trophic level index using quality indicators that are known by affecting eutrophication with limited applicability. The Carlson trophic status index (TSI) has long been established to evaluate the trophic state of lots of reservoirs and lakes and is determined using the procedures explained by Carlson [26]. Carlson trophic status index TSI has been commonly used approach-and separately estimated from total nitrogen concentration, Secchi depth (SD), (chl-a) and total phosphorus concentration (TP) [27]. This study has, therefore, tried to elucidate the use of weighted average (WA), CCME and TSI water quality indices to categorize the water quality of Lake Hawassa Watershed and identify the trophic state of Lake Hawassa.

## 2.2. Materials and Methods

### 2.2.1. Study Area

Lake Hawassa watershed is located in the center of the Rift Valley Lakes basin, between latitudes of 6°4′45″ N to 7°14′49″ N and longitudes of 38°16′34″ E to 38°43′26″ E [28,29]. Amongst the seven lakes in the Rift Valley Lakes basin, Lake Hawassa is located between the latitude of 6°33′–7°33′ N and longitude of 38°22′–38°29′ E (Figure 2.1). The Lake Hawassa watershed is located in Oromiya and Sidama regional state, having a total area of 1407 km$^2$ and 113 km$^2$ of which is Lake surface area [30]. Streams from the eastern catchment flow to Lake Cheleleka and are drained by the Tikur-Wuha River that feeds the Lake Hawassa. This river water has been extensively affected by various point sources [31]. The lake has no surface water outflow except evaporation and abstraction and it is used for commercial fishing and tourist destinations [32].

The months from April to October are wet and humid; the main rainy season is between July and September, having mean annual precipitation of about 955 mm. The mean minimum precipitation is 17.8 mm in December (dry season) and the mean maximum precipitation is 119.8 mm in August (rainy season) [33]. The long-term mean annual temperature is around 19 °C while the mean monthly evapotranspiration in the low lands ranges from 39 mm in July to 100 mm in January [34].

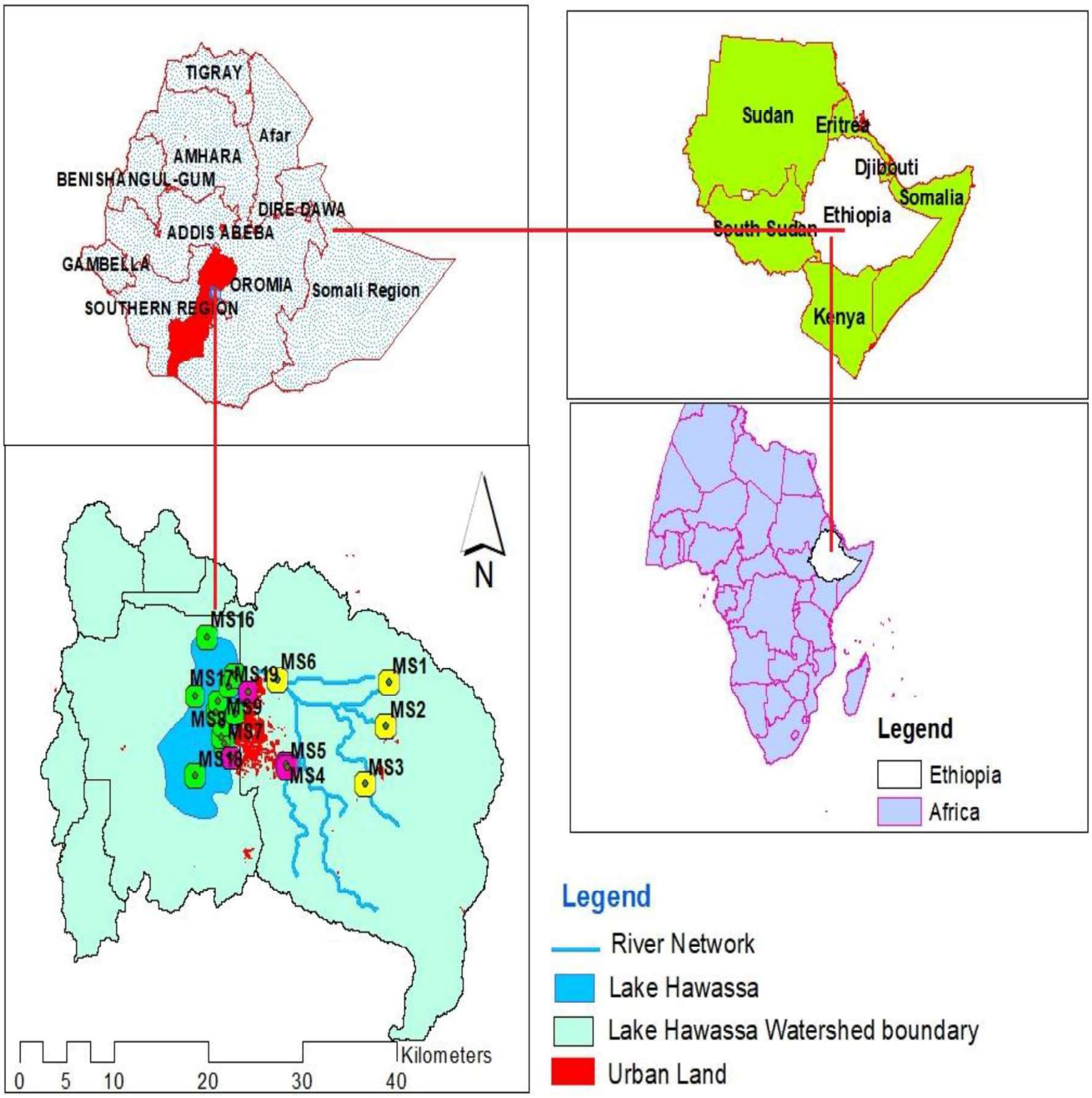

Figure 2.1. Location of Lake Hawassa Watershed and monitoring stations

### 2.2.2. Sampling and Analysis of Monitoring Parameters

Water and effluent samples were collected from rivers, point sources and different monitoring points from Lake Hawassa Watershed depending on the Lakes exposure to anthropogenic activities. The coordinate of each sampling station was determined applying GNSS.

In total 19 monitoring sites were selected purposively in close proximity to potential pollutants, accessibility, availability of point and non-point sources and level of disturbance where their effluents end up in the lake.

Four (4) monitoring sites selected from the eastern catchment of Lake Hawassa Watershed that exclusively comprises rivers namely Wesha (MS1), Hallow (MS2), Wedessa (MS3) and Tikur-Wuha (MS6) river mouths of the respective sub-watersheds. Eleven (11) monitoring sites were evenly distributed along the entire course of Lake Hawassa for estimation of the eutrophic status of the lake and water quality monitoring. Three (3) monitoring sites were selected from the industrial disposal site and one monitoring site is from the health care center as shown in Table 2.1 and Figure 2.1.

Samples of lakes and rivers were collected from different depths and intervals of the entire water column and mixed to make the sample composite. Referral hospital, Hawassa Industrial park, St. George Brewery industry (BGI) and Moha soft drinks factory effluents were collected from their respective oxidation ponds and discharge points using pre-cleaned 2 L polyethylene plastic bottles sterilized for Biochemical oxygen demand ($BOD_5$) and Chemical oxygen demand (COD).

The physicochemical and biological properties of water quality parameters can be monitored based on the required water parameters of concern. BOD and COD were selected to assess the presence of organic pollution. TN, TP, Nitrate ($NO_3^-$) and Soluble reactive phosphorous (SRP) were selected to monitor non-point sources pollution from agricultural land, urban drainage and residential lawns and the use of inorganic nitrogen fertilizers. Magnesium ion ($Mg^{+2}$), Calcium ion ($Ca^{+2}$), Sodium ion ($Na^+$), Potassium ion ($K^+$) and their empirical values, i.e. Sodium Adsorption Ratio (SAR), Kelly's ratio (KR), Magnesium Adsorption ratio (MAR) and Soluble sodium percentage (SSP) were selected to test the suitability of water for agricultural use and $Mg^{+2}$, $Ca^{+2}$, $Na^+$, $K^+$ were also selected to monitor water suitability for drinking purposes. Nitrite ($NO_2^-$) and Ammonia ($NH_3$) were selected to monitor the toxic effect of water for human consumption and marine life. Recreational water suitability is based on turbidity, Secchi depth (SD), Dissolved oxygen (DO) and BOD. TN, TP, Secchi depth and chlorophyll a (chl-a) were selected to monitor the trophic state of lake Hawassa. Turbidity was selected to measure the presence of suspended material whereas EC and TDS were used to monitor the amount of total dissolved substances in water or effluent. pH was selected to survey acidity or alkalinity of water or effluent and the temperature was selected as it is correlated negatively or positively with most of the water quality parameters. All the parameters analyzed in Table 2.2 below were generally selected by taking into consideration the appropriateness of water for human consumption, agricultural use, marine life and recreational uses.

Table 2.1: Monitoring stations in Lake Hawassa Watershed

| Code | Monitoring Sites | Latitude (Y) | Longitude (X) | Altitude (Z) |
|---|---|---|---|---|
| MS1 | Wesha river | 783,404 | 457,401 | 1746 |
| MS2 | Hallo river | 779,736 | 457,149 | 1724 |
| MS3 | Wedessa river | 774,914 | 454,915 | 1764 |
| MS4 | BGI effluent discharge site | 776,594 | 446,537 | 1686 |
| MS5 | Moha soft drinks factory | 776,274 | 446,603 | 1671 |
| MS6 | Tikur-Wuha river | 783,685 | 445,564 | 1677 |
| MS7 | Amora-Gedel (Fish market) | 778,279 | 439,983 | 1676 |
| MS8 | Amora-Gedel (Gudumale) | 778,862 | 439,661 | 1672 |
| MS9 | Nearby Lewi resort | 779,941 | 439,791 | 1683 |
| MS10 | Central part of lake (Towards FH) | 780,752 | 441,161 | 1681 |
| MS11 | Fikerhayk(FH) Recreation center | 780,917 | 439,074 | 1690 |
| MS12 | Center of the lake (towards HR) | 781,802 | 439,253 | 1682 |
| MS13 | Nearby Haile resort | 783,146 | 440,463 | 1685 |
| MS14 | Tikur-Wuha site | 784,000 | 441,060 | 1675 |
| MS15 | Referral Hospital | 777,088 | 440,668 | 1686 |
| MS16 | Ali-Girma site (opposite to HR) | 787,245 | 438,164 | 1690 |
| MS17 | Sima site (opposite to mount tabor) | 782,325 | 436,885 | 1686 |
| MS18 | Dore-Bafana Betemengist | 775,606 | 436,876 | 1683 |
| MS19 | Hawassa Industrial Park | 782,669 | 442,464 | 1690 |

The site codes indicated in Figure 1, FH designates Fikerhayk and HR designates Haile resort

Table 2.2: Analytical methods and instruments used for analysis

| **Parameters** | **Analytical Method and Instrument** |
|---|---|
| pH, EC, TDS and Temperature | Portable multi-parameter analyzer, Zoto, Germany |
| Turbidity | Nephelometeric (Hack, model 2100A) |
| DO | Modified Winkler |
| $BOD_5$ | Manometric, BOD sensor |
| COD | Closed Reflux, Colorimetric |
| SRP and TP | Spectrophotometrically by molybdovandate, HACH, model DR3900 |
| Secchi depth | Standard Secchi disk of 20 cm, Secchi disk, LaMotte 20 cmD, USA |
| $NO_3^-$ | Photometric measurements, Wagtech Photometer 7100 at 520 nm wavelength |
| $NO_2$- and TAN ($NH_4^+$-N + $NH_3$-N) | Spectrophotometrically by salicylate, (Hach, model DR3900) |
| TN | Spectrophotometrically by TNT Persulfate digestion, (HACH, model DR3900) |
| $Mg^{+2}$, $Na^+$, $K^+$ and $Ca^{+2}$ | Atomic Absorption Spectrophotometer, AAS, (Hach, model NOVAA400) |

TAN designates Total Ammonium nitrogen

Water sample collection, handling, preservation and treatment techniques followed the standard methods outlined for the examination of water and wastewater by the American public health association guidelines [35].

### Un-Ionized Ammonia Determination from Total Ammonium Nitrogen (TAN)

The mass action law in its logarithmic form (1) calculated the un-ionized free ammonia. The pKa as function of temperature was taken from [36]:

$$\%\ \text{Un - ionized}\ \ NH_3 - N = \frac{1}{\left(1 + 10^{(pK_a - pH)}\right)} \tag{1}$$

$$pK_a = \frac{0.09108 + 2729.92}{(T_k)} \tag{2}$$

where, $T_k$ is temperature in kelvin (273 + °C).

### 2.2.3. Weighted Arithmetic Water Quality Index Method (WA WQI)

In the literature, the weighted arithmetic water quality index method (WA WQI) was developed [10,20,37–40] in a large number of studies.

WQI was determined by utilizing the weighted arithmetic index method in the following steps. Water quality parameters (n) and quality rating ($q_n$) associated to the nth parameter is a number defining the relative value of this parameter in the polluted water with respect to its standard value.

**Methodology in Calculating WQI Using the WA WQI Method**

WQI initially proposed by [41] and advanced by Brown et al. [42] as cited by [20,43,44].

Calculate unit weight ($W_n$) for the nth parameters:

$$W_n = \frac{K}{S_n} \tag{3}$$

Define proportionality constant "K" value using formula:

$$K = \frac{1}{\sum_{i=1}^{n} \frac{1}{S_n}} \tag{4}$$

Sub-index or quality rating ($q_n$) for nth parameter can be calculated using the following formula:

$$q_n = 100 * \left(\frac{V_n - V_i}{V_s - V_i}\right) \tag{5}$$

where, $v_s$ is Standard value for the nth parameter, $v_n$ is measured value of the nth parameter, $v_i$ is the ideal value of nth parameter and in most cases $v_i = 0$ except for pH (7) and DO (14.6) [45].

Quality rating ($q_n$) for pH and DO can be determined using the formula given below.

$$q_{pH} = 100 * \left( \frac{V_{pH} - 7}{V_s - 7} \right) \tag{6}$$

$$q_{DO} = 100 * \left( \frac{V_{DO} - 14.6}{V_s - 14.6} \right) \tag{7}$$

The water quality index (WQI) determined using the formula below and the water quality rating {46] depicted in Table 3.

$$WQI = \frac{\sum_{i=1}^{n} q_n * W_n}{\sum_{i=1}^{n} W_n} \tag{8}$$

Table 2.3: Water quality index (WQI) and water quality rating

| WQI | Water Quality Rating |
|---|---|
| 0–25 | Excellent |
| 26–50 | Good |
| 51–75 | Poor |
| 76–100 | Very poor |
| >100 | Unsuitable |

### 2.2.4. Canadian Council of Ministries of the Environment Water Quality Index (CCME WQI)

In CCME WQI, the WQI can easily be adopted to the local situations as it permits flexibility in selecting parameters. A number of studies applied CCME WQI in different parts of the world for the evaluation of suitability of water quality for drinking, irrigation and aquatic life [47] in Turkey [48], India [12,49,50], Albania [51] and Iran [52,53] and in different parts of Ethiopia [10,54,55] and elsewhere.

In CCME WQI, three factors, Scope (F1); Frequency (F2) and Amplitude (F3) are integrated mathematically from designated water quality objectives [52].

They provide an arithmetic value of CCME WQI water quality status in between 0 (poor) and 100 (excellent) in five descriptive classes as described in Table 2.4 [16, 48, 56, 57].

Table 2.4: Canadian Council of Ministries of the Environment Water Quality Index (CCME WQI) Water quality categorization.

| WQI | Water Quality Status | Remark |
|---|---|---|
| 95–100 | Excellent | Water quality is protected with a virtual absence of threat or impairment; conditions very close to the natural or pristine conditions. These index value can be obtained if all measurements are within objectives virtually all of the time. |
| 80–94 | Good | Water quality is protected with only a minor degree of threat or impairment: conditions rarely depart from natural or desirable levels. |
| 65–79 | Fair | Water quality is usually protected but occasionally threatened or impaired; conditions sometimes depart from natural or desirable levels. |
| 45–64 | Marginal | Water quality is frequently threatened or impaired; conditions often depart from natural or desirable levels. |
| 0–44 | Poor | Water quality is almost always threatened or impaired; conditions usually depart from natural/desirable level. |

**CCME WQI Calculation Methods**

The WQI was computed based on the three parameters F1, F2 and F3 for the intended purposes. $F_1$ (Scope) represents the number of water quality variables that violate the standards:

$$F_1 = \left( \frac{\text{Number of failed variables}}{\text{Total number of variables}} \right) * 100 \qquad (9)$$

$F_2$ (Frequency) represents the number of times the standards are violated:

$$F_2 = \left( \frac{\text{Number of failed tests}}{\text{Total number of tests}} \right) * 100 \qquad (10)$$

$F_3$ (Amplitude) represents the amount by which the standards are not met and determined in three steps.

The number of times by which an individual concentration is greater than (or less than, when the objective is a minimum) is termed excursion and expressed as follows:

When the test value must not exceed the objective,

$$\text{Excursion}_i = \left( \frac{\text{Failed test value}}{\text{Objective } j} \right) - 1 \qquad (11)$$

When the test value must not fall below the objective,

$$\text{Excursion}_i = \left( \frac{\text{Objective } j}{\text{Failed test value}} \right) - 1 \tag{12}$$

$$\text{nse} = \sum_{i=1}^{n} \frac{\text{Excursion } j}{\text{Total number of tests}} \tag{13}$$

F3 is then determined by an asymptotic function that scales the normalized sum of the excursions from objectives (nse) to yield a range between 0 and 100:

$$F_3 = \left( \frac{\text{nse}}{0.01\text{nse} + 0.01} \right) \tag{14}$$

Finally, CCME WQI:

$$\text{CCMEWQI} = 100 - \left( \frac{\sqrt{F_1^2 + F_2^2 + F_3^2}}{1.732} \right) \tag{15}$$

### 2.2.5. Evaluation of the Trophic Status Using Carlson Trophic State Index (TSI) Model

The Carlson Trophic State Index is the conventional approach that depends on the changes in nutrient level of lakes and reservoirs that are responsible for algal biomass production and that were known by decreasing Secchi disk transparency [26]. The Carlson‘s Trophic State Index is the most widely used scheme [27]. It integrates all the parameters into a single form so that a general condition could easily be communicated [22,26 27].

### Method to Determine Trophic State Index

Various approaches have been established to quantify the trophic state (TS) of lakes. Carlson‘s Trophic Status Index was selected for the present study were given below in Table 2.5 [58]. Carlson‘s TSI is a common technique to distinguish a lake‘s trophic state and presented Range of the Carlson‘s Trophic Status Index (TSI) values and classification of lakes [27]. This method delivers a more detailed calculation of the trophic status than the other conservative approaches that only provide a coarse trophic state estimation presented in [22,59,60].

Table 2.5: Range of the Carlson‘s Trophic Status Index (TSI) values and classification of lakes

| TSI | Classification | Description |
|---|---|---|
| <40 | Oligotrophic | Deep lakes still exhibit classical oligotrophy, but some shallower lakes become anoxic in the hypolimnion during the summer. |
| 40 < = TSI < 50 | Mesotrophic | Water moderately clear, but increasing pro ability of anoxic in hypolimnion during summer. |
| 50 < = TSI < 70 | Eutrophic | Dominance of blue-green algae, algal scum probable, extensive macrophyte problems. |
| TSI > = 70 | Hypereutrophic | Algal scum, summer fish kills, few macrophytes, dominance of rough fish. |

The following equations can be used to compute the Carlson‘s TSI.

$$\mathrm{TSI\,(TN)} = 54.45 + 14.43 * \ln\,(\mathrm{TN})\,(\mathrm{mg/L}) \tag{16}$$

$$\mathrm{TSI\,(TP)} = 14.42 * \ln\,(\mathrm{TP}) + 4.15\,(\mu g/L) \tag{17}$$

$$\mathrm{TSI\,(Chl\,a)} = 9.81 * \ln\,(\mathrm{chla}) + 30.6\,(\mu g/L) \tag{18}$$

$$\mathrm{TSI\,(SD)} = 60 - 14.41 * \ln\,(\mathrm{SD})(\mathrm{m}) \tag{19}$$

where SD the Secchi depth, chla is chlorophyll a, TP is total phosphorous and TN is total nitrogen

Eutrophic ecosystems are described by referring to the supplies of growth-limiting nutrients and water having relatively large supplies of nutrients, and are termed eutrophic (well nourished), poor nutrient supplies (oligotrophic) and intermediate nutrient supplies are termed mesotrophic. They categorize the trophic status of the lake based on the total nitrogen (TN) and total phosphorous (TP) loads in Table 2.6 that are supposed to be accumulated in the lake bottom [61–63].

Table 2.6: Trophic classification of lakes based on total nitrogen and total phosphorous

| Trophic State | TN (mg/L) | TP (mg/L) |
|---|---|---|
| Oligotrophic | <0.35 | <0.01 |
| Mesotrophic | 0.35 < = TN < 0.65 | 0.01 < = TP < 0.03 |
| Eutrophic | 0.65 < = TN < 1.2 | 0.03 < = TP < 0.1 |
| Hypertrophic | TN > 1.2 | TP > 0.1 |

### 2.3. Result and Discussion

### 2.3.1. Water Quality Status for Envisioned Purposes

Selection of parameters is imperative for calculation of WQI and depends on the intended use. A selection of large number of parameters broaden the water quality index, pH, EC, TDS, turbidity, $NH_3$, $NH_3$-N, $NO_2$-, $NO_3^-$, $NO_3$-N, DO, BOD, COD, $Mg^{+2}$, $Ca^{+2}$, $Na^+$, $K^+$, temperature, SAR, KR, MAR, SSP and SD are used to evaluate the suitability of Lake Hawassa Watershed for drinking, irrigation uses, recreation and aquatic life [46].

#### 2.3.1.1. pH

In WQI, computation pH is an imperative parameter that determines the suitability of water for the various purposes. The results of the study depicted in Table 2.7 and Figure 2.2a. The pH value of the water indicated that the watershed is slightly alkaline as it varied between 7.6 (MS1) and 9.1 (MS5). However, the pH of the Lake Hawassa Watershed is within the permissible limits i.e., 6.5–8.5/9 [64–66] for rivers and lakes. A high value of pH is observed in the wet season, which might be due to the dissolution of carbon dioxide and nutrients produced during bacterial decomposition of domestic wastes near the lake [67].

The average pH values for the upper and middle monitoring stations of four rivers is 7.99 having an average value of 7.6 at (MS1), 8.1 at (MS2), 8.03 at (MS3) and 7.55 at (MS6) all of which are in accordance with the permissible limit prescribed by the WHO. The finding of this study is comparable with the previous studies conducted by Kebede et al. [30] and Teshome [55] on the eastern catchment of Lake Hawassa Watershed.

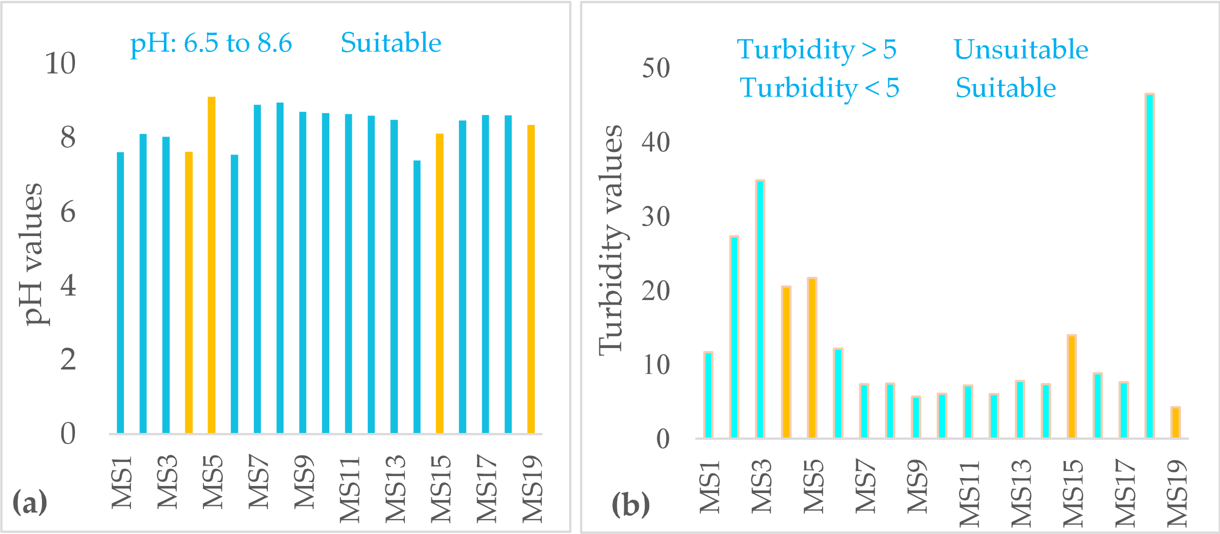

Figure 2.2. pH (a) and turbidity (NTU) (b) in the water and wastewater samples (n = 19) collected over 19 monitoring stations with wastewater samples labeled yellow in the Lake Hawassa Watershed.

The average value of pH measured from point sources in monitoring stations MS4, MS5, MS15 and MS19 were 7.62, 9.1, 8.1 and 8.34, respectively. The average pH value of the Lake Hawassa is 8.5 for this study and comparative observations were made in Lake Hawassa with previous studies conducted by Abiye [33] who found an average value (pH = 8.5) and showed an increment from the results of Worako [6] and Yogendra and Puttaiah [44] (pH = 7.5) elsewhere. It is very probable that the increased pH values are mainly due to the consumption of dissolved carbon dioxide by the autotrophic biomass in the upper layer of the eutrophic lake. These conditions may completely change in deeper layers, where due to the absence of light heterotrophic degradation processes should be dominant [68].

Table 2.7: Descriptive statistics: mean and standard deviation (in bracket) of the physicochemical characteristics for 19 monitoring stations in Lake Hawassa Watershed for evaluation of WA WQI for drinking, irrigation, aquatic life and recreational purposes.

| Parameters | S1/S2/S3/S4/S5 | MS1 | MS2 | MS3 | MS4 | MS5 | MS6 | MS7 | MS8 | MS9 | MS10 | MS11 | MS12 | MS13 | MS14 | MS15 | MS16 | MS17 | MS18 | MS19 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Turbidity | $5^{ac}$ $50^{d}$ | 11.7 | 27.3 | 34.8 | 20.5 | 21.7 | 12.2 | 7.4 | 7.4 | 5.7 | 6.1 | 7.2 | 6 | 7.8 | 7.3 | 14 | 8.8 | 7.6 | 46.5 | 4.2 |
| | | (3.7) | (18.3) | (8.7) | (14.2) | (10.1) | (0.2) | (2.5) | (0.4) | (1.3) | (0.5) | (0.1) | (0.8) | (1.7) | (3.4) | (1.7) | (0.2) | (0.1) | (5.9) | (0.6) |
| TDS | $1000, 2000^{ab}$ | 84.3 | 83 | 79 | 1704 | 2129 | 224 | 391 | 484 | 417 | 458 | 464 | 464 | 412 | 247 | 1491 | 476 | 475 | 518 | 776 |
| | | (6.9) | (24) | (11.7) | (183) | (312) | (132) | (4) | (48.6) | (37) | (21) | (2.1) | (4.7) | (0.8) | (157) | (199) | (9.2) | (5.1) | (61) | (409) |
| EC | $1500,3000^{ab}$ | 169 | 166 | 158 | 3768 | 4257 | 446 | 776 | 835 | 822 | 932 | 924 | 928 | 799 | 491 | 2984 | 882 | 908 | 1084 | 1614 |
| | | (14) | (48) | (23) | (81) | (623) | (266) | (16) | (23) | (104) | (33) | (62) | (10) | (11) | (316) | (399) | (75) | (38) | (69) | (6.3) |
| pH | $6.5–9^{abcd}$ | 7.6 | 8.1 | 8 | 7.6 | 9.1 | 7.5 | 8.9 | 9 | 8.7 | 8.7 | 8.7 | 8.6 | 8.5 | 7.4 | 8.1 | 8.5 | 8.6 | 8.6 | 8.3 |
| | | (0.8) | (0.8) | (0.4) | (0.7) | (0.5) | (0.03) | (0.1) | (0.1) | (0.001) | (0.2) | (0.1) | (0.04) | (0.1) | (0.1) | (0.2) | (0.2) | (0.02) | (0.2) | (0.1) |
| $NH_4$-N | | 2.33 | 1.07 | 1.0 | 6.18 | 5.09 | 0.28 | 1.87 | 7.35 | 0.83 | 0.13 | 4.1 | 1.72 | 0.66 | 1.85 | 16.81 | 3.56 | 3.1 | 0.65 | 0.12 |
| | | (3.23) | (1.24) | (1.26) | (4.1) | (1.56) | (0.29) | (2.18) | (3.52) | (0.67) | (0.003) | (0.6) | (0.53) | (0.72) | (0.93) | (14.55) | (0.01) | (0.01) | (0.18) | (0.09) |
| $NH_3$ | $1.5,1.37^{b}$ | 0.14 | 0.19 | 0.1 | 0.43 | 8.9 | 0.01 | 1.23 | 4.47 | 0.29 | 0.04 | 1.34 | 0.46 | 0.14 | 0.41 | 2.25 | 0.75 | 0.95 | 0.23 | 0.02 |
| | | (0.2) | (0.27) | (0.13) | (0.36) | (6.31) | (0.01) | (1.52) | (1.29) | (0.22) | (0.01) | (0.48) | (0.14) | (0.14) | (0.15) | (2.36) | (0.22) | (0.07) | (0.14) | (0.01) |
| $NO_2^-$ | $3^{a}$ | 0.03 | 0.08 | 0.08 | 0.02 | 0.13 | 0.06 | 0.03 | 0.03 | 0.14 | 0.03 | 0.02 | 0.02 | 0.04 | 0.02 | 0.03 | 0.02 | 0.08 | 0.04 | 0.08 |
| | | (0.01) | (0.08) | (0.01) | (0.01) | (0.01) | (0.01) | (0.01) | (0.002) | (0.15) | (0.03) | (0.01) | (0.02) | (0.04) | (0.001) | (0.02) | (0.01) | (0.02) | (0.02) | (0.004) |
| $NO_3^-$ | $45,1^{ac}$ | 2.9 | 1.6 | 3.1 | 12.2 | 2.3 | 3.0 | 3.6 | 3.7 | 11.2 | 3.1 | 17.4 | 4.2 | 19.4 | 4.5 | 11.5 | 4 | 4.4 | 4.2 | 3.8 |
| | | (0.02) | (0.04) | (0.5) | (0.1) | (0.8) | (2.3) | (0.7) | (0.7) | (3.3) | (0.8) | (6.8) | (0.4) | (7.8) | (1.6) | (6) | (0.4) | (0.02) | (0.02) | (0.5) |
| SRP | $5^{b}$ | 5.3 | 14.3 | 4.5 | 20.2 | 76.8 | 4.1 | 2.3 | 3.2 | 2.3 | 2.5 | 1.8 | 2 | 2.9 | 3.6 | 28 | 3.5 | 2.7 | 6.9 | 8 |
| | | (1.9) | (4.7) | (4.8) | (1.8) | (47) | (2.3) | (0.2) | (1.1) | (0.8) | (0.04) | (0.2) | (0.3) | (0.2) | (0.2) | (9.8) | (0.5) | (0.1) | (1) | (2.1) |
| DO | $5^{cd}$ | 5.4 | 4.8 | 5.1 | 1.8 | 0.9 | 4.8 | 4.9 | 5.2 | 4.1 | 4.5 | 3.4 | 4.6 | 3.6 | 3.1 | 1.5 | 4.5 | 4.3 | 4.5 | 4.4 |
| | | (1.8) | (1.8) | (1) | (0.4) | (0.04) | (1.2) | (0.7) | (0.1) | (0.02) | (0.3) | (0.1) | (0.04) | (0.6) | (0.5) | (0.04) | (0.2) | (0.3) | (0.4) | (0.41) |
| BOD | $5^{acd}$ | 10.9 | 14.2 | 41 | 48 | 218 | 4.6 | 8.1 | 9.2 | 11.9 | 40.2 | 7.4 | 10.9 | 35.6 | 16.1 | 56.4 | 19.3 | 45 | 56.4 | 104 |
| | | (4.1) | (13.4) | (40) | (21.6) | (131) | (0.9) | (3.1) | (0.4) | (2.9) | (44.7) | (2.3) | (1.0) | (16.5) | (5.8) | (9.9) | (4.6) | (4.2) | (1.3) | (30.6) |
| COD | $20^{a}$ | 129 | 101 | 186 | 215 | 589 | 35 | 178 | 136 | 52.4 | 193 | 90 | 55.4 | 171 | 140 | 252 | 64.4 | 150 | 188 | 416 |
| | | (58) | (9) | (181) | (69) | (393) | (12.4) | (87.1) | (1.4) | (10.5) | (189) | (7.8) | (13.2) | (119) | (8.8) | (53.7) | (15.7) | 14.1) | (4.2) | (5.7) |
| $Mg^{2+}$ | $200^{a}$ | 10 | 16.9 | 84 | 12.2 | 5 | 4.3 | 5.4 | 4.1 | 14.1 | 5 | 5.2 | 7.5 | 11.2 | 5.7 | 10.6 | 2.9 | 12.3 | 14.7 | 14.4 |
| | | (4.2) | (10) | (98) | (1.1) | (3) | (2) | (0.5) | (0.2) | (1.9) | (0.4) | (0.3) | (3.7) | (3.3) | (0.9) | (44) | (0.4) | (2.5) | (1.9) | (5.5) |
| $Ca^{2+}$ | $100^{a}$ | 32.8 | 17.4 | 19 | 43.8 | 26.4 | 22.5 | 21.5 | 22 | 19.5 | 25 | 23.8 | 28.8 | 35 | 20.5 | 35.7 | 7.8 | 32.6 | 32.4 | 46.9 |
| | | (18) | (12) | (20) | (9.3) | (16) | (5.4) | (7.4) | (3.2) | (3.7) | (9.3) | (4.1) | (4.1) | (8.3) | (5.2) | (2.8) | (1.4) | (1.7) | (2.3) | (9.7) |
| $Na^+$ | $200^{a}$ | 28.4 | 22.6 | 22 | 429 | 895 | 83 | 204 | 217 | 189 | 217 | 199.4 | 218.2 | 249 | 110 | 316 | 182 | 143 | 232 | 261 |

| | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | (5.8) | (5.1) | (5.3) | (101) | (259) | (41) | (26) | (54) | (4.6) | (10.1) | (8.1) | (9.6) | (45) | (58) | (148) | (21) | (22) | (17) | (58) |
| $K^+$ | $20^a$ | 6 | 7.3 | 5.7 | 18 | 18.2 | 7.9 | 19.2 | 21.1 | 20.4 | 19.6 | 19.1 | 23.9 | 18.5 | 12.1 | 94.6 | 15.8 | 15.7 | 17.8 | 21.7 |
| | | (0.9) | (1.1) | (1.5) | (2.5) | (1.6) | (2.2) | (1.3) | (1.5) | (0.5) | (0.6) | (2.2) | (0.8) | (0.7) | (6.5) | (70.6) | (3.2) | (3.2) | (1.8) | (1.2) |
| Temperature | $15–20^{ac}$ | 17.4 | 16.6 | 17.2 | 33.6 | 30 | 23.2 | 22.6 | 22.3 | 22.2 | 20.6 | 22.6 | 21.6 | 23.2 | 20 | 25.4 | 22.1 | 23.1 | 23.8 | 21.36 |
| | | (2.5) | (1.56) | (1.2) | (0.37) | (1.4) | (1.94) | (0.26) | (0.68) | (0.79) | (0.91) | (0.83) | (1.5) | (1.1) | (1.06) | (2.12) | (0.93) | (1.6) | (1.05) | (0.16) |
| SAR | $26^b$ | 0.25 | 0.3 | 0.14 | 10.9 | 0.93 | 0.4 | 0.97 | 1.1 | 0.85 | 0.95 | 0.93 | 1.02 | 0.7 | 0.62 | 3.62 | 1.22 | 0.59 | 0.65 | 0.7 |
| | | (0.1) | (0.03) | (0.04) | (0.05) | (0.37) | (0.12) | (0.2) | (0.02) | (0.03) | (0.15) | (0.16) | (0.06) | (0.07) | (0.37) | (2.81) | (0.12) | (0.09) | (0.04) | (0.14) |
| KR | $1^b$ | 0.13 | 0.14 | 0.05 | 0.24 | 0.6 | 0.23 | 0.57 | 0.64 | 0.4 | 0.53 | 0.52 | 0.5 | 0.3 | 0.37 | 1.6 | 1.08 | 0.26 | 0.27 | 0.28 |
| | | (0.08) | (0.01) | (0.03) | (0.01) | (0.4) | (0.08) | (0.19) | (0.02) | (0.02) | (0.12) | (0.12) | (0.04) | (0.07) | (0.23) | (1.3) | (0.02) | (0.02) | (0.002) | (0.1 |
| MAR | $50^b$ | 34.9 | 60.2 | 70.2 | 32 | 24 | 24.4 | 30.3 | 23.8 | 54.7 | 26 | 26.9 | 30 | 34.5 | 32.2 | 32.6 | 38.6 | 38.4 | 42.9 | 33.3 |
| | | (3.5) | (30.5) | (39.7) | (6.7) | (0.25) | (13.2) | (5.5) | (3.6) | (8.1) | (8.7) | (4.53) | (13.3) | (1.3) | (8.8) | (10.9) | (1.26) | (3.67) | (1.42) | (4.1) |
| SSP | $50^b$ | 30.8 | 28.1 | 12.9 | 78.3 | 92.6 | 60.9 | 79.2 | 81.7 | 72.7 | 79.4 | 78.5 | 76.2 | 73 | 66.7 | 82.1 | 89.4 | 62 | 70.3 | 68.5 |
| | | (14.9) | (1.96) | (8.5) | (1.97) | (5.8) | (12.8) | (6.2) | (1.8) | (0.06) | (5) | (2.8) | (0.3) | (1.9) | (14.7) | (0.34) | (0.33) | (1.24) | (0.42) | (1.8) |

All units are in mg/L except turbidity, EC, temperature, SAR, KR, MAR, SSP and pH which were expressed in NTU, µS/cm, °C, meq/L, % and non-dimensional, respectively. (a) Labels drinking use, (b) irrigation water use, (c) express water use for aquatic life and (d) designates recreational water use. S1 labels Standard values taken from World Health organization (WHO), S2 labels Standard values taken from Environmental protection Agency (EPA) of US or Ethiopia, S3 labels Standard values taken from Canadian Council of Ministries of the Environment (CCME), S4 labels Standard values taken from Food for Agricultural organization (FAO) and S5 labels standard values taken from Health Canada (HC).

#### 2.3.1.2. Turbidity

The turbidity in monitoring stations ranges from 4.24 to 46.5 NTU. The average turbidity value for rivers were 21.5 NTU, Lake Hawassa was 10.7 NTU and point sources were 15.1 NTU. The turbidity of the study watershed is higher than the recommend value by [16, 65, 69] for drinking and aquatic life, except at MS19 (4.24). The highest value of turbidity was recorded at MS18 (46.5 NTU) followed by MS3 (34.8) sampling stations; whereas, the minimum value of turbidity was recorded at MS19 (4.24 NTU) sampling station (Table 2.7 and Figure 2.2b).

The high values of turbidity could be attributed to agricultural and urban runoff from the catchment area, the loading of rivers and the lake with silt during the wet season and high human intervention in the river and lake water for multi purposes, and discharge of effluents from MS4, MS5, MS15 and MS19. The high turbidity value from industries might be due to organic matter decomposition present in the effluents [9, 10, 67, 70]. There is also a moderate positive correlations observed between turbidity with chl-a ($r = 0.6$ at $p < 0.005$) and COD values ($r = 0.6$at $p < 0.005$). The result of this study also showed Lake Hawassa water clarity is low as evidenced by lower SD (0.76 m) and TSI of 65.4 leading to high nutrient concentrations, high algal blooms but low light penetration and low water clarity. Lack of clarity limits the light penetration rendering greater impacts on algae and macrophytes while degradation of organic matter in deeper layers can lead to the depletion of oxygen and subsequently fish kill [71]. The recreational use of water is reduced due to lack of clarity as the value of Secchi depth for lake Hawassa was lower than the recommended limit of 1.2 m [72] and turbidity value was higher [73]. Most natural waters have turbidities less than 50 NTU [74].

High turbidity also reduces the efficiency of disinfectant in water supplies for drinking purposes and cause a health risk by enhancing the growth of bacteria during storage. Hence, special attention ought to be given to the turbidity of Lake Hawassa Watershed as its value lies within a level that could pose a health risk and reduces the disinfection process in water supplies.

#### 2.3.1.3. Nitrate ($NO_3^-$), Nitrate-Nitrogen ($NO_3$-N) and Nitrite ($NO_2^-$), Nitrite Nitrogen ($NO_2$-N)

The WHO guideline recommends 50 mg/L for nitrate ion, (11 mg/L) as $NO_3$-N and 3 mg/L of nitrite ion and (0.9 mg/L) as $NO_2$-N for safe human consumption. In the studied watershed, these values were far below the prescribed limit. The average nitrate ($NO_3^-$), nitrate-nitrogen ($NO_3$-N) and nitrite ($NO_2^-$) concentrations of rivers were 2.7, 0.6 and 0.06 mg/L respectively and that of point sources were 7.5, 1.7 and 0.06 mg/L, respectively. The average nitrate ($NO_3^-$), nitrate-nitrogen ($NO_3$-N) and nitrite ($NO_2^-$) concentrations of Lake Hawassa were 7, 1.7 and 0.04 mg/L, respectively (Table 2.7 and Figure 2.3). The study conducted by Camargo and Alonso [75] have shown that a $NO_3$-N concentration of 10 mg/L $NO_3$-N can adversely affect sensitive aquatic animals in the course of long-term exposure.

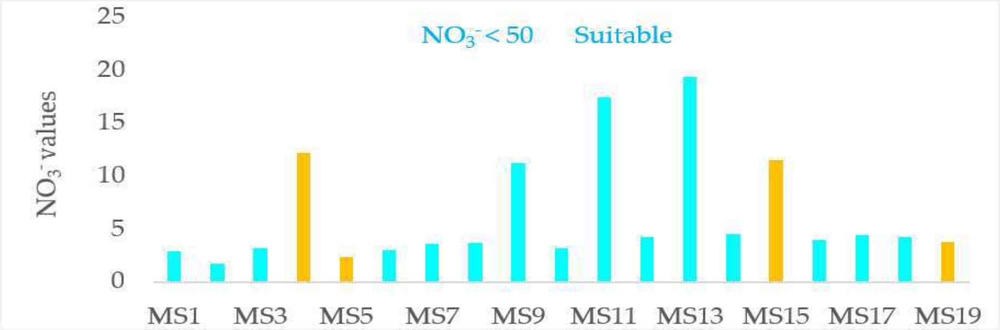

Figure 2.3. Nitrate (NO3-) concentrations (mg/L) in the water and wastewater samples (n = 19) collected over 19 monitoring stations with wastewater samples labeled yellow at the Lake Hawassa Watershed.

