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Dissertation

Zelalem Abera Angello

Selection of Optimal Pollution Management Strategy for the Little Akaki River, Ethiopia, Based on Determination of Spatio-temporal Pollutant Dynamics and Water Quality Modeling

PROFESSUR **Wasserwirtschaft**

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Foreword

River water quality is threatened worldwide by emissions from point source and diffuse sources but also from insufficient self-purification capacities. On a conceptual level, we know very well that that water quality is a combined result of external and internal factors. However, translating this concept into detailed systems analysis is hardly tackled, to date, due to missing information of all relevant impacts and insufficient understanding of cause-effect relationships. These challenges become even more severe under in regions with limited financial resources and deficient institutional capacities.

Zelalem Abera Angello addresses this complex of problems by setting up a complete framework of i) allocation and quantification of emission sources, ii) quantitative analysis of instream processes, iii) setup of a water quality model, iv) model application to develop/assess management options.

In contrast various other studies, his approach is not based on estimated load data or model parameters from literature but consequently derived from a well-designed monitoring campaign, performed by his own. The acquired data itself are of high value and are consequently assessed statistically and used for model calibration/validation. Furthermore, his work does not end with the model but continues with application of the model to evaluate the effectiveness of various external and instream measures or a combination of both. In this consequence, the work is a good science-in engineering example. The lean but highly effective design of the developed approach makes it applicable and adaptable to other urban rivers worldwide.

However, systems analysis is only the first step for improving water quality. In this regard, I deeply wish for this thesis not only inspiring other scientists, but leading to the design and implementation of serious impact mitigation measures.

Prof. Dr.-Ing. habil. Jens Tränckner

Universität Rostock

Traditio et Innovatio

Selection of Optimal Pollution Management Strategy for the Little Akaki River, Ethiopia, Based on Determination of Spatio-temporal Pollutant Dynamics and Water Quality Modeling

Cumulative 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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Dedication

I dedicate this dissertation to my late friend Mesfin Tadesse, whom I lost in the middle of this study. Losing someone so dear like you is devastating and no words can ever really relieve the pain I am suffering መስፍኔ. Rest in ethernal peace my dear.

Acknowledgement

First and foremost, I thank God for giving me courage, hope and strength. I have no words to praise him for everything that he had done in my life. Virgin Mary, whom I call when I am in desperate need of something, and that she didn't turn down my prayers, thank you for your abundant love and blessings.

Dear Prof. Jens Tränckner,

I would like to express my gratitude from the bottom of my heart for your exceptional guidance and timely advice to complete my thesis successfully. My research proved to be a landmark effort towards the success of my future career at large because of your scientific and technical supervision. Without your critical comments and continuous guidance, it could probably be impossible to achieve my goal. Your support at every bit of my research progress was outstanding.

Dear Dr. Beshah Mogesie,

I can't thank you enough for your generous help in my life. You are the one among very few people that I have a meaningful place in my heart. Your help and sympathetic attitude at every point during my study period has clearly helped me to accomplish my research on time.

I would like to pass 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. Mekonnen Ayana's contribution for the realization of my PhD study. All my friends in AMU and Rostock, you are simply the best. My appreciation also extends to Dr. Ing. Thomas Torora and Dr. Daniel Reddy Thota for their valuable comments, critical review and editing of some parts of the manuscripts and thesis. If I am allowed to count on someone special person in my life, I would definitely start with Dr. Yechale Kebede-you are just unique. Dr. Ing. Abdella Kemal and Dr. Samuel Dagalo, kindly accept my heartfelt appreciation for your generous help during my research stay in Ethiopia.

My families, you were on my side all the way and your prayers have helped me a lot.

Summary

With competing demand on limited water resources, the urban river pollution has remained the prime challenge and worrisome phenomenon in Ethiopia. Despite the widespread social and economic benefits, the water quality of the rivers is deteriorating rapidly necessitating greater efforts to restore the natural ecology of the rivers. However, previous studies on the Ethiopia's urban river pollution management have focused on the cause-effect correlation based on snap-monitoring events. Furthermore, the water quality management and pollution control system were often based on short-term monitoring campaign and usually ignore river ecological restoration approaches and the management mechanism is deemed ineffective. In this study, an optimum water quality management and pollution reduction approaches were identified for one of the heavily polluted urban rivers in Ethiopia, the Little Akaki River (LAR). The study was carried out in four sequential parts: constituent characterization, pollution load estimation, water quality modeling and development and evaluation followed by selection of optimum pollution reduction approaches.