The measured concentrations are significantly higher than the study conducted by Tilahun and Ahlgren [29] on Hawassa and Chamo lakes and reported that the mean concentration of $NO_3$-N was about 0.0025 and 0.003 mg/L in Lakes Hawassa and Chamo respectively. This indicates a dramatic worsening of the situation in Lake Hawassa in the last 10 years. This might be due to input of fertilizer application by agricultural land, effluents from industrial facilities and sewage from health care centers and domestic sewage from service rendering facilities and urban run off as compared to the last decade. Similarly, Tibebe et al. [76] and Fetahi [77] reported lower average results of $NO_3$-N (0.21) and (0.042) mg/L in Lakes Zeway and Hayq. Currently, the people in the peripheries of the city uses the lake for drinking purpose as well.

**Nitrite-nitrogen ($NO_2$-N)**

The average nitrite-nitrogen ($NO_2$-N) concentrations of rivers, point sources and Lake Hawassa were 0.02, 0.01 and 0.02 mg/L respectively (Table 2.7). Nitrite in excess concentration is toxic to fish and aquatic species [75]. The mean $NO_2$-N concentration observed in this investigation (0.01

mg/L) for Lake Hawassa was comparable to that of Tamire and Mengistou [78] who reported 0.01 mg/L and lower than Tibebe et al. [76] who reported 0.5 mg/L for Lake Ziway, respectively.

#### 2.3.1.4. Dissolved Oxygen (DO)

The current investigation showed the variation in the DO value of Lake Hawassa Watershed ranged from 3.12 to 5.2 mg/L and the highest value was recorded at MS1 (5.4) Wesha river in the upper catchment and the lowest value was recorded at MS5 (0.9) at Moha soft drinks factory factory). The average DO value of rivers were 5 mg/L, Lake Hawassa was 4.3 mg/L and point sources were 2.2 mg/L (Table 2.7).

The DO levels were below the acceptable limit (<5 mg/L) of EPA for samples collected from lakes, indicating the impairment of the water body for aquatic life [79]. The major cause for lowering of DO was the point sources having the average DO value of 2.2 mg/L. The findings of this study agree with the previous studies conducted by Abiye [33], Zemede et al. [10] and are much lower than that of Worako [6] on Lake Hawassa.

The amount of DO regulates how the species of phytoplankton and zooplankton are distributed in aquatic ecosystems [44]. Decomposition of nutrient and submerged plants on the lake, biodegradable organic matter and urban and agricultural runoff might be the reason for the presence of low dissolved oxygen [80,81]. Most of the species of fish can survive short-term exposure to the lowered DO [82] and the threshold of 3 mg/L dissolved oxygen level should be maintained to safeguard from significant critical effects [83].

#### 2.3.1.5. Chemical Oxygen Demand (COD) and Biological Oxygen Demand ($BOD_5$)

#### Chemical Oxygen Demand (COD)

COD represents the total oxygen demand of the organic matter, independent from its origin and degradability. The average COD value of rivers were 113 mg/L, Lake Hawassa was 129 mg/L and point sources had an average value of 368 mg/L (Table 2.7 and Figure 2.4b). COD of the industrial point sources can be clearly assigned to primary pollution while a COD of the lake water may be partly caused by the phytoplankton.

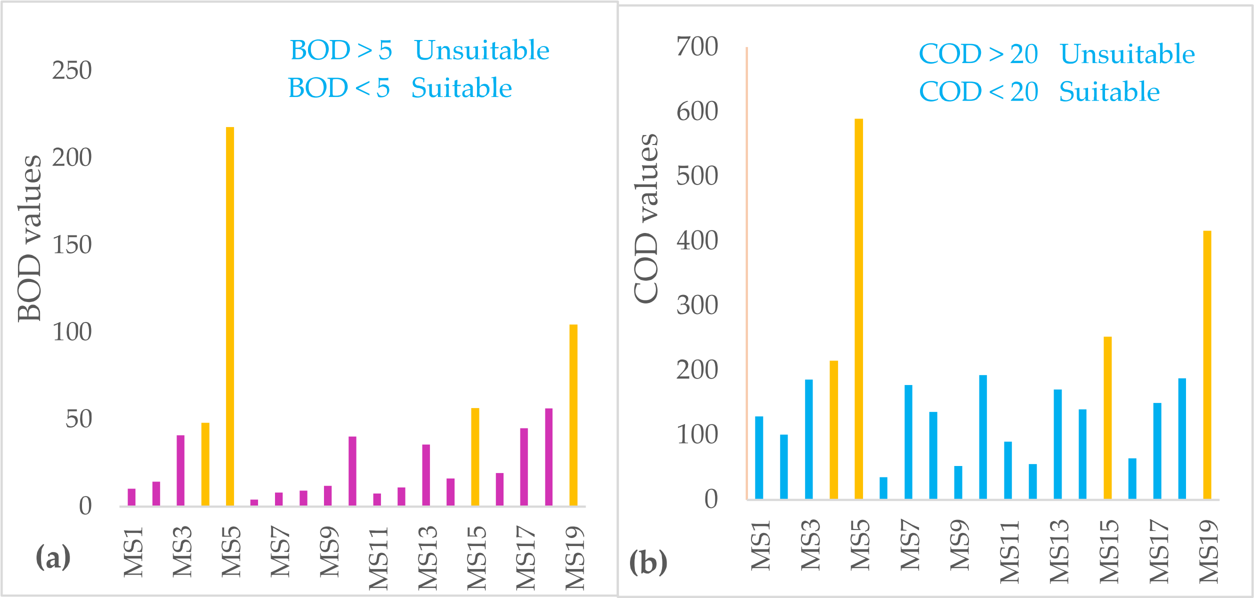

Figure 2.4. Biological oxygen demand (BOD) (a) and chemical oxygen demand (COD) (b) concentrations (mg/L) in the water and wastewater samples (n = 19) collected over 19 monitoring stations with wastewater samples labeled yellow at the Lake Hawassa Watershed.

The COD analysis for Lake Hawassa ranges from 52 mg/L (MS9) to 193 mg/L (MS10) and higher values of COD were observed at sampling locations of MS7 (178 mg/L), MS8 (136 mg/L), MS10 (193 mg/L), MS13 (171 mg/L), MS14 (140 mg/L), MS17 (150 mg/L) and MS18 (188 mg/L). The most heavily polluted site was MS10 (Fikerhayk recreation center), where there are hotels, restaurants, cafés, boating activities and it is that part where the lake experiences maximum human intervention almost every day whereby flushing and forgetting is business as usual. MS7 (Amora-Gedel) and MS8 (Gudumale) was heavily polluted sites where there was a small fish market around that site. Additionally, the Gudumale recreation center situated near this site was serving as a location for marriage ceremonies, for various events like gatherings, and the people of Sidama celebrate a new year (Fiche-Chambala) at this site. All the waste products were discharged from the two sites to the nearby lake in diffused form and also people around these site uses the lake water for cloth washing and bathing purposes. MS17 and MS18 monitoring sites were located on the western (North West to southwest) sides of the lake. Although there is no point source pollution in these parts of the lake but there are enormous anthropogenic activities in the form of nonpoint source of pollution from the recreational activities, agricultural runoff and animal waste. MS13 monitoring stations located near Haile resort and Hawassa industrial park where the park directly discharges its effluent directly to the lake. MS14 was also located on the northeast part of the lake where Tikur-Wuha River joins the lake at this station and there are recreational and fishing activities. Moreover, the urban runoff makes its way to the lake from the above monitoring stations during the rainy season. Generally, the COD value were higher in monitoring stations indicating the presence of higher organic matter impeding the lake water quality. Hence, designing and implementing riparian buffers strips of vegetation and grasses around the periphery of Lake Hawassa is imperative to safeguard it. The findings are higher than that of Abiye [33] who found an average value of 78 mg/L for lake Hawassa owing to the impact of urbanization-related activities, such-as domestic sewage and urban runoff that contains organic matter. This reveals that there has been a visible change of water quality impediment isn the last 13 years due to the domestic and industrial sewage and urban runoff.

**Biological Oxygen Demand ($BOD_5$)**

The average $BOD_5$ value of rivers were 17.3 mg/L, Lake Hawassa was 23.6 mg/L and point sources were 106.6 mg/L showing point sources are the cause for pollution of the lake (Table 2.7 and Figure 2.4a). Rivers or lakes are considered unpolluted if the average value of BOD < 3 mg/L, however, BOD > 5.0 mg/L was recorded in all 19 monitoring stations signposting possible pollution [38].

Releasing liquid wastewater with higher BOD causes impairments in water quality such as DO decline and fish kills in the receiving water bodies [84]. The concentration of BOD5 in the area under investigation is beyond the permissible limits of WHO and EPA guidelines (<5 mg/L) for human consumption and aquatic life in the study watershed; which indicates the water in the watershed is highly polluted by organic matter.

BOD is a parameter used to judge the presence of organic load in a water body and also used as an indicator of whether a water body is in a eutrophied state. Higher BOD levels of a water body are associated with lower dissolved oxygen levels [44]. Those involved in recreational facilities are probably most at risk due to eutrophic conditions [85]. The findings are lower than that of Zemede et al. [82] who recorded an average value of 44.9 mg/L for Lake Hawassa.

### 2.3.1.6. Total Ammonia Nitrogen ($NH_4$-N + $NH_3$-N)

Total ammonia nitrogen (TAN) is the sum of ammonium nitrogen in ionized form ($NH_4$-N) and un-ionized ammonia nitrogen ($NH_3$-N) that are the principal water quality indicators, with their relative concentrations dependent on both pH and temperature. The un-ionized form is toxic as it is neutral and can penetrate gill membranes more readily than the $NH_4^+$ ions. Studies showed the toxicity of total ammonia ascribed due to the effect of free ammonia only [86,87].

Aquatic organisms are extremely sensitive to elevated levels from the natural ammonia level and the un-ionized form of ammonia is deadly to aquatic animals including fish. At the pH of 8.75 to 9.75, unionized ammonia and ammonium ions coexists in aqueous state and the fraction of un-ionized ammonia increases with temperature and pH. When the pH (<8.75), ammonium ions are the principal species in water bodies, unionized ammonia becomes the pre-dominant species at pH (>8.75) [88–89]. In the lake watershed under investigation, the mean ammonium nitrogen ranges from 0.12 mg/L (MS19) to 16.8 mg/L (MS15). The average ammonium nitrogen value of rivers was 1.17 mg/L, Lake Hawassa was 2.35 mg/L, and point sources were 7.2 mg/L (Table 2.7). The findings revealed the point sources were the major source for ammonium nitrogen to the rivers and Lake Hawassa. While ammonium is less toxic and the most desirable source for phytoplankton growth, it becomes toxic to fishes and may result in eutrophication of lakes at higher concentrations [91,92].

On the other hand, a good quality water body must have an ammonia levels less than 0.05 mg/L and when this level goes beyond 2 mg/L fish are killed [75,93,94]. Nonetheless, in the watershed under investigation, the mean ammonia ranges from 0.01 mg/L (MS6) to 8.9 mg/L (MS5). The average ammonia value of rivers was 0.11 mg/L, Lake Hawassa was 0.94 mg/L, point sources were 2.9 mg/L, and these values are higher than the recommended value (Table 2.7). In addition, point sources were contributing larger amounts of ammonia to the river and Lake Hawassa. The findings are in line with the previous studies conducted by Kebede et al. [30] and Teshome [55] on the eastern catchment of Lake Hawassa. Ammonia is an indicator for elevated pollution from organic substances producing a noxious odors and are often indicative of sewage pollution and agricultural runoff [51,89].

### 2.3.1.7. Soluble Reactive Phosphorus (SRP)

The mean values of SRP ranged from 1.8 to 76.8 mg/L and higher values observed at MS5 (Moha soft drinks factory). The recommended concentration of phosphate for good quality water that maintains the aquatic life is in the range of 0.005 to 0.02 mg/L [69].

The average SPR concentration in the upper catchment of three rivers (MS1, MS2 and MS3) was 6.56 mg/L which is higher than the study conducted by Kebede et al. [30]. Moreover, the SPR of the four rivers including Tikur-Wuha river (MS1, MS2, MS3 and MS6) was 6.5 mg/L (Table 2.7), that is greater than the study conducted on the eastern catchment by Teshome [55]. This might be due to increased population due to urbanization, use of detergents, the practice of open defecation, and intensive usage of fertilizers in agricultural land.

The overall mean of SRP concentration in Lake Hawassa was 3.34 mg/L that is greater than the previously reported value of Zinabu et al. [95], Tilahun and Ahlgren [29] and Tamire and Mengistou [78] which was 0.035, 0.01 and 0.029 mg/L respectively. Hence, the phosphate level in the study watershed exhibited non-conformity with the standard values that can exacerbate eutrophication in fresh water systems and loss of aquatic biodiversity. This might be due to an increased usage of fertilizers in agricultural lands, industrial effluents, excessive usage of detergents in domestic and industrial facilities, soil erosion, and increased sewage pollution showing an ongoing pollution of the lake. Additionally, phosphate carrying pollutants like fertilizers, domestic wastewater, detergents, industrial effluents, runoff from agricultural and urban setup leading to algal blooms, eutrophication and elevated BOD [85,96]. The results of this study showed an increment from the previous studies conducted on the eastern catchment of Lake Hawassa by Kebede et al. [30], Teshome [55] and on Lake Hawassa conducted by Worako [6].

### 2.3.2. Summary of Irrigation Indices

#### 2.3.2.1. Total Dissolved Solids (TDS) and Electrical Conductivity (EC)

TDS plays a critical role in estimating the suitability of water bodies for both domestic and agricultural uses [97]. The overall mean value of TDS and EC in the study watershed was 598.7 mg/L and 1207.4 µS/cm, respectively (Table 2.7 and Figure 2.5a, b). The samples in the study watershed fell well below the prescribed values (<2000 mg/L) for TDS and (<3000 µS/cm) for EC recommended for human consumption and agricultural purposes [65,98]. However, samples collected from MS4, MS5 and MS15 were far above the recommended limits for human consumption and agricultural purposes. The mean value of TDS in this study for Lake Hawassa (455.6 mg/L) were greater than that of Lake Ziway (200 to 400 mg/L) conducted by Hengsdijk and Jansen [99].

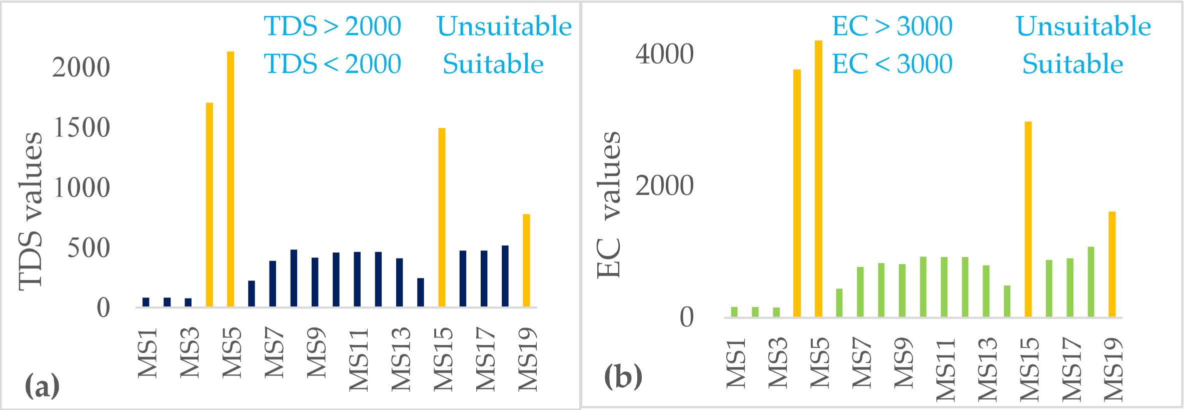

Figure 2.5. Total dissolved solids (TDS) (a) concentrations (mg/L) and electrical conductivity (EC) (b) concentrations (µS/cm) in the water and wastewater samples (n = 19) collected over 19 monitoring stations with wastewater samples labeled yellow at the Hawassa Watershed

The major source for TDS is due to livestock waste, landfills and dissolved minerals [100]. Electrical conductivity can be categorized low when EC< = 250 µS/cm (C1), medium when 250–750 µS/cm (C2), high when it ranges from 750–2250 µS/cm (C3) and very high when > 2250 µS/cm (C4) [100–101]. If applied for irrigation, high salt concentration (high EC) in water leads to formation of saline soil and a high sodium concentration leads to development of an alkaline soil.

### 2.3.2.2. Sodium Adsorption Ratio (SAR) and Kelly Ratio (KR)

The appropriateness of water bodies for agricultural purpose was estimated by computing several parameters like salinity (EC), sodium absorption ratio (SAR), Kelly's ratio (KR), soluble sodium percentage (SSP) and magnesium adsorption ratio (MAR) [100]. The above parameters were categorized based on the literature review [98,103].

The average EC in the study watershed ranged from 168.62 µS/cm (MS1) for Wesha River to 4257.4 µS/cm (MS5) for the Moha soft drink factory. The intake of water by plants decreases with increasing TDS or electrical conductivity value of water. Hence, the maximum yield reduction of crops occurred when the EC in agricultural water exceeds 3000 µS/cm [98,104]. SAR values for each water sample were calculated by using the following Equation [101].

$$\mathrm{SAR} = \frac{\mathrm{Na}^{+}}{\sqrt{\left(\frac{\mathrm{Ca}^{+2} + \mathrm{Mg}^{+2}}{2}\right)}}, \qquad (20)$$

All the ions are expressed in meq/L.

Water for agriculture can be considered excellent if SAR <10, good when SAR is 10–18, fair if SAR is 18–26, and SAR values above 26 are unsuitable for agricultural use [100,101].
In the present study, all the monitoring stations fell in the excellent class, i.e., the SAR values <10 except for one sampling site (MS4) collected from BGI which fell under the good category. Samples categorized under excellent and good could be used for agriculture with respect to SAR values (Table 2.7 and Figure 2.6).

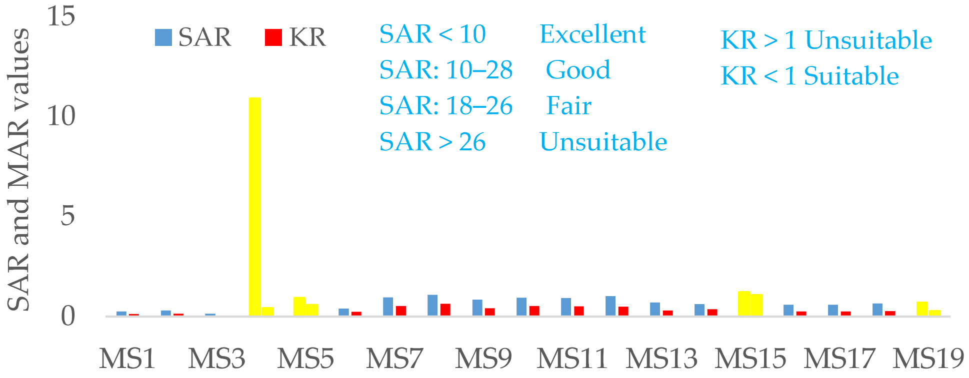

Figure 2.6. Sodium adsorption ratio (SAR) (meq/L) and Kelly's ratio (KR, meq/L) in the water and wastewater samples (n = 19) collected over 19 monitoring stations with wastewater samples labeled yellow at the Lake Hawassa Watershed.

The exchangeable sodium ratio higher than 1 is an indication of an excess level of sodium in waters in comparison to calcium and magnesium. Thus, waters with a KR ratio more than one are unsuitable for irrigation, while those with a ratio less than one are suitable. In the Lake Hawassa watershed, KR ranged from 0.05 (MS3) to 1.08 (MS5) indicating that nearly all sampled water values are less than the prescribed limit and suitable for irrigation [105].

$$KR = \frac{Na^{+}}{Mg^{+2} + Ca^{+2}} \tag{21}$$

All the ions are expressed in meq/L.

### 2.3.2.3. Soluble Sodium Percentage (SSP) and Magnesium Adsorption Ratio (MAR)

Wilcox [106] has suggested a classification system for ranking agricultural water use depending on SSP and estimated using the formula below.

$$SSP = \frac{Na^{+}}{Na^{+} + ca^{+2} + Mg^{+2}} * 100, \quad (22)$$

All the ions are expressed in meq/L.

SSP values above 50% mean the sampled water is not suitable for agricultural use and values lower than 50% indicate good quality of water [106]. The values of SSP in the watershed under investigation were far above the recommended limit (>50%) by Wilcox except samples collected from monitoring stations MS1 (30.79%), MS2 (28.14%) and for MS3 (12.86%) (Table 2.7 and Figure 2.7).

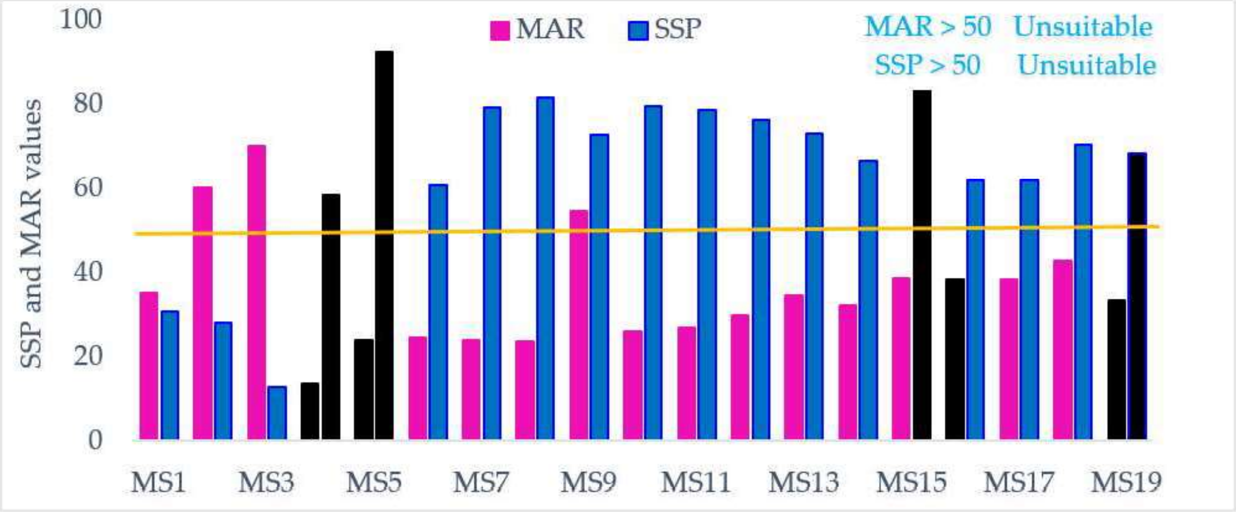

Figure 2.7. Soluble sodium percentage (SSP) and magnesium adsorption ratio (MAR) values (%) in the water and wastewater samples (n = 19) collected over 19 monitoring stations with wastewater samples labeled black at the Lake Hawassa Watershed.

Extreme concentrations of $Mg^{+2}$ in agricultural water might be injurious to crops owing to the reduced availability of $K^{+}$ in soils where magnesium concentrations are elevated. In Lake Hawassa Watershed, all samples but three were found to fall under the “suitable” class for MAR. Samples taken from the upper catchment (Wesha, Hallo and Wedessa rivers) and one sample taken from Lake Hawassa near Lewi resort deviates from the permissible level (MAR >50%) [107].

$$\mathrm{MAR} = \frac{\mathrm{Mg}^{+2}}{\mathrm{Ca}^{+2} + \mathrm{Mg}^{+2}} * 100, \qquad (23)$$

All the ions are expressed in meq/L

### 2.3.3. Determination of WQI and Status of Lake Hawassa Watershed

#### 2.3.3.1. Weighted Arithmetic Water Quality Index (WA WQI)

WA WQI and CCME WQI were used to integrate diverse parameters and their dimensions into a single score. The upshots of the physicochemical parameters of water for Lake Hawassa Watershed in 19 monitoring stations are presented in (Table 2.7, Figures 2.8 and 2.9) and water quality status for each monitoring stations evaluated for drinking, irrigation, aquatic life and recreational purposes using WA WQI's and ranked based on Table 2.3.

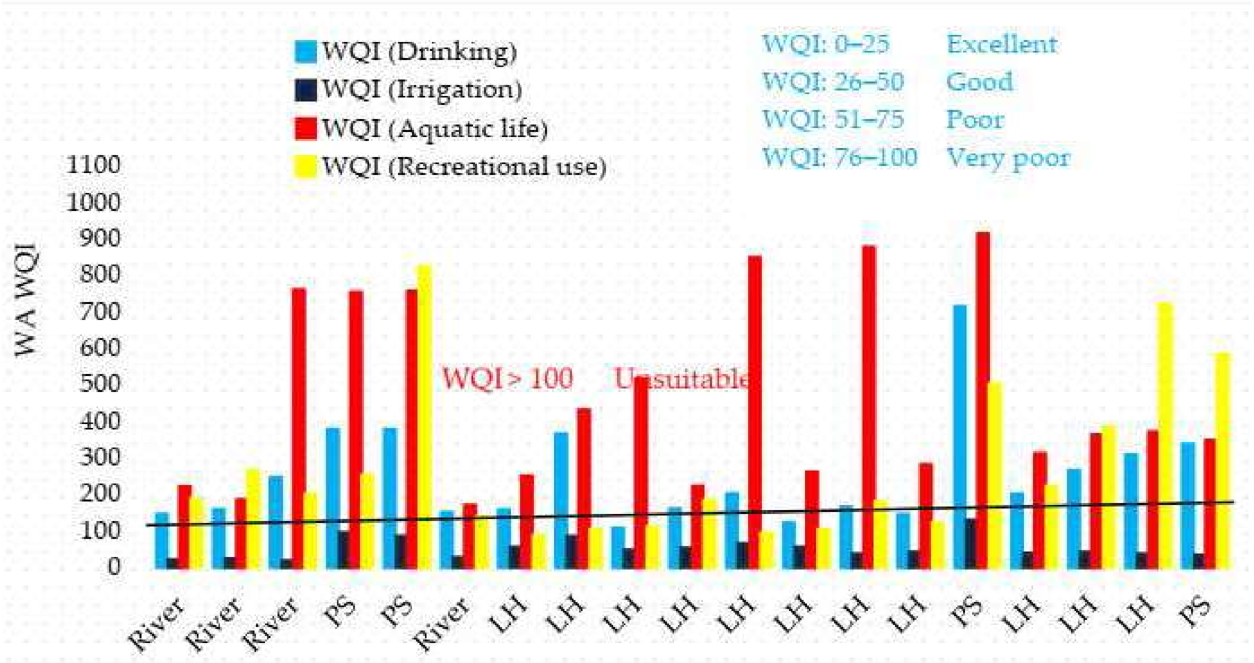

Figure 2.8. Weighted arithmetic water quality index (WA WQI) for drinking, irrigation, recreation and aquatic life in samples collected from rivers, PS (point source) and LH (Lake Hawassa) of the water and wastewater samples (n = 19) collected over 19 monitoring stations at the Lake Hawassa Watershed.

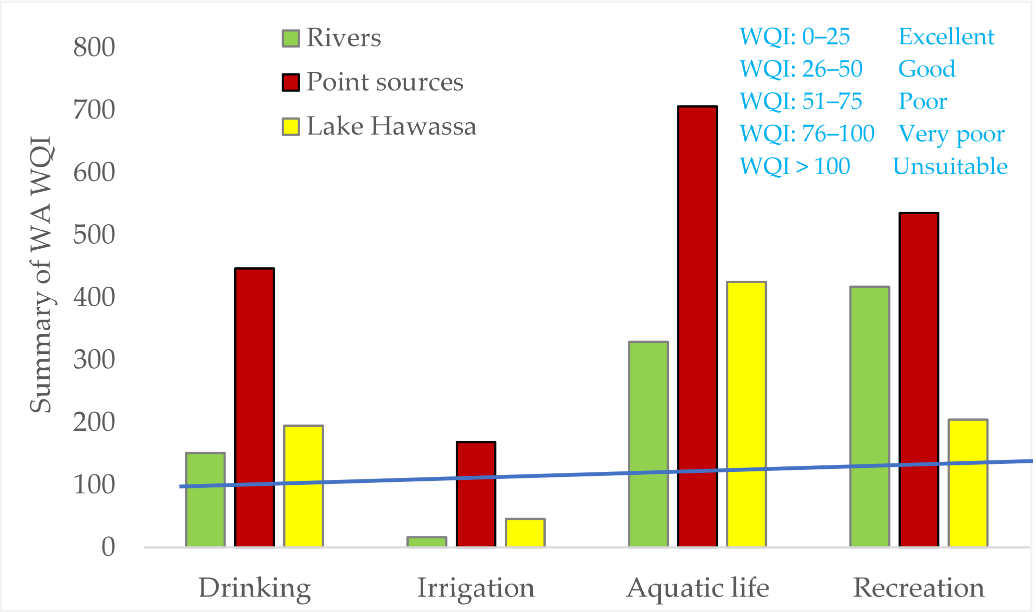

Figure 2.9. Summary of results for weighted arithmetic water quality index for drinking, irrigation, recreation and aquatic life for rivers, Point source and Lake Hawassa

This water quality rating undeniably showed that WA WQI for the drinking use for rivers ranged from 81 (MS1) to 186 (MS3) and for Lake Hawassa it ranged from 72 (MS1) to 289 (MS3) and, therefore, can be categorized as unsuitable for drinking purposes (Figure 2.8).

WQI for irrigation for rivers ranged from 11.4 (MS3) to 20.8 (MS6), and for Lake Hawassa it ranged from 29 (MS13) to 66 (MS14). Amongst monitoring stations, samples analyzed from all rivers were categorized as excellent and the analyzed samples from Lake Hawassa were categorized under good for irrigation purposes.

Additionally, WA WQI was also computed to evaluate the suitability of the studied watershed for aquatic life and recreational purposes. It was observed that the computed WQI for rivers ranged from 159 (MS2) and 168 (MS1) and for Lake Hawassa it ranged from 210 (MS7) and 860 (MS13) for the aquatic life and, therefore, can be categorized as unsuitable. The water bodies in the studied watershed were also very poor and unsuitable for recreational purposes as the WA WQI was above 80 in all monitored water sources.

To compare monitoring stations, we divided them in to three categories by taking into consideration the upper catchment, the middle catchment and Lake Hawassa. WA WQI was computed separately for rivers in the upper catchment (MS1–MS3 and MS6), Industrial effluents and the Referral Hospital (MS4, MS5, MS15 and MS19) and Lake Hawassa (MS7–MS18) to pinpoint where the problem precisely lies.

The findings revealed that the water quality of rivers in the upper catchment namely Wesha, Hallo, Wedessa and Tikur-Wuha (middle part) and Lake Hawassa was generally unsuitable for drinking, aquatic life and recreational purposes. However, the rivers possessed excellent water quality and Lake Hawassa water quality was good for irrigation purposes (Figure 2.9).

The topo to raster interpolation is among areal interpolation techniques that depict the spatial distribution of parameters. The interpolation result of appropriateness of water for agricultural use in Lake Hawassa Watershed revealed the irrigation water quality of the rivers on the uppermost part of the catchment is in the excellent and good classes that are in agreement with WA WQI and CCME WQI. The irrigation water quality of the watershed was reduced towards the industrial sites. The water quality deterioration is because the two point sources (Moha soft drinks factory and BGI) releasing their effluents into the adjoining rivers. Additionally, the result also showed unsuitability of water quality for irrigation in some points of the watershed due to samples taken from Referral Hospital, BGI, Moha soft factory showing the point sources were not in a good condition. Generally, this interpolation result also revealed the city of Hawassa takes the lion's share in Lake Hawassa pollution followed by agricultural land use contribution. Here, the topo to raster interpolation was not applied for the western part of the Lake Hawassa Watershed, as there are no perennial streams feeding the lake (Figure 2.10).

Furthermore, the topo to raster interpolation of Lake Hawassa was conducted separately and the result showed that nearly all the sampling points are in the category of good quality for irrigation except one of the sampling points, the result of which was found to be poor for the sample taken from MS8 (Gudumale). This is because there was a small fish market near the site and it is nearer to the recreational facility that was serving for marriage ceremonies and for various events. Additionally, the site is near to the city of Hawassa, and as a result the urban runoff makes its way to the lake via this site. Additionally, this site is near to referral hospital and the service rendering facility. Due to this, the irrigation water quality is poor at this particular site. Generally, it was possible to conclude that the overall water quality of Lake Hawassa was in a good class for irrigation purposes, which is in agreement with WA WQI (Figure 2.11).

The findings are contrary to the previous studies conducted on the eastern catchment by Teshome [55] who found that higher values for WA WQI indicate the water quality of rivers and lake were unsuitable for all purposes. Also, the study conducted by Zemede et al. [10] on Lake Hawassa whose findings demonstrated Lake Hawassa is unfit for all purposes. Therefore, the cumulative result of WA WQI for drinking, aquatic life and recreational uses showed that the environmental situation has become worse in the last few decades, Hence, Lake Hawassa watershed has been polluted and frequent monitoring of the watershed is necessary for proper management.

A number of parameters affect the suitability of water for drinking, aquatic life and recreational purposes. Hence, dedicated efforts should be exerted to mitigate their release in to the rivers and Lake. Pollution prevention and control measures should be pursued as a matter of urgency by the pertinent figures.

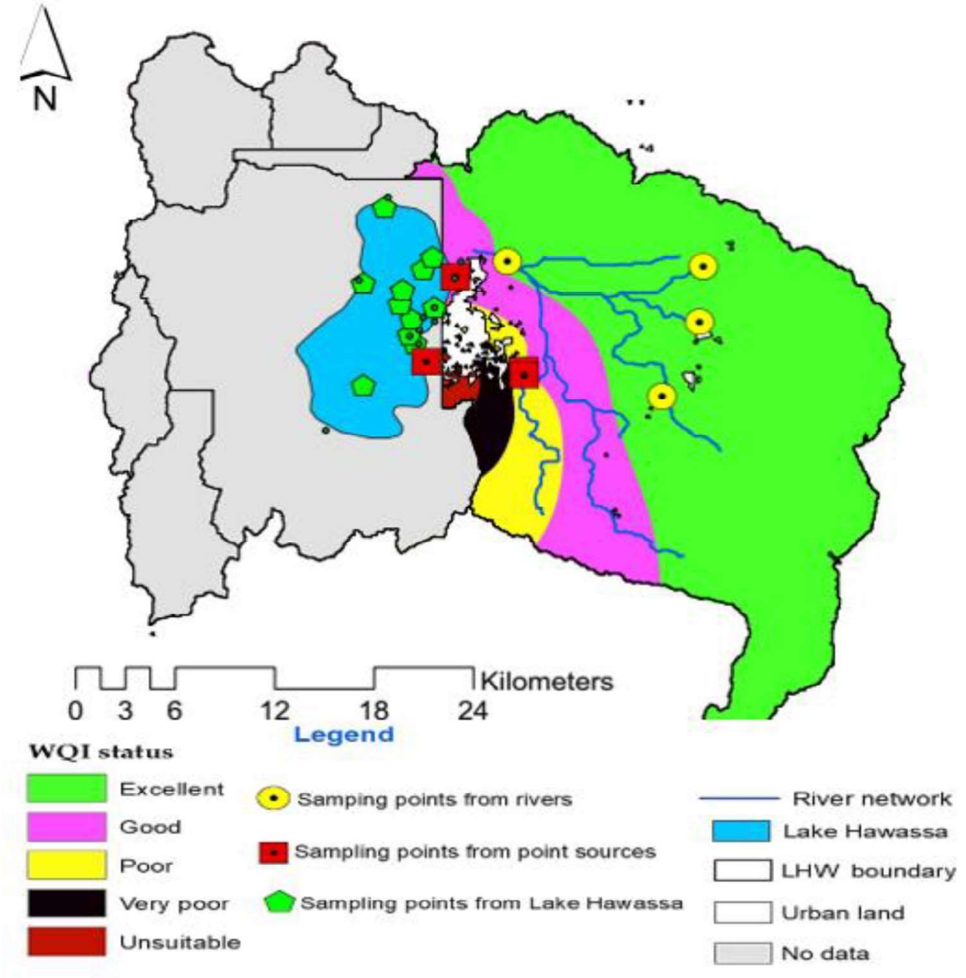

Figure 2.10. Topo to raster interpolation for estimation of Irrigation water suitability using WA WQI in the water and wastewater samples (n = 19) collected over 19 monitoring stations at the Lake Hawassa Watershed.

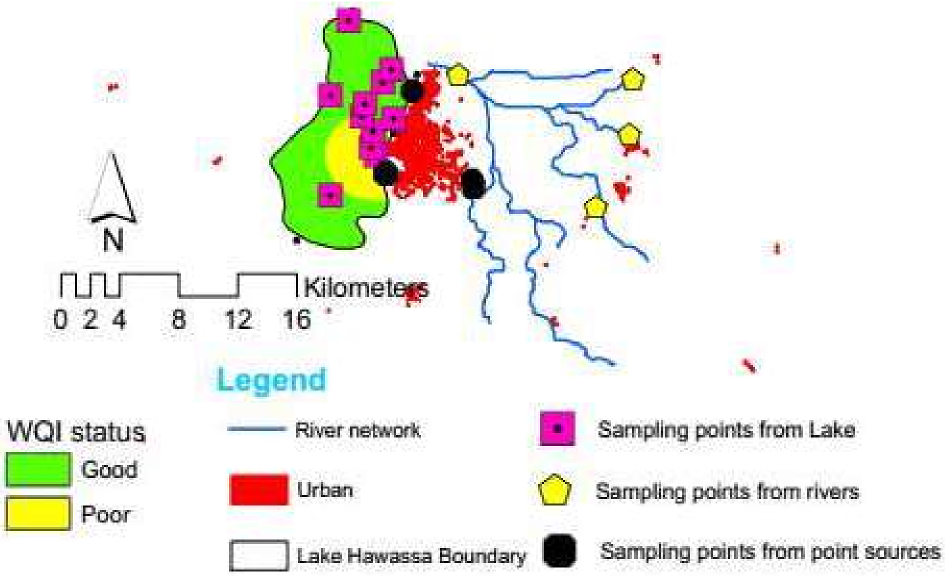

Figure 2.11. Topo to raster interpolation for estimation of Irrigation water suitability using WA WQI in the water samples (n = 11) collected over 11 monitoring stations at the Lake Hawassa.

#### 2.3.3.2. Canadian Council of Ministries of the Environment Water Quality Index (CCME WQI)

In this study, CCME WQI was employed using 21 water quality parameters (pH, EC, TDS, Turbidity. $NH_3$, $NH_3$-N, $NO_2^-$, $NO_3^-$, $NO_3$-N, DO, BOD, COD, $Mg^{+2}$, $Ca^{+2}$, $Na^+$, $K^+$, Temperature, SAR, KR, MAR, SSP and SD) from May 2021 to December 2021 to evaluate the suitability of Lake Hawassa Watershed for drinking, irrigation uses, recreational use and aquatic life.

CCME WQI gives parameter values mathematically to confirm each parameter contributes sufficiently in the ultimate quality index. The values of each analyzed parameter were compared to the limits set by various international and national standards like WHO, CCME, EPA, FAO and other recommendations for those envisioned purposes. After the CCME WQI value was calculated in relation to monitoring site, month and the watershed, water quality was ranked as per the CCME WQI category (Table 2.4).

The results of the physicochemical parameters of water for Lake Hawassa Watershed in months and parameters were presented in Table 2.8 and Figure 2.12. The water quality status of four rivers in the upper and middle catchments (Wesha, Hallo, Wedessa and Tikur-Wuha) and four point sources in the middle of the catchments (BGI, Moha soft drinks factory, Hawassa Industrial park and Referral Hospital) and Lake Hawassa and its suitability evaluated for drinking, irrigation, aquatic life and recreational purpose using CCME WQI's. The CCME WQI assessment result for rivers and Lake Hawassa showed that they are unsuitable for monitored parameters for marine life and recreation and marginal for drinking and irrigation purposes. However, the CCME WQI results for rivers fell in the good quality class, whereas the lake water assessment showed the CCME WQI result is marginal for irrigation purposes. This might be due to CCME WQI is sensitive to failed parameters and values change gradually between the lower classes.

Table 2.8: The physicochemical characteristics of four rivers (Wesha, Hallo, Wedessa and Tikur-Wuha) for evaluation of CCME WQI in Lake Hawassa Watershed for drinking, irrigation, aquatic life and recreational purposes.

| Parameters | MAY Rivers | JUNE Rivers | JULY Rivers | AUG Rivers | SEP Rivers | OCT Rivers | NOV Rivers | DEC Rivers | S1/S2/S3/S4/S5 |
|---|---|---|---|---|---|---|---|---|---|
| Turbidity | 37.4 | 31.7 | 26.0 | 20.3 | 18.9 | 17.5 | 16.0 | 14.8 | $5^{ac}$ $50^{d}$ |
| TDS | 87.5 | 85.8 | 84.0 | 82.3 | 94.6 | 126.5 | 148.8 | 170.0 | 1000, $2000^{ab}$ |
| EC | 178 | 173 | 169 | 165 | 179 | 253 | 298 | 340 | 1500, $3000^{ab}$ |
| pH | 8.1 | 8.2 | 8.2 | 8.3 | 8.0 | 7.7 | 7.5 | 7.2 | 6.5–$9^{abcd}$ |
| $NH_3$ | 0.4 | 0.33 | 0.17 | 0.02 | 0.04 | 0.003 | 0.002 | 0.001 | 1.5, $1.37^{c}$ |
| $NH_3$-N | 0.33 | 0.27 | 0.14 | 0.02 | 0.03 | 0.002 | 0.001 | 0.001 | $5^{b}$ |
| $NO_2^-$ | 0.13 | 0.10 | 0.08 | 0.05 | 0.05 | 0.04 | 0.04 | 0.04 | $3^{a}$ |
| $NO_3^-$ | 2.0 | 2.2 | 2.4 | 2.6 | 2.6 | 2.9 | 3.0 | 3.1 | 45, $1^{ac}$ |
| $NO_3$-N | 0.4 | 0.5 | 0.5 | 0.6 | 0.6 | 0.7 | 0.7 | 0.7 | $10^{b}$ |
| DO | 6.2 | 6.2 | 6.1 | 6.1 | 5.6 | 4.7 | 3.9 | 3.4 | $5^{cd}$ |
| BOD | 8.0 | 6.8 | 5.6 | 4.4 | 11.8 | 20.2 | 28.1 | 35.6 | $5^{acd}$ |
| COD | 126 | 104 | 83 | 61 | 85 | 109 | 131 | 162 | $20^{a}$ |
| $Mg^{2+}$ | 7.6 | 7.2 | 6.8 | 6.4 | 22.4 | 38.8 | 54.9 | 71.6 | $200^{a}$ |
| $Ca^{2+}$ | 39.5 | 36.3 | 33.1 | 30.0 | 25.1 | 18.5 | 12.4 | 8.4 | $100^{a}$ |
| $Na^+$ | 30.2 | 28.6 | 27.0 | 25.3 | 33.9 | 41.2 | 49.2 | 56.8 | $200^{a}$ |
| $K^+$ | 5.5 | 5.6 | 5.6 | 5.6 | 6.3 | 7.1 | 7.8 | 8.4 | $20^{a}$ |
| Temperature | 20.6 | 20.3 | 20.0 | 19.7 | 19.1 | 18.1 | 17.3 | 16.7 | 15–$20^{ac}$ |
| SAR | 1.2 | 1.2 | 1.2 | 1.2 | 1.5 | 1.8 | 2.2 | 2.5 | $26^{b}$ |
| KR | 0.6 | 0.6 | 0.6 | 0.7 | 0.8 | 0.9 | 1.2 | 1.4 | $1^{b}$ |
| MAR | 26.0 | 24.4 | 23.4 | 23.4 | 49.1 | 59.6 | 65.3 | 69.2 | $50^{b}$ |
| SSP | 35.6 | 36.1 | 37.4 | 40.1 | 35.8 | 37.4 | 40.6 | 41.8 | $50^{b}$ |

All units are in mg/L except turbidity, EC, temperature, SAR, KR, MAR, SSP and pH which were expressed in NTU, µS/cm, °C, meq/L, % and non-dimensional, respectively. (a) Labels drinking use, (b) irrigation water use, (c) express water use for aquatic life and (d) designates recreational water use. S1 labels Standard values taken from World Health organization (WHO), S2 labels Standard values taken from Environmental protection Agency (EPA of US or Ethiopia), S3 labels Standard values taken from Canadian Council of Ministries of the Environment (CCME), S4 labels Standard values taken from Food for Agricultural organization (FAO) and S5 labels standard values taken from Health Canada (HC).

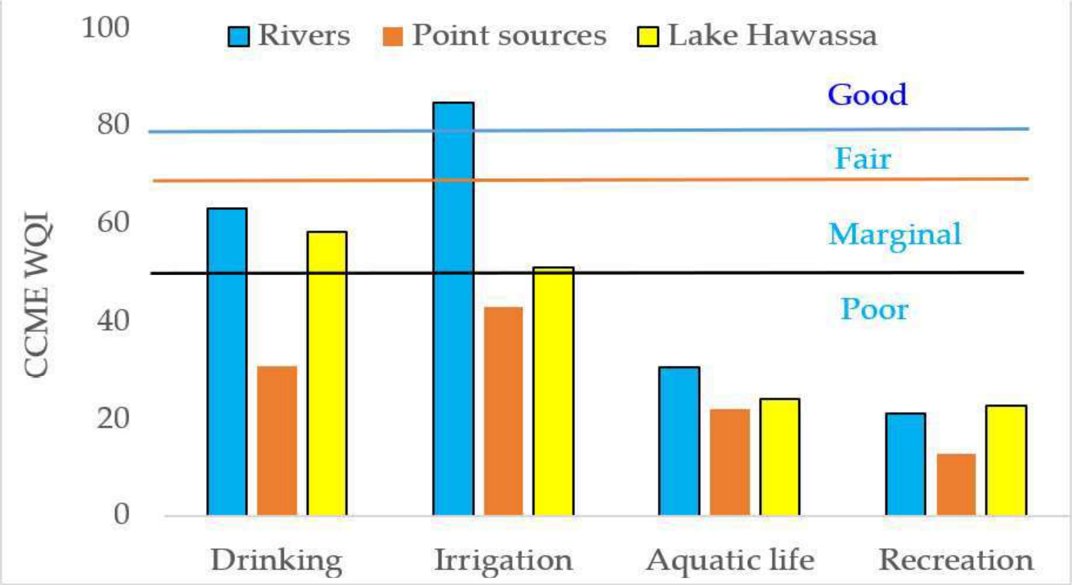

Figure 2.12. Summary of results for CCME WQI for drinking, irrigation, recreation and aquatic life for rivers, Point source and Lake Hawassa.

The CCME WQI calculation for the envisioned water uses on Lake Hawassa Watershed was estimated for rivers, Lake Hawassa and point sources solely. The investigation depicted the four rivers in the upper and middle catchments (Wesha, Hallo, Wedessa and Tikur-Wuha) falls under good category for agricultural purposes (CCME WQI 85), marginal and poor for domestic (CCME WQI 64), marine life (CCME WQI 39) and recreational purposes (CCME WQI 21) respectively **(**Figure 2.12**).**

CCME WQI were computed for four point sources in the middle of the catchments (BGI, Moha soft drinks factory, Hawassa Industrial park and referral Hospital) separately. The findings exhibited poor or (impaired/threatened) water quality status for drinking (CCME WQI 39), aquatic life (CCME WQI 25), recreational uses (CCME WQI 13) and irrigation having the index value of (CCME WQI 43).

As far as Lake Hawassa is concerned, the water quality suitability was also evaluated for drinking and irrigation purposes and fell under the marginal category (CCME WQI 61, 51 respectively) and was poor for aquatic life and recreational purposes (CCME WQI 29, 23 respectively). The results of this study were comparable to the previous studies conducted by Zemede et al. [10] whose assessment result was marginal for all purposes and Worako [108] whose assessment showed the lake water is marginal for drinking and recreation but fair for irrigation and aquatic life on Lake Hawassa (Table 2.9).

The findings prove that there was a higher level of contamination for a broad range of substances. The point sources were the stronger polluter of the lake and, in particular, the Moha soft drinks factory and Referral Hospital were releasing extremely high values of some pollutants to the receiving environments.

The water bodies in Lake Hawassa Watershed was found to be impaired or unsuitable for the best uses of water especially for human consumption, recreational activities and aquatic life and in some cases for irrigation use as well due to agricultural run-off, effluents from surrounding industrial sectors.

Table 2.9: The physicochemical characteristics of Lake Hawassa for evaluation of CCME WQI for drinking, irrigation, aquatic life and recreational purposes.

| Parameters | LH MAY | LH JUNE | LH JULY | LH AUG | LH SEPT | LH OCT | LH NOV | LH DEC | S1/S2/S3/S4/S5 |
|---|---|---|---|---|---|---|---|---|---|
| Turbidity | 9.8 | 10.9 | 10.9 | 11.4 | 11.1 | 10.7 | 10.4 | 10.0 | $5^{ac}$ $50^{d}$ |
| TDS | 466 | 427 | 412 | 402 | 419 | 436 | 453 | 471 | 1000, $2000^{ab}$ |
| EC | 941 | 852 | 821 | 778 | 811 | 844 | 876 | 911 | 1500, $3000^{ab}$ |
| pH | 9 | 8.7 | 8.5 | 8.3 | 8.4 | 8.5 | 8.5 | 8.6 | 6.5–$9^{abcd}$ |
| $NH_3$ | 2.8 | 1.3 | 0.45 | 0.1 | 0.22 | 0.4 | 0.54 | 0.9 | 1.5, $1.37^{c}$ |
| $NH_3$-N | 2.3 | 1 | 0.37 | 0.08 | 0.18 | 0.33 | 0.44 | 0.74 | $5^{b}$ |
| $NO_2^-$ | 0.1 | 0.1 | 0.1 | 0.03 | 0.03 | 0.03 | 0.04 | 0.04 | $3^{a}$ |
| $NO_3^-$ | 3.3 | 6.2 | 10.4 | 12.3 | 10.3 | 8.3 | 6.3 | 4.3 | 45, $1^{ac}$ |
| $NO_3$-N | 0.7 | 1.4 | 2.3 | 2.8 | 2.3 | 1.9 | 1.4 | 1.0 | $10^{b}$ |
| $PO_4^{3-}$ | 3.8 | 6.7 | 9.6 | 12.6 | 11.8 | 11.0 | 10.3 | 9.4 | |
| DO | 4.3 | 4.3 | 4.3 | 4.3 | 4.3 | 4.2 | 4.2 | 4.1 | $5^{cd}$ |
| BOD | 26.1 | 20.1 | 17.7 | 15.5 | 19.7 | 23.9 | 28.1 | 32.4 | $5^{acd}$ |
| COD | 122.0 | 106.3 | 113.2 | 118.6 | 126.8 | 134.9 | 143.0 | 151.2 | $20^{a}$ |
| $Mg^{2+}$ | 8.4 | 7.2 | 8.4 | 7.3 | 7.8 | 8.2 | 8.6 | 9.2 | $200^{a}$ |
| $Ca^{2+}$ | 33.3 | 28.1 | 24.9 | 19.8 | 21.2 | 22.5 | 23.8 | 25.2 | $100^{a}$ |
| $Na^+$ | 211.1 | 182.7 | 175.6 | 164.9 | 181.4 | 197.6 | 213.7 | 230.8 | $200^{a}$ |
| $K^+$ | 16.8 | 17.1 | 18.2 | 18.1 | 18.9 | 19.8 | 20.4 | 16.9 | $20^{a}$ |
| Temperature | 23.1 | 22.2 | 21.5 | 21.6 | 21.8 | 22.0 | 22.2 | 23.4 | 15–$20^{ac}$ |
| SAR | 10.3 | 11.4 | 11.5 | 11.7 | 12.3 | 13.1 | 13.9 | 14.7 | $26^{b}$ |
| KR | 5.5 | 6.3 | 6.7 | 7.4 | 7.4 | 7.6 | 7.9 | 8.3 | $1^{b}$ |
| MAR | 33.1 | 40.8 | 45.3 | 51.4 | 51.2 | 50.8 | 50.2 | 49.8 | $50^{b}$ |
| SSP | 70.8 | 78.3 | 78.8 | 79.7 | 80.5 | 80.9 | 81.1 | 80.3 | $50^{b}$ |
| SD | 83.1 | 74.7 | 78.4 | 71.4 | 73.9 | 76.1 | 78.1 | 81.3 | $120^{d}$ |

All units are in mg/L except turbidity, EC, temperature, SAR, KR, MAR, SSP and pH which were expressed in NTU, µS/cm, °C, meq/L, % and non-dimensional, respectively. (a) Labels drinking use, (b) irrigation water use, (c) express water use for aquatic life and (d) designates recreational water use, LH designates Lake Hawassa. S1 labels Standard values taken from World Health organization (WHO), S2 labels Standard values taken from Environmental protection Agency (EPA of US or Ethiopia), S3 labels

Standard values taken from Canadian Council of Ministries of the Environment (CCME), S4 labels Standard values taken from Food for Agricultural organization (FAO) and S5 labels standard values taken from Health Canada (HC).

### 2.3.4. Estimation of the Trophic Status of Lake Hawassa

#### 2.3.4.1. Analysis of Trophic State Variables

Total phosphorus (TP), total nitrogen (TN), chlorophyll-a (Chl-a) and Secchi depth (SD) for the analysis of the trophic status of Lake Hawassa are shown in Figure 2.13.

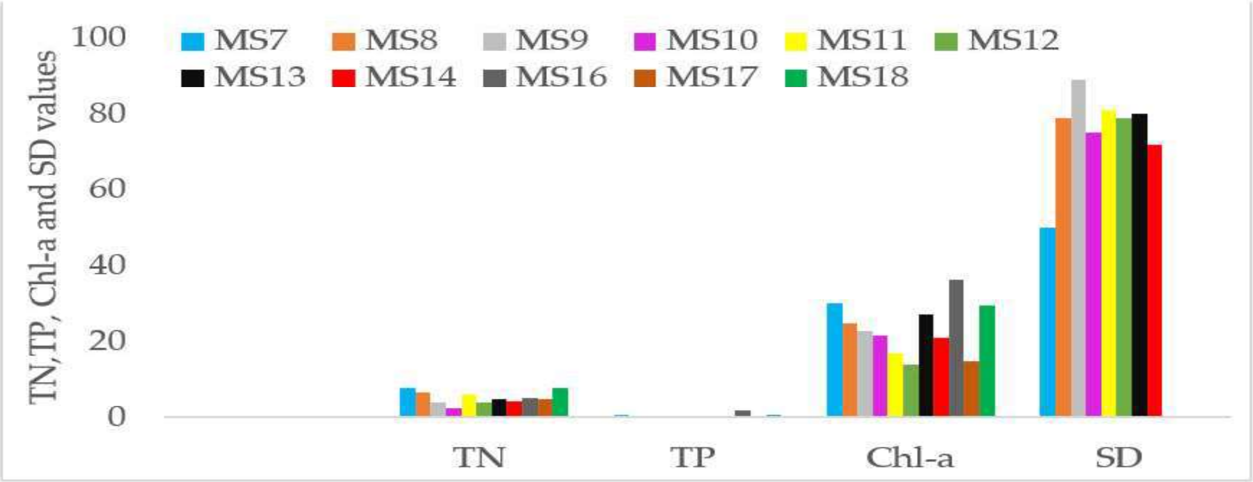

Figure 2.13. Figure 2.2.13. TN and TP concentrations (mg/L), SD depth (cm) and Chl-a concentrations (µg/L) in the water samples (n = 11) collected over 11 monitoring stations at Lake Hawassa.

**Total Phosphorus (TP) and Total Nitrogen (TN)**

TP ranged from 1 µg/L to 1843.75 µg/L with an average concentration of 317.5 µg/L TN ranged from 2.23 mg/L (MS10) to 7.87 mg/L (MS18) with mean concentration of 5.33 mg/L. The Kruskal–Wallis test result showed that TP and TN concentrations among sampling sites were not statistically different ($p > 0.05$). Gurung et al. [63] and Lau et al. [61] classified the trophic status based on the level of phosphorous and nitrogen. The lake is labelled as oligotrophic when TN < 0.35 mg/L, TP < 0.01 mg/L, mesotrophic if TN (0.35–0.65) mg/L, TP (0.01–0.03) mg/L, eutrophic when TN (0.65–1.2) mg/L and TP (0.03–0.1) mg/L and hypertrophic if TN > 1.2 mg/L and TP > 0.1 mg/L (Table 2.6).

Hence, Lake Hawassa is categorized as hypertrophic having mean TP and TN value of 320 µg/L and 5.33 mg/L, respectively. Phosphorus concentration greater than 300 µg/L [109] shows the impairment of the lake water by anthropogenic factors. The findings are comparable to the previous studies conducted on Lake Hawassa by Worako [87] and lower than the findings of Tibebe et al. [76] conducted on Zeway Lake.

### Total Nitrogen to Total Phosphorus (TN:TP) Ratio

The TN:TP ratio in lakes and reservoirs is a key element as it gives an idea of which of these nutrients are either in excess or limiting to growth, and it was used to estimate the nutrient limitation in the lake. According to Smith [110] blue-green algae (cyanobacteria) had a capacity to dominate in the lake section when the TN:TP ratio was less than 29 and it tends to be rare in the lake when TN:TP >29.

On the other hand, Fisher et al. [111] used more conservative ratio of the TN:TP and the ratio >20 designated as phosphorus limitation and nitrogen limitation when the ratio is <10, while TN:TP ratio 10 to 16 demonstrates either phosphorus or nitrogen (or both) are limiting for growth. The estimated ratio for Lake Hawassa was 31.1 which is higher than 20 and 30 in the lake under investigation revealing cyanobacteria dominance in the lake section is rare. The TN:TP ratio >20 in Lake Hawassa indicated that phytoplankton growth in the lake might be phosphorous deficient. Studies conducted on some Rift Valley lakes, namely Lakes Ziway and Hawasa, by Tilahun and Ahlgren, [29] and Lake Zeway by Tibebe et al. [76] revealed that the lakes were found to be phosphorus limiting having a TN:TP ratio higher than 20.

### Secchi Depth (SD) Chlorophyll a (Chl-a)

The average SD in Lake Lake Hawassa ranged between 0.5 m to 0.89 m with a mean value of 0.76 m. Smith et al. [112] categorizes the status of the lake based on the Secchi depth and the lake is designated as hypertrophic if SD (m) <1, eutrophic when SD (1–2), mesotrophic if SD (2–4) and oligotrophic if SD >4. Hence, Lake Hawassa is categorized as hypertrophic since the mean SD is 0.76 m. Chlorophyll a ranged between 14 μg/L and 30 μg/L with a mean of 23.6 μg/L in this study **(**Figure 2.12)**.** A study conducted by Fetahi and Mengistou [113] and Tilahun and Ahlgren [29] showed the phytoplankton biomass measured on Lake Hawassa was 10.4 to 25.2 and 13 to 26, respectively, and the results are comparable to the present study.

### 2.3.4.2. Evaluation of the Trophic Status Using Carlson Trophic State Index (TSI) Model

The average TSI-TP, TSI-TN, TSI-Chl-a and TSI-SD value were 56.6, 77.8, 61.2 and 64.2, respectively. The trophic state is classified as oligotrophic (TSI < 40), mesotrophic (40 < = TSI < 50), eutrophic (50 < = TSI < 70) and hypertrophic (TSI > = 70) according the TSI values [22,60]. TSI values of TN of Lake Hawassa was above the eutrophic threshold. The whole average TSI of Lake Hawassa was 65.4 and, hence, the overall class of the lake falls under eutrophic state (Table 2.5 and Figure 2.14). The findings of this study were different from that of Zemede et al. [10] whose finding was hypertrophic as the assessment result depended only on the Secchi depth and also Worako [6] who found an average TSI of 72.6 (hypereutrophic) for Lake Hawassa. Eutrophication causes the impairment of activities, discomfort and visual unpleasantness that hamper the recreational use of water severely [85].

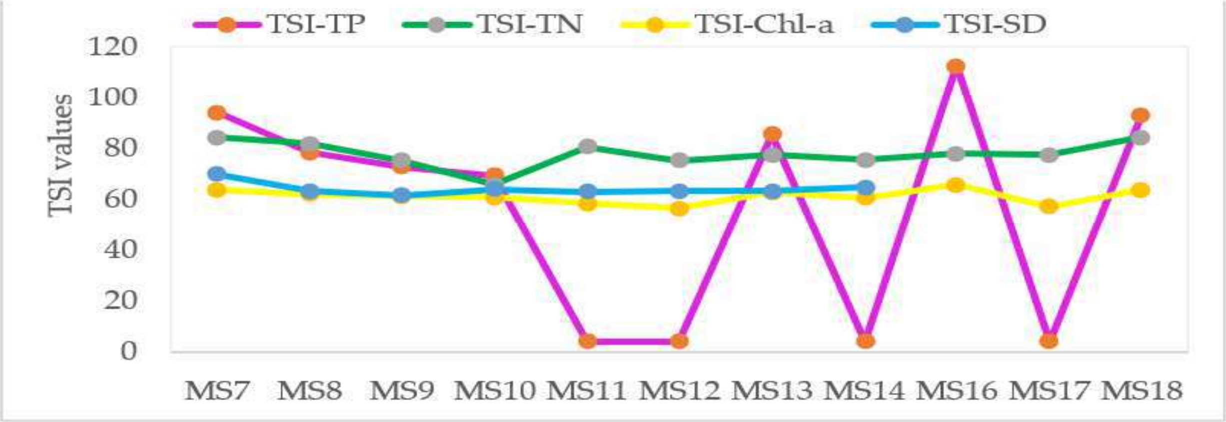

Figure 2.14. Figure 2.2.14. TSI-TN concentrations (mg/L), TSI-TP and TSI-Chl-a concentrations (µg/L) and TSI-SD depth (cm) of trophic variables in the water samples (n = 11) collected over 11 monitoring stations at Lake Hawassa.

## 2.4. Conclusions

WQIs connote analysis of a variety of parameters into a sole value that offers the chance to evaluate existing water quality situations by classifying water bodies into definite classes. Likewise, in WQIs a communal summary for reference is provided for ranking different water bodies and identifying variations in quality conditions. Despite the various uses, WQI might not convey satisfactory information about the existing water quality statuses of water bodies. Therefore, the water users and water authorities may adopt the WQIs with slight modifications to conform to local situations.

This investigation made use of two different WQI indices to evaluate the water quality status of Lake Hawassa Watershed in order to obtain comparative performance of the different approaches. In addition, Carlson's TSI, were used to obtain a comprehensive visualization of the quality of Lake Hawassa. The water quality of the watershed was broadly classified into unsuitable to excellent based on the envisioned usage and sampling locations. The findings of the water quality index of rivers and lakes showed, they were unsuitable for drinking, marine life and recreational purposes. In particular, in WA WQI classifications rivers fall in the excellent category and Lake Hawassa falls in the good category for irrigation purposes; while, the CCME WQI is a conservative approach whose range of values change gradually between the lower classes and rivers fall in the good category and Lake Hawassa falls in the marginal category for irrigation purposes. Hence, the discrepancy in the results of the two indices observed are imperative in order to consider measures that are more reliable. The topo to raster interpolation were carried out for both the watershed and Lake Hawassa separately and the results were in line with the findings of WA WQI and CCME WQI. To sum up, according to all indices, both lake and river water are unsuitable for drinking, marine life and recreational purposes. Even for irrigation purposes, the lake water is not suitable. Similarly, the overall category of Lake Hawassa falls under the eutrophic state and the lake is phosphorous-deficient. Similarly, the overall category of Lake Hawassa falls in the eutrophic state and the lake is phosphorous-deficient. These alarming assessments show the urgent need for pollution mitigation and control measures as a matter of urgency.

The findings publicize that the lake is suffering from various deficits, high nutrient concentrations, ammonia toxicity and oxygen depletion. The high COD and BOD values are partly due to direct emissions but also to the growth of organic matter in the lake water. Its degradation leads to reduced DO levels or even anaerobic conditions in deeper layers. The resulting threat to marine life is also endangering the fishery in the lake.

Also, the observed high nutrient concentrations and ammonia toxicity were attributed to TN, TP, $NO_2^-$, $NO_3^-$, TP, SRP and the un-ionized form of ammonia. These values emanated from the direct release from point sources that are the principal contributors and non-point sources such as agricultural land use (inorganic nitrogen and phosphorous fertilizers) and urban runoff during rainy season.

The findings of the study showed the environmental situation became worse in the last decade and Lake Hawassa watershed is known to be polluted. The dramatic worsening of the situation in Lake Hawassa Watershed was due to urbanization, usage of fertilizers in agricultural lands, effluents from industrial facilities, excessive usage of detergents in domestic and industrial facilities, soil erosion, increased sewage pollution, practice of open defecation and urban runoff. On top of that, there is insufficient sanitation in Lake Hawassa Watershed from diffused sources like sewage, animal waste pollution and the practice of open field defecation. The point sources have been known to take the leading role in contributing more pollutants to the river and Lake Hawassa followed by non-point sources from agricultural and urban runoff showing an ongoing pollution. The monitored point sources indicate that the city of Hawassa and its numerous industrial discharges are key polluters, requiring a fast and consequent set-up of an efficient wastewater infrastructure, accompanied by a rigorous monitoring of large point sources (e.g., industry, hospitals and hotels). In spite of the various efforts, the recovery of Lake Hawassa may take long time as it is hydrologically closed. Therefore, to ensure safe drinking water supply, a central supply system according to WHO standards also for the fringe inhabitants still using lake water is imperative. Introducing the riparian buffer zones of vegetation and grasses can support the direct pollution alleviation measures and is helpful for reducing the dispersed pollution coming from the population mostly using latrines. Additionally, integrating aeration systems like pumping atmospheric air into the bottom of the lake using solar energy panels or diffusers are effective mitigation measures that will improve the water quality of the lake. In parallel, implementation and efficiency control of measures requires coordinated environmental monitoring with dedicated development targets.

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# 3. Characterization of water quality and Identification of pollution sources

**Abstract**: The magnitude of pollution in Lake Hawassa has been exacerbated by population growth and economic development in the city of Hawassa, which is hydrologically closed and retains pollutants entering it. This study was therefore aimed at examining seasonal and spatial variations in the water quality of Lake Hawassa Watershed (LHW) and identifying possible sources of pollution using multivariate statistical techniques. Water and effluent samples from LHW were collected monthly for analysis of 19 physicochemical parameters during dry and wet seasons at 19 monitoring stations. Multivariate statistical techniques (MVST) were used to investigate the influences of an anthropogenic intervention on the physicochemical characteristics of water quality at monitoring stations. Through cluster analysis (CA), all 19 monitoring stations were spatially grouped into two statistically significant clusters for the dry and wet seasons based on pollution index, which were designated as moderately polluted (MP) and highly polluted (HP). According to the study results, rivers and Lake Hawassa were moderately polluted (MP), while point sources (industry, hospitals and hotels) were found to be highly polluted (HP). Discriminant analysis (DA) was used to identify the most critical parameters to study the spatial variations, and seven significant parameters were extracted (electrical conductivity (EC), dissolved oxygen (DO), chemical oxygen demand (COD), total nitrogen (TN), total phosphorous (TP), sodium ion (Na+), and potassium ion (K+) with the spatial variance to distinguish the pollution condition of the groups obtained using CA. Principal component analysis (PCA) was used to qualitatively determine the potential sources contributing to LHW pollution. In addition, three factors determining pollution levels during the dry and wet season were identified to explain 70.5% and 72.5% of the total variance, respectively. Various sources of pollution are prevalent in the LHW, including urban runoff, industrial discharges, diffused sources from agricultural land use, and livestock. A correlation matrix with seasonal variations was prepared for both seasons using physicochemical parameters. In conclusion, effective management of point and non-point source pollution is imperative to improve domestic, industrial, livestock, and agricultural runoff to reduce pollutants entering the Lake. In this regard, stringent management that requires a comprehensive application of technologies such as fertilizer management, ecological ditches, constructed wetlands, and buffer strips should complement proper municipal and industrial wastewater treatment, especially. Furthermore, application of indigenous aeration practices such as the use of drop structures at critical locations would help improve water quality in the lake watershed.

**Keywords:** monitoring; mitigations; spatial and temporal variabilities; principal component analysis; cluster analysis; discriminant analysis; water quality; pollution; correlation

## 3.1. Introduction

Studies have shown that urban, agricultural, and industrial discharges have a direct effect on surface water quality. Similarly, urban wastewaters cause fecal contamination of surface waters, and urban stormwater runoff, which contains large amounts of fecal microbes, also affects surface water quality [1]. Surface water bodies are vital natural resources that are vulnerable to pollution. The contaminants are chemical, physical, and biological constituents resulting from anthropogenic activities and are of greater environmental consideration [2]. Surface water bodies are extensively used as the major sources for domestic, non-domestic, industrial, and irrigation purposes. Therefore, monitoring and assessment of water bodies is imperative to obtain reliable information on water quality for effective management [3]. Anthropogenic uses of the waterbodies in the study basin can degrade the quality of surface water and impair its usability as potable water supply or for industry, agriculture, recreation, or other purposes. Hence, regular monitoring of water quality of rivers and lake is indispensable [4,5]. The most affected river stretches are those that flow through urbanized and exceedingly populated urban areas where there is no adequate sanitation. Upstream rural areas are mainly affected by pollutants from non-point sources such as agricultural runoff, whereas urban areas are polluted by point sources, sewage discharges, urban runoff, and pollutants from upstream areas [6,7].

Studies have shown that some lakes and wetlands around the world have disappeared or are showing changes in their ecosystem. Furthermore, factors such as intensive land use for urbanization and agriculture have had significant impact on the hydrology, ecology, and ecosystem services of lakes, which has eventually led to a decline in lake levels [8]. In addition, pollutants have long been a concern, as their accumulation can have serious effects on fauna, flora, and human health when the huge amount of urban and industrial wastewater reaches the shores [9].

Lake Hawassa is located near the city of Hawassa and is surrounded by agricultural land, industries and residential areas. Therefore, it is susceptible to a variety of pollutants that enter the lake directly or indirectly. On the other hand, the Lake Hawassa Watershed is experiencing rapid land cover change, and natural resources have overwhelmingly diminished. The lake is hydrologically closed and has no apparent outlet, so all pollutants entering the lake are retained. As a result, the lake faces numerous problems, and the water quality deteriorates over time, threatening biodiversity [10].

Significant industrialization, augmented with rapid urbanization and increasing economic development, has increased the extent of pollution [11]. The pollution is mainly from non-point sources caused by urban and agricultural runoff, overgrazing, deforestation, soil erosion, land development, and industrial effluents. This leads to numerous environmental concerns that have resulted in substantial hydrological disturbances. The main factories in the study area are a ceramics factory, a flourmill, a cement products factory, a Moha soft drink factory, a BGI (St. George Brewery factory), an Etabs soap factory, an industrial park in Hawassa, and other small-scale industries. They are virtually all concentrated along the main road, which is close to the shallow swamp, and discharge their effluents into the lake through streams. On the other hand, deforestation and irrigation of the land have caused the drying up of Lake Cheleleka by reducing the streamflow [12].

Various studies have been conducted to examine water quality in the LHW catchment and identify sources of pollution. Teshome [11] investigated the eastern catchment of Lake Hawasa Watershed to assess the seasonal water quality and its suitability for the designated uses. The findings revealed that the rivers in the eastern part of Lake Hawassa Watershed are suitable for agriculture and livestock but unpleasant for aquatic life, and the lake is hypereutrophic.

Amare [13] investigated the primary sources of non-point source pollution and their relative contribution in Lake Hawassa Watershed using the Annualized Agricultural Non-Point Source (AnnAGNPS) model. The pollutant-loading model revealed non-point source pollutants originating from agricultural lands and associated with deleterious anthropogenic activities responsible for the water quality impairment of Lake Hawassa. These point sources have been determined to be the source of numerous pollutants in the lake ecosystem if the effluent control system put in place is unsuitable [14].

Kebede [15] studied the impact of land cover changes on water quality and streamflow in Lake Hawassa Watershed and concluded that water quality in the upper watershed of the three rivers was better than the lower sections of the catchment with respect to the parameters studied, which might be correlated to the observed land use.

A study conducted by Lencha et al. [16] at Lake Hawassa revealed that most of the population, including the inner part of the city, are using latrines. Larger buildings have conventional flushing systems but without any wastewater treatment. Furthermore, industrial and commercial point sources are known to discharge their effluents into streams or rivers that end up in the Lake. In addition, Hawassa Industrial Park and Referral Hospital discharge their effluents directly into the lake. This is a threat to the people who rely on rivers, streams, and the lake for domestic and other purposes and to the survival of aquatic life as well.

To sum up, some studies regarding the water quality have been conducted in either the eastern or the western catchment of Lake Hawassa, while others have been carried out only at Lake Hawassa. Nonetheless, there is no sufficient water quality study to connect agricultural and urban land use with the watershed pollution level to identify the sources of pollution. The previous studies mainly relied on random monitoring and data from literature and focused only on a few water quality parameters, which cannot reflect the whole picture of water quality in the watershed. Additionally, some previous studies also obtained contradictory findings. On the other hand, urbanization, industrialization, commercial activities, and population growth are increasing rapidly, which could increase sewage and effluents production. Through monitoring data, consistent data analysis, and homogenization of parameters, this study aimed to (1) statistically analyze multiple-parameter data by using principal component analysis (PCA), cluster analysis (CA), and discriminant analysis (DA); (2) investigate the broad-spectrum variation in the parameters of LHW; and (3) cluster monitoring stations with similar characteristics and identify potential sources of pollution in LHW.

## 3.2. Materials and Methods

### 3.2.1. Study Area

Lake Hawassa Watershed (LHW) is located 275 km from the capital Addis Ababa, in the capital of Sidama regional state, on the main road leading to Nairobi, Kenya via Moyale. LHW has a total area of 1431 km$^2$ and lies between 6°45′ to 7°15′ N latitude and 38°15′ to 38°45′ E longitude (Figure 3.1). LHW comprises five sub-watersheds [17].

The watershed is known for its flat plains and dissevered undulating landscape with elevation ranging from 1571 to 2962 m above sea level [18]. The area comprises mountains and low-lying areas, with a wide flat wetland called Cheleleka. Perennial rivers and streams on the north and northeast sides of the catchment and runoff on the east wall feed Cheleleka. The sub-basin of Tikur-Wuha consists of only a tributary called Tikur-Wuha that flows into Lake Hawassa. In this lake system, no surface water flows out from the lake except by evaporation and abstraction, so the catchment can be considered hydrologically closed [15]. The climate of the Hawassa sub-basin is sub-humid and distinctly seasonal. The months from April to October are wet and humid, and the main rainy season is between July and September, with a mean annual precipitation of about 955 mm. The mean minimum precipitation is 17.8 mm in December (dry season) and the mean maximum precipitation is 119.8 mm in August (rainy season) [19].

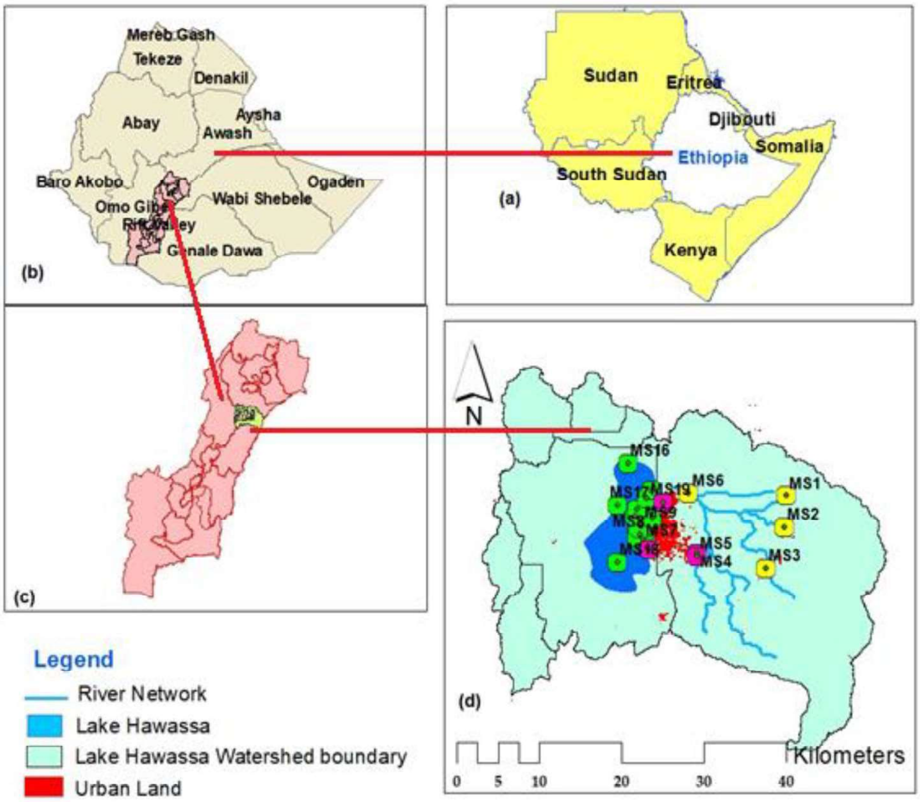

Figure 3.1. Study area map and monitoring station locations ((a) = countries sharing boundaries with Ethiopia, (b) = major river basins in Ethiopia, (c) = Rift Valley lake basin and (d) = Lake Hawassa sub-basin and monitoring stations).

### 3.2.2. Sampling and Monitoring Parameters

The monitoring sites and sampling strategy were planned to cover a wide range of factors contributing to the water quality of the river, taking into account tributaries and point sources whose effluents end up in the lake and have a substantial impact on the water quality of the lake. The criteria for selecting monitoring points were hydrological, with confluence of sub-basins having distinct characteristics and land use types, with the intention of transferring parameters to unmonitored sub-basins. Furthermore, factors such as availability of point and non-point sources, land use type, and urban and wastewater drains were considered in the selection of monitoring sites.

Hence, a total of nineteen (19) monitoring stations were selected (Table 3.1 and Figure 3.1). Four (4) monitoring sites were selected purposively at the Wesha, Hallow, Wedessa, and Tikur-Wuha river mouths of the respective sub-watersheds.

Eleven (11) monitoring sites were distributed evenly along the entire course of Lake Hawassa for water quality monitoring. Three (3) monitoring sites were selected near the industrial disposal site, and one (1) was at the health care center.

The monitoring sites in the Tikur-Wuha catchment were Wesha River (MS1), Hallo River (MS2), and Wedessa River (MS3), which are located in the upstream part of Lake Hawassa, where agricultural runoff from the catchment flows directly or through its tributaries into the Cheleleka wetland. The three rivers were purposively selected based on their size and spatial location to represent their respective sub-basins. Monitoring station 6 (MS6) is a critical area with mostly fresh water where factories discharge their effluent into the Tikur-Wuha River, and the river eventually flows into Lake Hawassa. This is an area where river inputs to the lake are high.

Table 3.1: Monitoring stations in Lake Hawassa Watershed

| No | Monitoring Stations | Site Code | Location |
|---|---|---|---|
| 1 | Wesha River | MS1 | LHW upstream |
| 2 | Hallo River | MS2 | LHW upstream |
| 3 | Wedessa River | MS3 | LHW upstream |
| 4 | BGI effluent discharge site | MS4 | LHW middle |
| 5 | Pepsi factory oxidation pond | MS5 | LHW middle |
| 6 | Tikur-Wuha River | MS6 | LHW middle |
| 7 | Amora-Gedel (fish market) | MS7 | Eastern side of LH |
| 8 | Amora-Gedel (Gudumale) | MS8 | Eastern side of LH |
| 9 | Nearby Lewi resort | MS9 | Eastern side of LH |
| 10 | Fikerhayk center (FH) | MS10 | Center of LH |
| 11 | Fikerhayk (meznegna) | MS11 | Eastern side of LH |
| 12 | Center of LH (Towards HR) | MS12 | Center of LH |
| 13 | Nearby Haile resort | MS13 | Eastern side of LH |
| 14 | Tikur-Wuha site | MS14 | Eastern side of LH |
| 15 | Referral Hospital | MS15 | Eastern side of LH |
| 16 | Ali-Girma site (opposite to HR) | MS16 | Western side of LH |
| 17 | Sima Site (opposite to Mount Tabor) | MS17 | Western side of LH |
| 18 | Dore-Bafana Betemengist | MS18 | Southern part of LH |
| 19 | Hawassa Industrial Park | MS19 | LHW middle |

The site codes are indicated in Figure 1. FH designates Fikerhayk, HR labels Haile Resort, LHW designates Lake Hawassa Watershed, LH designates Lake Hawassa

Monitoring sites for point sources were selected from available industries in the catchment that directly or indirectly feed Lake Hawassa. The selected sites were the St. George Brewery factory, BGI (MS4), and the Moha soft drink factory (MS5), whose effluents discharge into the Cheleleka wetland and eventually enter Lake Hawassa via Tikur-Wuha River, as well as the Referral Hospital (MS15) and Hawassa Industrial park (MS19), which discharge their effluents directly in to Lake Hawassa.

The monitoring stations for Lake Hawassa were selected based on the presence of major pollution sources in the lake, existence of point sources, health facilities and industrial effluent emission sites. Also availability of boating and recreational activities, presence of service rendering facilities such as Haile and Lewi resorts, fish market (Amora-Gedel and Gudumale) and the central part of the lake where the disturbance is minimum. For this purpose, eight (8) monitoring sites were selected in the eastern part (northeast to southeast) of the lake and designated as MS7, MS8, MS9, MS10, MS11, MS12, MS13, and MS14.

The other three (3) monitoring sites were located on the western (northwest to southwest) sides of the lake and were designated as MS16 for the local village Ali-Girma site (opposite Haile Resort), MS17 for Sima site that is opposite side of Mount Tabor, and MS18 for Dore-Bafana Betemengist site. In this part of the lake, although there is no point source pollution, there is enormous anthropogenic activity in the form of non-point source pollution from recreational activities, agricultural runoff, and animal waste.

The analyses of physicochemical water quality parameters at selected sites and periods were conducted from May 2020 to January 2021 to see seasonal variation. Sample collection for the wet season was event-based, i.e., samples were collected after rainfall events. The coordinates of each sampling stations was determined using GNSS.

Composite samples were collected in pre-cleaned 2L polyethylene plastic bottles (sterilized glass bottles were used for biochemical oxygen demand (BOD) and chemical oxygen demand (COD) analyses) for different parameters. The bottles were washed with concentrated nitric acid and distilled water before sample collection and thoroughly rinsed with sample water during collection to avoid possible contamination. The water samples were aseptically handled, labelled, preserved in sterile glass bottles, stored in the cooler (Mobicool v30 AC/DC, Germany) and ice box, and transported to the laboratory of Hawassa University Environmental Engineering, Addis Ababa

City Government Environmental Protection, and Green Development Commission and Engineering Corporation of Oromiya for analysis.

The collection, handling, preservation, and treatment of the water samples followed the standard methods outlined for the examination of water and wastewater by the American Public Health Association guidelines [20] and all the parameters were presented with their respective analytical methods and instruments used for analysis in Table 3.2 below.

Table 3.2. Analytical methods and instruments used for analysis

| Parameter | Analytical Method and Instrument |
|---|---|
| pH, EC, TDS, and Temperature | Portable multi-parameter analyzer (Zoto, Germany) |
| Turbidity | Nephelometric (Hach, model 2100A) |
| DO | Modified Winkler |
| BOD | Manometric, BOD sensor |
| COD | Closed Reflux, colorimetric |
| SRP and TP | Spectrophotometrically by molybdovandate (Hach, model DR 3900) |
| TN | Spectrophotometrically by TNT Persulfate digestion (Hach, model DR 3900) |
| $NO_2^-$ and TAN ($NH_3$–N + $NH_4$–N) | Spectrophotometrically by salicylate (Hach, model DR 3900) |
| $NO_3^-$ | Photometric measurements, Wagtech Photometer 7100 at 520 nm wavelength |
| SS | Filtration by standard glass fiber filter |
| $Mg^{2+}$, $Na^+$, $Ca^{2+}$, and $K^+$ | Atomic Absorption Spectrophotometer, AAS, model NOVAA400 |

Total ammonium nitrogen (TAN), electrical conductivity (EC), total dissolved solids (TDS), dissolved oxygen (DO), biochemical oxygen demand ($BOD_5$), chemical oxygen demand (COD), soluble reactive phosphorous (SRP), total phosphorous (TP), nitrate ($NO_3^-$), nitrite ($NO_2^-$), magnesium ion ($Mg^{+2}$), sodium ion ($Na^+$), potassium ion ($K^+$), calcium ion ($Ca^{+2}$), and suspended solids (SS).