In the first part, characterization of water quality constituents in LAR was carried out at selected river stations where monitoring of constituents was conducted on bimonthly time step. The study was carried out to investigate the physico-chemical properties of water quality constituents in the LAR that influence river pollution. Multivariate Statistical Analysis (MSA) techniques were used to evaluate the constituents' spatial and temporal variability beginning with determining the descriptive statistics followed by source apportionment and spatial clustering using factor analysis (FA) and cluster analysis (CA). Before applying MSA statistical measure, the raw data was z-standardized, outlier corrected and normality was checked. Furthermore, based on the pre-defined source profile, a Multivariate Receptor Model (MRM), UNMIX, was used to estimate pollution source contribution and composition for the individual constituents. Both MSA and MRM findings revealed that the pollution load in the LAR had exceeded the river's normal load carrying capacity. Analyzed data also showed that domestic, industrial, and nonpoint sources (mainly urban land use washouts and small-scale urban agricultural) are accounting for the majority of the pollution load in the river in both dry and wet seasons. Key recommendation from this study revealed that middle and downstream segment of the LAR were heavily polluted and hence needs clear strategic plan to restore the natural ecology of the river. Besides, these segments require periodic monitoring and assessment, which should be prioritized in the pollution management plan. In such data-scarce areas, the combined application of MSA and MRM could be used in preliminary pollution assessment.

In the second part, process-based modeling was applied to quantify point and diffuse sources pollution load in the LAR. Accordingly, the pollutants load contributed by various land uses to the LAR was determined and quantified using an integrated Chemical Mass Balance (CMB) analysis and a watershed nonpoint sources model (PLOAD) based on the pollutants loading rate or export coefficient (ECf). The ECf play critical role in determining and defining the diffuse sources pollution load which is missing in many developing countries including Ethiopia due to lack of monitored data. However, a local ECf was generated and used for the estimation of the uncharacterized nonpoint source load in the study area from ECf collected from other watersheds. Based on the estimated ECf values and measured water quality data, the PLOAD model was calibrated and used to calculate the pollution load in the catchment. The findings revealed that the diffuse source is the dominant pollution source in the LAR accounting for more than 50% of the pollution load. Based on the study findings, it is recommended that priority should be given to pollution management in the LAR, with more focus on nonpoint source reduction, particularly in the middle and downstream segments of the river where urban land use prevails. Accordingly, this study suggests the use of integrated CMB-PLOAD approach which is relatively effective for developing preliminary water quality management programs in data-scarce areas.

Part three focused on simulating water quality constituents based on the calibration and validation of water quality model, QUAL2Kw. The model was found effective in many watersheds globally and used in water quality management and pollution load reduction programs. The rate parameters, constants, reaction rates and other coefficients were taken from literatures and customized to the study area conditions as per the model requirement. The water quality constituent's simulation in LAR was quite good (maximum percentage error: PBIAS of 15%) and the model output was hence used for further interpretation of water quality management and pollution control programs in this study. Accordingly, the model is more suitable for data-scarce areas and this study recommends the application of the QUAL2Kw for water quality management and pollution control development programs.

The fourth part focused on the development and evaluation of five targeted water quality management and pollution load reduction options in QUAL2Kw model. The evaluated water quality management options were: modification of point sources load, modification of nonpoint sources load, simultaneous modification of point and nonpoint sources load, application of instream measures (local oxygenators) such as cascaded rock ramps and integrated scenarios. First, the water quality simulation was performed and found successful when evaluated based on the performance indication criteria. Then, evaluation was conducted on the QUAL2Kw model based on the five predefined scenarios. The river's response to the changing scenarios was assessed until the required water quality objective (WQO) in the LAR was met. The evaluation of all scenarios revealed that none of the individual scenarios was able to restore the required water quality level in the LAR and hence the WQO was not met. However, the integrating scenarios (i.e., combining source-based pollution reduction and instream measures) significantly reduced the pollution load in the river. Key recommendation from the study showed that, to restore the LAR natural ecology, an optimal combination of source-based pollution reduction and instream measures, with a nutrient (such as phosphate and nitrate) removal rate of more than 75% and an organic pollution load (such as BOD) removal rate of more than 80% from both point and nonpoint sources to be applied so that optimum management and better water quality would be maintained in the LAR.