### Un-ionized Ammonia Determination from Total Ammonium Nitrogen (TAN)

The un-ionized free ammonia was calculated by the mass action law in its logarithmic form (1). The pKa as function of temperature was taken from Emerson et al. [21]:

$$\%\ \text{Un-ionized}\ NH_3\text{-}N = \frac{1}{\left(1 + 10^{(pK_a - pH)}\right)} \tag{3}$$

$$pK_a = \frac{0.09108 + 2729.92}{(T_k)} \tag{4}$$

where $T_k$ is temperature in Kelvins (273 + °C).

## 3.3. Multivariate Statistical Techniques and Data Treatment

### 3.3.1. Multivariate Statistical Techniques

Multivariate statistical techniques (MVST) are a valuable tool to estimate efficiently the spatio-temporal variability in a watershed and the influences of human intervention on the characteristics of physicochemical parameters at monitoring stations [22]. In addition, MVST like cluster analysis (CA), discriminant analysis (DA), and PCA/factor analysis can be implemented to interpret complex databases to offer better visualization of water quality in the studied watershed [23]. The statistical techniques PCA, CA, and DA are vital to determine the primary relationships among the physicochemical parameters measured in experimental data standardized to the Z- scale to avoid inaccurate grouping because of the huge variability in the data dimensionality [5, 24–26].

Principal component analysis (PCA), cluster analysis (CA) and discriminant Analysis (DA) were carried out to examine the seasonal variations, identify possible pollution sources, and analyze and interpret surface water quality data to draw meaningful information in China [2,7,27–30], South Asia-Bangladesh [31], the Middle East-Iran [3], India [23,32,33], South African [34], Ethiopia [23,35], South Asia -Malaysia [36], the Middle East-Lebanon [6,37], Spain [38], and Serbia [39]. XLSTAT 2016 (Addinsoft, New York, USA), Microsoft Excel 2016, and “Statistical Package for the Social Sciences Software, IBM SPSS 25 for Windows” were employed to perform statistical analysis integrally.

### 3.3.2. Data Treatment and Multivariate Statistical Methods

PCA is sensitive to outliers, missing data, and poor linear correlation among variables due to insufficient assigned variables. Thus, the data treatment needs to be performed for missing data and outliers in the monitored water quality data before executing multivariate statistical analysis. There might be a real shift in the value of an observation that arises from non-random causes. In this study, outliers were detected according to Grubbs [40] test method using XLSTAT 2016. On the other hand, data collection and analysis were conducted with great prudence to minimize the amount of missing data. However, the incidence of missing data is inevitable and was handled by the multiple imputation of missing values technique using Markov Chain Monte Carlo (MCMC) [41].

The raw water quality parameters were standardized to a mean of 0 and variance of 1 using Z-scale transformation to examine the normality of the distribution of data sets and to ensure that the different variables were equally weighted in the statistical analyses [36]. The data were further checked for normality using Kaiser–Meyer–Olkin (KMO) and Bartlett's sphericity tests to determine if our measured variables may be factorized efficiently. KMO is the degree of sampling adequacy, which shows the percentage of variance that is likely attributable to the underlying factors. Generally, the KMO index ought to be greater than 0.5 for satisfactory factor analysis. When the KMO index is close to 1, the PCA of the variables is suitable; however, when it is close to 0, the PCA is not relevant. In this study, the KMO had a value of 0.68. Bartlett's test of sphericity shows whether the correlation matrix is an identity with variables that are unrelated. The significance level, which is 0 in this study (less than 0.05), indicates that there are significant relationships among the variables.

### 3.3.2.1. Principal Component (PCs)/Factor Analysis (FA)

PCA reduces the dimensionality of the data set by explaining the correlations amongst a large number of variables in terms of a smaller number of underlying factors without losing much information [42,43]. The original variables of PCs produce loadings that have correlation coefficients with PCs. The PCs' formula was taken from [33,36]:

$$\mathcal{Y}mn = \mathcal{Z}m1\mathcal{X}1n + \mathcal{Z}m2\mathcal{X}2n + \mathcal{Z}m3\mathcal{X}3n \ldots + \mathcal{Z}mi\mathcal{X}in \qquad (5)$$

where *z* is the component loading, *y* is the component score, *x* is the measured value of a variable, m is the component number, n is the sample number, and m is the total number of variables.
Meanwhile, FA attempts to extract a lower-dimensional linear structure from the data set and extracts the new group of variables known as varifactors (VFs) via rotation along the PCA axis. In FA, the basic concept is borrowed from [33,36]:

$$\mathcal{Y}mn = \mathcal{Z}p1P1m + \mathcal{Z}p2P2m + \mathcal{Z}p3P3m + \cdots + \mathcal{Z}p\mathcal{r}P\mathcal{r}m + epm \qquad (6)$$

where *y* is the measured value of the variable, *z* refers to the factor loading, *p* is the factor score, m is the sample number, n is the variable number, r is the total number of factors, and e is the residual term accounting for errors or other sources of variation.
In this study, PCA was employed for qualitative determination of pollution sources.

### 3.3.2.2. Discriminant Analysis

DA was used for discriminating between and among groups by applying discriminating variables. These variables measure characteristics regarding which the groups are expected to differ [44]. DA applies a linear equation of a regression analysis on raw data with prior knowledge of membership of objects to particular clusters and provides statistical classification of samples, expressed in the following equation [43,45]:

$$f(Gi) = Ki + \sum_{i=1}^{n} (Wij * Pij) \qquad (7)$$

where Ki is a constant specific to each particular group, i is the number of groups (G), n is the number of parameters used in group classification, and Wij is the weight coefficient designated by DA for the specific parameter (Pij).

Independent variables are entered into DA either all together or stepwise, using both backward and forward approaches. In the first approach of variable entry, the discriminant function is calculated by engaging all the independent variables at once. This approach is used when there are a limited number of independent variables in the interest of discovering how well certain variables perform as discriminants in the absence of others. The stepwise method, on the other hand, involves entering the independent variables into the discriminant function (DF) one at a time. This stepwise input is based on the fact that variables with relative importance to the cluster variables with greater discriminant weights were entered first [46].

In this study, standard, forward, and backward stepwise approaches of DA were applied to each matrix of the primary data. In the forward stepwise mode, discriminant function analysis (DFA) variables were added stepwise until no significant change occurred, while in the backward stepwise mode, variables were removed starting from least significant until a significant change occurred. For this purpose, two groups obtained from CA were selected for spatial evaluations [35].

### 3.3.2.3. Pollution Index (PI)

Pollution index (PI) is a simple technique to examine surface water quality and was applied by Tiwan EPA. The parameters such as DO, BOD, SS, and $NH_3$-N employed to determine PI were classified into four index scores (Table 3.3) and computed using the equation formulated by

[47,48]. In particular, PI refers to the arithmetic mean of the index values with respect to the water quality.

$$\mathrm{PI} = \frac{1}{4}\sum_{K=1}^{4} \mathrm{Si} \qquad (8)$$

PI classifies water quality into four categories: (0–2) for good or non-polluted, (2–3) for slightly polluted, (3–6) for moderately polluted, and (> 6) for highly polluted. Anthropogenic activities have been associated with water quality degradation [47,49].

Table 3.3: Classification system for pollution index

| | **Rank** | | | |
|---|---|---|---|---|
| Item | Non-Polluted (Good) | Slightly Polluted (LP) | Moderately Polluted (MP) | Highly Polluted (HP) |
| DO (mg/L) | >6.5 | 4.6–6.5 | 2.0–4.5 | <2.0 |
| $BOD_5$ (mg/L) | <3 | 3.0–4.9 | 5.0–15.0 | >15 |
| SS (mg/L) | <20 | 20–49 | 50–100 | >100 |
| $NH_3$–N (mg/L) | <0.5 | 0.5–0.9 | 1.0–3.0 | >3.0 |
| Index score | 1 | 3 | 6 | 10 |

### 3.3.3. Cluster Analysis

Hierarchical agglomerative CA was carried out on the normalized data set using Ward's approach, where Euclidean distances were used as the degree of similarity among samples, and a distance was represented by the distinction among analytical values. In hierarchical clustering, sequentially higher clusters formed [23,45,50–52]. In cluster analysis, cases are classified into classes based on similarities between two samples, which are usually given by the Euclidean distance between analytical values of the two samples. The squared Euclidean distance can be calculated by [53]:

$$\text{Distance } (Q_i, Q_j) = \sum_{j=1}^{n} (X_{1i}-X_{2j})^2 \qquad (9)$$

where Qi is the *ith* object, and Xij is the value of the *jth* variable of the *ith* object.

The dendrogram provides a visual summary of the clustering process to classify a sample of entities into a smaller number of mutually exclusive groups on the basis of multivariate similarities among entities [33].

Therefore, CA, DA, PCA, and pollution index were applied in this study to identify the underlying interrelationship among the parameters and monitoring stations. CA was applied based on prior knowledge of monitoring stations and the results of DA and pollution index to accurately cluster monitoring stations. PCA was employed to qualitatively identify pollution sources and the type of contaminants contributing to pollution.

## 3.4. Results and Discussion

### 3.4.1. Correlation Matrix Evaluation and Seasonal Variation

Correlation coefficients are established to portray a correlation among variables and measure statistical significance between pairs of water quality variables [54,55]. Correlation analysis measures the proximity between the identified dependent and independent variables. Correlation coefficients that are close to −1 or +1 demonstrates a strong correlation between x and y, which have a linear correlation. The correlation between the parameters is referred to as strong from (+0.8 to 1.0) or (−0.8 to −1.0), moderate from (+0.5 to 0.8) or (−0.5 to −0.8) and weak from (+0.0 to 0.5) or (−0.0 to −0.5) [56]. In cases where the correlation coefficient between variables is zero, there could be no correlation with a degree of $p < 0.05$ between the two variables [57]. In this study, a correlation matrix was constructed for each dry and wet season using the physicochemical parameters. Pearson's correlation coefficient (r) is determined using correlation matrix to identify the highly correlated and interrelated water quality parameters. To test the significance of the pair of parameters, the $p$-value is determined.

In the wet season, strong positive correlations were observed between TDS values and EC, temperature, TP, TN, and $Na^+$ values (r = 0.992, r = 0.874, r = 0.850, r = 0.836; $p < 0.05$), and strong negative correlations between TDS and DO with −0.825 at $p < 0.05$. Moderate positive correlations were found between TDS and $PO_4$-P, BOD, COD, and $K^+$ values (r = 0.797, r = 0.698, r = 0.695, r = 0.523; $p < 0.05$), and low positive correlation between TDS and pH with r = 0.26; $p < 0.05$ (Table 3.4). Strong negative correlations were found between DO and EC, TDS, TP, and TN (r = −0.825, r = −0.850, r = −0.851, r =−0.806; $p<0.05$), and moderate negative correlations were observed between DO and temperature, BOD, COD, and Na+ values (r = −0.526, r = −0.544, r = −0.692, r = −0.599; $p< 0.05$) (Table 3.4).

Table 3.4: Correlation matrix Pearson (r) and alpha (p) values for the wet season

| Parameters | TDS | EC | $NH_3$−N | $NO_3^-$N | $PO_4$−P | DO | BOD | COD | TN | TP | Temp | $Mg^{2+}$ | $Ca^{2+}$ | $Na^+$ | $K^+$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| TDS | **1** | | | | | | | | | | | | | | |
| EC | **0.992** | **1** | | | | | | | | | | | | | |
| $NH_3$−N | 0.446 | 0.379 | **1** | | | | | | | | | | | | |
| $NO_3$−N | 0.183 | 0.172 | −0.030 | **1** | | | | | | | | | | | |
| $PO_4$−P | **0.797** | **0.824** | 0.416 | −0.116 | **1** | | | | | | | | | | |
| DO | **−0.825** | **−0.850** | −0.216 | −0.275 | **−0.793** | **1** | | | | | | | | | |
| BOD | **0.698** | **0.719** | 0.106 | −0.173 | **0.712** | **−0.526** | **1** | | | | | | | | |
| COD | **0.695** | **0.714** | 0.204 | −0.111 | **0.730** | **−0.544** | **0.965** | **1** | | | | | | | |
| TN | **0.874** | **0.855** | **0.481** | 0.059 | **0.825** | **−0.851** | **0.587** | **0.602** | **1** | | | | | | |
| TP | **0.850** | **0.871** | 0.249 | 0.255 | **0.602** | **−0.806** | **0.485** | **0.482** | **0.736** | **1** | | | | | |
| Temperature | **0.860** | **0.864** | 0.331 | 0.410 | **0.594** | **−0.692** | 0.454 | 0.447 | **0.669** | **0.82** | **1** | | | | |
| $Mg^{2+}$ | −0.005 | 0.029 | −0.317 | 0.070 | −0.013 | −0.085 | 0.224 | 0.159 | 0.046 | 0.09 | −0.020 | **1** | | | |
| $Ca^{2+}$ | 0.375 | 0.397 | −0.085 | −0.080 | 0.350 | −0.394 | **0.523** | **0.528** | 0.429 | 0.24 | 0.137 | 0.401 | **1** | | |
| $Na^+$ | **0.836** | **0.853** | 0.314 | 0.268 | **0.709** | **−0.599** | **0.619** | **0.632** | **0.572** | **0.68** | **0.849** | −0.062 | 0.19 | **1** | |
| $K^+$ | **0.523** | 0.431 | **0.531** | 0.155 | 0.290 | −0.429 | 0.149 | 0.190 | **0.700** | 0.34 | 0.320 | −0.080 | 0.20 | 0.19 | **1** |

Values in bold are different from 0 with a significance level alpha = 0.05.

Strong positive correlations were observed between temperature and the values of EC, TDS, $Na^+$ and TP (r = 0.86, r = 0.864, r = 0.849, r = 0.821; $p < 0.05$), and a moderate positive correlation was observed between temperature and the values of TN and $PO_4$-P (r = 0.525, r = 0.669, r = 0.594; $p < 0.05$). There was also a moderate negative correlation between temperature and DO, with r = −0.692 at $p < 0.005$. There was a weak correlation between temperature and the values of COD and BOD (r = 0.447, r = 0.454; $p < 0.05$).

$NH_3$-N had a moderate positive correlation with $K^+$, with r = 0.531 at $p < 0.005$, and weak positive correlations with TN and temperature (r = 0.331, r = 0.481 at $p < 0.05$). $NO_2$-N correlated moderately positively with BOD and COD (r = 0.721, r = 0.664 at $p < 0.05$) and weakly positively with $PO_4$-P and $Ca^{+2}$ (r = 0.449, r= 0.404 at $p < 0.05$).

A strong positive correlation was found between $PO_4$-P and TN, with r = 0.825 at $p < 0.005$, moderate positive correlations were found between $PO_4$-P and COD, BOD, TP, and temperature (r = 0.712, r = 0.709, r = 0.730, r = 0.602, r = 0.594; $p < 0.05$), and a moderate negative correlation was observed between $PO_4$-P and DO values (r = −0.793; $p < 0.05$). No statistically significant difference was found between pH and $NO_3$-N and the rest of the parameters of LHW ($p > 0.05$).

In the dry season, strong positive correlations were observed between TDS values and EC, TP, $Na^+$, $PO_4^-$P, and temperature values (r = 0.999, r = 0.814, r = 0.899, r =0.839, r = 0.933; P < 0.05), moderate positive correlations were observed between TDS and BOD, COD, $K^+$ and TN values (r

= 0.686, r = 0.561, r = 0.645, r = 0.534; P < 0.05), and a strong negative correlation was found between TDS values and DO (r = −0.819 at $p < 0.05$).

Strong negative correlations were observed between the values of DO and TDS, EC, and Na$^+$ (r =**−0.819,** r = 0.817, r = −0.826; $p$ <0.05), moderate negative correlations were observed between DO and TN, TP, BOD, K$^+$, and temperature values (r = −0.577, r = −0.568, r = −0.687, r = −0.639, r = −0.729; $p < 0.05$), and a moderate negative correlation was observed between DO and $NO_3^-$N with r = −0.464 at $p < 0.005$).

Strong positive correlations were found between temperature and EC and TDS (r = 0.839, r = 0.842; $p < 0.05$), and moderate positive correlations were found for temperature with TP and $PO_4$-P (r = 0.730, r = 0.532; $p < 0.05$). There was also a moderate negative correlation observed between temperature and DO, with r = −0.729 at $p < 0.005$. $NH_3$-N had a moderate positive correlation with COD, TP, temperature, and **Na**$^+$ (r = 0.476, r = 0.484, r = 0.550, r = 0.343; $p < 0.005$).

A strong positive correlation was found between $PO_4$-P and TP, with r = 0.921 at $p < 0.005$, moderate positive correlations were found for $PO_4$−P with BOD, COD, TP, Na$^+$, and temperature (r = 0.749, r = 0.647, r = 0.680, r = 0.76; $p < 0.05$), and a moderate negative correlation was found between $PO_4$-P and DO values r = −0.626; $p < 0.05$) (Table 3.5).

Table 3.5: Correlation matrix Pearson (r) and alpha (p) values for dry season

| Parameters | TDS | EC | $NH_3$−N | $NO_3$−N | $PO_4$−P | DO | BOD | COD | TN | TP | Tem | $Mg^{2+}$ | $Ca^{2+}$ | $Na^+$ | $K^+$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| TDS | **1** | | | | | | | | | | | | | | |
| EC | **0.999** | **1** | | | | | | | | | | | | | |
| $NH_3$−N | 0.433 | 0.419 | **1** | | | | | | | | | | | | |
| $NO_3$−N | 0.208 | 0.212 | −0.10 | **1** | | | | | | | | | | | |
| $PO_4$−P | **0.814** | **0.815** | 0.383 | −0.04 | **1** | | | | | | | | | | |
| DO | **−0.82** | **−0.82** | −0.31 | **−0.46** | **−0.63** | **1** | | | | | | | | | |
| BOD | **0.686** | **0.686** | 0.450 | −0.12 | **0.749** | **−0.58** | **1** | | | | | | | | |
| COD | **0.561** | **0.564** | **0.476** | −0.19 | **0.647** | −0.41 | **0.871** | **1** | | | | | | | |
| TN | **0.645** | **0.642** | 0.410 | 0.184 | **0.680** | **−0.57** | **0.520** | **0.619** | **1** | | | | | | |
| TP | **0.899** | **0.899** | **0.484** | −0.03 | **0.921** | **−0.69** | **0.804** | **0.683** | **0.535** | **1** | | | | | |
| Temperature | **0.839** | **0.842** | 0.343 | 0.237 | **0.532** | **−0.73** | 0.436 | 0.344 | 0.291 | **0.730** | **1** | | | | |
| $Mg^{2+}$ | −0.27 | −0.27 | −0.25 | −0.13 | −0.04 | 0.305 | −0.13 | −0.20 | −0.16 | −0.13 | −0.42 | **1** | | | |
| $Ca^{2+}$ | 0.385 | 0.392 | −0.19 | 0.398 | 0.091 | −0.33 | 0.235 | 0.324 | 0.208 | 0.17 | 0.455 | −0.33 | **1** | | |
| $Na^+$ | **0.933** | **0.931** | **0.550** | 0.173 | **0.760** | **−0.83** | **0.813** | **0.694** | **0.601** | **0.881** | **0.788** | −0.38 | 0.37 | **1** | |
| $K^+$ | **0.534** | **0.531** | 0.182 | 0.419 | 0.261 | **−0.64** | 0.237 | 0.240 | **0.701** | 0.197 | 0.335 | −0.39 | 0.42 | **0.53** | **1** |

Values in bold are different from 0 with a significance level alpha = 0.05.

The pH of rivers was 7.4 (7.1 to 7.6) in the dry season and 8.2 (7.5 to 8.7) in the wet season, and the pH of lake was 8.2 (7.3 to 8.9) in the dry season and 8.5 (7.5 to 9) in the wet season. The pH of point sources was 8.3 (7.1 to 9) in the dry season and 8.3 (8.1 to 8.7) in the wet season. The recommended pH as per the standard for drinking, irrigation, and aquatic life is 6.5–8.6, and the pH of LHW was within the accepted limit (Table 3.6). The EC (TDS) of rivers was 148mg/L (297 µS/cm) in dry seasons and 89 mg/L (179 µS/cm) in wet seasons, and EC (TDS) of lakes was 453 mg/L (877 µS/cm) in dry season and 421 mg/L (829 µS/cm) in wet seasons. The EC (TDS) of point sources was 1655 mg/L (3509 µS/cm) in dry season and 1395 mg/L (2809 µS/cm) in wet seasons. This shows that the EC (TDS) of rivers, lakes, and point sources increases significantly with increasing temperature. The $NO_3$-N concentration of rivers was 0.5 mg/L, $NO_3$-N concentration of Lake Hawassa was 1.4 mg/L, and that of point sources was 1.5 mg/L for the dry season. In the wet season, the $NO_3$-N concentration was 0.7, 1.9, and 1.9 for rivers, Lake Hawassa, and point sources, respectively. The value of $NO_3$-N increases in the rainy season due to the contribution of agricultural runoff and use of fertilizers. The $PO_4$-P concentration of rivers was 6.5 mg/L, $PO_4$-P of Lake Hawassa was 3.3 mg/L, and that of point sources was 43.8 mg/L in dry season. In the wet season, the $PO_4$-P concentration was 7.4, 2.9, and 25.7 for rivers, Lake Hawassa, and point sources, respectively (Table 3.6). Similarly, Gebre-Mariam [58] reported that Ethiopian Rift Valley lakes generally have lower EC values in the rainy season than in the dry season, due to dilution by rain coupled with minimal evaporation rates during the rainy season.

Table 3.6: Descriptive statistics (mean and standard deviation) of the physicochemical characteristics of LHW collected during dry season

| Codes | SS | TDS | EC | pH | $NH_3$–N | $NO_3$–N | $PO_4$–P | DO | BOD | COD | TN | TP | $Mg^{2+}$ | $Ca^{2+}$ | $Na^+$ | K+ | Temperature |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| MS1 | 17.3 | 89 | 178 | 7.1 | 0.04 | 0.6 | 3.6 | 4.1 | 13.8 | 88.3 | 5.8 | 0.001 | 7.2 | 20 | 32.5 | 6.7 | 19.2 |
|  | (1.6) | (4) | (7) | (0.2) | (0.01) | (0.01) | (2) | (0.7) | (1.5) | (26.9) | (1.5) | (0) | (2.1) | (7.4) | (1.5) | (0.6) | (0.8) |
| MS2 | 27.3 | 100 | 200 | 7.6 | 0.16 | 0.4 | 10.2 | 3.5 | 23.7 | 107.5 | 7.2 | 0.5 | 54.0 | 9 | 26.2 | 8.1 | 17.7 |
|  | (5.8) | (15) | (30) | (0.5) | (0.07) | (0.04) | (6.7) | (1) | (7.2) | (32.5) | (1.8) | (0.5) | (16.4) | (8.4) | (3) | (0.6) | (1) |
| MS3 | 54.5 | 87 | 175 | 7.7 | 0.10 | 0.6 | 5.9 | 4.4 | 69.0 | 313.8 | 7.5 | 0.001 | 153.4 | 4.6 | 25.8 | 6.8 | 18.1 |
|  | (3) | (6) | (12) | (0.3) | (0.01) | (0.1) | (0.1) | (0.4) | (20.5) | (93.3) | (2.5) | (0) | (50.2) | (4.2) | (3) | (0.6) | (0.7) |
| MS4 | 58.0 | 1575 | 3825 | 7.1 | 7.60 | 2.8 | 18.7 | 1.5 | 63.3 | 263.7 | 23.8 | 15 | 11.4 | 50.4 | 501.1 | 19.8 | 33.8 |
|  | (10.4) | (59) | (108) | (0.4) | (1.49) | (0.5) | (2.9) | (0.1) | (10.8) | (84.9) | (5.9) | (3) | (0.1) | (5.6) | (83) | (0.3) | (0.3) |
| MS5 | 27.7 | 2349 | 4698 | 9.5 | 12.35 | 0.6 | 118.3 | 0.9 | 190 | 600 | 41.3 | 6.5 | 2.9 | 15.0 | 1078.1 | 19.3 | 29 |
|  | (1.5) | (193) | (385) | (0.6) | (5.15) | (0.05) | (40) | (0.1) | (1.3) | (241) | (16.7) | (1.6) | (1.8) | (10.6) | (178) | (0.8) | (0.6) |
| MS6 | 23.3 | 317 | 635 | 7.6 | 0.06 | 1 | 6.3 | 4 | 5.3 | 26.3 | 11.3 | 0.001 | 5.7 | 18.7 | 111.8 | 9.4 | 24.5 |
|  | (0.1) | (63) | (126) | (0.1) | (0.03) | (0.2) | (0.6) | (0.5) | (1.8) | (5.8) | (3.7) | (0) | (1) | (0.7) | (24) | (0.9) | (0.4) |
| MS7 | 10.6 | 388 | 765 | 8.8 | 0.37 | 0.9 | 2.5 | 4.5 | 5.9 | 116 | 6.8 | 0.8 | 5.1 | 16.2 | 221.9 | 20.1 | 22.8 |
|  | (1.4) | (7) | (25) | (0.003) | (0.08) | (0.02) | (0.5) | (0.5) | (0.3) | (88) | (1.2) | (0.2) | (0.7) | (1.1) | (15.9) | (0.3) | (1) |
| MS8 | 13.6 | 518 | 851 | 8.9 | 11.75 | 1 | 4.3 | 5.3 | 9.5 | 135 | 4.5 | 0.4 | 3.9 | 24.2 | 255.0 | 22.2 | 22.8 |
|  | (0.1) | (26) | (32) | (0.02) | (3.9) | (0.02) | (0.1) | (0.3) | (1.5) | (5) | (1.5) | (0.1) | (0.1) | (1.8) | (30.1) | (0.8) | (1) |
| MS9 | 9.0 | 392 | 748 | 8.7 | 0.38 | 2 | 3.0 | 4 | 9.9 | 45 | 3 | 0.001 | 12.8 | 22.2 | 191.9 | 20.0 | 22.7 |
|  | (1.2) | (3) | (24) | (0.1) | (0.11) | (1) | (0.1) | (0) | (0) | (0) | (0) | (0) | (1) | (1.9) | (5.4) | (0.3) | (1.8) |
| MS10 | 10.8 | 473 | 955 | 8.5 | 0.12 | 0.6 | 2.5 | 4.3 | 71.8 | 326 | 1.1 | 0.1 | 5.2 | 18.4 | 224.2 | 20.0 | 21.3 |
|  | (0.4) | (8) | (5) | (0.04) | (0.04) | (0.1) | (0.7) | (0.3) | (22.8) | (104) | (0.1) | (0.1) | (0.5) | (1.4) | (7.9) | (0.1) | (1.4) |
| MS11 | 13.5 | 463 | 880 | 8.6 | 3.71 | 3.1 | 2.0 | 3.3 | 9.0 | 96 | 4.5 | 0.001 | 5.4 | 20.9 | 205.1 | 20.7 | 23.1 |
|  | (0.2) | (3) | (20) | (0.04) | (1.23) | (1.8) | (0.3) | (0.1) | (1) | (20.5) | (1.5) | (0) | (0.1) | (0.1) | (4.9) | (0.3) | (1.3) |
| MS12 | 10.3 | 460 | 921 | 8.6 | 1.34 | 1 | 2.3 | 4.5 | 10.1 | 46 | 4.0 | 0.001 | 10.1 | 26 | 225.0 | 23.4 | 22.6 |
|  | (1.8) | (18) | (35) | (0.2) | (0.56) | (0) | (0.4) | (0) | (0.4) | (1.8) | (1.8) | (0) | (1.9) | (1.9) | (10.9) | (2.7) | (1.1) |
| MS13 | 12.5 | 411 | 807 | 8.5 | 0.15 | 3.1 | 3.1 | 4.0 | 47.3 | 255 | 6.9 | 0.5 | 13.5 | 40.9 | 280.8 | 19.0 | 23.2 |
|  | (3) | (9) | (33) | (0.2) | (0.03) | (2.1) | (0.6) | (0.5) | (8.8) | (55) | (2.1) | (0.1) | (2.5) | (7.1) | (29.2) | (0.7) | (1.3) |
| MS14 | 9.3 | 358 | 714 | 7.3 | 1.19 | 1.3 | 3.8 | 3.5 | 20.2 | 134 | 3.8 | 0.001 | 6.3 | 16.9 | 150.8 | 16.7 | 20.8 |
|  | (1.3) | (82) | (166) | (0.1) | (0.38) | (0.1) | (0.8) | (0.5) | (4) | (23.8) | (1.2) | (0) | (0.3) | (0.2) | (37.3) | (3.3) | (0.9) |

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| MS15 | 24.2 | 1632 | 3266 | 8.3 | 24.97 | 1.6 | 36.7 | 1.5 | 63.5 | 290 | 49.5 | 5.6 | 13.7 | 33.7 | 420.2 | 44.7 | 23.9 |
| | (0.9) | (39) | (78) | (0.005) | (7.06) | (0.8) | (6.8) | (0.03) | (9.1) | (40) | (15.5) | (1.9) | (2.1) | (2.9) | (41.3) | (3.3) | (0.8) |
| MS16 | 16.6 | 483 | 935 | 8.6 | 0.96 | 1.0 | 3 | 4.2 | 22.6 | 75.5 | 6.3 | 3.8 | 3.2 | 8.8 | 197.2 | 17.8 | 21.5 |
| | (0.8) | (8) | (45) | (0.1) | (0.78) | (0.1) | (0.3) | (0.1) | (3.1) | (10.5) | (0.8) | (1.2) | (0.3) | (1.3) | (13.7) | (2.3) | (0.3) |
| MS17 | 14.3 | 479 | 935 | 8.6 | 3.17 | 1 | 2.7 | 4.2 | 48 | 160 | 5.3 | 0.001 | 14.1 | 33.8 | 159.0 | 18.0 | 22.0 |
| | (0.2) | (1) | (25) | (0.01) | (0.04) | (0.01) | (0.1) | (0.1) | (3) | (10) | (0.2) | (0) | (1.7) | (1.3) | (16.3) | (2.3) | (0.5) |
| MS18 | 96.4 | 561 | 1133 | 8.7 | 0.86 | 1 | 7.8 | 4.3 | 55.5 | 185 | 12.3 | 0.8 | 16 | 34 | 243.7 | 19.1 | 23 |
| | 3.0 | (34) | (48) | (0.1) | (0.21) | (0.01) | (0.7) | (0.3) | (1.5) | (5) | (2.7) | (0.2) | (1.7) | (2) | (11.2) | (1.2) | (0.3) |
| MS19 | 7.2 | 1065 | 2246 | 8.4 | 0.05 | 0.8 | 9.8 | 4.2 | 126 | 420 | 12.8 | 2 | 18.3 | 53.7 | 301.4 | 20.9 | 21.2 |
| | (0.8) | (215) | (469) | (0.1) | (0.02) | (0.04) | (1.4) | (0.1) | (3) | (10) | (2.3) | (0.3) | (3.8) | (4.9) | (25.5) | (0.05) | (0.4) |

All units in mg/L except pH (Dimensionless), Temperature (°C), EC (µS/cm) and Turbidity (NTU).

The TN (TP) of rivers was 8 (0.12) mg/L in dry seasons and 5(0.26) mg/L in wet season, and TN (TP) of lakes was 5.3 (0.2) mg/L) in dry season and 5.2 (0.6) mg/L in wet season. Hence, there is an obvious increase of TN in rivers and Lake Hawassa when temperature increases due to lower dilution and greater agricultural contribution from the upper stream by irrigation, whereas TP in rivers and Lake Hawassa increases in wet seasons due to greater agricultural, rural, and urban runoff. The TN (TP) from point sources was 31.8 (7.2) mg/L in dry season and 13.9 (5.4) mg/L in wet season. This shows that TN (TP) of point sources increases significantly with increasing temperature due to lower dilution. The $NH_3$−N of rivers was 0.2 mg/L, $NH_3$−N of Lake Hawassa was 0.83 mg/L, and that of point sources was 4.72 mg/L in dry season. In the wet season, the $NH_3$−N values were 0.03, 0.71, and 3.6 for rivers, Lake Hawassa, and point sources, respectively. The decreases in $NH_3$-N level in the rainy season might be due to dilution effect (Table 3.6).

The positive correlation between temperature and TN, TP, EC, TDS, $NH_3$-N, and $PO_4$−P indicates the increase in the concentration of nutrients as the temperature increases (dry period). It also confirms the major contributors of nutrients were the point sources that are releasing a relatively higher amount of pollutants than the agricultural and other sources, as this value lowers during the wet season due to dilution effect. However, the increase in nutrient ($NO_3$−N) concentration in rivers and Lake Hawassa in the wet season might be due to the increased contribution of agricultural runoff and use of fertilizers.

Sodium, calcium, magnesium, and potassium concentrations of the rivers were 49.1, 13.06, 55.1, and 7.74 mg/L in dry season and 28.9, 32.7, 10.1, and 5.7 mg/L in wet seasons. Sodium, calcium, magnesium and potassium concentrations of the lake were 214, 23.8, 8.7, and 19.7 mg/L in dry season and 178.9, 25.1, 7.3, and 17.2 mg/L in wet season. The sodium, calcium, magnesium, and potassium concentrations of the point sources were 575.2, 38.2, 11.5, and 26.2 mg/L, respectively, in the dry season and 375.2, 38.2, 9.5, and 50.1 mg/L. respectively in the wet season (Table 3.6). There was an observed decrease in ions when the temperature decreased in the study area. This can be ascribed to the discharge of industrial and domestic effluents, which contribute large amounts of alkaline ions to the river system, as the conductivity depends mainly on the ion concentration in surface water [52]. The natural range of sodium ions in water and soil is so low that their existence can show river pollution caused by human activities. Calcium is added to water from soil, industrial wastes, and natural resources. Magnesium is an essential nutrient required for numerous biochemical and physiological functions [59].

The TDS of water generally increases with the level of dissolved pollutants (such as nitrate, ammonium, and phosphate). Conductivity of ions in water depends on water temperature, and ions move faster when water is warm. Hence, conductivity apparently increases when water has a higher temperature [60]. In addition, Taylor et al. [61] pointed out a strong relationship between these variables or ions, such as nitrate, ammonium, and phosphate, and stated that high concentrations of EC indicate high concentrations of soluble salts. There are strong correlations between EC/TDS, as evidenced by an increase in conductivity as the concentration of all dissolved constituents increases [62] Table 3.6.

The BOD (COD) of rivers was 19.7 (96.5) mg/L in dry seasons and 6.9 (89.4) mg/L in the wet season, and the BOD and COD of lakes was 28.1 (133.3) mg/L in dry season and was 19.1 (112.9) mg/L in wet season. The BOD and COD concentrations for point sources were 116.2 (398.6) mg/L in dry season and 111.6 (353.7) mg/L in wet season (Table 6). The DO of rivers was 3.5 mg/L in dry season and 6 mg/L in wet season, and the DO of lakes was 4.2 mg/L in dry season and 4.4 mg/L in wet season. The DO of point sources was 2 mg/L in dry season and 2.3 mg/L in the wet season (Table 3.6).

The DO of the rivers in the dry seasons and Lake Hawassa were well below the standard value. This indicates that the discharge of industrial and domestic effluents has resulted in serious organic pollution of these rivers, as the decrease of DO was mainly caused by the decomposition of organic compounds. Moreover, an extremely low DO content usually indicates the degradation of an aquatic system [63].

The DO showed a negative correlation with most parameters in both dry and rainy seasons, revealing the value of DO decreases with the increase in other water quality parameters. This could explain the temporal variations, as more oxygen was available for reaction with the pollutants, especially metals and organic pollutants, during dry seasons. Additionally, the characteristics of temporal variation in water quality of LHW were affected by DO. DO was strongly correlated with organic matters, nutrients, and metals, and thus seasonal variation should be considered when DO is used as an indicator to evaluate surface water quality. Low dissolved oxygen (DO) is primarily the result of excessive algal growth caused by nutrients. As the algae die and decompose, this process consumes dissolved oxygen. This may result in insufficient dissolved oxygen for fish and other aquatic life. Temperature was significantly correlated with water quality parameters such as EC, TDS, TP, $PO_4$-P, and DO in both seasons. Temperature had significant negative correlation with DO in the dry and wet seasons, indicating that when water temperature increases, the metabolic rate of microorganisms also increases, and the amount of DO in the water decreases. This might be because faster biodegradation of organic matter during dry seasons can effectively improve water quality. The solubility of oxygen was inversely related to temperature, as the water becomes warmer and more easily saturated with oxygen, hence holds less DO during the dry season. Singh et al. [32] observed the inverse relationship between temperature and DO in natural processes, as water can hold less DO with increasing temperature.

### 3.4.2. Pollution Index (PI)

The mean pollution index of the rivers in the lake watershed was 4.5 in dry and 3.3 in wet season, indicating a moderately polluted condition of rivers. Lake Hawassa PI was 5 in both dry and rainy season, indicating that the quality of the lake was moderately polluted. Anthropogenic activities were causing deterioration of the water quality of the rivers and Lake Hawassa, and the overall status of the water quality is moderately polluted. The PI for the point sources was measured for comparison purposes, and it was found to be highly polluted, having a PI index of 6.8 and 7.3 for the wet and dry seasons, respectively (Table 3.7).

Table 3.7: Average concentrations of monitoring stations for rivers, Lake Hawassa, and point sources (PS) observed in both dry and wet seasons

| Parameters | Seasons | Rivers | Lake Hawassa | PS |
|---|---|---|---|---|
| DO (mg/L) | dry seasons | 4.2 | 4.2 | 1.7 |
| | wet seasons | 6 | 4.3 | 2.1 |
| $BOD_5$ (mg/L) | dry seasons | 19.7 | 28.1 | 116.2 |
| | wet seasons | 6.9 | 19.1 | 111.6 |
| SS (mg/L) | dry seasons | 30.6 | 19.7 | 29.3 |
| | wet seasons | 51.1 | 20.9 | 28.1 |
| $NH_3$-N (mg/L) | dry seasons | 0.2 | 0.8 | 1.2 |
| | wet seasons | 0.002 | 0.71 | 14.4 |
| PI | dry seasons | 4.5 | 5 | 7.3 |
| | wet seasons | 3.3 | 5 | 6.8 |
| Rank | dry seasons | MP | MP | HP |
| | wet seasons | MP | MP | HP |

### 3.4.3. Cluster Analysis

#### Spatial and Temporal Similarities

Cluster analysis was applied to find out if the monitoring stations had similar characteristics in terms of water quality parameters. It was implemented with the water quality data set to group comparable monitoring sites (spatial variability) spread over the watershed. Results from CA display high homogeneity within clusters and high heterogeneity between clusters [64]. Hierarchical agglomerative CA was carried out with the normalized data set employing Ward's method, using Euclidean distances as a measure of similarity. In this approach, the analysis of variance method is used to evaluate the distances between clusters, attempting to reduce the sum of squares of all clusters that can be made at each step. In this method, the clusters are grouped sequentially, beginning with the most comparable pair of objects and establishing better clusters one after the other, demonstrated through a dendrogram [2,65].

The dendrogram presents a visual summary of the clustering processes and provides the map of the groups with a dramatic reduction in the dimensionality of the original records [2,5,32,43,44]. The CA grouped all 19 monitoring stations into two statistically significant clusters for the dry and wet seasons in LHW, and the dendrogram displays the grouping of stations for the wet and dry seasons, as demonstrated in Figure 3.2. Regarding the clustering for the dry and wet seasons, monitoring stations from most of the watershed upstream, from the eastern and western sides of the lake, and from the center of Lake Hawassa have been grouped in Cluster 1. Stations in these clusters typically consist of rivers and Lake Hawassa and are categorized as moderately polluted. The monitoring stations in these clusters are MS1-MS3, MS6-MS14, and MS16-MS18, which can be labeled as “moderate anthropogenic effect”. This cluster received pollution from point sources and non-point sources, consisting of animal waste and runoff. It is characterized by moderate anthropogenic impact and labelled as moderately polluted.

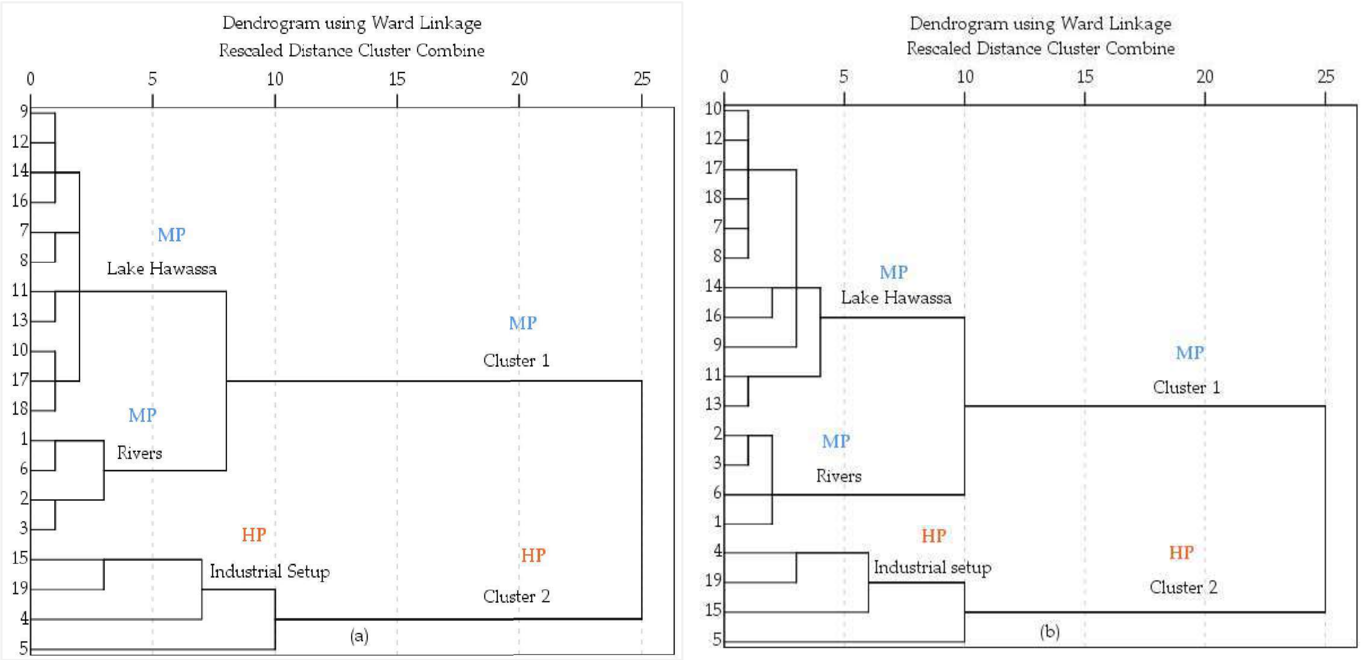

Figure 3.2. Dendrogram for LHW based on Ward’s method showing the clustering of 19 monitoring stations into two significant clusters for both dry (a) and wet (b) seasons.