To summarize, the high pollution load in the LAR, combined with lack of technical skill on river restoration programs, poor water quality management plan, and low capital budget, have resulted in unsuccessful and unsustainable river water quality management system in the river. Owing to the river's social and economic benefits, it is now more than ever important to carefully consider the optimum pollution management alternatives available based on integrated water resource management approaches. If appropriate water quality management options are implemented and the pollution reduction mechanisms in this study are applied, oxygen level of the river will be improved which creates a conducive environment to aquatic biota. Besides, with an improved water quality in the river, the natural ecology of the river will be restored and economy of the community residing at the periphery of the LAR could be secured. Key recommendations from the overall study are nonpoint source pollution management prioritization, empowerment of environmental pollution policy, rehabilitation of existing sanitation infrastructure and improved water quality monitoring programs need to be the prime focus areas.

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List of Abbreviations

AA	Addis Ababa
AACA	Addis Ababa City Administration
AACRA	Addis Ababa City Roads Authority
AAEPA	Addis Ababa Environmental Protection Authority
AAWSA	Addis Ababa Water and Sewerage Authority
AGNPS	Agricultural Non-point Source Pollution Model
ANOVA	Analysis of Variance
APCS-MLR	Absolute Principal Component Score-Multiple Linear Regression
APHA	American Public Health Association
BAR	Big Akaki River
BCM	Billion Cubic Meter
BMP	Best Management Practices
BOD	Biochemical Oxygen Demand
CA	Cluster Analysis
CMB	Chemical Mass Balance
COD	Chemical Oxygen Demand
CPP	Charge Per Pollution
DAAD	Deutscher Akademischer Austauschdienst
DO	Dissolved Oxygen
EC	Electrical Conductivity
ECf	Export Coefficient

ECPC	The Ethiopian Cleaner Production Center
EEPA	Ethiopian Environmental Protection Authority
EPA	Environmental Protection Agency
EPHI	Ethiopian Public Health Institute
FA	Factor Analysis
FDRE	Federal Democratic Republic of Ethiopia
GFAAS	Graphite Furness Atomic Adsorption Spectroscopy
GIS	Geographical Information System
HCA	Hierarchical Cluster Analysis
HSPF	Hydrological Simulation Program—FORTRAN
KMO	Kaiser-Meyer-Olkin
LAR	Little Akaki River
LART	Little Akaki River Tributary
LULC	Land Use Land Cover
MoH	Ministry of Health
MoUDH	Ministry of Urban Development and Housing
MoWIE	Ministry of Water, Irrigation and Electricity
MPCA	Minnesota Pollution Control Agency
MRM	Multivariate Receptor Model
MSA	Multivariate Statistical Analysis
NO_2-N	Nitrite Nitrogen
NO_3-N	Nitrate Nitrogen
NPS	Nonpoint Sources

NSE	Nash-Sutcliff
PAH	Polycyclic Aromatic Hydrocarbon
PAST	Paleontological Statistics
PBIAS	Percent Bias
PC	Principal Component
PCA	Principal Components Analysis
PMF	Positive Matrix Factorization
PO_4-P	Phosphate Phosphorus
RMSE	Root Mean Square Error
RWQM	River Water Quality Model
SOD	Sediment Oxygen Demand
SWAT	Soil and Water Assessment Tool
SWMM	Storm Water Management Model
TDS	Total Dissolved Solids
TKN	Total Kjeldahl Nitrogen
TP	Total Phosphorus
UNEP	United Nations Environmental Program
USEPA	United States Environmental Protection Authority
WHO	World Health Organization
WQO	Water Quality Objective
WWTPE	Wastewater Treatment Plant Effluent

1. Introduction

1.1. Urban River Pollution and Pollution Management: Global Perspective

Water is the ecosystem's primary natural resource that plays key role in various socio-economic sectors, such as agriculture, energy, industry, water supply, forestry and fisheries (Effendi, 2016). However, despite the widespread availability of the water resources, the amount of fresh water available is quite small, which accounts only 0.6% of the total water volume. Today, with tens of millions relying on fresh water, the necessity of wise use of the resources is quite crucial (Herschy, 2009). Globally, the percentage rise in water usage has surpassed twice that of population growth in recent decades. As a result, many more regions across the world are experiencing water stress, with existing water usage and consumption rates becoming unsustainable (Cosgrove & Loucks, 2015). However, accepting the prime importance of the fresh water resources and upholding it for economic and developmental activities is the major challenge (Effendi, 2016).