The pollution sources for monitoring stations MS1-MS3 were mainly anthropogenic activities from non-point pollution sources such as agricultural and sewage pollution, whereas pollution sources for monitoring stations MS6 (Tikur-Wuha river) and Lake Hawassa (MS7–MS14, MS16–MS18) were mainly industrial pollution, dispersed point sources, agricultural pollution, urban runoff, and sewage pollution.

Owing to their relative sources, all stations in this cluster were rivers and lakes, suggesting that clustering is reasonable for both dry and wet seasons.

The spatial trend of water quality was generally driven by anthropogenic activities from point and non-point sources of pollution, especially anthropogenic activities with respect to pollutant loading and land use.

Cluster 2 includes four monitoring stations in the middle part of the LHW and groups monitoring stations in this cluster as MS4, MS5, MS15, and MS19. Four point sources, specifically BGI, Pepsi Factory, Referral Hospital, and Industrial Park monitoring stations, were assigned to this cluster. Consequently, this cluster is characterized by comparatively heavy pollution.

### 3.4.4. Discriminant Analysis

Discriminant analysis (DA) was used to evaluate the spatial variations in water quality and to distinguish the most critical parameters in relation to variations between clusters. Both the standard and stepwise modes were applied to the primary data by dividing them into wet and dry seasons, and the two spatial groups resulting from CA were used in DA. In this case, the WQ parameters were treated as independent variables, while the clusters were considered as dependent variables. The confusion matrixes (CM) showed that 100%, 100%, and 100% of the data points were correctly classified in the standard, forward stepwise, and backward stepwise modes for both dry and wet seasons, respectively (Table 3.8).

Table 3.8: Classification matrix for standard, forward stepwise, and backward stepwise DA of spatial variation in LHW for both dry and wet seasons, showing percentage of correct assignation for discriminating parameters

| **Monitoring Stations** | **% Correct** | **Stations Assigned by DA** | |
|---|---|---|---|
| | | **C1** | **C2** |
| Standard DA mode for dry season | | | |
| C1 | 100 | 15 | 0 |
| C2 | 100 | 0 | 4 |
| Total | 100 | 15 | 4 |
| Standard DA mode for wet season | | | |
| C1 | 100 | 15 | 0 |
| C2 | 100 | 0 | 4 |
| Total | 100 | 15 | 4 |
| Forward stepwise DA mode for dry season | | | |
| C1 | 100 | 15 | 0 |
| C2 | 100 | 0 | 4 |
| Total | 100 | 15 | 4 |
| Forward stepwise DA mode for wet season | | | |
| C1 | 94 | 15 | 0 |
| C2 | 85 | 0 | 4 |
| Total | 84.5 | 15 | 4 |
| Backward stepwise DA mode for dry season | | | |
| C1 | 100 | 15 | 0 |
| C1 | 100 | 0 | 4 |
| Total | 100 | 15 | 4 |
| Backward stepwise DA mode for wet season | | | |
| C1 | 100 | 15 | 0 |
| C2 | 75 | 0 | 4 |
| Total | 87.5 | 15 | 4 |

C1: Includes stations (MS1-MS3, MS6-MS14, and MS16-MS18)

C2: Includes stations (MS4, MS5, MS15, and MS19).

The standard DA method builds DFs using eighteen parameters, while only three and seven parameters were the critical parameters useful to make distinction within the two pollution groups for both the forward stepwise modes and backward stepwise modes, respectively, for both dry and wet seasons. In forward stepwise mode, most of the parameters such as turbidity, TDS, pH, $NH_3$−N, $NO_3$−N, $PO_4$−P, DO, COD, $NO_2$-N, TN, TP, temperature, $Mg^{2+}$, $Ca^{2+}$, and $K^+$ were insignificant variables leading to less variation, and they were deleted in the further process. However, in the forward stepwise DA mode, the three significant variables that were useful to make distinctions within the two pollution groups with 100% correct assignation were EC, BOD, and $Na^+$. The backward stepwise mode deleted the least significant and identified seven significant variables: EC, DO, COD, TN, TP, $Na^+$ and $K^+$**.** These seven parameters, which were 100% correctly assigned, were the critical parameters useful to make distinctions within the two pollution groups. This implies that the expected spatial variation in water quality can be explained sufficiently using variables EC, DO, COD, TN, TP, Na$^+$, and K$^+$. Wilks' lambda shows that the discriminant distribution is skewed towards high concentrations.

On the other hand, the standard DA functions was constructed using eighteen parameters, of which three and four parameters were used for forward stepwise mode and backward stepwise mode, respectively, for wet season. In forward stepwise mode, the pollutants that were found to be insignificant variables and had less variation in terms of their spatial distribution were deleted in the further process. However, in the backward stepwise DA mode, the three significant variables that were useful to make distinctions within the two pollution groups with 84.5% correct assignment were EC, Na$^+$, and COD. The backward stepwise mode deleted the least significant and identified two significant variables: EC and Ca$^{+2}$. These two parameters were the critical parameters useful to make distinctions within the two pollution groups with 87.5% correct assignation (Table 8). This implies the spatial water quality variation can be sufficiently explained by using variables EC, Na$^+$, COD, and Ca$^{2+}$, with Wilks' lambda value showing discriminatory distribution is skewed toward high concentration, as shown in Figure 3.3.

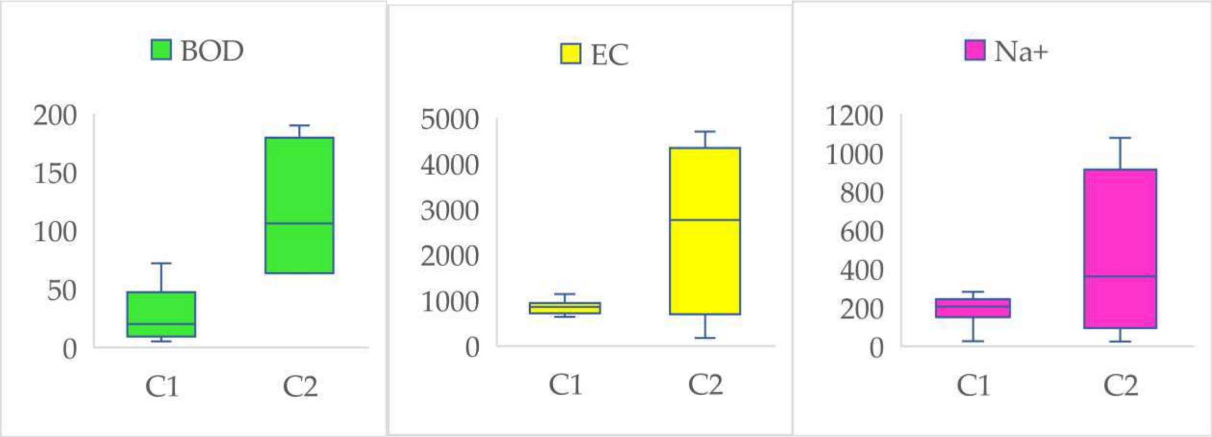

Figure 3.3. Box plot of the most discriminating parameters, BOD (mg/L), EC (µS/cm) and Na+ (mg/L) and Wilks' lambda showing skewedness of discriminatory distribution toward high concentration.

### 3.4.5. Pollution Source Identification of Monitored Variables

### Principal Component Analysis

PCA was applied to the normalized data and was able to identify three principal components (PCs) using the Kaiser criterion [66] based on loading higher than 0.5. The scree plot graphs are used widely to identify the number of PCs to be retained to understand the underlying data structure [26]. Based on the scree plot and the eigenvalues >1 criterion, three factors were chosen as principal factors. The variables with eigenvalues lower than 1 were removed due to their low significance [67].

In this study, the scree plot (Figure3.4) shows the sorted eigenvalues from large to small as a function of the number of PCs**.** This figure shows a pronounced change in slope after the third eigenvalue; three components were retained (Table 3.9). After the third PC (Figure 3.4a, b), beginning with the upward curve, the remaining components were circumvented. It was used to classify the number of PCs to be retained in order to figure out the underlying data structure [25]. Consequently, a new set of data is obtained that may explain the variation of data set having fewer variables.

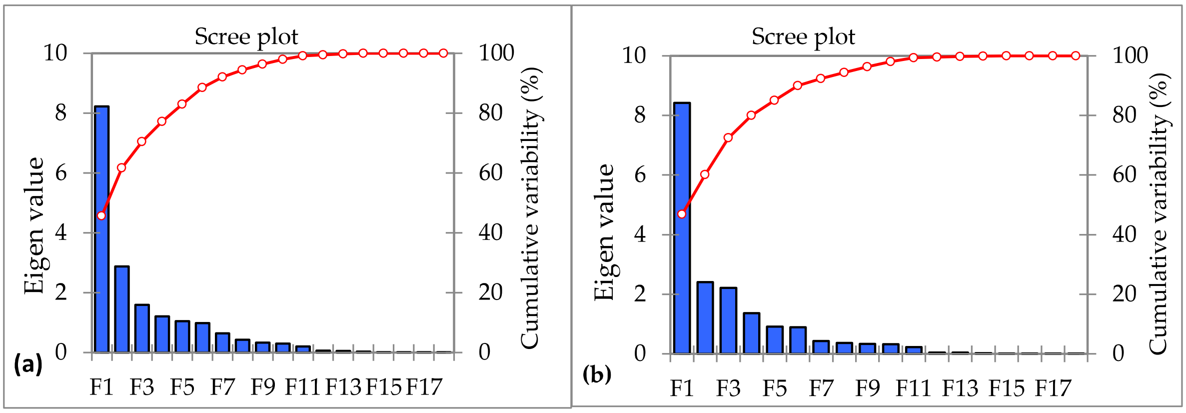

Figure 3.4. Factor loadings derived from scree plot and eigenvalue for LHW and three factors are retained for dry (a) and wet (b) seasons.

Table 3.9: Matrix of factor loadings calculated based on water quality parameters measured in the period from May to January in the Lake Hawassa Watershed and factor loadings of variables on the first three PCs extracted by using eigenvalue for both wet (a) and dry (b) seasons

| **Parameters** | **F1(a)** | **F2(a)** | **F3(a)** | **F1(b)** | **F2(b)** | **F3(b)** |
|---|---|---|---|---|---|---|
| Turbidity | 0.282 | −0.420$^{c}$ | **0.452**$^{c}$ | −0.032 | **−0.781**$^{a}$ | −0.320$^{c}$ |
| TDS | **0.974**$^{a}$ | 0.136 | 0.044 | **0.962**$^{a}$ | 0.020 | −0.084 |
| EC | **0.978**$^{a}$ | 0.078 | 0.079 | **0.961**$^{a}$ | 0.018 | −0.098 |
| pH | 0.285 | 0.324$^{c}$ | **−0.710**$^{b}$ | 0.056 | −0.178 | **0.775**$^{a}$ |
| $NH_3$−N | 0.416$^{c}$ | **0.516**$^{b}$ | −0.313$^{c}$ | 0.521$^{b}$ | −0.244 | **0.700**$^{c}$ |
| $NO_2$−N | 0.428$^{c}$ | −0.475$^{c}$ | **−0.620**$^{b}$ | −0.088 | **−0.531**$^{b}$ | −0.064 |
| $NO_3$−N | 0.131 | 0.398$^{c}$ | **0.507**$^{b}$ | 0.195 | **0.599**$^{b}$ | −0.168 |
| $PO_4$−P | **0.871**$^{a}$ | −0.035 | −0.174 | **0.830**$^{a}$ | −0.414$^{c}$ | −0.200 |
| DO | **−0.842**$^{a}$ | −0.055 | −0.365$^{c}$ | **−0.847**$^{a}$ | −0.246 | 0.186 |
| BOD | **0.784**$^{a}$ | −0.461$^{c}$ | −0.297 | **0.796**$^{a}$ | −0.394$^{c}$ | 0.015 |
| COD | **0.793**$^{a}$ | −0.388$^{c}$ | −0.302$^{c}$ | **0.721**$^{b}$ | −0.320$^{c}$ | 0.135 |
| TN | **0.898**$^{a}$ | 0.064 | 0.101 | **0.724**$^{b}$ | −0.015 | 0.047 |
| TP | **0.812**$^{a}$ | 0.139 | 0.436$^{c}$ | **0.897**$^{a}$ | −0.333$^{c}$ | −0.105 |
| Temp | **0.825**$^{a}$ | 0.290 | 0.194 | **0.783**$^{a}$ | 0.246 | −0.143 |
| $Mg^{2+}$ | 0.077 | **−0.654**$^{b}$ | 0.389$^{c}$ | −0.350$^{c}$ | **−0.567**$^{b}$ | −0.380$^{c}$ |
| $Ca^{2+}$ | 0.449$^{c}$ | **−0.627**$^{b}$ | 0.103 | 0.401$^{c}$ | **0.524**$^{b}$ | −0.246 |
| $Na^{+}$ | **0.832**$^{a}$ | 0.205 | −0.116 | **0.973**$^{a}$ | 0.001 | 0.076 |
| $K^{+}$ | **0.477**$^{c}$ | 0.335$^{c}$ | 0.035 | **0.572**$^{b}$ | 0.522$^{b}$ | 0.106 |
| Eigenvalue | 8.4 | 2.4 | 2.2 | 8.2 | 2.9 | 1.6 |
| Variability (%) | **46.8** | **13.4** | **12.3** | **45.7** | **16** | **8.8** |
| Cumulative % | 46.8 | 60.2 | **72.5** | 45.7 | 61.7 | **70.5** |

$^{a}$ strongly correlated factor loadings, $^{b}$ moderately correlated factor loadings, $^{c}$ weakly correlated factor loadings.

Moreover, scree plots are used to visually evaluate which components or factors elucidate the maximum variability in the data.

The PCA results, which include the loadings (participation of the original variable in the new one), are summarized in Table 3.9. The FA in LHW extracted three factors by retaining the PCs through varimax rotation that explained 72.5% of the total variance for the wet season. An eigenvalue offers a degree of the importance of the factor, and factors having the highest eigenvalues are the most significant. Eigenvalues of 1.0 or more are considered significant. Liu et al. [26] additionally categorized the factor loadings as ‘strong’, ‘moderate’, and ‘weak’, corresponding to absolute loading values of > 0.75, 0.75–0.50, and 0.50–0.30, respectively.

The first factor (F1), accounting for 46.8% of the total variance, showed strong positive loadings of TDS, EC, $PO_4$-P, BOD, COD, TP, TN, $Na^+$, and temperature with factor loadings of 0.974, 0.978, 871, 0.811, 0.784, 0.793, 0.898, 0.812, 0.825, and 0.832, respectively; a weak positive loading of $K^+$ (0.477); and strong negative loading of DO (−0.842) (Table 9). High positive loadings of temperature and high negative loading of DO might suggest the impact of seasonal variation, and temperature is inversely related to DO. The strong and moderate positive loading of BOD and COD signify biodegradation of organic matter and are negatively affected by DO of water bodies. F1 stands clearly for pollution by BOD or COD, and nutrients and oxygen depletion is a consequence. When the temperature of water bodies decreases, the biodegradation of organic matter decreases, and the solubility of oxygen in the water increases. Similar reports of high concentrations of BOD and COD exist elsewhere [42,44,45]. Similarly, the strong negative DO loading indicates the utilization of DO under anaerobic conditions in rivers and lakes for the degradation of organic matter. F1 showed strongly positive loadings for both COD and BOD, while the loading for DO was strongly negative. This indicates a group of purely organic pollution indicator parameters from industrial effluents, domestic discharges, and livestock affecting water bodies [23,27,51].

High nutrient loadings of factors such as TN and TP represent pollution from point and non-point sources from industrial setup, agriculture areas, domestic sewage, and urban runoff. The high loading of metals demonstrates the influences of industrial effluents and agriculture activities. Phosphorus and nitrogen can originate from point sources such as sewage pollution, industrial facilities and livestock, as well as from non-point sources, mainly from agricultural activities, runoff from rural and urban areas, soil erosion, and livestock. These results are consistent with findings of other reports elsewhere [27,68]. Consequently, the component is more likely to be explained by the combination of domestic pollution and industrial factors. These factors are characteristic of the monitoring stations in the upper catchment (MS1 and MS2), in the middle section including point sources (MS5 and MS15), along Tikur-Wuha River (MS6), and on the eastern side of Lake Hawassa

(MS7, MS9, MS12, MS13, and MS14), where domestic and industrial effluents and agricultural runoff are predominant.

The strongly positive loadings of $Na^+$ and weak positive loadings of $K^+$ are likely due to industrial effluents discharged into the river Tikur-Wuha and Lake Hawassa. Reports also indicate that the sources of $Na^+$ and $K^+$ might be domestic sources, fertilizers, and residential waste in addition to industrial effluents [69]. During field observation, it was found that the major industries are discharging their treated and untreated effluents directly into the Tikur-Wuha River and the lake during the rainy period when the flow rate is high, resulting in high dilution, but during the dry period, the dilution effect is lower and consequent pollution is higher.

On the other hand, the strong loadings of TN and TP in F1 suggest higher contribution from point sources in industry and non-point sources such as agricultural land use, urban drainage, and residential areas during the rainy season. In general, these factors are symbolic of a blended source of contamination, encompassing industrial discharges, urban runoff, and agricultural land use. The results are in agreement with those of other studies [5,24,67,69]. Hence, they can be considered as the contamination index for surface water [44,45].

The second factor (F2) explained 13.4**%** of the total variance. It had a moderately negative loading of $Mg^{2+}$ and $Ca^{2+}$ (−0.654, −0.627) and a moderately positive loading of $NH_3$–N (0.516). This factor's moderately negative loading of $Mg^{2+}$ and $Ca^{2+}$ is likely to originate from industrial wastewater discharged into the Tikur-Wuha River and Lake Hawassa, usually from carbonate minerals, which are naturally present in the soils of the Lake Hawassa watershed. This factor is more pronounced at monitoring stations affected by point sources, agricultural lands, and rural and urban runoff, such as MS3 in the upper catchment, MS19 in the middle section (point source), and MS8, MS11, MS16, and MS18 monitoring stations on both eastern and western sides of Lake Hawassa.

A moderately positive loading of $NH_3$−N (0.7) indicates biodegradation of organic matter. This variable is primarily from runoff, with high loading of solids and wastes from point sources of pollution from domestic and industrial areas. Furthermore, $NH_3$−N is triggered by the decomposition of organic matter, indicating the discharge of domestic sewage to surface water. Studies elsewhere have showed comparable results [42,44,45,69,70].

The third factor (F3), explaining 12.3% of the total variance, had a moderately negative loading for pH (−0.710), suggesting the dominance of physical reactions by aquatic plants and natural weathering of the basin, possibly due to industrial impact from different sources [22]. It had weak positive loading of turbidity (0.452), moderate negative loading of $NO_2$−N (−0.620), and moderate positive loading of $NO_3$−N (0.507). $NO_3$–N may additionally have derived from agricultural areas in the region, where inorganic nitrogen fertilizers are in common use and the role of domestic waste is strong, and hence, this component can be best explained by a ''nutrient'' factor representing influences from non-point sources such as agricultural runoff and the domestic pollution factor. The reports of Yilma et al. [35] in Ethiopia and Zhang et al. [27] elsewhere were comparable with this result. This factor is typical of the monitoring stations in the middle section including point sources and eastern and western sides of Lake Hawassa (MS4, MS10, and MS17), where domestic sewage, industrial effluents, and agricultural runoff are predominant.

The FA in LHW extracted three factors by retaining the PCs through varimax rotation that explained 70.5% of the total variance for the dry season. The first factor (F1), accounting for 45.7% of the total variance, showed strong positive loadings of TDS, EC, $PO_4$–P, BOD, DO, TP, $Na^+$, and temperature, having factor loadings of 0.962, 0.961, 0.830, 0.796, 0.897, 0.783, and 0.973, respectively; moderate positive loadings of K+, COD, and TN (0.572, 0.721, 0.724); and strong negative loadings of DO (−0.847). Strong positive loadings of temperature and strong negative loadings of DO might suggest the impact of seasonal variations. The strong and moderate positive loading of BOD and COD signify biodegradation of organic matters and negatively affect DO of water bodies. F1 stands clearly for pollution by BOD or COD, and nutrients and oxygen depletion is a consequence. High temperature increases biodegradation and reduces solubility of oxygen in the water. This PC was correlated with COD and $BOD_5$, indicating a group of purely organic pollution indicator parameters from uncontrolled domestic discharges caused by rapid urbanization and industrial effluents. Biodegradation of organic matter causes concentrations of BOD and dissolved oxygen in water [23,27,51].

A high loading of nutrients represents pollution from industrial setup and domestic wastewater. High loading of metals demonstrates the influences of industrial discharges. Phosphorus and nitrogen may originate from point sources such as sewage pollution, agricultural runoff in the upper stream due to irrigation, industrial facilities, and livestock. Consequently, this component is more likely to be explained by the combination of domestic pollution factors and industrial factors. Strongly positive loading of $Na^+$ and moderate positive loadings of $K^+$ are likely to originate from industrial effluents discharged directly into the Tikur-Wuha River and Lake Hawassa. These results are also supported by similar findings obtained elsewhere [27,69].

This factor is more pronounced at monitoring stations in the upper catchment (MS1 and MS3), monitoring stations in the middle section including point sources (MS4, MS5, MS15 and MS19), Tikur-Wuha River (MS6), and monitoring stations from both eastern and western sides of Lake Hawassa (MS9, MS10, MS14, MS16, and MS17), where domestic sewage, industrial effluents, and agricultural activities are predominant. The major industries discharge their treated and untreated effluents directly into Tikur-Wuha River and the lake during the dry period when the flow is low, which might lead to higher pollution. On the other hand, the strong loadings of TN and TP at F1 suggest a higher contribution of point sources from industrial facilities and agricultural runoff in the upper stream due to irrigation. Generally, these factors suggest a blended source of contamination encompassing municipal and industrial point source and livestock. This result is also confirmed by other studies [5,23,33,67,69]. Hence, it can be considered to be the contamination index for surface water [44,45].

The second factor (F2) explained 16% of the total variance and had a strong negative loading of turbidity (−0.781), a moderate negative loading of $NO_2$–N and $Mg^{+2}$ (−0.567, −0.531), and a moderate positive loading of $NO_3$–N and $Ca^{+2}$ (0.599, 0.524). $NO_3$–N could be mainly from point sources, and the role of domestic waste is also strong. Hence, this component can be explained by the ''nutrient'' factor, which represents influences from non-point sources such as the domestic pollution factor [24,27,32,35,66,69]. A moderately positive loading of $K^+$ and a moderately negative loading of $Mg^{2+}$ in this factor likely originate from industrial discharges into the Tikur−Wuha River and Lake Hawassa. This PC is more influenced by industrial discharges, and monitoring stations from the LHW, where industry is predominant, are more pronounced. This factor is more pronounced in monitoring stations in the upper catchment (MS2) and the monitoring stations in the eastern and western sides of Lake Hawassa (MS11, MS12, MS13, and MS18), where domestic, industrial, and agricultural activities are predominant in the upper stream due to irrigation..

The third factor (F3), explaining 8.8% of the total variance, had a strong positive loading of pH (0.775), suggesting the dominance of physical reactions by aquatic plants and natural weathering of the basin, and attributed to industrial impact from different sources [22]. A moderate positive loading of $NH_3$–N (0.7) indicates the biodegradation of organic matter causing concentrations of waterborne factors such as $NH_3$-N. This variable originated primarily from wastes from point sources of pollution from domestic and industrial areas. Furthermore, $NH_3$–N is triggered by organic matter decomposition, indicating the discharge of domestic sewage to surface water. Reports elsewhere support the findings of this study [42,44,45,70]. This factor is more pronounced in monitoring stations on the eastern side of Lake Hawassa (MS7 and MS8), where domestic sewage, industrial effluents, and agricultural activities are prevalent.

The bi-plot of PCs on key parameters TDS, EC, $PO_4$-P, DO, BOD, COD, TN, TP, temperature, $Na^+$, $K^+$, Turbidity, $NO_2$–N, $NO_3$–N, $Mg^{2+}$ and $Ca^{2+}$ that *c*haracterize monitoring stations from rivers in the upper and middle catchment, point sources in the middle catchment, and the eastern and western sides of Lake Hawassa are presented in Figure 3.5a, b for dry and wet seasons. In fact, the average values of EC, TDS, BOD, COD, $Na^+$, $K^+$, $Mg^{2+}$, $Ca^{2+}$, and $NH_3$–N of point sources were exceedingly higher than that of rivers in the upper and middle catchment (MS1–MS3, and MS6) and Lake

Hawassa (MS7-MS14, MS16 and MS18) in Table 6. In addition, $NO_3-N$, $NO_2-N$, TN, TP, and $PO_4-P$ were the main parameters characterizing the stated monitoring sites in both seasons. These stations predominantly include rural areas, urban and peri-urban areas, and industrial sites from which domestic sewage, urban runoff, and effluents are discharged into the lake. Furthermore, the influence of agricultural activities in the upper catchment and Tikur-Wuha River feeding the lake was evident. The results of this investigation were comparable to the findings of the studies conducted by Tibebe et al. [71] and Meshesha et al. [72] on Lake Ziway. In particular, higher EC and TDS values were recorded for similar monitoring stations in both seasons (Table 3.6). In an aquatic environment, EC is used to categorize the pollution status of surface waters, and an increase in conductivity indicates the presence of dissolved ions that can affect aquatic life and water quality [73].

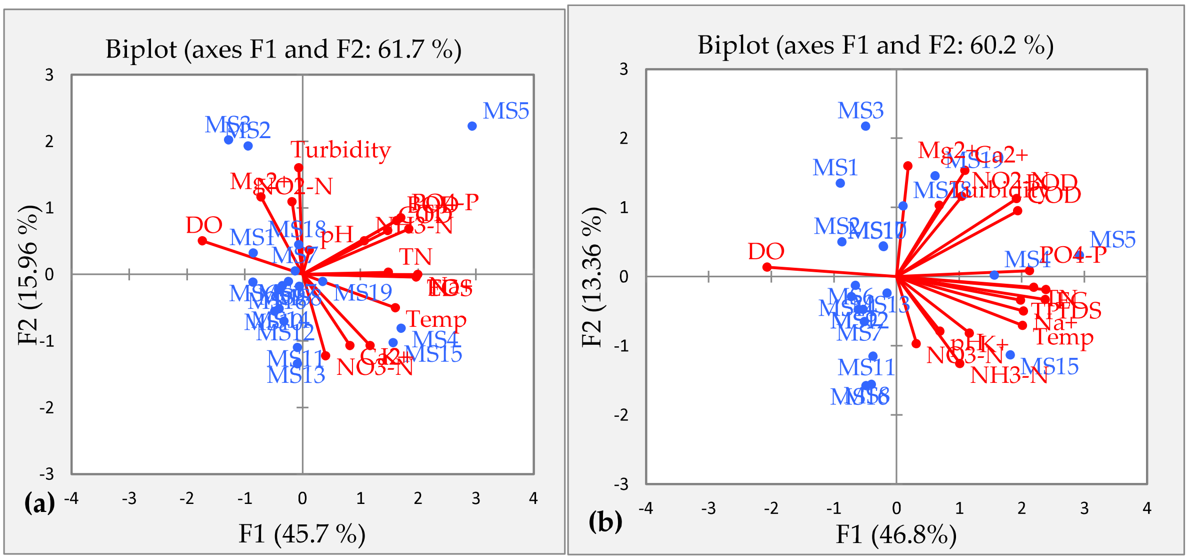

Figure 3.5. PCA biplots (a) and (b) suggest the projection of the monitoring sites (blue dots) and the variable loadings of the primary components (F1 and F2). The biplots additionally display the relationship between highly correlated variables and monitoring stations for dry (a) and wet (b) seasons. High and low values indicate strong positive and negative correlation, respectively, while values close to 0 imply weak correlation between F1 and F2 and the respective parameter.

### 3.4.6. Total Nitrogen to Total Phosphorus (TN:TP) Ratio

The TN:TP ratio in lakes and reservoirs is a key element, as it gives an idea of which of these nutrients is either in excess or limiting to growth, and it was used to estimate the nutrient limitation in the lake. According to Smith [74], blue-green algae (cyanobacteria) has a capacity to dominate in the lake section when the TN:TP ratio was less than 29, and it tends to be rare in the lake when TN:TP > 29. On the other hand, Fisher et al. [75] used a more conservative ratio of TN:TP. According to them, the ratio > 20 is designated as the phosphorus limitation and nitrogen limitation when the ratio is <10, while a TN:TP ratio of 10 to 16 demonstrates either phosphorus or nitrogen (or both) are limiting for growth. The estimated ratio for Lake Hawassa was 31, which is higher than 20 and 30, revealing cyanobacteria dominance in the lake section, which is rare. The TN:TP ratio > 20 in Lake Hawassa indicated that phytoplankton growth in the lake might be phosphorous deficient.

### 3.5. Conclusions

Multivariate statistical techniques help researchers to scrutinize the relationships between parameters in a broader fashion by applying different approaches such as cluster analysis, correlation, factor analysis, discriminant analysis, and multiple regressions to determine the association between dependent and independent variables. They reduce the dimensionality of data so that the whole picture can be visualized more easily than looking at specific cases allows. Furthermore, multivariate techniques provide powerful significance testing compared to univariate techniques. Despite their various merits, the results of multivariate statistical modeling are not easy to interpret and require a large data set to get meaningful results due to the high standard errors. In particular, PCA/FA is likely to lose information if PCs or factors are not chosen judiciously.

This study was conducted to evaluate seasonal and spatial variations in water quality and to identify potential sources of pollution using multivariate statistical techniques for the Lake Hawassa Watershed. The results of this study show that the condition of Lake Hawassa Watershed was classified into moderately and highly polluted categories in both dry and wet seasons. In data-limited developing countries such as Ethiopia, it is especially clumsy to identify possible sources of pollution due to certain contaminants, as this requires frequently monitored water quality data, which are often not available. To address this serious problem, this study applied MVST. Multivariate statistics were used to perform temporal and spatial assessment of surface water quality to reduce the number of monitoring stations and chemical parameters in LHW. In this study, we used Pearson correlation, PCA/FA**,** CA, and DA to evaluate spatial and temporal variance in surface water quality. CA grouped the monitoring stations into two statistically significant clusters for the dry and wet seasons, labelled MP and HP, using PI. Accordingly, this resulted in a dendrogram with two clusters for the dry and wet seasons. The findings of the study revealed that rivers in the upstream and middle portion of the lake watershed and Lake Hawassa were moderately polluted (MP)**,** while point sources (industries, hospitals, and hotels) in the middle of the LHW were found to be highly polluted (HP).

DA was used to identify the most critical parameters to investigate the spatial variations and extracted seven significant parameters: EC, DO, COD, TN, TP, $Na^+$, and $K^+$, with spatial variance to distinguish the pollution statuses of the groups obtained using CA.

PCA/FA techniques helped to identify the potential sources of water quality degradation. This study comprehensively analyzed the water quality of LHW and identified three significant sources responsible for pollution of Lake Hawassa Watershed in dry and wet seasons affecting the water quality. Accordingly, the pollution is due to mixed sources including point sources such as municipal and industrial effluents, natural processes, livestock, urban runoff, and non-point sources from agricultural activities.

Poor industrial effluent management combined with non-point sources from agriculture and urban runoff contribute significantly to the pollution of Lake Hawassa. Discharge of industrial effluents into the surface water system is the largest point source of anthropogenic pollution. Diffuse sources that contribute enormously to LHW come from agricultural activities, i.e., intensive farming and livestock (F1, F2, and F3).

We conclude that effective management of point and non-point source pollution is imperative to improve domestic, industrial, livestock, and agricultural runoff to reduce pollutant inputs into the lake. A stringent management that requires a comprehensive application of technologies such as fertilizer management, ecological ditches, constructed wetlands, and buffer strips should complement proper municipal and industrial wastewater treatment set-up.

Furthermore, application of indigenous aeration practices such as the use of drop structures at critical locations would help improve water quality in the lake watershed.

**Acknowledgments**

We are grateful to the German Academic Exchange Service (DAAD) for offering a stipend for the first author in the course of the study.

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# 4. Estimating point and non-point source pollutant flux

**Abstract**: Increasing pollutant emissions in the Lake Hawassa watershed (LHW) has led to a severe water quality deterioration. Allocation and quantification of responsible pollutant fluxes are suffering from scarce data. In this study, a combination of various models with monitoring data has been applied to determine the fluxes for Chemical Oxygen Demand (COD), Biochemical Oxygen Demand ($BOD_5$), Total Dissolved Solid (TDS), Total Nitrogen (TN), Nitrate and Nitrite-nitrogen ($NO_x$-N), Total Phosphorous (TP) and phosphate ($PO_4$-P). Water, wastewater and stormwater samples were collected and analyzed at eight monitoring stations from rivers and point sources and six monitoring stations of stormwater samples. The flow simulated with soil and water assessment tool (SWAT) could be very well calibrated and validated with gauge data. This flow from SWAT model, measured flow during monitoring and pollutant concentrations were used in FLUX32 to estimate pollutant fluxes of main rivers and point sources in LHW. The daily rainfall data that was collected from Ethiopian meteorology Agency was used to determine the total annual rainfall for the year 2020 and to calculate the stormwater pollutant flux. The integration of HEC-GeoHMS and SCS-CN with the catchment area enabled to determine stormwater pollution load of Hawassa City. The estimated pollutant flux at each monitoring stations showed that the pollutant contribution from the point and nonpoint sources prevailing in the study area, where the maximum fluxes were observed at Tikur-Wuha sub-catchments. This station was located downstream of the two point sources and received flow from the upper streams where agricultural use is predominant. Furthermore, Hawassa city has been identified as a key pollutant load driver, owing to increased impacts from clearly identified point sources and stormwater pollutant flux from major outfalls. Agricultural activities, on the other hand, covers a large portion of the catchment and contributes significant amount to the overall load that reaches the lake. Thus, mitigation measures that are focused on pollutant flux reduction to the lake Hawassa have to target on the urban and agricultural activities.

**Keywords:** pollutant loading estimator (PLOAD); FLUX32; water quality; pollutant export coefficients; point and non-point source pollutant flux

## 4.1. Introduction

Currently due to the rapid advances in modelling, numerous water quality models were developed with various modelling algorithms for various land use and water bodies for pollutants at different spatio-temporal scales [1,2] The data demand for water quality models increase with the complexity and scope of application [3].

Generally, most developed countries, namely the US or European countries have established better and advanced surface water quality models [2]. One of pivotal factors in the primary goals of environmental management would be assessing the water quality despite limited observations [4]. In the developing world reliable application of water quality models is often challenging owing to lack of sufficient and quality data and access to patented software is limited by finances. Furthermore, nearly for all rivers the gauged data are limited and fragmented. The Rift Valley Lake basin is among the data scarce areas of Ethiopia and the historical measured pollutant flux including sediment data is very limited [5,6]. In Hawassa, on the other hand, wastewater management is a big concern because most residents use latrines. Wastewater treatment plants for the partly existing sewer system for buildings with flushing systems is missing and stormwater is discharged without any treatment [7]. Furthermore, Lake Hawassa is encircled by agricultural land, residential places, industrial and commercial hubs and is located near the city of Hawassa. As a result, it is prone to a range of environmental risks and the water quality deteriorates over time, posing a danger to the biodiversity [8]. Hence, studying the pollutant load of the basin is necessary to obtain more realistic information [5].

The estimation of pollutants load from non-point sources is usually accomplished by means of watershed models. However, due to the intensive input data requirements and complexity by most of the models, it is disconcerting to quantify diffuse source loads in developing countries such as Ethiopia owing to limited hydrological, meteorological and water quality data [9,10].

In order to fulfil the existing gaps in the developing world such as Ethiopia, setting up frequent monitoring and assessment is a critical task. In this sense, simple models that do not require intensive input datasets are worthwhile common approaches for the prediction of diffuse pollutions from various land uses including urban and industrial land uses [11–13].

On such occasion, a common approach such as pollutant export coefficients representing the rate of pollutant loadings by land area, that predict an annual load from land to water, are often a discretionary means to estimate loadings from non-point sources [6,14,15]. Export coefficients modelling is a simple approach that can be adopted for data-poor areas and for preliminary assessments connecting land use to water quality. It is generally based on the postulation that a particular land use will export distinctive magnitudes of pollutants to a downstream water body on a yearly basis [16]. To justify this postulation, the pollutant export coefficients must be developed for the locally specific conditions [15]. If this is achieved, reliable and relatively accurate pollutant transport models can be set up to support watershed level point and nonpoint source pollution management [17].

Therefore, in this study we employed pollutant loading estimator (PLOAD) to determine the pollution loads with the help of export coefficient modelling. The approach was used as a means of preliminary pollutant load estimation at different watersheds in Ethiopia [6,9], Tanzania [18], China [10,19], USA [20], Japan [15], UK [12], Lithuania [21], Egypt [22], Philippines [23] and Rwanda [24].

The watershed of Lake Hawassa comprises rural and urban areas. So, for conducting a comprehensive pollutant flux in the watershed, pollutant flux of (i) rivers, (ii) point sources (PS) and (iii) urban stormwater runoff have to be investigated. Namely, the impact of stormwater runoff has so far not been addressed and requires a deeper investigation. A prerequisite for this is a reliable runoff information at watershed scale. In recent decades a number of hydrological models have been developed and used to envisage the runoff information in different hydrological units over years. A widely used approach to estimate runoff from spatial data is the Soil Conservation Service curve number (SCS-CN) method [25,26]. In this study, we also applied the SCS-CN method to estimate rainfall-runoff depth for the city of Hawassa.

A characteristic problem in the watershed under investigation is the lack of sufficient monitoring water quality data due to budget constraint. This complicates prediction of pollutant loads from point and non-point sources, as land use, emissions and ambient water quality cannot be linked directly. Currently the government focuses on the reduction in the point source pollution. However, estimation of pollutant flux from nonpoint sources in data-limited watersheds in Ethiopia (in general and in the study area in particular) are perplexing, due to lack of baseline data to direct development targets. Thus, the use and identification of simple, cost effective and economical water quality models is greatly imperative to estimate the pollutant flux of rivers and point sources that are in turn helpful for surface water quality management. To support this target, this study is aimed at determining the annual pollutant loads contributions from point, nonpoint sources and stormwater to the Lake Hawassa watershed, identify the probable pollution flux hotspots and calibration of pollutant export coefficient for the study area by integrating PLOAD, SWAT, FLUX32, HEC-GeoHMS and SCS-CN with monitoring data.

## 4.2. Materials and Methods

### 4.2.1. Study Area

Ethiopia has endowed with several lakes of volcanic and tectonic origins, among which Lake Hawassa is an endorheic freshwater lake formed in collapsed calderas and located in Lake Hawassa Watershed (LHW) [27]. Within the Central Ethiopian Rift Valley Basin, the Lake watershed is located between 6°45′ and 7°15′ N latitude and 38°15′ to 38°45′ E longitude, in Sidama and Oromiya Regional States (Figure 4.1), covering 1431 km$^2$ [28].

Streams from the eastern catchment flow to Lake Cheleleka wetland and are drained by the Tikur-Wuha River that feeds Lake Hawassa. Tikur-Wuha River is the main rivers in Lake Hawassa watershed, located in the middle section of the catchment where most of the untreated household and industrial wastewater are discharged. The Lake has been used as the main source for drinking, irrigation, aquatic life and recreational uses. Despite this, the lake and its tributaries has been affected by various sources of pollution [7].

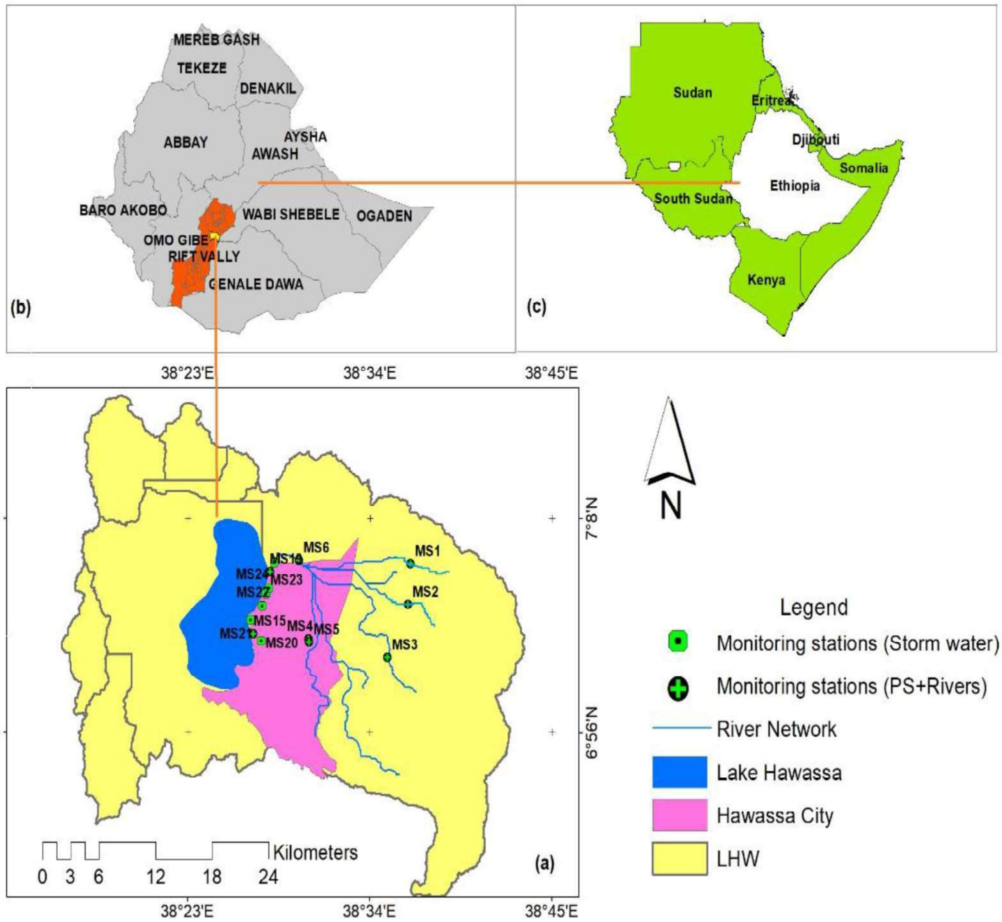

Figure 4.1. Study area map and monitoring station’s location. (a) Lake Hawassa watershed (LHW) and monitoring stations from point source (PS), rivers and stormwater, (a) Major river basins in Ethiopia, (b) countries sharing boundaries with Ethiopia (c).

The climate of the Hawassa sub-basin is sub-humid and distinctly seasonal. The months from April to October are wet and humid, and the main rainy season is between July and September, the area receives a mean precipitation of 1028 mm rainfall annually. The mean minimum precipitation is 17.8 mm in December (dry season) and the mean maximum precipitation is 119.8 mm in August (rainy season) [29]. The long term mean annual temperature of the area varies from 12.5 to 26 °C [30]**,** whereas the mean monthly evapotranspiration in the low lands ranges from 39 mm in July to 100 mm in January [29].

### 4.2.2. Sampling and Analysis of Monitoring Parameters

Water, wastewater and stormwater sample were collected and analyzed for some selected physicochemical parameters in the Lake Hawassa watershed from March 2020 to December 2020. Sample collection for the wet season were conducted after rainfall events. The locations of monitoring stations were determined using Global navigation satellite system. Water temperature, pH, total dissolved solids and conductivity were determined onsite. For the estimation of pollutant flux in the Lake Hawassa watershed, water and wastewater samples were collected from eight monitoring stations from rivers and point sources (Figure 4.1, Tables 4.1 and 4.2). Monitoring stations for stormwater in Hawassa City were established at the major outlets to monitor the urban stormwater quality. The urban runoff samples were collected from six monitoring stations for two rainfall events (Figure 4.1 and Table 4.3)**.**

Table 4.1: Monitoring stations from rivers in Lake Hawassa Watershed.

| Code | Monitoring Sites | Latitude (Y) | Longitude (X) | Area (ha) |
|---|---|---|---|---|
| MS1 | Wesha River | 7°5′13.8″ | 38°36′51.3″ | 5754.9 |
| MS2 | Hallo River | 7°3′14.4″ | 38°36′43.2″ | 4152.3 |
| MS3 | Wedessa River | 7°0′21.6″ | 38°35′6.0″ | 14,615.5 |
| MS6 | Tikur-Wuha River | 7°5′22.6″ | 38°30′25.4″ | 61,479.8 |

Table 4.2: Monitoring stations from point sources in Lake Hawassa Watershed.

| Code | Monitoring Sites | Latitude (Y) | Longitude (X) | Altitude (Z) |
|---|---|---|---|---|
| MS4 | BGI effluent discharge site | 7°1′31.8″ | 38°30’57.4″ | 1686 |
| MS5 | Moha Soft Drinks Factory | 7°1′26.9″ | 38°30’47.5″ | 1671 |
| MS15 | Referral Hospital | 7°1’47.6″ | 38°27′46.1″ | 1686 |
| MS19 | Hawassa Industrial Park | 7°4’49.4″ | 38°28’44.4″ | 1690 |

Table 4.3: Monitoring stations for stormwater from outfalls of drainage system in Hawassa City.

| Code | Monitoring Sites | Latitude (Y) | Longitude (X) | Area (ha) |
|---|---|---|---|---|
| MS20 | Near Referral Hospital | 7°01′28.71″ | 38 °28′14.63″ | 306 |
| MS21 | Near Amora-Gedel | 7°02′30.67″ | 38 °27′37.83″ | 206.6 |
| MS22 | Near Fiker Hayk | 7 °03′12.99″ | 38 °28′18.46″ | 97 |
| MS23 | Near Chambalala Hotel | 7 °03′48.37″ | 38 °28′31.07″ | 377.4 |
| MS24 | Near ELPA office | 7 °04′4.86″ | 38 °28′41.68″ | 95 |
| MS25 | Near South spring Hotel | 7 °05′29.34″ | 38 °28′56.12″ | 123.6 |

Composite samples were collected in pre-cleaned 2 L polyethylene plastic bottles that are sterilized for biochemical oxygen demand (BOD) and chemical oxygen demand (COD) analyses. The bottles were washed with concentrated nitric acid and distilled water before sample collection and placed in a cooler box, kept under 4°C and immediately transported to the laboratory for analysis. Samples of nitrate and phosphate were prefiltered at site and kept in a cooler box before analysis. The analytical methods and instruments used for analysis are shown in Table 4.4. All the analytical methods were carried out according to the standard methods for the examination of water and wastewater [31].

Table 4.4: Table 4.4. Analytical methods and instruments used for the analysis of selected parameters in LHW.

| Parameters | Analytical Methods and Instruments |
|---|---|
| TDS | Portable multi-parameter analyzer, Zoto, Germany |
| $BOD_5$ | Manometric, BOD sensor |
| COD | Closed Reflux, Colorimetric |
| $PO_4$-P and TP | Spectrophotometrically by molybdovandate (Hach DR-3900) |
| $NO_3$-N | Photometric measurements, Wagtech Photometer 7100 at 520 nm wavelength |
| $NO_2$-N | Spectrophotometrically by salicylate, (Hach DR-3900) |
| TN | Spectrophotometrically by persulfate digestion (Hach DR-3900) |

### 4.2.3. Data Treatment

The data treatment needs to be performed for missing data and outliers in the climate and monitored water quality data before executing SWAT, PLOAD, FLUX32 and Gumbel's theory of distribution. Hence, outliers were treated according to Grubbs [32] test approach with XLSTAT 2016. However, missing data was handled by the multiple imputation of missing values technique using Markov Chain Monte Carlo method (MCMC) [33].

### 4.2.4. Estiation of Flow

Instantaneous flow in study basin has been measured at the time of sample collection using the current meter (Toho Dentan CMS-11C, Tokyo, Japan). Since flow and pollutant concentrations are dynamic, determination of time series data of flow is crucial besides the instantaneous flow. In the study watershed under investigation, there are four monitoring stations in the study area out of which only one station is gauged and having stream flow records, the other three lack stream flow records. The problem of missing records can be circumvented by model based flow estimations [9,15]. In order to estimate the discharge at the ungauged sites, we applied the soil and water assessment tool (SWAT), a semi-distributed, process-oriented hydrological watershed-scale model [34]. The input data to the model-like land use map, digital elevation model (DEM), soil map, hydrology (stream flow) and weather data were collected from Ministry of Water, Irrigation and Electricity, Ethiopian meteorology Agency. The basic concept of the model is to subdivide a basin into sub-basins and further combine land cover, soil and slope to obtain the hydrologic response unit (HRU) where all land areas have homogeneous land use, soil and slope combinations. In each HRU, hydrological components are calculated for surface water, soil and groundwater [35]. Accordingly, the SWAT model was simulated from 1996–2015 where two-year warmup period, twelve years (1998–2009) calibration and 6 years (2010–2015) of validation for the full data available. The flow calibrated and validated by SWAT at Tikur-Wuha catchment was used to generate flow in the ungauged sub-catchment outlets (monitoring stations) in Tikur-Wuha catchment and later used as an input for FLUX32 for pollutant load estimation along with the instantaneous flow and measured pollutant concentrations.

In this juncture, the area ratio-based method was among the streamflow transfer techniques that has been used to estimate the streamflow at ungauged stations from the SWAT calibrated flow. In the area ratio technique, the single source area ratio method is widely used and the easiest approach to determine the runoff at ungauged stations [36]. The transfer of flow from the gauged to the ungauged was reasonable as the ungauged catchments are located within the gauged catchment having similar hydrological, meteorological, land use and soil properties. Hence, the streamflow at an ungauged site is estimated by using Equation (1) taken from [37].

$$\frac{Q_y}{Q_x} = \frac{A_y}{A_x} \qquad (1)$$

where, $A_x$ and $A_y$ are the drainage area of the ungauged and gauged site, respectively, $Q_x$ is the observed streamflow at a gauged site, and $Q_y$ is the estimated discharge at an ungauged site.

#### 4.2.5. Watershed odel Selection

Examination of pollutant loads from point and non-point sources that are contributing to pollution of surface water bodies are crucial for watershed management. A number of physical and empirical models has been established to comprehend complex hydrological and ecological processes associated with point and nonpoint source pollution [38].

The mechanistic watershed models can provide more accurate results on pollutant losses, but such models need a huge amount of input data. These intensive input data requirements make such a modelling a highly challenging task hindering its use [39]. Thus, for estimation of pollutant load the local conditions and data availability should be taken in to consideration for selection of models [10].

There exist various watershed and river models with different focus and abilities. Before selecting an appropriate approach, we reviewed commonly applied models with regard to our goals and data availability (Table 4.5).

Table 4.5: Some selected modelling tools and their selection criteria evaluation.

| Name of the Model and References | Characteristics | Application Domain of the Model | Accessibility of the Software | Input Data Requirement |
|---|---|---|---|---|
| AGNPS [40] | A distributed model that evaluates the agricultural NPS pollution and simulates the transport of sediments and chemicals | Catchment | Public domain | Data-intensive |
| GWLF [41] | A semi-distributed/lumped model that estimates runoff, sediment and nutrient loadings | Catchment | Public domain | Moderate |
| MONERIS [42] | A conceptual model, which allows the quantification of nutrients emissions via various point and diffuse pathways into river systems | river | Public domain | Data-intensive |
| MIKE 11 [43] | A distributed hydrodynamic model of flow and water quality in streams and simulates solute transport and transformation in complex river systems | River | Proprietary | Data-intensive |
| QUAL2E [44] | A one dimensional and steady-state model typically used for water quality modelling of pollutants in rivers, streams and well-mixed lakes | River/Lake | Public domain | Minimum |
| SPARROW [45] | Semi distributed statistical regression model that is designed to account for the spatial variability in contaminant flux in stream water quality to impose the mass balance | Catchment/ River | Proprietary | Data-intensive |
| HSPF [46] | An analytical tool designed to simulate hydrology and water quality for conventional and toxic organic pollutants | Catchment/ River | Public domain | Data-intensive |
| PLOAD in BASINS 4.5 System [47] | A Simple or an export coefficient based method that is used to estimate NPS contribution from each land use by incorporating point source and GIS-based land-use data | Catchment level | Public domain | Minimum |
| SWMM [48] | A distributed physically based, dynamic, continuous urban stormwater runoff quantity and quality model | Urban catchment | Public domain | Data-intensive |
| WASP [49] | A surface water quality modelling tool used to analyse a variety of water quality problems in water bodies such as ponds, rivers/streams, lakes/ reservoirs, estuaries and coastal waters | River/Lake | Public domain | Data-intensive |
| SWAT [35] | A semi-distributed model that is used for the prediction of the effects of alternative land use management practice on water, sediment, crop growth, nutrient cycling, and pesticide in watersheds with varying soils, land use and management conditions | Catchment level | Public domain | Data-intensive |
| AGWA [50] | A distributed multipurpose hydrologic analysis system that integrated several sub-models to predict runoff and erosion rates | Catchment level | Public domain | minimum |

Among the reviewed models, BASINS (better assessment science integrating point and nonpoint sources) model is a comprehensive watershed model framework that integrates numerous watershed models such as SWAT (Soil and Water Assessment Tool, Austin, TX, USA), HSPF (Hydrological Simulation Program FORTRAN, Athens, GA, USA), GWLFE (Generalized Watershed Loading Function, Ithaca, NY, USA), SWMM (Stormwater Management Model, Cincinnati, OH, USA), PLOAD (Pollutant Loading Estimator, Athens, GA, USA) and instream water quality models such as AQUATOX and WASP (Water Quality Analysis Simulation Program, Athens, GA, USA) as plug-ins was found to be the most plausible option for the watershed under investigation [47].

Many researchers were in favour of PLOAD model due to its capability and adaptability in different watersheds [6,9,10]. Angello et al. [9] and Belachew et al. [6] engaged PLOAD model to estimate the point and nonpoint source pollutant loads in data-scarce Little Akaki and Borkena Rivers in Ethiopia, respectively and both suggested the use of PLOAD model in data-poor catchments for point and nonpoint source pollutant load estimation. In this study, therefore, we used the PLOAD model due to its adaptability and small number of input data requirement.

PLOAD (pollutant loading Estimator) is a BASINS plugin, developed by Cornell, Howland, Hayes, Merryfield and Hill (CH2M-HILL) is a simple model that uses GIS-based data sources such as land use, watershed shapefile, export coefficient (EC) and allows best management practices (BMP) specifications and point sources load. In PLOAD the point and non-point nutrient loads from each land use for the physicochemical parameters (BOD, COD, TN, $PO_4$-P, NOx-N and TDS) were estimated based on the export coefficients and can be applied for urban, suburban and rural areas [20,51,52].

PLOAD uses two approaches to estimate the point and the nonpoint sources load contribution: simple and export coefficient method. Both approaches can be applied based on data availability and applicability on a watershed. However, a simple method is used in smaller watersheds, usually, less than 1 square mile, whereas the export coefficient approach was used to compute the annual pollutant loads in a mixed land use and can be run for multiple scenarios [6,11,20,47,51,52].

In the study area, we used the export coefficient approach where pollutant loads in PLOAD are calculated by

$$PL = \sum_{i=1}^{n} EC * ALu \qquad (2)$$

where PL is the pollutant loading rate for land use type (kg $yr^{-1}$), ALu is the area of the land use type Lu (ha). To estimate diffuse pollution, each land use category has been assigned the export coefficient values (kg $ha^{-1}$ $yr^{-1}$).

### 4.2.6. Pollutant Export Coefficient

The export coefficients (ECs) are distinct values of the specific attributes for a particular land-use and a measure of the total quantity of pollutants exported from each unit area in the watershed over a specified time period [6,11]. Each land use is assumed to contribute to the pollutant load per land area when predicting catchment non-point source load contribution by ECs.

The watershed in our study area was delineated using ArcSWAT and land use was reclassified into seven groups using the USGS classification system, as Wondrade et al. [29] quotes Anderson et al. [53], as bare lands, cultivated land, forest land, range land, urban or built up area, water bodies, and wetlands. Accordingly, Cultivated Land encompasses the highest share (50.65%); followed by rangeland (16.58%), forest Land (13.11%), Bare Land (6.75%), Water Body (6.43%), Builtup (5.47%) and Wetland (1.02%), (Figure 4.2).

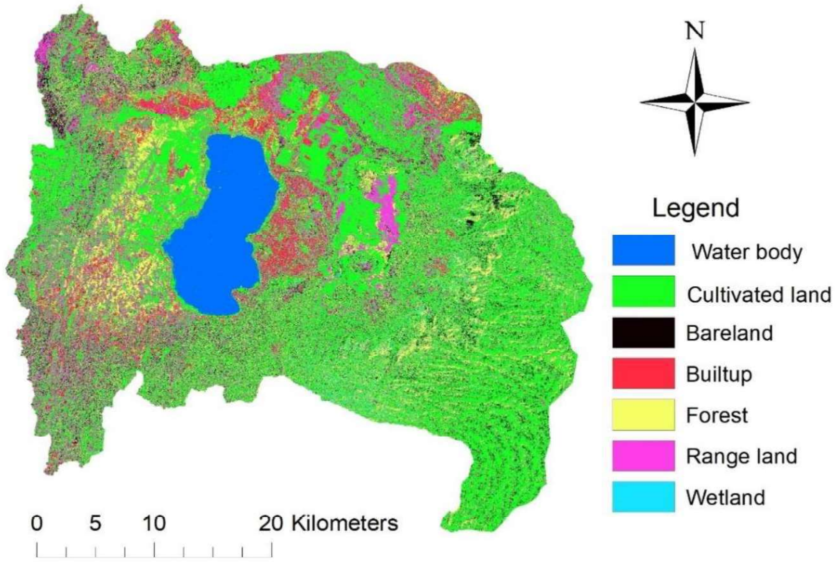

Figure 4.2. Land Use map of Lake Hawassa Watershed.

Mathematically, the pollutant load using export coefficient with an inclusion of precipitation induced pollution can be expressed by Johnes [12].

$$L_{i,j} = \sum_{k=1}^{n} (E_{k,j} * A_{k,j} + P_{i,j}) \qquad (3)$$

where $L_{i,j}$ is calculated load of constituent i at the sub-catchment outlet j (kg. $yr^{-1}$); n is the number of land uses contributing; $E_{k,i}$ is the export coefficient of land use k for the constituent i (kg $ha^{-1}$ $yr^{-1}$); $A_{k,j}$ is area of land use k for the sub-catchment j; $P_{i,j}$ is precipitation induced constituent i load at a sub-catchment j (kg $yr^{-1}$). $P_{i,j}$ is assumed negligible for the case of Lake Hawasa Watershed.

The use of reasonable export coefficients is decisive for simulation accuracy of all export coefficient models [19]. Since this is the first comprehensive investigation carried out so far on export coefficient modelling in Lake Hawassa Watershed, defining export coefficients appropriate for the Lake watershed is difficult. In this regard, the export coefficients of the Lake watershed were determined by borrowing the values from literature review (Table 4.6) from the studies conducted in Ethiopia [6,9]. Tanzania, Uganda and Kenya [18], china [10,19,54–56], USA [20,57,58], Japan [15], UK [12], Lithuania [59], Egypt [22], Philippines [23] and Rwanda [24].

Table 4.6: Range of published export coefficients (kg ha−1 yr−1) selected for PLOAD calibration for various land uses in LHW.

| **Land Use** | **Export Coefficient from Literatures, kg ha$^{-1}$ yr$^{-1}$** | | | | | | |
|---|---|---|---|---|---|---|---|
| | **TN** | **TP** | **TDS** | **BOD$_5$** | **COD** | **NOx** | **PO$_4$-P** |
| Urban | 1.5–36.9 [7] | 0.19–6.23 [9] | 292–2263 [5] | 2238 [8] | 3196 [8] | 95 [8] | 1.73 [3] |
| Agriculture | 2.1–79.6 [1,2] | 0.05–18 [1,2] | 2280 [8] | 76 [8] | 260 [6] | 36.1 [8] | 14 [11] |
| Forest | 1.0–6.3 [1] | 0.007–1.11 [1,2] | 250 [5] | 50 [10] | 66.5 [10] | 2.12 [3] | 0.7 [3] |
| Bare land | 0.51–6 [1] | 0.05–0.25 [1,2] | 100 [10] | 3.47 [4,12] | 1–5 [12,4] | 67.3 [11] | 5.1 [11] |
| Water | 0.69–3.8 [2] | 0.09–0.21 [2] | 10–150 [10] | 50 [10] | 50 [10] | 0.46 [3] | 10.1 [11] |
| Range land | 3.2–14 [1,2] | 2–18 [1,2] | 24–101 [5] | 0.5 [4] | 0.5 [4] | 0.46 [3] | 2.1 [4] |
| Wetlands | 2.33 [5] | 0.14 [5] | 128 [5] | 5.85 [5] | 36 [12,5] | 1.8 [5] | 0.05 [5] |
| | Export coefficient selected for PLOAD calibration in LHW, kg ha$^{-1}$ yr$^{-1}$ | | | | | | |
| | TN | TP | TDS | BOD$_5$ | COD | NOx | PO$_4$-P |
| Agriculture | 55 | 2 | 2220 | 67 | 88 | 33 | 14 |
| Bare Land | 5 | 0.2 | 100 | 3.4 | 5 | 67 | 4.8 |
| Range Land | 12 | 2 | 100 | 0.5 | 0.5 | 0.45 | 2 |
| Forest | 6 | 1 | 250 | 50 | 50 | 2 | 0.7 |
| Urban | 36 | 2 | 2260 | 2195 | 2340 | 91 | 1.7 |
| Water | 0.75 | 0.2 | 150 | 50 | 50 | 0.45 | 10 |
| Wetlands | 2.3 | 0.13 | 100 | 5.85 | 35.5 | 1.8 | 0.05 |

[60][1],[5][2],[17][3], [8][4],[61][5],[20][6],[40][7], [21][8],[14][9],[22][10],[23][11],[52][12], NOx reported in literature as $NO_3 + NO_2$.

### 4.2.7. Estimation of Pollutant Loads at the Catchment Outlets

FLUX32 is a window-based program designed by the US Army Corps of Engineers in collaboration with the Minnesota Pollution Control Agency for estimating pollutant loads from intermittent quality data and continuous flow data [62]. The software estimates pollutant flux using six different methods such as averaging, flow weighted mean concentrations, integration, ratio and regression methods. Using the FLUX32 program, pollutant loads at river catchment outlets were predicted using multiple regression approach. Since the flow and pollutant concentrations are both time series, a regression approach (Method 6) was preferred for load calculation in the lake watershed under consideration [6,9]. Regarding the pollutant flux for point sources (industrial setup), a direct load averaging (method 1) was applied as the point source load is supposed to be relatively constant across flows and seasons [6,63]. Based on the recommended coefficient of variation (CV), the simulation performance of the FLUX32 program was excellent for CV (0–0.1), good for CV (0.1–0.2), fair for CV > 0.2, and generally unsuitable for CV > 0.3 [62].

Hence, the load in FLUX32 at each monitoring station and sub-catchment outlets were calculated by using the equation expressed:

$$W_i = \sum \exp\left[ a + (b+1) * \ln(Qi) + \frac{SE^2}{2} \right] \quad (4)$$

where Qi = mean flow on day i ($m^3/s$); ci = measured constituent concentration (mg/L); a = intercept of ln(c) vs. ln (q) regression; b = slope of ln (c) vs. ln (q) regression; SE = standard error of estimate for ln(c) vs. ln (q) regression and qi is instantaneous flow (m3/s); $W_i$ = pollutant load/flux (kg/yr).

### 4.2.8. Calibration and Validation of PLOAD

In the PLOAD, nonpoint source load from each land use for selected physicochemical parameters ($BOD_5$, COD, TN, $PO_4$-P, NOx and TDS) were calculated using export coefficients. After having assigned the land uses with their respective ECs, the PLOAD model efficiency has been assessed by measuring the percentage error using Equation (5) by comparing the uncharacterized nonpoint source load from each sub catchment outlet as a measured load (Table 4.7).

Table 4.7: Coefficient of variation (CV) for monitoring stations in LHW.

| **Monitoring Stations** | **COD** | **$BOD_5$** | **TN** | **TDS** | **TP** | **$PO_4$-P** | **$NO_3$-N** | **$NO_2$-N** |
|---|---|---|---|---|---|---|---|---|
| MS1 | 0.01 | 0.001 | 0.06 | 0.003 | 0.001 | 0.06 | 0.005 | 0.0 |
| MS2 | 0.005 | 0.03 | 0.043 | 0.001 | 0.04 | 0.02 | 0.03 | 0.04 |
| MS3 | 0.003 | 0.05 | 0.04 | 0.04 | 0.04 | 0.014 | 0.023 | 0.0004 |
| MS6 | 0.001 | 0.001 | 0.0004 | 0.0 | 0.001 | 0.001 | 0.001 | 0.0004 |

Since PLOAD does not have a direct calibration interface, the export coefficients were calibrated using the Excel solver [64]. Then, the sum of the percentage errors from four sub-catchments outlets were used to calibrate the export coefficient values of the land use applied in the PLOAD model. The total relative error was chosen as an objective function to be minimised in the GRG nonlinear method [65].

$$\%\,\text{Relative error} = \frac{\sum(\text{Measured load - Predicted load})}{\text{Measured load}} * 100 \quad (5)$$

The model performance and validation were calculated using another set of data for the same season following the same procedure.

### 4.2.9. Estimates of rainfall and runoff depth

#### 4.2.9.1. Estimates of the total rainfall depth for the year 2020

The Ethiopian meteorological agency provided the daily 24-hour rainfall data from 1996 to 2020, and the daily 24-hour rainfall data for 2020 was extracted. Accordingly, the total yearly rainfall for the year 2020 for the area was computed.

#### 4.2.9.2. Estimates of Runoff Depth

The soil Conservation Services and Curve Number (SCS-CN) is the most widely used and well-documented conceptual technique for identifying the association between runoff and storm rainfall depth [3,4]. This method accounts for the catchment runoff characteristics that are responsible for producing the direct runoff like soil type, land use and antecedent moisture conditions [5]**.** Due to its popularity, the SCS-CN method has been the object of many studies in rainfall-runoff modelling [6], analysing the impact of land use changes such as urbanization on runoff values [7], for the assessment of runoff generation from rainfall events across the globe [8,9]. This data basis along with the simplicity and the universality of the method makes the SCS-CN method very effective for runoff estimation in poorly gauged regions [10].

According to SCS-CN, the relationship between the rainfall depth, direct runoff and catchment retention can be described in the equation (12) as described by [3].

$$Q = \frac{(P - Ia)^2}{P - Ia + S} \tag{12}$$

Here, Q is calculated the storm runoff, Ia is the rainfall lost as initial abstractions and **S** is the maximum retention storage of the soil. P-Ia is also regarded as effective rainfall.

The initial abstraction accounts for all water losses due to interception, depression storage, surface detention, evaporation and infiltration before runoff begins. Typically, the amount of initial abstraction is normally set to 20% of maximum retention storage [71] depicted in Equation (13).

$$Ia = 0.2S \tag{13}$$

Combining Equations (12) and (13) gives

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)} \tag{14}$$

On the other hand, in contemporary studies [73-76] the amount of initial abstraction of 5% of maximum retention storage is considered to be more appropriate and Equation (14) becomes**:**

$$Q = \frac{(P - 0.05S)^2}{(P + 0.95S)} \qquad (15)$$

The maximum potential storage can be expressed as function of the curve number CN [66,77]:

$$S = 25.4(\frac{1000}{CN} - 10) \qquad (16)$$

Here, S is expressed in mm, and CN is a non-dimensional quantity ranging from 0 (no runoff) to 100 (all effective rainfall becomes runoff).

### 4.2.10. Estimation of Curve Number (CN)

With the above postulated relation between Ia and S, the curve number is the only parameter of the SCS-CN method for calculating runoff volume and peak discharges [66]**.** This makes it very comfortable to link spatial data to hydrologic modelling, using Geographical Information Systems (GIS). Here, we used HEC-GeoHMS and ArcGIS 10.3 as a hydrologic modelling software to estimate CN [67,78]. HEC-GeoHMS is an extension of geospatial hydrological modelling developed by HEC for the efficient manipulation of hydrological models [79]. We generated CN by combining soil layer, the digital elevation model (DEM) and land use layer with CNLookup tables, as described in [80].

## 4.3. Result and Discussion

### 4.3.1. Flow Simulation and Pollutants Flux in the LHW

The SWAT model was calibrated in Figures 4.3 and 4.4 having a coefficient of determination ($R^2$), Nash–Sutcliffe efficiency (NSE), mean percentage error (MPE), mean absolute percentage error (MAPE) and percent bias (PBIAS) values of 0.8, 0.76, 0.69, 10.3 and −11.6 during calibration and 0.8, 0.76, 3.9, 11.6 and −3.9 during validation, respectively. The goodness of fit ($R^2$, NSE, MPE, MAPE and PBIAS) was found to be very good indicating the performance of the model output for the intended purpose was acceptable. The model performance determined by the Nash-Sutcliff (NSE) was 0.8 during calibration and validation in the study area, which is good for interpreting the model output [5]. Similar results were reported elsewhere [81-83] for the model simulation and observation.

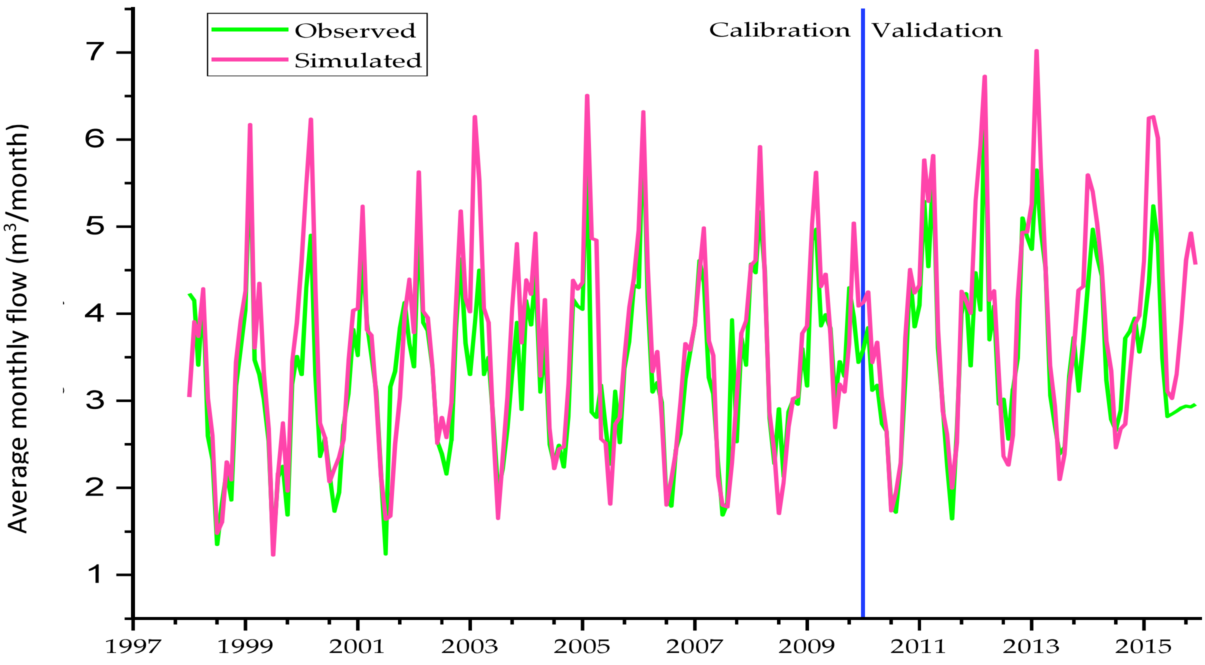

Figure 4.3. Observed and simulated average monthly flow for Lake Hawassa watershed (calibration and validation).

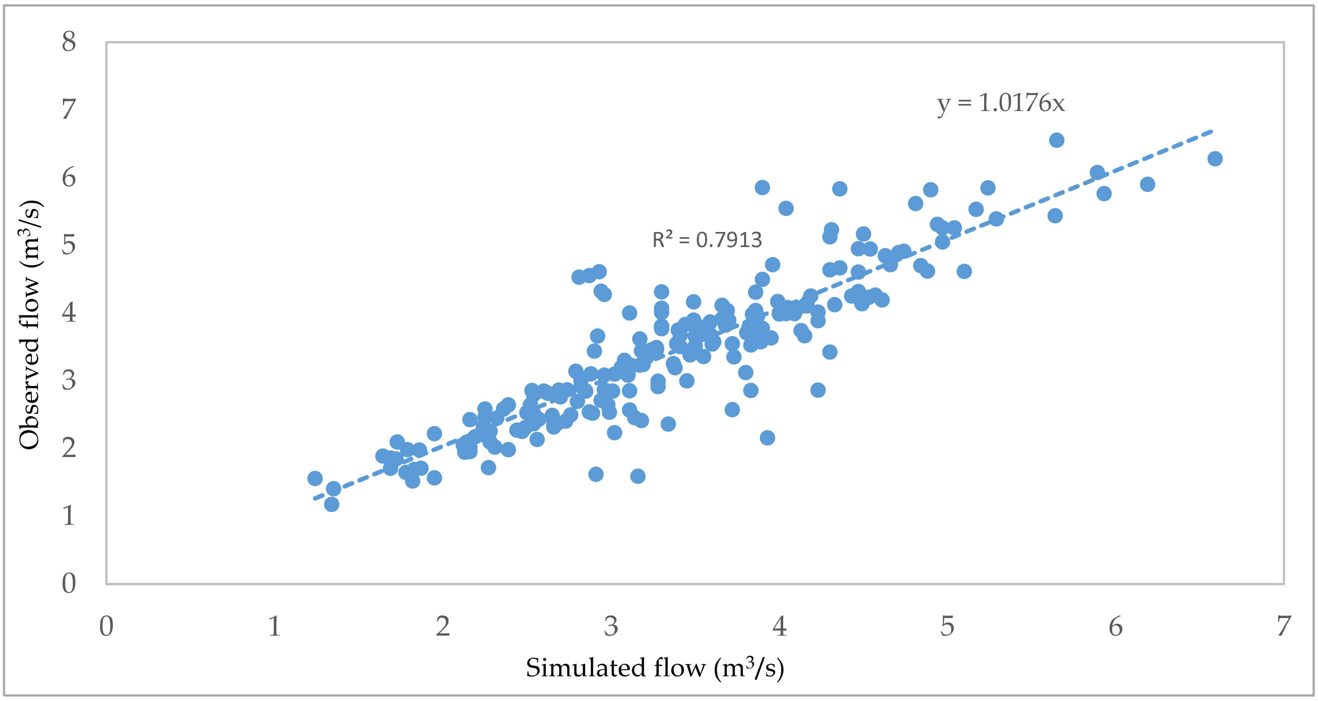

Figure 4.4. Best fit curve for flow calibration and validation.

The SWAT generated flow at sub-catchment outlet was used to calculate the load in FLUX32. Accordingly, the flow-weighted concentration calculated by method 6 (Equation (4)) was less than 0.2 of all other methods in FLUX32. The residual plot of bias for flow, date and month at each sub-basin outlet in LHW was in the range of 0–0.05, indicating it is acceptable. Similarly, the plot of slope significance was in the range of 0.8–0.99. The recommended coefficient of variation (CV) is in the range of 0–0.2 during flow-weighted load calculation and it is in the range of 0–0.058, showing surprisingly good performance of FLUX32 in the watershed under investigation (Table 4.7). Similar trends were also reported by Angello et al. [9] and Belachew et al. [6] in Ethiopia for FLUX32 program simulation performance indicators.

### 4.3.2. Calibration of the PLOAD Model

Pollutant loads estimated via selected export coefficients (Table 6) by employing the PLOAD model as an initial estimate, whilst loads calculated with FLUX32 at selected sub-basin outlets (monitoring stations) in LHW were used for the PLOAD model calibration. During calibration of PLOAD in Excel Solver, the export coefficients were used as independent variables, and their range of values were considered as constraints to set the upper and lower bounds based on the literature during optimization.

Accordingly, at the initial stage of calibration or pre-optimization, the total percentage error between the model predicted and measured load at all monitoring stations for the investigated pollutant parameters are presented in Table 4.8. The PLOAD prediction for the COD, $BOD_5$ and $PO_4$-P were already relatively accurate before calibration and could be further improved. In contrast**,** the total relative errors of PLOAD predictions at all monitoring stations for TDS, TN, TP and $NO_X$ before optimization were in the order of hundreds or thousands of magnitudes. By optimizing the export coefficients using the solver function, the model error could be reduced considerably.

Table 4.8: The total percentage error between measured and simulated load at the initial stage of calibration/pre-optimization and after optimization in all monitoring stations in LHW.

| **Sub-Basin** | **COD** | | **$BOD_5$** | | **TDS** | | **TN** | | **TP** | | **$PO_4$-P** | | **$NO_x$-N** | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Pre-Optimization** | **Optimization** | **Pre-Optimization** | **Optimization** | **Pre-Optimization** | **Optimization** | **Pre-Optimization** | **Optimization** | **Pre-Optimization** | **Optimization** | **Pre-Optimization** | **Optimization** | **Pre-Optimization** | **Optimization** |
| MS1 | 41.54 | 0.0002 | 9.5 | 0.00 | 798.4 | 0.01 | 193.3 | 0.0001 | 298.6 | 0.011 | 28.7 | 0.0003 | 1161 | 0.004 |
| MS2 | 41.62 | 0.0001 | 1.9 | 0.00 | 84.7 | 0.00 | 92.8 | 0.00 | 33.7 | 0.0 | 25.1 | 0.0001 | 65.6 | 0.003 |
| MS3 | 59.81 | 0.0003 | 26.7 | 0.0003 | 1062 | 0.9 | 251.7 | 0.003 | 670 | 0.001 | 39.4 | 0.001 | 1328 | 0.037 |
| MS6 | 90.03 | 0.0023 | 87.1 | 0.001 | 2419 | 3.12 | 254.3 | 91.97 | 1001 | 0.023 | 99 | 0.005 | 1754 | 63.24 |
| ∑abs. error | 233 | 0.003 | 125.2 | 0.001 | 4364 | 4.03 | 792.1 | 92 | 2003 | 0.035 | 192.1 | 0.006 | 4309 | 63.3 |

Still, the PLOAD model underestimated the TDS load at Wedessa (MS3) and Wesha sub-basin (MS1) which are located at the upstream portion of LHW, TN and $NO_X$-N at Tikur-Wuha River catchment outlet (MS6). There is a general trend that the total error increases with the size of the sub-basin. Belachew et al. [6] in Kombolcha catchment and Angello et al. [9] in the Akaki River catchment, Ethiopia, have also come up with similar findings.

For COD, $BOD_5$, TP, and $NO_X$, the export coefficients after optimization showed significant differences for urban, forest land, range land and cultivated land uses. Wetland, bare land and water bodies showed the least variance in pollutant loading, which could be attributable to decreased area coverage and EC contribution in the watershed. Angello et al. [9] also found similar findings in the Akaki River in Ethiopia.

The pollutant loading estimator was also performed using the mean and median values obtained from the optimized export coefficients. At all monitoring stations, the overall percentage error between the model predicted and measured load was 123.83% for mean and 125.33% for median. Furthermore, the observed PLOAD prediction for both mean and median at monitoring stations demonstrated either an overestimation or underestimation of pollutant loads. As a result, the loads calculated using the mean and median ECs were left out of the equation. Consequently, area-specific ECs has been proven to be a useful technique for estimating pollutant loads in the LHW. For effective pollutant load estimations, Angello et al. [9], Cheruiyot and Muhandiki [91] and Shrestha et al. [15] advised the use of area-specific and local ECs. The optimized EC's values can be further used for effective management of the nonpoint source pollution in the Watershed. Likewise, the PLOAD was validated for a different data set without change in the optimized export coefficient and showed the model prediction is acceptable with a relatively smaller sum of total errors.

The calibrated pollutant ECs showed that the urban land use showed varying export coefficients as the pollutant loading rate for urban land use for COD, $BOD_5$, TDS, TP and NOx-N varied with location. The contributions of nonpoint sources among the various urban land uses, as well as the basin's size, are responsible for the observed spatial differences in ECs (Table 4.9).

Table 4.9: Range of export coefficients after calibration of PLOAD for various land uses in LHW.

| **Land Uses** | **Export Coefficient from Literatures, kg ha$^{-1}$ yr$^{-1}$** | | | | | | |
|---|---|---|---|---|---|---|---|
| | **TN** | **TP** | TDS | $BOD_5$ | COD | NOx-N | $PO_4$-P |
| Agriculture | 11.9–62.5 | 0.02–3.3 | 62–211.4 | 42.9–76 | 68.4–260 | 0.03–36.1 | 11.1–14.4 |
| Bare Land | 5 | 0.2 | 93–100 | 3.46 | 5 | 7–67 | 4.8–5.1 |
| Range Land | 11.6–11.8 | 0.24–2.64 | 93.8–100 | 0.5 | 0.5 | 0.46 | 2 |
| Forest Land | 5.85–6 | 0.43–1.02 | 167–250 | 46.6–51 | 48.3–56 | 2–2.1 | 0.7 |
| Urban | 36 | 1.95–2.53 | 2096–2243 | 1490–2238 | 1950–3196 | 88.2–98.02 | 1.7 |
| Water Body | 0.75 | 0.2 | 150 | 50 | 50 | 0.45 | 10 |
| Wetlands | 2.3 | 0.12–0.15 | 100–123 | 5.85 | 35.5 | 1.8 | 0.05 |

The agricultural land use for the calibrated pollutant EC's showed significant variations among monitoring stations. The contribution of pollutant loading rate for agricultural land for COD, $BOD_5$, TDS TN and NOx-N demonstrated, the agricultural land use varies spatially in pollutant loading rate contribution. TP and $PO_4$-P, on the other hand, have revealed a slight variation among the stations.

### 4.3.3. Pollutants Flux in LHW by Using PLOAD

The pollutant flux at each of the sub-basin outlets were calculated with the help of FLUX32. A similar approach was also followed by Angello et al. [9], Belachew et al. [6], Xin et al. [85], Liu et al. [56], Gurung et al. [20], Lin and Kleiss, [51], Edwards and Miller [52] and Shen et al. [10]. The estimated pollutant flux at each monitoring stations showed that the organic pollution contribution from the point and nonpoint sources prevailing in the study area, where the maximum COD and $BOD_5$ load was observed at MS6 with 4976.35 and 3543.54 t/y, respectively (Table 4.10). This station was located downstream of the two-point sources (the BGI effluent discharge site and the Moha soft drinks factory), as well as receiving flow from the upper streams that make a confluence.

Table 4.10: Pollutant flux at catchment outlets of LHW by using PLOAD, t/y.

| **Catchment Outlets** | **COD** | **$BOD_5$** | **TDS** | **TN** | **TP** | **$PO_4$-P** | **$NO_X$-N** |
|---|---|---|---|---|---|---|---|
| MS1 | 635.4 | 327 | 659.2 | 50.9 | 1.69 | 49.3 | 11.2 |
| MS2 | 531.8 | 197.1 | 238.8 | 43.6 | 1.09 | 31.6 | 7.84 |
| MS3 | 2665.5 | 881.8 | 2229.5 | 65.9 | 2.19 | 115.4 | 21.1 |
| MS6 | 4976.4 | 3543.5 | 8741.5 | 149.6 | 3.28 | 284.9 | 43.1 |

Furthermore, at the same monitoring station, the $PO_4$-P, TN, TP and NOx-N loads were calculated, and the results revealed that the pollutant flux at MS6 (downstream) is greater than the rest of the catchment outlets at upper streams. This is because the land uses at MS6 monitoring stations are dominated by urban lands (large- and small-scale industries), followed by agricultural activities and residential settlements. This river section is highly polluted as most of the untreated household wastes, stormwater runoff from urban and rural areas and industrial effluents are discharged onto it.

The non-point source contribution, on the other hand, was well demonstrated at sub-basins of monitoring stations located in the upper catchment (MS1 to MS3) with the COD and $BOD_5$ load, as shown in Table 10, indicating that the pollutant flux from non-point sources is significant even if no identified point sources were present. Moreover, the catchments were dominated by agricultural land uses with small urban areas. Similar findings were also reported by the studies conducted by Belachew et al. [6] in Ethiopia and Jain et al. [93] elsewhere. This could be due to relatively small flow and less anthropogenic influence in the upper catchment.

### 4.3.4. Pollutant Flux from Point Sources in Hawassa City

Saint George Brewery, BGI (MS4) and Moha soft drinks factory (MS5) have all discharged their effluents into a wetland that feeds the Tikur-Wuha River, which flows into Lake Hawassa. According to the findings of the study, as shown in Table 4.11, both point sources contributed significant amounts of pollutant loads to the Tikur-Wuha River (MS6) on top of the non-point pollutant loads from the upper catchment that later joined Lake Hawassa.