Besides its limited availability, the fresh water resources are also the most endangered natural resource mainly due to the human interferences (Rizo-Decelis et al., 2017). Land use alteration (Ding et al., 2015; Tahiru et al., 2020), climate change (Hosseini et al., 2017), urbanization (Cerqueira et al., 2020; McGrane, 2016; Rashid et al., 2018) and improper use of the water resources (Chakkaravarthy & Balakrishnan, 2019) are the major drivers that cause water quality deterioration nowadays. Due to an increased pollution source, contamination of surface water resources specifically of urban areas are becoming severely degraded and threatens sustainability of urban systems. Recently, owing to its wider economic and social benefits, the study of river pollution and pollution management has become a major focus area globally (Barakat et al., 2016; Fan et al., 2010; Hajigholizadeh & Melesse, 2017; Ouyang et al., 2006; Tena et al., 2017; Uncumusaoğlu & Akkan, 2017).

Nowadays, urban areas specifically of developing countries are expanding rapidly, often informally and without proper water and wastewater management (Costa et al., 2016). The ever increasing pollution load, mainly associated with the booming economies, urbanization and high population growth, have triggered a huge bottleneck for the development in those countries (Reder et al., 2017). As a result, the amount of wastewater generated by industries, homes, agriculture, and urban land uses is increasing, causing significant water quality deterioration and altering the aquatic environment's life (Xu et al., 2014). This is partly due to an uncontrolled urban expansion and population growth that changes the urban demography initiating water consumption and ultimately increasing the wastewater generation rate (Mishra et al., 2017) and the pollution in the rivers have exceeded the pollution load carrying capacity posing serious environmental and public health problems (Zhang et al., 2012). Whereas wastewater is discharged directly into nearby rivers of most developing countries, the nature of the pollutants in the receiving river is alarmingly becoming more complex than ever (UNESCO, 2005).

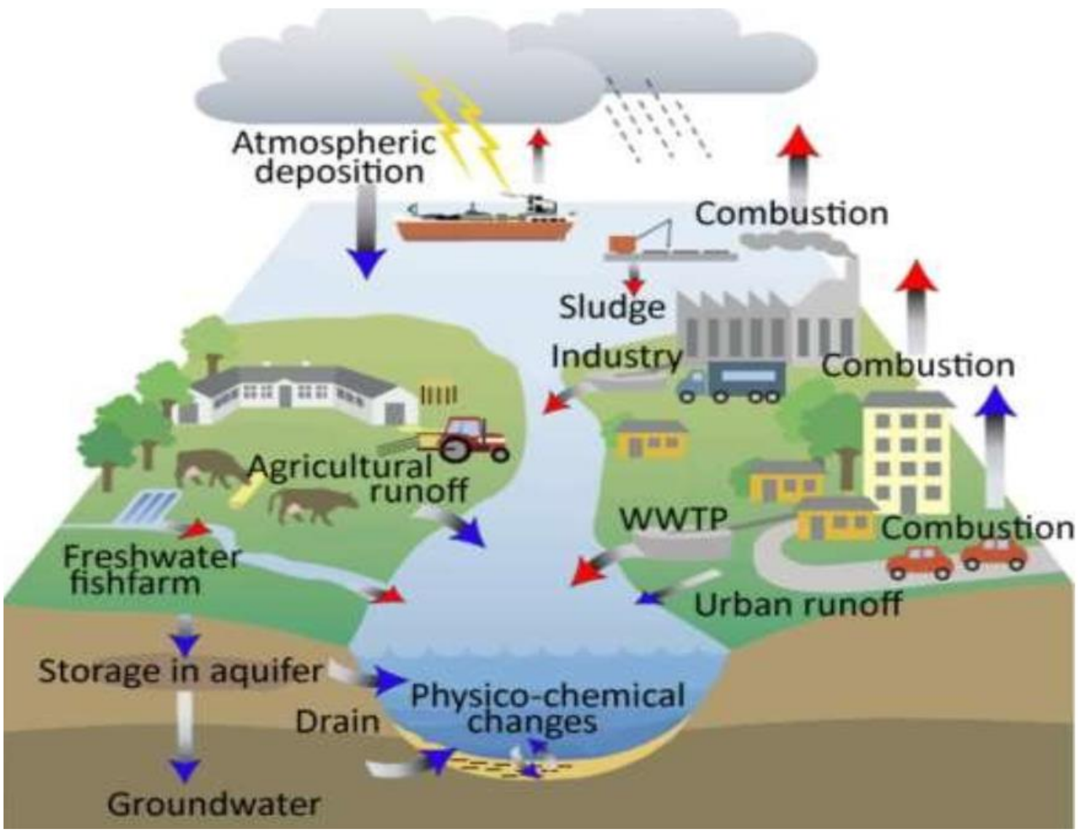

Figure 1.1: Surface water pollution sources (Source : www.lab.visual-logic.com)