Table 4.11: Point source (PS) loads of selected physicochemical parameters using FLUX32 in Hawassa City, t/y.

| Monitoring Sites | COD | $BOD_5$ | TN | TDS | TP | $PO_4$-P | $NO_X$-N |
|---|---|---|---|---|---|---|---|
| MS4 | 106.2 | 25.6 | 8.9 | 932.9 | 7.1 | 12.3 | 1.894 |
| MS5 | 92.0 | 31.7 | 3.7 | 287.6 | 1.5 | 11.5 | 0.074 |
| MS15 | 14.9 | 3.3 | 2.1 | 93.9 | 0.2 | 1.7 | 0.171 |
| MS19 | 211.7 | 53.7 | 4.3 | 287.4 | 0.7 | 3.6 | 0.510 |

On the other hand, Referral hospital and Hawassa Industrial Park were two of the point sources that release their effluents in to Lake Hawassa directly. Referral Hospital is the major known single source for pollutant load contribution to lake Hawassa. Additionally, it may threaten the lake by release of various hazardous substances and pollutants, which are not covered by the investigated parameters. Having known the impact of wastes, Hawassa University constructed a waste stabilization ponds (WSP's) with the intention that the wastewater released are treated based on the discharge standards of the effluents into the water bodies. Nevertheless, the findings of the study revealed that the existing WSP's is not efficient enough to treat the effluent with the desired treatment level as it contributes huge amount of pollutant loads into the lake. The hospital contributes 14.9 tons COD, 3.3 tons $BOD_5$, 2.1 tons TN, 93.9 tons TDS, 0.2 tons TP, 1.7 tons $PO_4$-P and 0.171 tons NOx-N annually. Additionally, Hawassa industrial park was designed initially to comply the zero-emission standard, with no pollutants discharged directly into the Lake. However, during the study periods, huge amounts of pollutants were discharged directly into the Lake as evidenced by personal observation and informal interview. The result on Table 11 showed that Hawassa industrial park contributes COD, $BOD_5$, TN, TDS, TP, $PO_4$-P and NOx loads with their annual loads of 211.7, 53.7, 4.3, 287.4, 0.7, 3.6 and 0.51 tons, respectively.

### 4.3.5. Estimation of Rainfall Depth for the City of Hawassa

The daily rainfall data were collected from the Ethiopian Meteorological Authority and the monthly rainfall data was summarized as shown in Figure 4.5. Accordingly, the total annual rainfall for 2020 was calculated as 1267 mm for Hawassa city. Stormwater quality monitoring was conducted twice a year where the rainfall depth was 47.1 on June 17, 2020 and 57.8mm on July 23, 2020. Likewise, the average daily rainfall depth of 52.5mm was used to calculate the runoff depth.

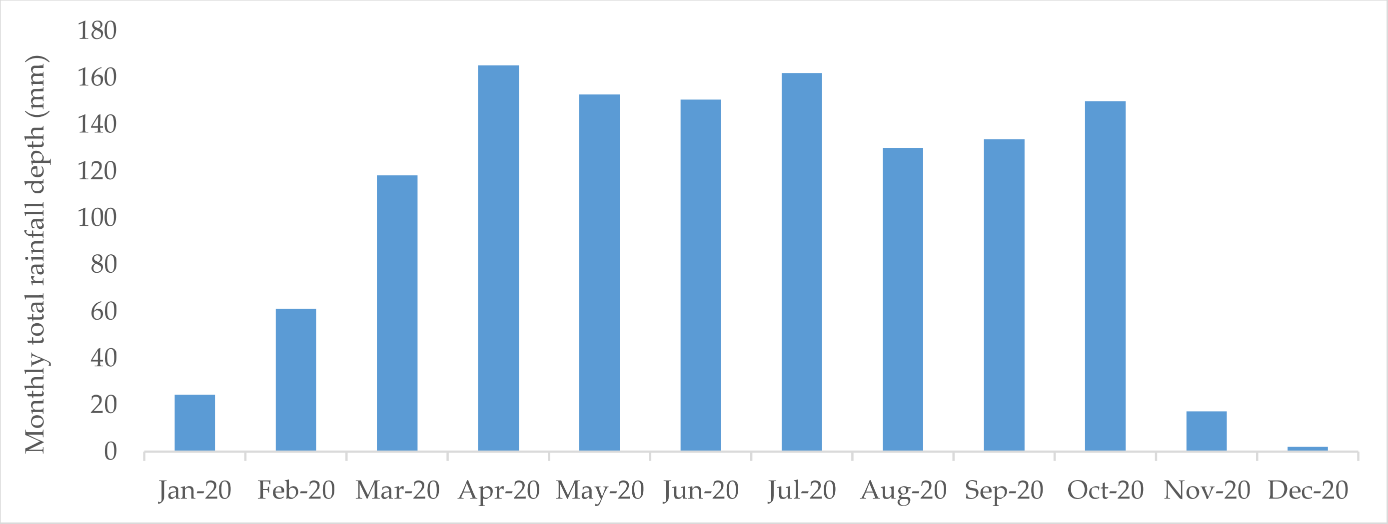

Figure 4.5. The total monthly distribution of rainfall (mm) for the year 2020 for Hawasa city

### 4.3.5.1. Estimation of Curve Number (C) for the city of Hawassa

The soil layer, the digital elevation model and land use layers were clipped for Hawassa City. Thereafter, the land use of Hawassa City was reclassified, the hydrologic soil group maps and the land use layer were merged. The CNLookUp table was prepared for land use and sinks in DEM was filled. The land use map, soil hydrologic map and DEM of Hawassa City is shown below in Figure 4.6.

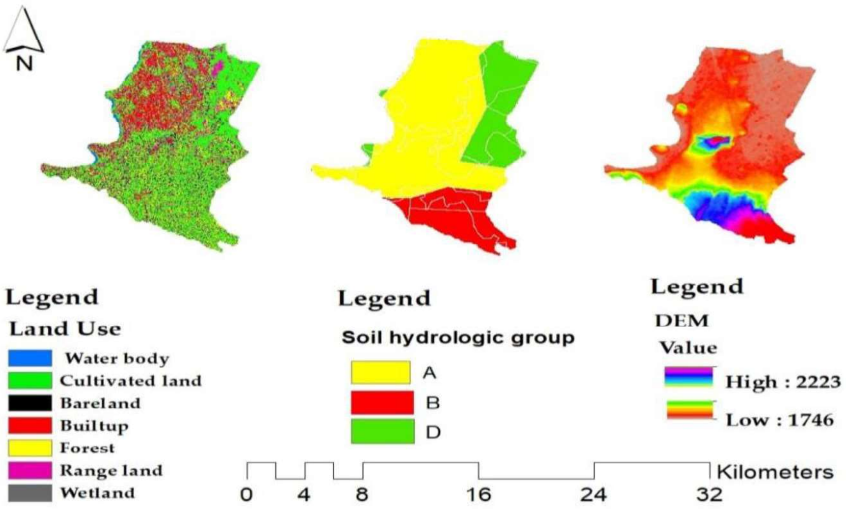

Figure 4.6. The land use map, soil hydrologic map and DEM of Hawassa City.

Subsequently, the merged land use and hydrologic soil group maps, DEM and the CNLookUp table were combined to create the CN grid using HEC-GeoHMS following the procedures stated by Merwade [80]**.** Accordingly, the curve number for monitoring stations in Hawassa City was obtained and used to estimate the runoff depth as shown in Figure 4.7.

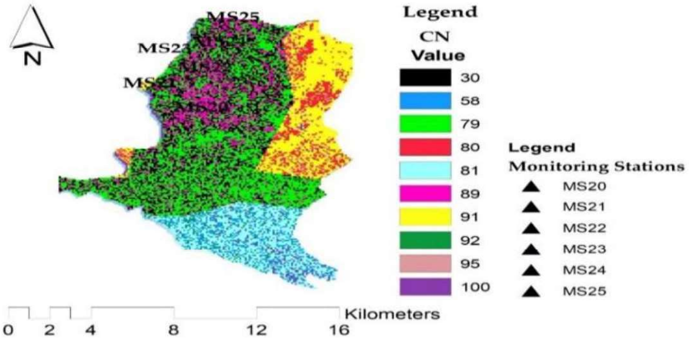

Figure 4.7. Curve number for stormwater samples collected over six (n = 6) monitoring stations in Hawassa City.

The result showed that the values of CN in Hawassa City ranged from 30–100 indicating high CNs (81–100) corresponding to the urbanized areas of the watershed which has the capability for producing the highest amount of runoff during a storm event. The CN values varies with the subtype of urban land use (i.e., residential, commercial, industrial). Whilst low curve numbers (30–77) corresponding to the forested and cultivated areas that generate little runoff due to high infiltration rate. The result of the study revealed that the CN ranged from 81 for MS21 and MS23 to 89 for MS20, MS22, MS24 and MS25.

### 4.3.5.2. Estimation of Runoff Depth for Hawassa City

The runoff depth (Q) can be estimated using Equation 15 based on the average 24-hr rainfall depth for the year 2020 (figure 4.5), curve number (figure 4.7) and maximum potential storage (Equation 15). As a result, the direct runoff result for the corresponding monitoring stations is depicted in figure 4.8.

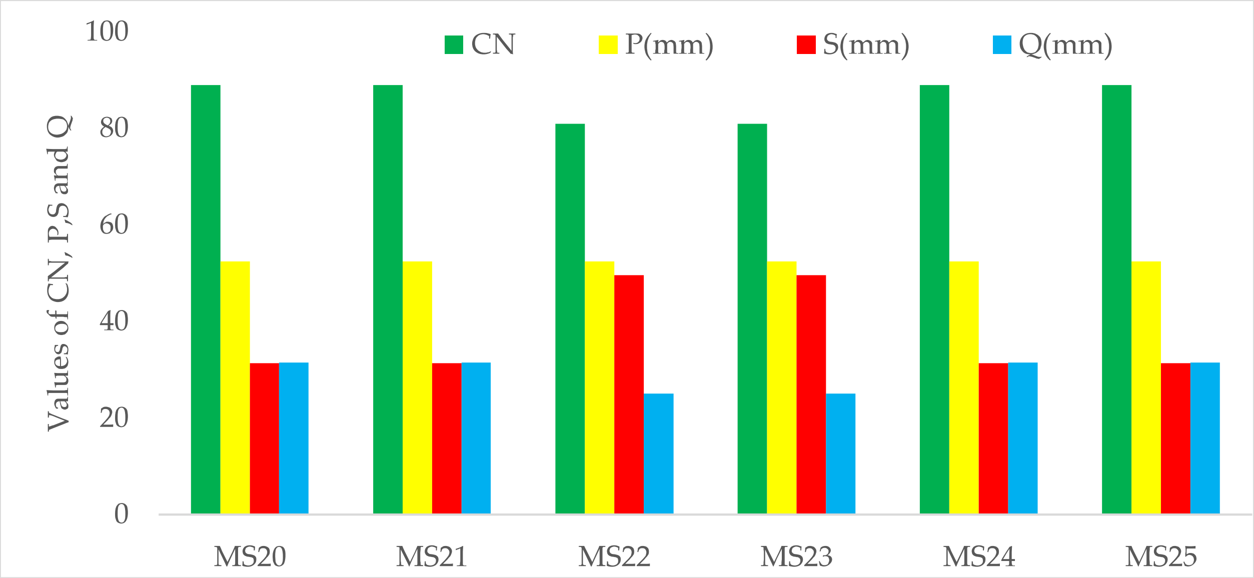

Figure 4.8. The runoff depth (mm) for the stormwater samples collected over six monitoring stations in Hawassa City.

### 4.3.6. Stormwater Pollutant Flux in Hawassa City

The city of Hawassa has various urban catchments that can convey urban storm runoff with open storm drains and the urban runoff joins the lake at various outfalls. For selected parameters, the stormwater quality characteristics were determined and the results of concentrations of stormwater at monitoring stations were depicted in Figure 4.9.

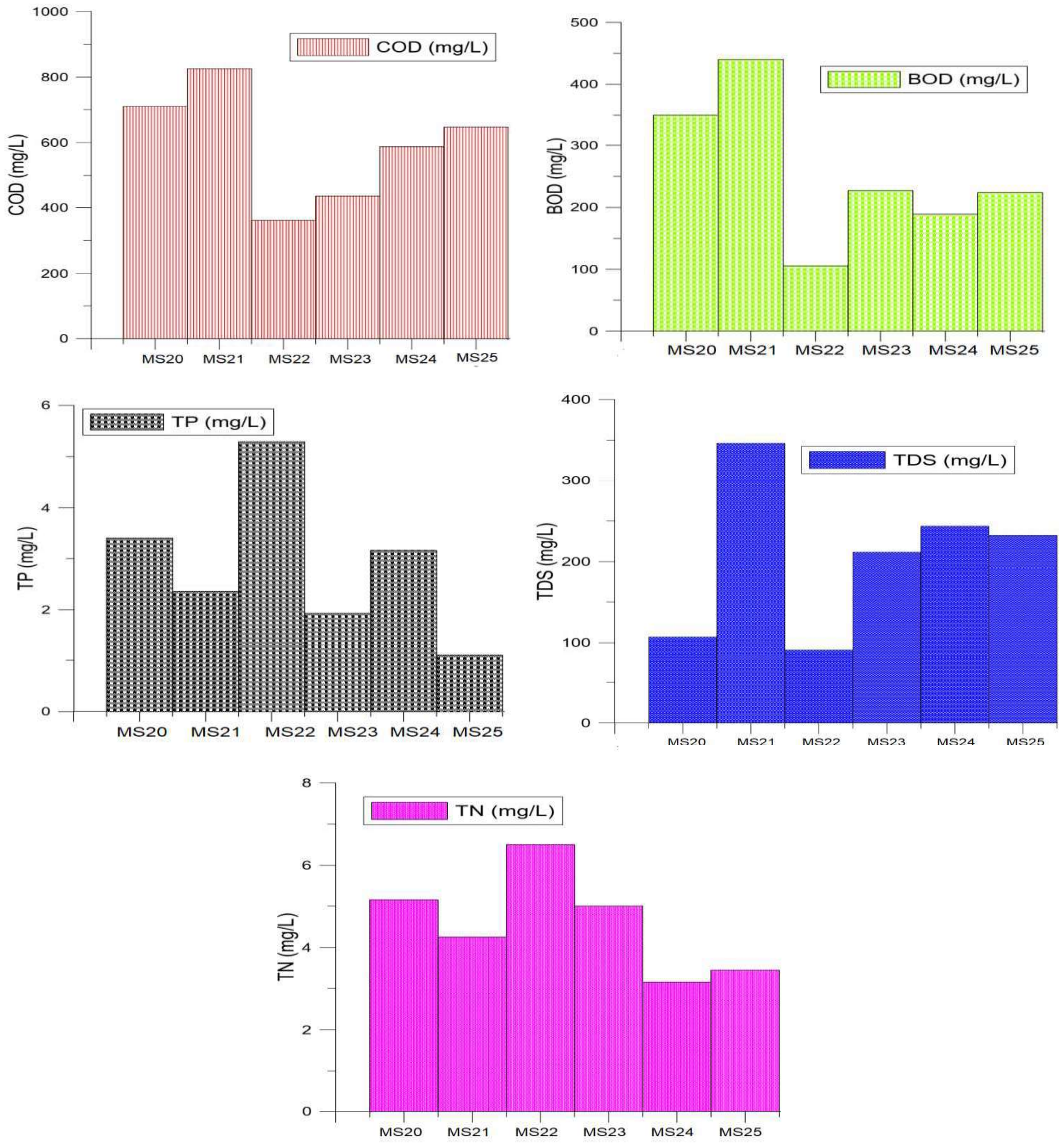

Figure 4.9. Selected physicochemical parameters concentrations (mg/L) in the stormwater samples collected over six monitoring stations from Hawassa City.

The findings of investigations were higher than that of Wondie [93,94], a study conducted in Bahir-dar city, despite the fact that Rădulescu et al. [95] and Li et al. [96] reported comparative findings in Romania and China, respectively. The annual pollutant loads (t/y) for selected physicochemical parameters for each monitoring outfall were estimated utilizing the catchment area (ha) and the corresponding direct runoff determined using the 24 h rainfall frequency (mm) for a two-year return period. As a result, the stormwater pollutant loads of selected physicochemical parameters in Hawassa City were tabulated in tons per year (Table 4.12).

Table 4.12: Stormwater pollutant loads of selected physicochemical parameters in Hawassa City, t/y

| **Monitoring Sites** | **Contributing to** | **COD** | **BOD$_5$** | **TDS** | **TN** | **TP** |
|---|---|---|---|---|---|---|
| MS20 | Lake Hawassa | 1652.1 | 814.4 | 249 | 12 | 7.9 |
| MS21 | Lake Hawassa | 1296.1 | 691.2 | 543.6 | 6.7 | 3.7 |
| MS22 | Lake Hawassa | 212.2 | 62 | 53.5 | 3.8 | 3.1 |
| MS23 | Lake Hawassa | 993.9 | 519.3 | 483.8 | 11.4 | 4.4 |
| MS24 | Lake Hawassa | 424 | 136.5 | 176 | 3 | 2.3 |
| MS25 | Lake Hawassa | 607.6 | 210.5 | 218 | 3.2 | 1.0 |

The most heavily contaminated site, according to this research, was MS20 (near Referral Hospital), which encompasses residential settlements, commercial centers and institutions (hotels, restaurants, cafeteria, hospitals). MS21 (near Amora-Gedel), MS23 (near Chambalala Hotel), MS25 (Near South spring Hotel) sites include residential settlements, businesses and commercial centers, all of which contribute significantly to pollution load. In those sites, there are resort, hotels, cafeterias, a fish market, a recreation center were existing and at Gudumale site, the people of Sidama celebrate their New Year festivities. Consequently, a considerable amount of pollutant load was released into the nearby lake during storm occurrences.

### 4.3.7 Summary of pollutant source contribution

The percentage of pollutant flux for the Lake Hawassa watershed for various sources contributing to Lake Hawassa was shown in Figure 4.10. The plot of pollutant fluxes for organics and nutrients in the lake watershed shows that the percentage contribution of the Tikur-Wuha sub-catchment (MS6) is higher than that of the other sub-catchments because this river is fed by the upper streams (MS1-MS3). Moreover, the Tikur-Wuha River receives additional pollution load from point sources such as BGI factory (MS4) and Moha soft drink factory (MS5). In general, the results showed that the modelling of the export coefficient using PLOAD at monitoring stations (MS3 and MS6) resulted in a higher value for land uses. After that, pollutant flow from stormwater of

Hawassa city at monitoring stations (MS20, MS21 and MS23) is the next significant contributor. In addition, MS1, MS2, MS15 and MS19 are the least contributing sources. In the case of MS15 and MS19, the lower pollutant flux is due to the low and constant flows throughout the year and the flux estimation of these monitoring stations did not take into account the catchment area compared to the streams in the upper catchments and the pollutant fluxes from stormwater in Hawassa City. The studies of Zinabu et al. [6] in Ethiopia and Shrestha et al. [15] elsewhere were comparable with this result.

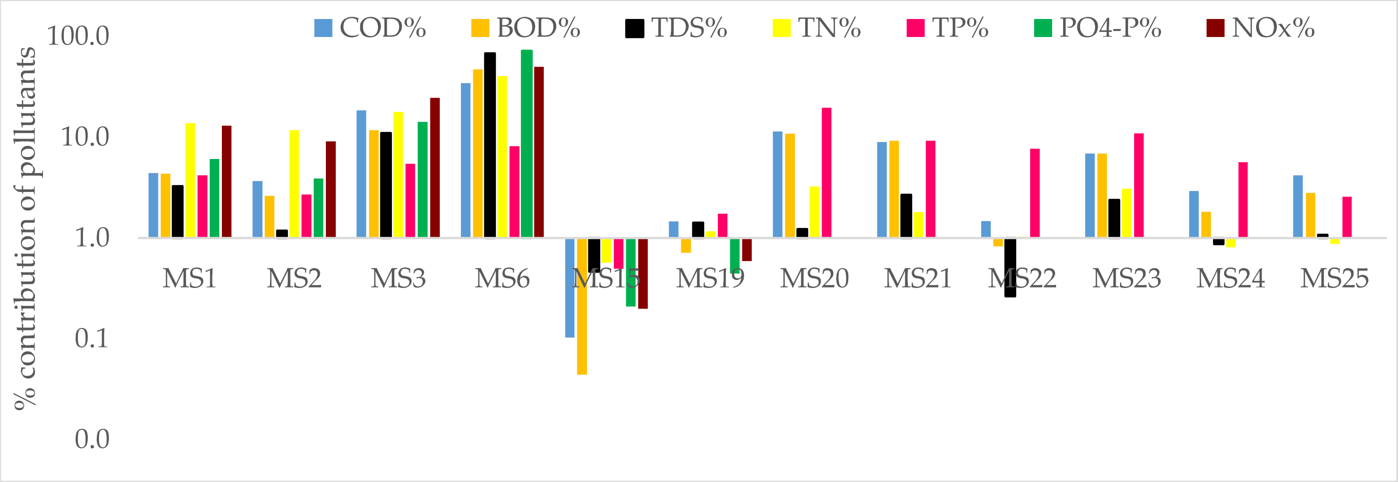

Figure 4.10.Summary of results for pollutant source contribution (%) for samples collected from rivers (MS1, MS2, MS3, MS6), point sources (MS15, MS19) and stormwater (MS20 - MS25)

### 4.4. Conclusions

In this study, we applied a combination of various models (PLOAD, SWAT, FLUX32, HEC-GeoHMS and SCS-CN) with monitoring data to estimate the pollutant flux in the data-limited LHW. The chosen approach was effective in reckoning the annualized diffused source pollution load and is capable to estimate the impact of the spatially distributed emissions on the pollutant flux of receiving streams. It helps to identify the primary source of scattered pollution and provides an effective way for determining organic pollutants and nutrient loads in data-scarce areas.

Estimates of export coefficients from land use in Ethiopia is hardly common and there have been few previous experiences with estimating pollutant loads from the catchments. Thus, transformation of published export coefficients from other studies to characteristics of study area (land use, soil type, slope, climate) was made. In the catchments with no frequent data, estimation of pollutant flux with ECs involved uncertainties**.** However, the error can be significantly reduced by calibrating with monitored data. Generally, more detailed studies incorporating frequent monitoring of water quality and quantity for the main rivers are advisable to derive the land use specific pollutant loads that better conform to reality.

The estimated pollutant flux at each monitoring stations showed that the organic and nutrient pollutant contribution from the point and nonpoint sources prevailing in the study area, where the maximum pollutant loads were observed at Tikur-Wuha sub-catchments. This station was located downstream of the two-point sources and received flow from the upper streams where agricultural use is predominant. The integration of HEC-GeoHMS and SCS-CN with the catchment area enabled to determine stormwater pollution load of Hawassa City. Accordingly, Hawassa city has been identified as a key pollutant load driver, owing to increased impacts from clearly identified point sources and stormwater pollutant flux from major outfalls. Agricultural activities, on the other hand, cover a large portion of the catchment and are a considerable contributor to the overall load that reaches the lake. Thus, mitigation measures that are focused on pollutant flux reduction to the lake Hawassa have to target the urban and agricultural activities.

**Acknowledgments**

The authors are indebted to the German Academic Exchange Service (DAAD) and the Ethiopian government for supporting this research through the Engineering Capacity Building Program (ECBP), which offered a three-year fellowship to the first author.

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# 5. Synthesis, Recommendations and Prospective Research Directions

## 5.1. Synthesis

This cumulative thesis contributes to efforts to manage and control surface water pollution in the Lake Watershed of the Rift Valley Basin of Ethiopia and to better understand water quality management in tropical rivers and lakes. Lake Hawassa and the Tikur-Wuha River receive effluent from several factories and agricultural activities in the lake watershed occur both during the rainy season (rain-fed) and the dry season (irrigation is booming), with most of the annual diffuse loads being transported to the rivers and lakes. As a result, the LHW is one of the most heavily polluted watersheds in Ethiopia and there is an urgent need for integrated water quality management. However, due to financial restraints, technical incompetence and lack of commitment, water quality management and environmental protection in the LHW have been neglected. This study is therefore the first of its kind and includes small-scale monitoring with limited frequency during the dry and wet seasons (Chapter 3).

Thus, this study is conducted with the overall objective of estimating pollutants fluxes contributed by various landuses that are entering into Lake Hawassa from point and nonpoint sources based on water quality monitoring and modelling for the Lake Hawassa Watershed. This general objective has been divided into specific objectives, as explained in Chapter 1 (Section 1.4). Accordingly, each chapter, starting with 2 to 4, describes specific objectives, and together these chapters contribute to the above overall objective. The intention of this final chapter (Chapter 5) is therefore to discuss in detail and consolidate the results of each chapters, and then to come up with better water quality management options in the LHW.

In chapter 2, water quality monitoring and assessment by means of water quality indices and evaluating trophic status (i.e. CCME WQI, WA WQI and TSI) and suitability for anthropogenic uses in the Lake Hawassa Watershed were discussed solely.

Cost and logistical issues have limited continuous monitoring, as a result the water and wastewater databases is inadequate. Thus, this study focused on the monitoring of metals, nutrients and organics from streams and rivers, lakes, industrial effluents and stormwater. The criteria for selecting monitoring points were hydrological in nature, with a confluence of sub-basins with different characteristics and types of land use with the intention of transferring parameters to unmonitored sub-basins. Additionally, factors such as the availability of point and non-point sources, type of land use, and urban runoff and wastewater drains were considered in the selection of monitoring sites. Hence, a total of twenty five (25) monitoring stations were selected (Figure 1.2).

Accordingly, four (4) monitoring sites were selected from the river mouths of the respective sub-catchments in the eastern part of the Lake Hawassa watershed. These monitoring sites are located in the upstream part of Lake Hawassa, where agricultural runoff from the catchment flows directly or through its tributaries into the Cheleleka wetland. Moreover, Tikur-Wuha monitoring station is a critical area where the factories discharge their effluent into the Tikur-Wuha River.

Three (3) monitoring sites were selected near the industrial disposal site and one (1 at the referral hospital. These monitoring sites were selected from available industries and health institute in the watershed that directly or indirectly feed Lake Hawassa. Among monitoring stations, 11 were evenly distributed along the entire course of Lake Hawassa for estimation of the eutrophic status of the lake and water quality monitoring. Lake Hawassa monitoring stations have been established based on the presence of major sources of pollution, the presence of health facilities, industrial effluent emission sites, the availability of boating and recreational activities, presence of service rendering facilities such as Haile and Lewi Resorts, Fish Market and the central part of the lake, where interference is minimal.

Besides, three (3) monitoring sites were located on the western shores of the lake. Although there is no point sources of pollution, there is tremendous anthropogenic activity in the form of non-point source pollution from recreation activities, agricultural runoff and animal waste.

In order to monitor the quality of urban stormwater runoff, stormwater monitoring stations were established at the major outfalls in in Hawassa City. Urban runoff samples were collected from six monitoring stations for two rainfall events. These monitoring sites are encompasses residential settlements, businesses and commercial centers, and institutions (hotels, resorts, restaurants, cafeteria, hospitals), and a fish market, a recreation center and Gudumale, where the people of Sidama celebrate their New Year festivities. Consequently, a considerable amount of pollutant load was released into the nearby lake during storm occurrences. This was followed by the analysis of specified water quality parameters and the assessment of the suitability of the water for anthropogenic use and the compliance of industrial effluents to benchmarks for discharge to the receiving environment.

Furthermore, physicochemical and biological properties of water quality parameters were monitored based on the required water parameters of concern. BOD and COD were selected to assess the presence of organic pollution. While, TN, TP, Nitrate ($NO_3^-$) and Soluble reactive phosphorous (SRP) were selected to monitor non-point sources pollution from agricultural land, urban drainage and residential lawns and the use of inorganic nitrogen fertilizers.

Magnesium ion ($Mg^{+2}$), Calcium ion ($Ca^{+2}$), Sodium ion ($Na^+$), Potassium ion ($K^+$) were selected to monitor water suitability for drinking purposes and irrigation purposes. Nitrite ($NO_2^-$) and Ammonia ($NH_3$) were selected to monitor the toxicity of the water for human consumption and marine life. TN, TP, Secchi depth and chlorophyll a (chl-a) were selected to monitor the trophic status of lake Hawassa. Moreover, Turbidity was selected to measure the presence of suspended material whereas EC and TDS were used to monitor the amount of total dissolved substances in water or effluent. pH was selected to survey acidity or alkalinity of water or effluent and the temperature was selected as it is correlated negatively or positively with most of the water quality parameters. Analyses of physicochemical water quality parameters were conducted from May 2020 to January 2021 to see seasonal variation. Sample collection for the wet season was event-based, i.e., samples were collected after rainfall events.

This has relatively improved the database and understanding of point and non-point source pollution (Chapter 2, Chapter 3 and Chapter 4) and identified wastewater, agricultural and urban runoff management as key areas for improvement. Besides, this study has identified that metals, nutrient and organic fluxes from streams and river and industrial facilities in the city of Hawassa and its surroundings negatively affecting the ecological health of the receiving Lake (Chapter 2 and 3).

Accordingly, the findings showed that the water quality of the watershed is inthe worst-case scenario as it is unsuitable for drinking water purposes, aquatic life and recreational purposes while it is excellent to unsuitable for irrigation purposes based on the WA and CCME water quality indices. The WA WQI classifications place rivers in the excellent category and Lake Hawassa in the good category for irrigation., The CCME WQI is a conservative approach whose range of values change gradually between the lower classes and rivers fall in the good category and Lake Hawassa falls in the marginal category for irrigation purposes. Hence, the discrepancy in the results of the two indices observed are imperative in order to consider measures that are more reliable and the overall category of Lake Hawassa falls under a eutrophic state was discussed solely in chapter 2 [1].

The chemical characterization and spatiotemporal variations of water quality parameters in LHW were discussed solely in chapter 3 [2] where the possible sources of pollution were identified. The monitored water quality data are further analyzed to qualitatively determine the sources of LHW pollution using MVST interpretation and the spatial pollutant hotspots and seasonal impacts on rivers and lakes were determined. Accordingly, the study identified two major pollution sources for domestic, industrial discharges, diffused sources (agricultural and strormwater runoff) and livestock discharges in the LHW.

The spatiotemporal characterization of physicochemical parameters was based on recurring sampling of river or Lake, industrial effluent monitoring in areas where hydro-meteorological and water quality data are limited. However, poor urban landuse management, lack of appropriate sanitation and treatment technologies for domestic and stormwater in rural and Urban areas, poor industrial effluent management and lack of protection mechanisms for riverside or lakeside are exacerbating the pollutant flux from point and diffuse sources in the Lake watershed.

Quantification of pollutant flux from point and nonpoint source is one of the most difficult issues that developing countries face while implementing watershed pollution management and control (Li et al., 2011). In this study, the nonpoint source load prevailing in the study area (Table 4.10). Besides, decision support systems for managing lake basins are poorly implemented due to sparse scientific information and limited access to proprietary pollution estimation software. With no local data for choosing effective organic and nutrient export coefficients parameters, export coefficients from other similar catchments were used in the model and provides reasonable estimates for COD, $BOD_5$, TDS, NOx-N, $PO_4$-P, TN and TP loads in small catchments. Studies reveal that developing local pollutants export coefficients is crucial for accurate determination of diffuse sources pollutants load [3]. This study offers the generation of local pollutants export coefficient (EC's) based on global export coefficients having similar characteristics of landuse, soil type, slope and climate. The EC's generated were used for estimation of nonpoint sources load in the study area using pollutant loading estimator (PLOAD) after calibration using monitored load. Based on the quantified pollution source contribution, a preliminary nonpoint source load management mechanism was developed. Namely, the stormwater pollution load determination in the Ethiopian cities are not common. The SCS-CN method of calculating runoff volume and peak flows was used in this study to estimate the curve number (CN). For this purpose, the spatial data are linked to hydrological modelling using geographic information systems (HEC-GeoHMS) to produce a CN that is used to estimate the runoff depth [4–6] at monitoring station in Hawassa City. Runoff depth, monitored water quality data and catchment area are then combined to determine the stormwater pollutant flux from the major outfalls for the city of Hawassa in this study in Chapter 4 [7].

Moreover, the research findings helped to identify the major point and non-point pollution hot spots and quantify the contribution of each landuse that will help in assigning appropriate mitigation measures. As a result, the estimated flux of pollutants at each monitoring station was estimated and reported in Table 4.10. The results revealed the contribution of organic and nutrient pollution from point and non-point sources, where the maximum COD and $BOD_5$ loads were observed at MS6 with 4976.35 and 3543.54 t/y respectively, and the maximum loads of TN, TP, $PO_4$-P and $NO_x$-N were observed at the same station with 149.6, 3.28, 284.9 and 43.1 t/y respectively.

Therefore, the central part of the lake basin (Tikur-Wuha River) was identified as a future focus area for water quality management. Moreover, this monitoring station is located downstream of the two point sources and received an inflow from the upper streams with predominant agricultural use.

Therefore, water quality modelling has proved effective in bridging this gap by incorporating the impact of both sources of pollution that can justify pollution control and associated remedial actions. However, due to factors such as the lack of technical skills and expertise with monitored hydro-meteorological data and modelling tools, this approach is almost completely disregarded in Ethiopia. In this regard, there is an obvious need for capacity building both during the studies and for lifelong learning professionals. Therefore, Universities in Ethiopia need to take responsibility for establishing and maintaining models and building capacity for professionals. The determination of nonpoint sources pollution load in LHW contributed by each landuses in the catchment is helpful for planning appropriate pollution management strategies. It also provided information about emission and transport of pollutants in the Lake Watershed. Based on the output of the modelling, further investigation will be conducted to develop an improved water quality management and pollution control plans and hence it shall assist policymakers to develop an integrated pollution management plans in Ethiopia. Generally, in Ethiopia surface water quality management is often based on the determination of point source loads solely, while the critical impact of non-point sources load is often flouted. Thus, this study investigated appropriate models to estimate COD, $BOD_5$,TDS, $NO_x$-N, $PO_4$-P, TN and TP loads from point source, non-point source and stormwater, based on the management in the catchment specific criteria to evaluate and present the use of PLOAD in the BASINS 4.5 system and HEC-GeoHMS (Chapter 4). However, in catchments without frequent data, estimating pollutant fluxes using EC is fraught with significant uncertainty in model parameterization. However, calibration using monitored data can significantly reduce errors.

In general, sufficiently frequentand long-term monitoring and further investigation of water quality and quantity in major rivers is recommended to derive land-use specific pollutant loads. Moreover, the simple export coefficient approach only estimates pollutant loads on an annual basis. This is useful for preliminary estimation of pollutant fluxes in areas where data are scarce. The findings of this study showed that the concentrations of metals, nutrients and organic loads affect the water quality of the rivers (Wehsa, Wedessa, Hallo and Tikur Wuha) and Lake Hawassa (chapter 2, 3 and 4). In addition, this work not only provided directions for future research, but also shared some useful recommendations for water quality management and pollution control interventions.

### 5.1.1. Influence of landuses proportion on nonpoint sources pollution contribution in the LHW

Various studies have shown that the impacts of nonpoint sources in watersheds is highly dependent on the type of landuse and management practices [8]. Landuse management to control NPS pollution requires substantial efforts and is costly [9]. To properly manage NPS pollution, the critical source areas susceptible to NPS pollution must first be identified. Several models have also been used to identify areas in need of NPS pollution control and management [10,11]. Visibly poor landuse management existed in the watershed of Lake Hawassa, resulting in severe pollution of Tiku-Wuha River and Lake Hawassa from agricultural and urban runoff and industrial facilities. In this study, clustering and PCA approaches were implemented based on monitoring station prior knowledge and pollution index results to accurately group monitoring stations and identify pollution sources and types of pollutants contributing to contamination chapter 2[2]. Consequently, the overall category of Lake Hawassa becomes eutrophic and phosphorus is the most probable limiting nutrient for phytoplankton growth in Lake Hawassa as discussed in Chapter 1 [1]. The contribution of nonpoint sources  pollution transfer from each landuse into streams or rivers in the upper stream (Wesha, Hallo and Wedessa) and Tikur-Wuha river in the LHW were discussed in Chapter 3 [7]. Regarding the distribution and proportions of landuse in the lake watershed, this study identified seven landuse classes and presented their proportions (Figure 4.2). Cultivated landuse comprises the largest portion in the catchment compared to others. Percentage contribution of pollutants for samples collected from rivers (MS1, MS2, MS3 and MS6), point sources (MS15 and MS19) and stormwater (MS20 to MS25) are presented in figure 4.10. The plot of pollutant fluxes of organics and nutrients in the lake watershed showed that the percentage contribution of the Tikur-Wuha sub-basin (MS6) is higher than the other sub-catchments as it is fed by streams from upper catchment (MS1 to MS3). Moreover, the Tikur-Wuha River receives additional pollution load from point sources such as BGI factory (MS4) and Moha soft drink factory (MS5). Generally, the calibrated export coefficients of agriculture dominated landuses yielded the highest values, despite TP load, which is highest in urban areas. In addition, cultivated landuse, densely populated urban areas, informal settlements and industries predominate in the middle and lower reaches of the Tikur-Wuha-River.

Also in this section, most of the domestic waste and stormwater from the settlement area flows into Tikur-rivers or urban drains or ditches, usually ending up in lakes. The loading of organic pollutants such as COD and BOD leads to oxygen depletion, and the presence of excess nutrients such as NOx-N, $PO_4$-P, TN and TP causes eutrophication of Lake Hawassa. Organic waste and nutrient loading intensities were found to be more congested at the Tikur-Wuha outlet to Lake Hawassa, where a more mixed landuse pattern prevails.

Furthermore, organic pollution load in the study area was notable in cultivated land, urban stormwater and industrial landuses where the nutrient pollution was more prominent. Streams in the upstream of LHW is also found by relatively moderate anthropogenic interference.

The high nutrient loadings downstream of cultivated areas are expected. However, high organic loadings downstream of cultivated land may be because of the following justification. Globally, 2.5 billion people still live without improved sanitation and 15% of the population (1.1 billion people) practice open defecation and Ethiopia was one of the countries mentioned in this report [12]. Open defecation is primarily a rural phenomenon, most prevalent in South Asia and sub-Saharan Africa. In sub-Saharan Africa, 45% of the population uses shared or non-improved sanitation facilities and an estimated 25% practice open defecation [13]. The Ethiopian Mini-Demographic health survey reported that majority of households do not use improved sanitation facilities and some families have no toilet facilities at all and practice open defecation [14]. In this regard, Tesfaye et al.[15], in a study of Latrine use and related factors in rural Kebeles in the Lake Hawassa watershed, reported that most households were less likely to use latrines. Moreover, the Sidama Regional Health bureau reported that half of the population in the Lake Hawassa watershed has no improved sanitation and practicing open defecation. Therefore, this untreated domestic sewage dumped in to the receiving environment might be the reason for the high organic loading in agricultural lands.

### 5.1.2. Influence of industrialization on the point sources pollution contribution in the LHW

As explained in Chapter 2 [1], the rapid growth of urbanization, industrialization and poor wastewater management practices have led to an intense water quality impediment in Lake Hawassa Watershed. The result revealed that monitored point sources in the city of Hawassa and its numerous industrial discharges are key polluters. The findings showed that industrial pollution in the Lake catchment has led to the accumulation of metals, organics and nutrients in the receiving water bodies. Emissions of metals, particularly $Na^+$ from BGI, Referral Hospital, Hawassa Industrial Park and Moha soft drink factories and $K^+$ from Referral Hospital and Hawassa Industrial Park effluents were high and exceeded national emission limits.

Consequently, metal concentrations of the Lake Hawassa were often found at toxic levels for designated uses (Chapter 1 and Chapter 2). In this study, organics (COD and BOD) and nutrient ($NO_3^-$, $PO_4^{-3}$, TP, TN, $NO_2^-$) emissions from BGI, Referral Hospital, Hawassa Industrial park and Moha Soft drinks factory were evaluated. It also showed that concentrations in these effluents exceeded national discharge guidelines, thus affecting the ecological health of receiving lakes. Nutrient concentrations (TN and TP) in effluents from BGI breweries were low compared with effluent data from BGI breweries in Kombolcha, Ethiopia [16] and other African countries [17]. The relative concentration of nutrients in industrial effluents becomes more important when river discharges are small reducing the dilution effect of receiving water [18]. This cumulative Thesis therefore, demonstrates the challenges of industrialization in the city of Hawassa and the urgent need for appropriate regulation to prevent further increases in nutrients, organics and metal emissions.

## 5.2. Recommendations

### 5.2.1. Non-point source pollution remediation and control options in the LHW

In this study, the level of pollution, potential sources contributing for pollution, quantification of pollutant flux in the lake watershed discussed in chapters 2 to 4. As a major forms of non-point pollution, continuous inputs of nitrogen and phosphorus lead to accumulation in the receiving water bodies. Excessive accumulation of nitrogen and phosphorus causes a variety of problems, including algal blooms, water degradation, fish kills and biodiversity loss [19]. As a result, nitrogen and phosphorus pollution has become a global problem due to the lack of effective control of non-point pollution from agriculture and domestic sewage. Since nearly half of the population in the upper part of the Lake watershed practices open defecation, high nutrient and organic loadings have been observed downstream of cultivated land. Thus, both agricultural runoff and untreated domestic sewage might be responsible for the high nutrient and organic loading in cultivated lands. Thus, adequate control of nitrogen and phosphorus are urgently needed before the pollutants are discharged into receiving water bodies.

According to the study's findings, the Tikur-Wuha River and Lake Hawassa were primarily caused by non-point sources of pollution, which also contributed the most to the pollution of metals, organics and nutrients. Thus, the landuse management process should prioritize the Tikur-Wuha River for the mitigation of nutrients and organics pollution loads.

One of Lake Hawassa roadmap for a sustainable future is the implementation of integrated watershed management strategies to efficiently and successfully achieve environmental and socio-economic management goals [20]. However, better landuse planning and management is lacking in LHW. As a result, the contribution of pollution flux from non-point sources in the study area are high. Therefore, effective lake and wetland management in the LHW could be achieved by estabilishing a landuse planning with stringent environment limits.

Hence, remediation of polluted water can be achieved by using either non-point source pollution control at the source, or process control or end treatment and domestic wastewater management (see 5.2.2). There are various engineering technologies that can be used to remediate contaminated water, but they are not rigorous enough to prevent contamination everywhere. Nevertheless, no single method is a panacea for remediating polluted water. Hence, hybrid techniques, which combine two or more single methods, are more widely recommended for their efficient control of agricultural runoff and domestic sewage [21]. Thus, adequate control of non-point source pollution requires extensive use of various control techniques such as vegetated buffer strips, which has been successfully applied in agricultural runoff control [23,24].