Many developmental activities in developing countries are often hampered by the degradation of surface water quality, necessitating the establishment of sustainable water quality and quantity management systems (Slaughter et al., 2017). Despite considerable efforts, few of the management programs have become successful in controlling urban river pollution. Due to the increased pollution load in the rivers of urban areas, many countries have adopted various water quality management and pollution controlling mechanisms such as implementation of sewage charge as seen in China (Zhao et al., 2020) and construction of wastewater treatment plant (Corcoran et al., 2010). However, studies suggest that the application of integrated water resource management (IWRM) based on multidisciplinary and coordinated approach is recognized as an efficient strategy not only for managing water resources but also for designing a framework to mitigate impacts (Keupers & Willems, 2017). In this regard, Kar et al. (2016) identified three requirements for the development of water management initiatives: identification, estimation and assessment of pollutants.

In many developing countries, river pollution management has remained a challenge due to lack of monitored data and difficulty in pinpointing of particular pollution sources. Once sufficient data is available, essential methodologies and necessary pathways and roadmaps for the contaminant fate, transport and dynamics in a river can easily be determined (Rizo-Decelis et al., 2017). However, despite a multitude of water-related environmental concerns, advanced instruments, models, and algorithms are now days being used to assess the dynamics of river water contaminants, develop pollution management techniques, and frame mitigation options. In the absence of clear management plan, the dynamics of fast-changing pollutants characteristics, driven mainly by land-use activities, spatial and temporal wastewater characteristics variability and hydrologic behavior, have a serious impact on the quality of the receiving water (Kamel, 2008). However, accurate determination of the management process depends on reliable data where the temporal and spatial release information can easily be represented by water quality models (Rizo-Decelis et al., 2017; Zhang & Huang, 2017). Hence, due to seasonal and spatial variability, periodic monitoring and assessment are needed to effectively maintain the water quality of surface water sources and establish a sustainable management plan (Singh et al., 2005).

The water quality management strategy involves a complex set of inter-disciplinary decisions based on the changing water quality properties. While much emphasis has previously been placed on determining water quantity and allocation, poor water resource management has resulted in numerous water quality problems, particularly in developing countries. The water quality management should therefore be incorporated as an important component and its management option thus needs to focus on the possible consequences of pollutants (Loucks & Beek, 2017) and if not, the future water crises in those countries could primarily be due to water quality deterioration than water scarcity (Biswas & Tortajada, 2011). In river water quality management, although accurate determination of the spatial and temporal river pollution and predicting the fate and transport of pollutants is quite difficult, mathematical models now days are gaining advantages and they have become relatively effective and assisting in the decision making process of water quality management and pollution control programs (Gao & Li, 2014). Besides, the determination of the complex relation between the surface water pollution sources and associated water qualities can best be represented by water quality models (Raj et al., 2007). Furthermore, the mathematical models are also used in determination of the interaction between waste load and the water bodies where they gain popularity in recent days for pollution management (Kori et al., 2013). The efficiency of the models in water quality management is high when there is harmonized data with high frequency that represent both spatial and temporal variability (MacDonal, 2010; Benedini and Tsakiris, 2013). Recently, researchers globally have used water quality models such as SWAT (Debele et al., 2008), MIKE-11 (Kanda et al., 2017), WASP (Ajeagah et al., 2017) and QUAL2Kw (Mateus et al., 2018) in many water quality management programs. Many of the water quality models have been used in different application areas of urban river water quality management programs such as development of river pollution remediation options (Wang et al., 2013), determination of nutrient load and transport (Brito et al., 2019), nutrient control and eutrophication (Larico & Medina, 2019), waste load allocations (Tsegaye, 2019), water quality management and pollution load reduction programs (Cox, 2003) and optimization of water quality monitoring and pollution control techniques (Rizo-Decelis et al., 2017).