A vegetated buffer strips represent a potential way to remove sediments and pollutants transported by agricultural runoff by filtration, deposition and infiltration [25]. Buffer vegetation acts as a filter by increasing surface roughness, which increases infiltration by reducing flow volumes and velocity [26,27]. The filter thus improves the deposition and filtration of sediments by vegetation, the adsorption of pollutants in soil and plant matter and the uptake of soluble pollutants by plants. The efficacy of vegetated buffers in controlling sediment and pollutants has been the subject of numerous studies and showed a positive effect in reducing the transport of sediments, nutrients and pesticides to surface waters [25,28–30]. In order to restore stream or lake corridors, the study recommends the identification and implementation of river or lake buffer zones.

In Ethiopia, arguably the most significant institutional development for lake management to date has been the adoption of the watershed or basin as the fundamental planning unit. Thus, an integrated watershed approach to management should better include participatory and collaborative methods. Moreover, ensuring active stakeholders (i.e. EPA, industry and the community) participation in land use management, protection and planning by raising tailored awareness and providing training is necessary.

This study therefore recommends the following key areas for improvement.

- To prevent further deterioration of Tikur-Wuha River and Lake Hawassa water quality and restore the beneficial use of the lake, management of nutrients such as nitrogen and phosphorous should be given urgent priority in the lake watershed. Identifying all pollutant sources exhaustively in the basin and allocating loads for each of the point and nonpoint sources discharges to the Tikur-Wuha River or Lake Hawassa is essential.
- Increased standardization of water quality monitoring should be established. The resulting scientific data is intended to inform policy makers on a case-by-case basis by taking into account social factors like land or Lake use (i.e. agriculture, fisheries).
- The Ethiopian Environmental Protection Authority (EEPA) should establish guidelines for the trophic status of freshwater bodies in the country through top-down discussions. It would be discouraged to dump waste and effluent directly into lakes and to conduct agricultural activities

close to lakes by establishing a standardized buffer zone system where land development is more restricted.

- Adopting ecological sanitation options like EcoSan for dispersed pollution coming from the population using latrines in rural areas.

### 5.2.2. Domestic wastewater pollution and subsequent remedial measures

The discharge of untreated wastewater into water bodies and the environment is a common practice, resulting in health risks, environmental degradation and disruption of ecological integrity. In Ethiopia, wastewater treatment plants are almost non-existent and badly managed when they exist. Even big cities like Addis Ababa suffer from poor drainage and sewage overflow from industries, institutions and residential areas [31]. According to the central statistical Agency (CSA), Hawassa has more than 300.000 inhabitants, several large hotels and industries and Institutions (University, colleges and health institutions). However, wastewater management is a big concern because most residents uses latrines and septic tanks for buildings with flushing systems.

In order to provide a quantitative assessment of the impact of pollutants from pit latrines on ground and surface water, researchers used a combined modelling approach. This comprised an analytical solution for steady-state reactive transport through the unsaturated zone, which was then used as the input to a groundwater-mixing model. This approach was selected as it combines sufficient complexity to incorporate the key processes with necessary simplicity due to lack of detailed field data. However, these use numerical models like HYDRUS and require detailed site data to characterize soil hydraulic properties [32]. In contrast, the British Geological Survey for assessing risk to groundwater from on-site sanitation has developed a highly simplified approach. However, this is used for local-scale assessments (i.e. at the scale of an individual borehole) [33]. Therefore, the standard advection-dispersion-reaction model was therefore used to estimate the transfer of pollutants into the subsurface, from the bottom of the pit to the top of the water table by some researchers [34]. However, there was little historical data on pollutant concentrations in aquifers and surface waters and site data on soil hydraulic properties in the study area. The lack of sufficient data therefore precludes the application of specific modeling approaches in the studied watersheds, leaving the monitoring and modeling of this to future studies.

On the other hand, lack of proper industrial wastewater treatment system, centralized and onsite wastewater treatment system combined with high pollution load in the watershed contributes to poor water quality management in the Lake watershed. Thus, pollution from the domestic and industrial wastewater, the non-point source (rural and urban runoff) calls for centralized and decentralized (onsite) wastewater treatment system for effective and sustainable management of Lake Watershed water quality and restore the natural ecology of the receiving water bodies.

In most developed countries, centralized treatment systems have played a major role in wastewater treatment and they will continue to effectively provide a valuable service in a densely populated and developed area. This systems have been regarded as the optimal solution for water pollution control and have prevailed in many industrial countries [35]. To a large degree, this centralized sewage treatment approach can solve the problems of sanitation very efficiently [36]. However, a complete replication of centralized technology are often plagued by high capital cost, improper operation and an over reliance on treatment technologies that are unaffordable to be maintained in areas with low populace densities and small rural communities in low-income countries [37,38]. Moreover, although a centralized systems satisfy the demand of highly populated areas, but it does not recognize options for water recycling and reuse as well as nutrients recovery and elimination of emerging pollutants [39]. Therefore, sustainable wastewater treatment systems in developing countries should focus on meeting local needs requiring minimal investment and less-sophisticated operation.

Various researchers and organizations are looking at decentralized wastewater management system as an alternative to centralized systems with the wastewater being treated near its origin. Furthermore, decentralized systems offer a proven, sustainable and cost-effective approach to solving the problems of effluent quality and minimizing surface water pollution in rural and suburban areas in developing countries, because they are more flexible, less resource intensive and more ecologically sustainable [36].

Among the decentralized systems, the ecological sanitation (EcoSan) is a sustainable approach that promotes a closed loop of resources and nutrients from sanitation to agriculture. It has the potential to improve sanitation coverage of unserved populations faster, as it is affordable for the poor, with little recurring cost to operate and maintain [40].

Currently, the research focus of ecological sanitation (EcoSan) has shifted to studies that identify and realize the recovery of nutrients and resources from source-separated human excreta and recover bioenergy [78]. In several studies, the development of technologies has been reported, which can safely use the nutrients of human excreta to obtain usable end products that condition the soil to increase the productivity of crop [41]. Moreover, EcoSan can effectively contribute in safely transforming human urines and faeces into high-potent organic fertilizers for eco-friendly agriculture and producing qualitative nutrient food-crops [40].

Various studies were conducted to identify the application of EcoSan systems for the production of alternative fertilizers and their suitability for the production of crops. Bonvin et al.[42] examined the uptake of recycled phosphorus and nitrogen from urine separated from synthetic sources by plants. Guza et al [43] evaluated the effects of human faeces and urine on maize production. Additionally, Heinonen-Tanski and Wijk-Sijbesma [44] studied the use of human excreta for crop production. On the other hand, Ade-Oluwa & Cofie [45] studied the effect of urine as an alternative fertilizer in amaranth production. The results of the studies showed that the yields of plants fertilized with excreta are similar to those obtained when mineral fertilizers are added in the same ratio.

Therefore, in the Lake catchment it is recommended to employ a combination of centralized, decentralized and on-site wastewater management systems to meet the city's overall sanitation. Thus, amalgamating decentralized and on-site wastewater management with centralized wastewater treatment could be a viable option for effective implementation of recovery programs and sustainable management of Lake Watershed water quality.

Additionally, this study recommends the following key improvement areas.

- The design and implementation of a separate sewerage (sewage and stormwater) and a centralized wastewater treatment system for Hawassa city is mandatory to significantly reduce the sewage discharged to the receiving environment. Depending on the settlement structure, additionally small decentralized on-site wastewater collection and treatment facility should be envisaged. However, their effectiveness depends strongly on the establishment of a management program that ensures regular inspection and maintenance of the system [37].
- Hawassa City municipal sewage disposal should include proper design and appropriate regulation and approval of sewage management options, as disposal of waste directly to surface waters waters (near the lake) requires testing and regulatory monitoring to meet

strict local standards for pollutant discharge limits to meet specified effluents by the Ethiopian National Environmental Standards for Quality Standards (EEPA).

- Implementing financial instruments like subsidies, fees and taxes for the wastewater released either through irregular dumping or through the urban drainage infrastructures to the Lake. It can be supported by duties and penalties.

### 5.2.3. Industrial wastewater pollution management strategies and empowerment of environmental pollution policy

#### 5.2.3.1. Industrial wastewater pollution management strategies

Ethiopia's industrial effluent guideline is based on industrial categories and uses Best Available Technology (BAT) permits. There are no established guidelines for effluent-receiving waters (for ecological protection) and this has prevented an accurate understanding of the impact of industrial wastewater discharge on receiving water bodies. On the other side, the Ethiopian government has established a strategy to expand industrial parks in various parts of the country. Therefore, this study proposes ideas for efficient and cost-effective measures to address the environmental concern of effluents.

In developing countries including Ethiopia, a small proportion of the wastewater is being treated and the effluent from the WSP system hardly meets the acceptable limit [46]. In Hawassa, industries (BGI brewery, Moha soft drink factory and Referral hospitals) have implemented WSPs and discharge their wastewater outside the authorized limits, which can pollute the aquatic ecology [1]. The poor performance of WSP can be attributed due to poor physical, chemical and process design and inadequate operation and maintenance issues. Therefore, the industrial effluent quality after conventional wastewater treatment might be improved after the application of biomethanation technology and waste valorization [47,48].

Over the past decades, CWs has gained popularity for treating agricultural runoff and agro-industrial wastewater due to its unique advantages of cost-effectiveness and low energy consumption. CWs have been successfully used to mitigate environmental pollution by removing a wide variety of pollutants from wastewater such as organic compounds, suspended solids, pathogens, metals, and nutrients [49], as well as pharmaceutical and personal care products [50,51]. Because of high removal efficiency, low cost, simple operation, and great potential for water and nutrient reuse, CWs have become an increasingly popular option for wastewater treatment [51,52].

In developing countries, CW has been used to treat domestic wastewater [53,54], but now the application of CW has also been extended to treat other types of wastewater, such as industrial wastewater [55], agricultural wastewater [56], lake or river water [57], sludge effluent [58], stormwater runoff [59], sugar mill wastewater [60], hospital wastewater [61] and landfill leachate [62]. Moreover, the evaluation of the treatment performance in wetlands constructed for treating agricultural runoff and agro-industrial wastewaters indicates that the hybrid systems can achieve the highest removal efficiency for TSS, $BOD_5$, COD, $NH_4$–N, TN, TP, $NO_3$–N [63].

On the other hand, most wastewater treatment plants implemented in industry aim to remove contaminants from industrial wastewater treatment without recycling or recovery of materials or energy [64]. However, the cost of wastewater treatment and disposal and the price of raw material supplies are expected to continue to rise and the recovery of metals, nutrients and other substances that can be returned to the material cycle remains a challenge for the future [65].

There are variety of potential technologies that have shown great potential for economical and sustainable use in reducing, reusing and recycling (3R) of industrial wastewater treatment technologies. Therefore, the right choice of wastewater treatment technology is the key to achieving the 3R’s to close the resource cycle in industry. The proposed solutions therefore is the ‘zero liquid discharge' (ZLD) or the more ambitious 'zero waste'. Key concerns driving the industry to reuse water resources, materials and energy include stringent regulations on industrial wastewater discharge and water scarcity due to increasing pressure on water resources [66,67]. These systems are beneficial for complying with environmental regulations, for reducing wastewater disposal costs, for supplementing water supplies and for protecting the environment. Thus, ZLD systems minimize waste, recover resources, treat polluting industrial wastewater more effectively, and mitigate potential water quality impacts in receiving waters.

Therefore, for a water resource conservation and pollution control, industrial effluents reclamation with the zero liquid discharge (ZLD) technologies is attracting the attention of scientific and industrial communities. ZLD implementation is growing globally as an important wastewater management strategy to reduce water pollution. Nevertheless, this ambitious strategy has long been criticized due to the high capital costs and intensive energy consumption that must be addressed for wider application of ZLD [68,69].

Hawassa Industrial Park (HIP) is located in the delicate RVLB ecosystem and the water quality impaired Lake Hawassa Watershed.  HIP is designed to reflect the 3R principles of industrial symbiosis and "zero impact" using ZLD water treatment technologies capable of treating 11 million liters of industrial wastewater and domestic sewage daily.

ZLD in the HIP is comprised of the receiving chamber, equalization basin, mechanical treatment technology, primary clarifier, biological treatment technology, filtration and evaporation treatment technologies and each treatment technologies needs to work properly for the successful implementation of ZLD. The industrial park development corporation (IPDC) took over responsibility for ZLD's plant operation, laboratory analysis, maintenance and repair and training of operating personnel. However, it seemed the industry getting in difficulty to sustain the treatment within ZLD level as evidenced by the discharge of large amounts of pollutants directly into the Lake Hawassa every day during the study period. However, industries in Ethiopia are unwilling to conduct detail investigation or provide the data required to pinpoint the issue. As a result, this research has not yet identified the treatment technology responsible for poor performance of ZLD in the HIP. However, compared to the level of effluent treatment in other industries (BGI Brewery and Moha Soft Drinks) in Hawassa City, Hawassa Industrial Park emits lower pollutant streams with lower pollution levels. This could be due to the implementation of ZLD, but effluent is still being discharged into Lake Hawasa without maintaining the permissible limit.

This study, therefore, recommends the following key improvement areas.

- Industries should design and built sustainable treatment technologies, which is suitable to reduce the relevant pollution parameters to the desired effluent standards.
- Industries should regularly and efficiently operate their effluent treatment plants and monitor their effluents to keep them within the standards set by the law.
- Integrating a single centralized industrial wastewater treatment system used by multiple industries within an industrial park could be a useful measure for sustainable industrial development.
- Approaches to water pollution control that focuses on wastewater minimization, in-plant modification of raw materials and production processes, recycling of waste products should be given priority over traditional end-of-pipe treatments.

- EPA and concerned authority should ensure that industries adopt efficient technology to reduce the discharge of industrial pollutants into water bodies to minimize their effects on the receiving water bodies and livelihoods.

This study suggests that policy makers should encourage developing emission criteria for water quality parameters based on self-purification capacity of receiving water bodies instead of merely developing the emission standards based on the type of the factory [70].

Currently, the existing waste stabilization ponds at the referral Hospital and Moha soft drinks factory are not functioning as designed. Therefore, sorting waste by type and introducing anaerobic or chemical pre-treatment followed by constructed wetlands as one technological option could help to reduce the discharge of pollutants into a river or lake.

#### 5.2.3.2. Empowerment of Environmental Pollution Policy

Despite the Ethiopian government's recognition of the potential impacts of pollution, it has clearly limited measures to protect human and ecological health. Ethiopia have developed environmental legislation with respect to effluent standards but its implementation is slow.

Lack of funding for environmental research and monitoring hinders access to reliable water quality information and undermines the ability to develop national water quality guidelines. This cumulative thesis highlights the need for significant changes in environmental agencies to harness this data and establishes GIS and remote sensing techniques for river monitoring and water quality modeling [71]. Environmental policies such as reducing emissions do not always work by simply setting general pollution reduction targets [72]. However, this requires commitment, continuous review and stricter policy enforcement.

On the other hand, environmental policy implementation is baffled by poor inspection and monitoring mechanisms. Policies developed to protect the aquatic environment are well documented, but law enforcement appears to be flimsy.

Ethiopia's ambient environmental standards guideline document is relatively good at controlling pollution, but poor in implementation and law enforcement and much needed to improve environmental quality standards [73]. Most standards were directly taken from developed countries that requires some adaptation to local conditions. Despite having many strengths, the Ethiopian ambient environmental quality standards are not uniform across institutions resulting in discrepancies.

This study, therefore, proposes the following to policy empowerment.

- The respective environmental pollution controlling authorities should take a strong conviction in the direction of the impelementation of environmental policies and laws.
- The government ought to maintain its robust dedication to water and environmental pollution and modify the environmental guideline requirements by way of customizing them to the local situations.
- Implementation of economic instruments like pollution tax, tradable emission permits and tax differentiation can be engaged for all wastewater-generating industries within the watershed. It is essential to maintain the current permit and inspection system and strength enforcement of the industrial wastewater management moratorium on unauthorized discharges.
- EPA and concerned authority should improve the law enforcement to control industrial pollutants. The legal, administrative and technical measures like restriction order, compounding offenses and fines has to put in place to reduce or eliminate the unnecessary discharge of pollutants.
- At the national level, the EPA should develop stringent pollution control regulations and standards especially for those parameters that have no standards and recommend schedule for monitoring of water quality.

### 5.2.4. Stormwater infrastructure, rehabilitation and expansion of the existing urban drainage networks and remedial measures

Although stormwater dilutes pollutants and brings more oxygen, there appear to be some additional non-point sources that are activated during rainfall. Despite the environmental degradation associated with poor stormwater drainage, urban stormwater management is generally inadequate or non-existent in developing countries like Ethiopia**.** Moreover, little attention is given to stormwater management in Ethiopia as a resource (i.e. not used for productive use) and thus it is directly discharged into receiving water bodies reducing its quality, as a result the rivers or Lakes are heavily polluted [74].

The Hawassa city administration has built open ditches to collect the urban runoff that flows into Lake Hawassa without quality control or treatment. On the other hand, flood problem prevails in different parts of Hawassa City; this is due to the insufficient capacity of the drainage channel. In order to solve these problems, new channel dimensions must be designed and implemented. Therefore, the design of stormwater drainage should strictly follow the standards of hydrological and hydraulic design criteria and take into account social and environmental concerns. Thus, the expansion and rehabilitation works underway in the city of Hawassa could have a positive impact on stormwater harvesting. However, stormwater collected from the various sources flows directly into Lake Hawassa without monitoring or pre-treatment, which would have a negative impact on the lake and aquatic ecology.

Furthermore, the expansion and rehabilitation works should take into account areas of rapid urbanization that are contributing a greater polluting load. On the other hand, the disposal of solid waste from various sources in the drainage channels clogs drainage structures. As a result, pollutants are accumulated along the ditches or storm drains are usually intensified by flooding during the rainy season from various landuses and open spaces. This is due to poor waste management in the study watershed resulting from a lack of public awareness and illegal dumping [75].

As discussed in Chapter 4 [7], stormwater is one of the major pollution sources in LHW and its stormwater pollutant fluxes are estimated for selected parameters in Hawassa City. The findings of the investigations revealed that the annual pollutant loads of selected physicochemical parameters for each monitored outfall were higher than studies conducted by Wondie [76] and Adugna et al. [77] in Bahir Dar and Addis Ababa Cities, respectively. Comparative results were reported in Romania and China, with studies conducted by Rădulescu et al. [78] and Li et al. [79], respectively.

In view of the relatively large pollutant load of Hawassa city from stormwater, more attention should be paid to the stormwater quality and its pollution source. This requires more accurately quantifying the stormwater loads and continuous stormwater quality monitoring program consisting of standardized sampling and runoff measurements.

Since, reliable data is a prerequisite for implementing best management practices to reduce these loads and improve stormwater quality. It is therefore clear that prevention and control of Lake water pollution are one of the most critical issues requiring urgent and informed action. These are summarized below:

- Implementing a separate stormwater collection and treatment system is a viable option, but requires a large initial investment. Separate stormwater collections of less polluted stormwater

(e. g. From roofs) from highly polluted stormwater (e.g. Main roads), that needs treatment. By doing so the treatment effort can be significantly reduced. For all outfalls, preliminary treatment for stormwater (like filtration) should be conducted before inflowing into the Lake. As Hawassa City is surrounded by low-lying areas, the identification and implementation of lake buffer zones and the application of riparian vegetation or the design and implementation of constructed wetlands can be used to direct stormwater to treat contaminants, thereby improving its quality before entering the Lake [80].

- The remediation and expansion of urban drainage networks will have a positive effect on reducing Lake pollution.
- It would be imperative to have a continuous and long-term monitoring program at selected sites. Moreover, the establishment of municipal wastewater and storm-water treatment plants for identified dischargers in the watershed, would be among the potential solution to improvement of the water quality.
- Improvement of stormwater quality can be obtained with urban best management practices. In this regard, Low Impact Development (LID) or Sustainable Urban Drainage Systems (SUDS) is the basis for stormwater management by using design techniques that infiltrate, filter, store, evaporate and detain runoff close to its source. Integrating other sustainable stormwater management system such as rainwater harvesting, green roofs, permeable pavements, vegetative swales, bio-retention cells and rain storage through rain barrels for controlling runoff, their design can be customized according to the local regulations and location restrictions [81].
- Solid waste disposal from various sources (residential, commercial and business centers) and street cleaners are the main causes of clogging of drainage channels. Raising public awareness of the usefulness of the stormwater drainage network is essential and recommended to avoid littering in the open-air drainage system.

Currently, the existing constructed wetland at the referral Hospital outfall is not functioning as intended. Therefore, it is recommended that this wetland be rehabilitated to prevent pollutants from stormwater entering the lake.

### 5.3. Prospectiv Research Directions

This study tried to establish water quality management and pollution control mechanisms after conducting water quality monitoring, assessment and modelling by means of

- Water quality indices (i.e. CCME WQI and WA WQI and TSI), evaluating trophic state (i.e. TSI) and suitability for anthropogenic uses,
- Characterizing pollutants in the LHW,
- Estimating point and non-point pollutant flux in the Lake watershed.
- To derive and prioritize effective pollution mitigation measures

One of the most important issues in estimating pollutant loads apportionment is monitoring of the surface water by a coordinated sampling and analytical program, including discharge measurements. In chapter 2 and 3 of this study, the water quality assessment, analysis and pollutants characterization was made based on the water quality monitoring on quarterly basis for a year (for dry and wet periods).

According to Li et al. [82], TSS, COD, TN and TP were transported in bulk in the first flushing flow to the sub-catchment outlets. Moreover, the high dynamics and heterogeneity of pollutant buildup and runoff require both, measuring of more events with different characteristics and addressing the relevant landuses by systematically planned sampling points. Since it is unfeasible to perform those monitoring programs everywhere, deriving and obtaining transferable land use-specific pollution loads ought to be the objective for modelling expected pollution loads and planning mitigation measures. Therefore, additional investigations on the pollution load of TSS, TDS, BOD, $PO_4$-P, $NO_X$-N, COD, TN, and TP will be needed in multiple precipitation events and at more number of areas, including rural, peri-urban and urban watersheds of the LHW. This helps in determining the amount of surface washouts required to treat and remove TSS, organics and nutrients and to design an appropriate treatment facilities.

In this cumulative Thesis, the organics and nutrients load from four rivers, factory units and six stormwater outfalls in the Lake Hawassa catchments were estimated. There is a need to extend the study towards the potential emissions of heavy metals from point or diffuse sources in the study watershed. Thus, future studies should consider monitoring of these heavy metals emissions from the industries, stormwater and rivers.

Moreover, most of the residents in the Lake watershed are using latrines and septic tanks for larger buildings having flushing system. However, this cumulative thesis did not comprehend the effect of pollutants from latrine on ground water and Lake or river. Therefore, future studies should consider monitoring and modeling the effects of latrine pollution in ground and surface water.

Solid waste, especially from nearby factories and the city of Hawassa, is partly disposed in municipal landfills, open fields and urban drainage canals. Therefore, additional study is needed to quantify the potential emissions of organics, nutrients and heavy metals to rivers and Lake Hawassa due to poor solid waste management.

The study of point and nonpoint sources load estimation was based watershed pollutant loading estimator model (PLOAD), much emphasis was given to methods that use minimum available data. This is because most recent watershed nonpoint source estimation techniques including complex models require large amount of data. However, the use of these complex models was hindered by financial constraint and data unavailability. To overcome this challenge, conducting direct estimation of nonpoint sources load by dividing the study area in to more reclassified landuses is recommended.

This cumulative Thesis presents a calibrated PLOAD model that is particularly useful for characterization of organic and nutrient pollution in the data-poor LHW. The export coefficients values are crucial modelling parameter for the PLOAD model, but this study has used literature-based values due to unavailability of local and regional export coefficient. Therefore, future studies should focus on field measurements of export coefficients for each reclassified landuse, the generation of basic and detailed spatial and temporal data, frequent monitoring and analysis of water quality samples and preparation of databases for fertilizer applications to minimize uncertainties.

Hydrological data are fundamental in water quality monitoring and modeling, but lack of sufficient data has become a tailback in the LHW, as a result, conducting modeling that helps in decision-making and water quality management and pollution control are absurd. Hydrological data inputs in this study partly focused on hydrological model outputs due to lack of monitored flow at some locations. As a result, flow was transferred from gauged to ungauged catchment. This may create processing error as it is influenced by the catchment characteristics, landuse and soil type that could lead to erroneous deduction. Moreover, the study has shown that the Wesha, Hallo, Wedessa Rivers contribute high loads of organics and nutrients to the Cheleleka Wetlands, which feeds Tikur-Wuha River. With agricultural intensification, encroachment into the wetland and growing industrialization in the city of Hawassa, organics, heavy metals and nutrient loads into the wetland is an environmental issue for future research to explore impacts on the ecology of Cheleleka wetlands and Lake Hawassa.

In situ sensor technology are rare and still expensive for constituents such as sediments and nutrients (nitrogen and phosphorus). Horsburgh et al. [83] considered sensor technology for water quality monitoring and suggest that water quality monitoring tools such as turbidity and specific conductivity, which are measured in situ at high frequency, can be used as surrogates for other water quality parameters that cannot be measured economically at high frequency.

Therefore, future studies should focus on the continuous monitoring of water quality and quantity with high frequency sample collection and analysis by installing automatic and manual river flow gauging stations at critical locations. Furthermore, the installed gauge recorders should be used to log water quality and sediment at selected stations to characterize the water quality and pollutant emissions.

In developing countries, the application of remote sensing to monitor water quality is still novel. Using improved spectral and spatial resolution sensors and geospatial modeling techniques, water quality parameters such as chlorophyll-a, algae bloom, turbidity, suspended sediments and mineral content in water bodies including groundwater are being monitored at low cost and with greater accuracy [84,85]. Therefore, future studies should integrate these technologies with field monitoring to successfully aid in identification of contaminated zones and sources of contamination to develop strategies for remediation. In addition, remote sensing and GIS technologies coupled with computer modelling are useful tools in providing a solution for future water resources planning and management.

Surface water quality studies in Ethiopia are often based on the determination of pollution cause-effect relationship between landuses metrics and stream water quality and assessment of in situ pollution status of the water resources. Determining this cause and effect relationship has significant impact on surface water pollution management and control. However, this study did not comprehensively examined the underlying cause to suggest sustainable options for pollution control. Therefore, future studies should incorporate a detailed investigation of these pollution sources and clearly define the potential entry points for effective management of the LHW.

Additionally, as landuses changes in the future, pollutant levels will change accordingly. Therefore, better landuses planning could alleviate some of the water quality problems. Therefore, future land development and management should be carefully considered.

Generally, there is a need to identify main predictors, both from anthropogenic and natural landscape characteristics of organic and nutrient loads. In addition, the studies should also include the impacts of atmospheric deposition and other background pollution sources such as contribution of ground water, rock weathering and precipitation induced pollution. This would particularly help to prioritize problems in decision-making and design effective nutrient management for catchments.

Most water quality concentrations data from industries in Ethiopia including Hawassa City are confidential and often not available. They are are not willing to requests of water quality data and onsite measurements. Due to lack of continuously monitored data, most of water quality concentrations and flow are assumed uniform. Without the input from point sources, river water quality management could not be successful and this often yields a crude estimation of the pollution load released from point sources. Consequently, future studies on the water quality and modelling of industrial wastewater should be based on long-term data and direct measurement of wastewater flow for accurate determination of the pollution load from the point sources. Moreover, the corresponding industries and institutions have to monitor the wastewater flow rate and concentrations during high and low flow periods. In this regard, each government agency (EEPA, SREPA and HEPA) should conduct frequent inspections, monitor overall performance and prepare an industrial wastewater database.

On the other hand, ZLD can be a strategy for sustainable water resources and environmental management. However, high cost and intensive energy consumption will remain the main barriers to its adoption. Therefore, future research should focus on technologies that can be adapted to the local conditions, the energy efficiency, environmental safety, economic viability and sustainability through waste valorization.

The catchment characteristics and the relation to pollutant concentrations and loads are important for the stormwater management. Identifying source areas that contribute the most pollutants (Chapter 4) can reduce the area required for LID and enable cost-effective stormwater quality management. Therefore, future studies should thoroughly evaluate the source area contributions and their significance to the design of decentralized LID controls and develop scenarios for selecting the best (optimal) management plans.

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# Appendix A: Original Published Paper 1

International Journal of
*Environmental Research
and Public Health*

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*Article*

# Assessing the Water Quality of Lake Hawassa Ethiopia—Trophic State and Suitability for Anthropogenic Uses—Applying Common Water Quality Indices

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**Abstract:** The rapid growth of urbanization, industrialization and poor wastewater management practices have led to an intense water quality impediment in Lake Hawassa Watershed. This study has intended to engage the different water quality indices to categorize the suitability of the water quality of Lake Hawassa Watershed for anthropogenic uses and identify the trophic state of Lake Hawassa. Analysis of physicochemical water quality parameters at selected sites and periods was conducted throughout May 2020 to January 2021 to assess the present status of the Lake Watershed. In total, 19 monitoring sites and 21 physicochemical parameters were selected and analyzed in a laboratory. The Canadian council of ministries of the environment (CCME WQI) and weighted arithmetic (WA WQI) water quality indices have been used to cluster the water quality of Lake Hawassa Watershed and the Carlson trophic state index (TSI) has been employed to identify the trophic state of Lake Hawassa. The water quality is generally categorized as unsuitable for drinking, aquatic life and recreational purposes and it is excellent to unsuitable for irrigation depending on the sampling location and the applied indices. Specifically, in WA WQI, rivers were excellent for agricultural uses and Lake Hawassa was good for agricultural uses. However, the CCME WQI findings showed rivers were good for irrigation but lake Hawassa was marginal for agricultural use. Point sources were impaired for all envisioned purposes. The overall category of Lake Hawassa falls under a eutrophic state since the average TSI was 65.4 and the lake is phosphorous-deficient, having TN:TP of 31.1. The monitored point sources indicate that the city of Hawassa and its numerous industrial discharges are key polluters, requiring a fast and consequent set-up of an efficient wastewater infrastructure, accompanied by a rigorous monitoring of large point sources (e.g., industry, hospitals and hotels). In spite of the various efforts, the recovery of Lake Hawassa may take a long time as it is hydrologically closed. Therefore, to ensure safe drinking water supply, a central supply system according to World Health organization (WHO) standards also for the fringe inhabitants still using lake water is imperative. Introducing riparian buffer zones of vegetation and grasses can support the direct pollution alleviation measures and is helpful to reduce the dispersed pollution coming from the population using latrines. Additionally, integrating aeration systems like pumping atmospheric air into the bottom of the lake using solar energy panels or diffusers are effective mitigation measures that will improve the water quality of the lake. In parallel, the implementation and efficiency control of measures requires coordinated environmental monitoring with dedicated development targets.

**Keywords:** water quality index; eutrophication; Lake Hawassa water quality; point sources; contaminants; monitoring and assessment

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**Citation:** Lencha, S.M.; Tränckner, J.; Dananto, M. Assessing the Water Quality of Lake Hawassa Ethiopia—Trophic State and Suitability for Anthropogenic Uses—Applying Common Water Quality Indices. *Int. J. Environ. Res. Public Health* **2021**, *18*, 8904. https://doi.org/10.3390/ijerph18178904

Academic Editors: Soon-Jin Hwang, Young-Seuk Park and Ihn-Sil Kwak

Received: 26 June 2021
Accepted: 19 August 2021
Published: 24 August 2021

# Appendix B: Original Published Paper 2

applied sciences

MDPI

*Article*

# Evaluation of Seasonal and Spatial Variations in Water Quality and Identification of Potential Sources of Pollution Using Multivariate Statistical Techniques for Lake Hawassa Watershed, Ethiopia

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check for updates

**Citation:** Lencha, S.M.; Ulsido, M.D.; Muluneh, A. Evaluation of Seasonal and Spatial Variations in Water Quality and Identification of Potential Sources of Pollution Using Multivariate Statistical Techniques for Lake Hawassa Watershed, Ethiopia. *Appl. Sci.* **2021**, *11*, 8991. https://doi.org/10.3390/app11198991

Academic Editor: Jorge Rodríguez-Chueca

Received: 2 August 2021
Accepted: 23 September 2021
Published: 27 September 2021

**Abstract:** The magnitude of pollution in Lake Hawassa has been exacerbated by population growth and economic development in the city of Hawassa, which is hydrologically closed and retains pollutants entering it. This study was therefore aimed at examining seasonal and spatial variations in the water quality of Lake Hawassa Watershed (LHW) and identifying possible sources of pollution using multivariate statistical techniques. Water and effluent samples from LHW were collected monthly for analysis of 19 physicochemical parameters during dry and wet seasons at 19 monitoring stations. Multivariate statistical techniques (MVST) were used to investigate the influences of an anthropogenic intervention on the physicochemical characteristics of water quality at monitoring stations. Through cluster analysis (CA), all 19 monitoring stations were spatially grouped into two statistically significant clusters for the dry and wet seasons based on pollution index, which were designated as moderately polluted (MP) and highly polluted (HP). According to the study results, rivers and Lake Hawassa were moderately polluted (MP), while point sources (industry, hospitals and hotels) were found to be highly polluted (HP). Discriminant analysis (DA) was used to identify the most critical parameters to study the spatial variations, and seven significant parameters were extracted (electrical conductivity (EC), dissolved oxygen (DO), chemical oxygen demand (COD), total nitrogen (TN), total phosphorous (TP), sodium ion ($Na^+$), and potassium ion ($K^+$) with the spatial variance to distinguish the pollution condition of the groups obtained using CA. Principal component analysis (PCA) was used to qualitatively determine the potential sources contributing to LHW pollution. In addition, three factors determining pollution levels during the dry and wet season were identified to explain 70.5% and 72.5% of the total variance, respectively. Various sources of pollution are prevalent in the LHW, including urban runoff, industrial discharges, diffused sources from agricultural land use, and livestock. A correlation matrix with seasonal variations was prepared for both seasons using physicochemical parameters. In conclusion, effective management of point and non-point source pollution is imperative to improve domestic, industrial, livestock, and agricultural runoff to reduce pollutants entering the Lake. In this regard, proper municipal and industrial wastewater treatment should be complemented, especially, by stringent management that requires a comprehensive application of technologies such as fertilizer management, ecological ditches, constructed wetlands, and buffer strips. Furthermore, application of indigenous aeration practices such as the use of drop structures at critical locations would help improve water quality in the lake watershed.

**Keywords:** monitoring; mitigations; spatial and temporal variabilities; principal component analysis; cluster analysis; discriminant analysis; water quality; pollution; correlation

# Appendix C: Original Published Paper 3

water

MDPI

*Article*

# Estimating Point and Nonpoint Source Pollutant Flux by Integrating Various Models, a Case Study of the Lake Hawassa Watershed in Ethiopia's Rift Valley Basin

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**Abstract:** Increasing pollutant emissions in the Lake Hawassa watershed (LHW) has led to a severe water quality deterioration. Allocation and quantification of responsible pollutant fluxes are suffering from scarce data. In this study, a combination of various models with monitoring data has been applied to determine the fluxes for Chemical Oxygen Demand (COD), Biochemical Oxygen Demand ($BOD_5$), Total Dissolved Solid (TDS), Total Nitrogen (TN), Nitrate and Nitrite-nitrogen (NOx-N), Total Phosphorous (TP) and phosphate ($PO_4$-P). Water, wastewater and stormwater samples were collected and analyzed at eight monitoring stations from rivers and point sources and six monitoring stations of stormwater samples. The flow simulated with soil and water assessment tool (SWAT) could be very well calibrated and validated with gauge data. This flow from SWAT model, measured flow during monitoring and pollutant concentrations were used in FLUX32 to estimate pollutant fluxes of main rivers and point sources in LHW. The formulas provided by Ethiopian Roads Authority and Gumbel's theory of rainfall frequency analysis was employed to determine the 2-years return period rainfall depth for the City of Hawassa. The integration of HEC-GeoHMS and SCS-CN with the catchment area enabled to determine stormwater pollution load of Hawassa City. The estimated pollutant flux at each monitoring stations showed that the pollutant contribution from the point and nonpoint sources prevailing in the study area, where the maximum fluxes were observed at Tikur-Wuha sub-catchments. This station was located downstream of the two point sources and received flow from the upper streams where agricultural use is predominant. Furthermore, Hawassa city has been identified as a key pollutant load driver, owing to increased impacts from clearly identified point sources and stormwater pollutant flux from major outfalls. Agricultural activities, on the other hand, covers a large portion of the catchment and contributes significant amount to the overall load that reaches the lake. Thus, mitigation measures that are focused on pollutant flux reduction to the lake Hawassa have to target on the urban and agricultural activities.

**Keywords:** pollutant loading estimator (PLOAD); FLUX32; water quality; pollutant export coefficients; point and non-point source pollutant flux

**Citation:** Lencha, S.M.; Ulsido, M.D.; Tränckner, J. Estimating Point and Nonpoint Source Pollutant Flux by Integrating Various Models, A Case Study of the Lake Hawassa Watershed in Ethiopia's Rift Valley Basin. *Water* **2022**, *14*, 1569. https://doi.org/10.3390/w14101569

Academic Editors: Xing Fang, Jiangyong Hu and Suresh Sharma

Received: 20 April 2022
Accepted: 11 May 2022
Published: 13 May 2022

## 1. Introduction

Currently due to the rapid advances in modelling, numerous water quality models were developed with various modelling algorithms for various land use and water bodies for pollutants at different spatio-temporal scales [1,2]. The data demand for water quality models increase with the complexity and scope of application [3].

Generally, most developed countries, namely the US or European countries have established better and advanced surface water quality models [2]. One of pivotal factors in the primary goals of environmental management would be assessing the water quality despite limited observations [4]. In the developing world reliable application of water

# Curriculum Vitae (CV)

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| Research area | ❖ Water Quality Management, Pollution Control, Environmental Remediation |

## WORK EXPERIENCE

### Head and Lecturer in WSEE, Institute of Technology, Hawassa University, Ethiopia

12/03/2013 to 26/09/2019

- ❖ As a department head coordinate and timely report department activities
- ❖ As a module team leader monitor and control the timely progress of courses and assessments
- ❖ Monitor and evaluate internship program and assess in continues manner.
- ❖ Coordinate pre-engineering profession of our school
- ❖ The member of department discipline committee and schools' competition committee for IOT
- ❖ Timely perform and report any other related duties
- ❖ Delivering courses, performing community services and conducting researches

01/07 2012 to
11/03/2013

**Coordinator of water supply and schemes administration core process in Areka Town Water supply enterprise, Wolaita Zone, Ethiopia.**

- As site engineer supervise different water supply and sanitation projects which are being executed in the site
- Ensure that the planning and implementation of the project activities are in accordance with the program principles.
- Review, summarize and submit monthly and quarterly report for the enterprise manager and Town Mayor concerning the project.
- Timely report and perform any other related duties.

1/11/2009 to
01/11/2010

**Vice director, department head and Chemistry teacher in Areka secondary and preparatory school**

- Mobilizing the community to participate in school issues
- Review, summarize and submit monthly and quarterly report for Town and Zone education office and department respectively
- Timely plan and perform the teaching learning process

## Skills

| | |
|---|---|
| Organisational/ managerial skills | As a department head and module team leader good leadership skill is gained through my experience as a department head, module team leader and involvement in different extra curricula activities |
| Communication skill | Good communication skills gained through my experience as Lecturer and department head |
| Basic computer skills | Basic computer skills like word processor, spread sheet, presentation softwares) |
| Softwares | PLOAD, FLUX32, Arc-GIS, SWAT, HEC-GeoHMS, AutoCAD, EPANET, SewerCAD, WaterCAD, xlSTAT and SPSS |

## Publications and conference presentation

Publication and conference presentation

- **Lencha, S.M., Ulsido, M.D., and Tränckner, J.** Assessing the Water Quality of Lake Hawassa Ethiopia—Trophic State and Suitability for Anthropogenic Uses—Applying Common Water Quality Indices. International Journal of Environmental Research and Public Health 2021, Volume 18, Issue 17, 8904, Pages 31.
- **Lencha, S.M., Ulsido, M.D., and Muluneh, A.** Evaluation of Seasonal and Spatial Variations in Water Quality and Identification of Potential Sources of Pollution Using Multivariate Statistical Techniques for Lake Hawassa Watershed, Ethiopia. Applied Sciences 2021, Volume 11, Issue 19, 8991, Pages 25.
- **Lencha, S.M., Ulsido, M.D., and Tränckner, J.** Estimating Point and Nonpoint Source Pollutant Flux by Integrating Various Models, a Case Study of the Lake Hawassa Watershed in Ethiopia's Rift Valley Basin. Water 2022, Volume 14, Issue 10, 1569, Pages 25.
- **Mathewos, M.; Lencha, S.M.; and Tsegaye, M.** Land Use and Land Cover Change Assessment and Future Predictions in the Matenchose Watershed, Rift Valley Basin, Using CA-Markov Simulation. Land 2022, Volume 11, Issue 10, 1632, Pages 31.
- **Ashenafi, M.; Daniel, F.; and Lencha, S.M**. Evaluation of Hospital Wastewater Treatment and Disposal: The Case of Wolita Soddo Teaching Referral Hospital, Wolaita Zone, Southern Ethiopia. Civil and Environmental Research 2017. Volume 9, No 5, pages 9.
- **Ulsido, M.D., Lencha, S.M., and Li M**. Multivariate Analysis of Water Quality along a Pollution Gradient: An Outline for Selection of Environmental Monitoring Indices. Proceeding of the 17th International Symposium on Sustainable Water Resources Development held at Arba Minch University from June 23-24, 2017.

Manuals and Reports

- Compiled a report on assessment of Water Quality for irrigation purposes Wunkiye watershed
- Compiled a report on assessment of Water Quality for drinking and irrigation purposes Omo-Gibe Basin Basin
- Compiled a report on assessment of Water Quality for drinking and irrigation purposes Rift Valley and Genale Dawa Basin
- Compiled a report on assessment of Water Quality for drinking and irrigation purposes on Bilate Watershed
- Prepared different manuals for Urban Water supply and Sewerage offices found in southern Ethiopia with Bafana Bafana Counltant office

## REFERENCES

| | |
|---|---|
| Prof. Dr. Ing. habil Jens Tränckner | ❖ Faculty of Agriculture and Environmental Sciences, University of Rostock, 18051 Rostock, Germany, (email: jens.traenckner@uni-rostock.de) |
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| Dessalegn Jawesso (PhD) | ❖ Ass. Professor and former head of school of Biosystems and Environmental Engineering, (email: dessejaw@gmail.com), (Mob. +251921452824) |

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