The concept of water quality modeling in water quality management and pollution control programs in data scarce areas is limited partly due to lack of monitored water quality and hydrometeorology data used to process the models. Besides, most of the water quality models are complex and uneconomical to process in an area with high financial and resource limitations. In this regard, an instream water quality model, QUAL2Kw, is often used in various water quality management applications particularly in data scarce areas due to its relatively less data requirement, simpler model structure, suitability to various watershed characteristics and simplicity of output interpretation (Holguin-Gonzalez et al., 2013; Reza et al., 2015; Vieira et al., 2013; Zhang et al., 2012). The impact of both point and nonpoint source pollution can be modeled and hence the model could be more effective if integrated with a watershed nonpoint source model such as PLOAD. The PLOAD has the capability of estimating the nonpoint sources load based on the characteristics of the land use and hydrological properties. Besides, the model is more suitable for integrating various targeted and working pollution reduction scenarios. Integrating such targeted scenarios has assisted and proved to be efficient in the development of many water quality management programs and was found effective in various watersheds globally (Kannel et al., 2007; Zhang et al., 2012; Zhang et al., 2014; Zhu et al., 2015). Developing such urban water quality management and pollution control programs using water quality models is based on the principle of linking the upstream pollution source with the downstream consequences. Thus, QUAL2Kw is an effective tool for validating pollutant load estimates into aquatic environments, establishing cause–effect relationships between pollution sources and water quality, and assessing the aquatic environment's response to various scenarios (Oliveira et al., 2012).

1.2. Urban River Pollution in Ethiopia: Management and Policy Implications

Ethiopia was once recognized as one of the least urbanized nations but now days among the fast urbanizing countries in the world, with the urban population accounting 27%-30% of the total population that is expected to triple in the coming two decades (Tesfaye, 2019). The fast economic development triggered the expansion of medium and large-scale industries and has realized the rapid urbanization in the country. Urbanization in developing countries like Ethiopia is often associated with the generation of a large quantity of solid and liquid waste that usually end up discharging in the nearby rivers and streams (Korkanç et al., 2017). In its ambition towards pollution management and control, the government of Ethiopia has ratified a wastewater management strategy in 2017 for the major cities of the country that could assist in urban environmental pollution management (MoWIE, 2017). However, the wastewater management strategy has put less emphasis on urban rivers and has failed to comprehensively integrate rivers as a major component of water environmental management.

In Ethiopia, the urban river pollution management system is influenced by a number of factors such as poor policy implementation framework that oversees the future water quality management directions and sustainable protection of it. Besides, lack of targeted strategic action plan for effective water quality management by prioritizing the core areas based on the understanding of social and economic circumstances becomes a bottleneck for efficient river water quality management in the country. Lack of attitude and commitment for timely monitoring and evaluation of the water quality programs in integrated approach has resulted in an increased pollution in the urban rivers of Ethiopia and coupled with uncontrolled release of various sources to the rivers has remained a challenge in the water quality management programs.

In Ethiopia, industrial wastewater is one of the most polluting sources of surface water resources (Aschale et al., 2016; Yilma et al., 2019). Despite the implementation of environmental pollution policy to regulate industrial wastewater and limit disposal to waterways, inspection and legal compliance are broadly missing. The inspection is often associated with on-the-spot constituent concentration assessment and reporting to the relevant government departments, while enforcing strict legal action is still a major gap. There were over 2000 large, medium and small-scale industries in the country's capital city decades ago, most of them founded near rivers (Gebre & Rooijen, 2009) that now increased to 2500 (Addis Ababa City Administration, 2017) and the future is still open for the establishment of medium to large scale industries. Most of the industries in the country do not have wastewater treatment facilities and they only discharge their untreated or partially treated wastewater to the nearby rivers in violation of the country's established standards (Ghebretekle, 2015).

Waste originating from households, open defecation and runoff from various land uses is contributing significant quantity of wastewater to the urban surface water resources in the country (Abegaz, 2005; Aschale et al., 2016). Besides, agricultural activities within the vicinity of the river banks contribute large quantity of waste load by discharging agricultural waste such as washouts of fertilizer, animal remains, and manure to the rivers (Mekonnen, 2007). With all the waste sources ending up in the nearby rivers that augments the waste load constantly, the water quality monitoring and management in the country remains prime challenge these days. This could partly be due to lack of coordinated and target action plan where the IWRM concept is neither been explicitly defined nor has the question of how it is to be implemented been fully addressed. This is mainly hindered by factors such as characters and intensity of the water problems (mainly water quality), lack of human resource and institutional capacity, cultural set-ups, and natural conditions.

At present, the Ethiopian government has taken good initiation on urban river water pollution management, nevertheless there is still much needed to be improved to fill the gaps. Proclamation of the Ethiopian Environmental Pollution Control under proclamation number 300/2002 stipulated on the federal Negarit Gazeta prohibits the release of pollutants into the environment, including water bodies (Negarit Gazeta, 2002). However, the actual ground fact in the country is in reverse where poor wastewater management is still the main cause for the pollution of the urban rivers in the country. On the other hand, the wastewater management strategy developed by MoWIE with a number of prime aims such as protection of the city's water resources and the environment, defining the urban wastewater management system and development of implementation strategies, and providing a roadmap that can sustainably use for effective management of water resources from pollution has aided the environmental pollution program in the country. Despite the development of the strategic plan, the implementation is quite slow, the focus given for the urban river pollution control was found insignificant and surface water quality management is unsuccessful.

1.3. Pollution Management in the Little Akaki River: An Overview

As a metropolitan and the only chartered city in the country, Addis Ababa is becoming the center of focus in an exemplary development of water and wastewater management program in Ethiopia. The city has three major rivers namely Kebena River, Big Akaki River (BAR) and LAR all originating at the foothills of Entoto Mountain and drains down to Aba Samuel Reservoir. The two sub-catchments in the Akaki River are the BAR and LAR both collectively forming one of the largest catchments in Awash Basin, which on the other hand is one of the twelve river basins of Ethiopia. Both LAR and BAR finally join at Aba Samuel Lake before flowing down to Awash River. The LAR flows from the North Western (predominantly agricultural and settlement in the upstream) to the Southern Addis Ababa before entering to Aba Samuel Reservoir covering a length of 32 km in the city. The river has many polluted tributaries such as Burayu, Gefersa, Leku, Qille, Gerbeja, Worenchiti, Melka Qorani, Kera, Mesalemya and Jaja (Jemo) streams. It crosses the densely populated urban center and industrial areas where the wastewater is discharged directly or with minimum treatment. Despite the fact that many studies revealed LAR is the most heavily polluted river in the country (Akele et al., 2016; Aschale et al., 2016; Gebre & Rooijen, 2009; Yilma et al., 2019), proper management and lack of pollution control strategy is not yet put into effect nor exclusively studied. Previous studies suggested that the disposal of domestic sewage without or minimal treatment, industrial effluent discharge and nonpoint sources pollution mainly from urban land uses are prevailing in the LAR. In one hand, though the government has set an industrial pollution regulation policy and has come in to effect in 2009 (FDRE Council of Ministers, 2009), the inspection and follow-up have remained trivial which make the LAR more polluted than ever. More than 90% of the industries in Addis Ababa discharge their wastewater directly to the river without treatment (Abdulshikur Mohammed, 2017) with an estimated total annual industrial waste released rate of 4.8 Mm^3 (Addis Ababa City Administration, 2017).

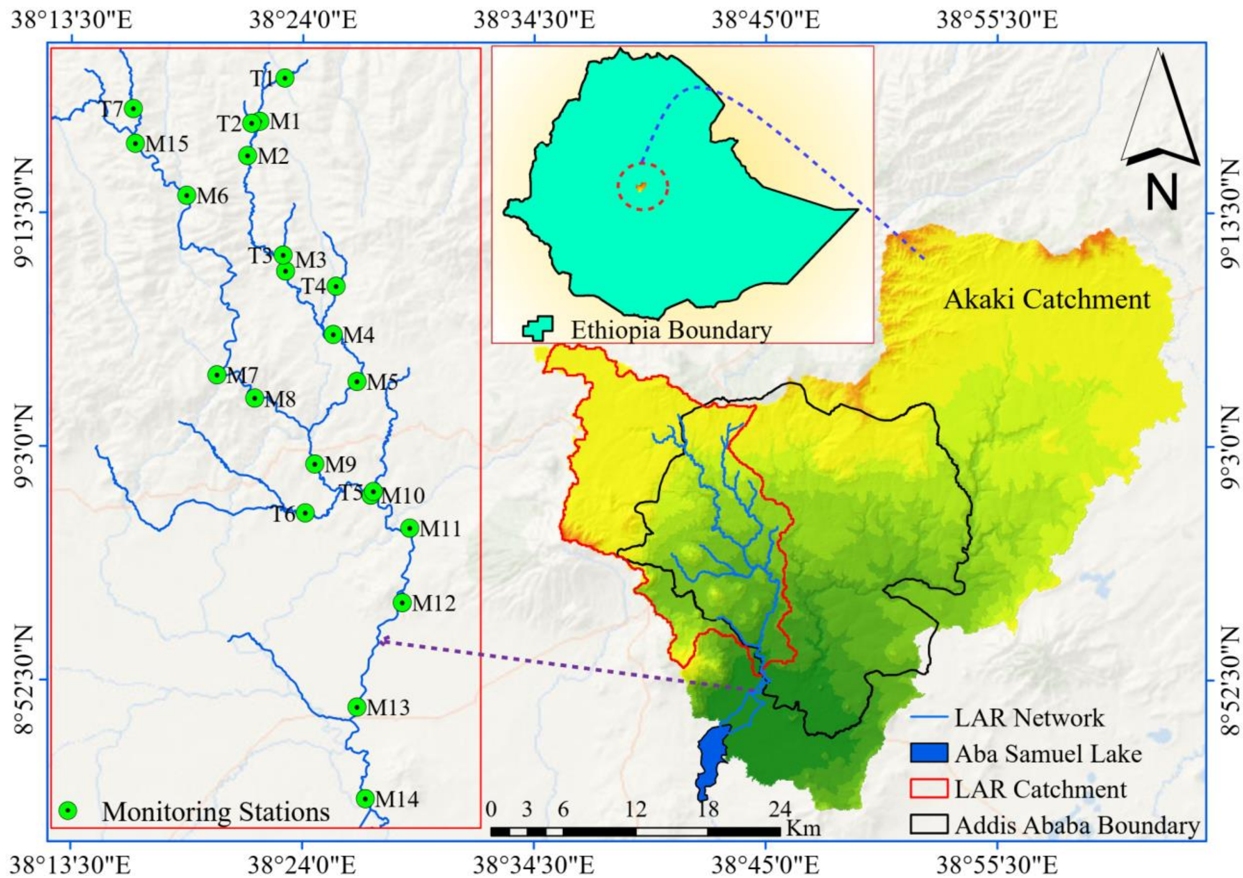

Figure 1.2: The Little Akaki River catchment and the water quality monitoring stations of this study

Lack of wastewater collection and treatment facilities in the city tends to affect the LAR to be overloaded by waste originating from point and diffuse sources partly due to poor wastewater management and lack of sanitation infrastructures. The poor river pollution management system is mainly emanated from two indispensable factors. First, the capital cost to cover such large waste-watershed for a country with multiple financial constraints has become a bottleneck. Second, the necessary technical skills that solve the river water quality management gap is not supported by up-to-date scientific understanding and hence is based on the personal judgement and experience. In support to this, Mekonnen (2007) revealed that lack of knowledge and technical capability on environmental impacts of uncontrolled waste from various sources coupled with relaxed environmental legislation has led to the high water environmental pollution in LAR.

Despite high population growth due to urbanization coupled with high economic development which triggers demand for sanitation infrastructures in Addis Ababa, majority of the city's populations use the onsite sanitation system. The government of Ethiopian has earlier planned to construct, rehabilitate and expand three wastewater treatment plants in Addis Ababa by dividing the city in three waste-watershed: Kaliti catchment, the Akaki catchment and the Eastern catchment (AAWSA, 2004). One of the three wastewater treatment plant was planned to be constructed that cover some part of LAR catchment and the construction of such large-scale treatment plant could largely reduce the uncontrolled waste release to the rivers by creating a more centralized wastewater treatment system and hence reducing the waste load entering to the LAR. With the construction and rehabilitation of the newly planned wastewater treatment plants, the city's wastewater management system will be greatly improved and the offline sanitation system will be adopted that could largely reduce pollution load in the LAR. However, the newly planned project could not fully cover the larger part of the LAR catchment especially in the middle segment where large pollution load originates affecting the river environment.

With respect to the urban river pollution management, control, and mitigation in Addis Ababa, the study conducted by Addis Ababa City Administration (2017) proposed three major mitigation components. First, due to the high impact of flood on the rivers that washes off the pollutants from urban land uses through drainage systems, engineering structures such as revetment, parapet or river wall need to be in place so as to control the flood and hence the pollutants entry. Secondly, development of environmental management system through control of solid and liquid waste such as implementation of strict policies on the use of both solid waste and wastewater. Lastly, the waste load in rivers is often related with the type of settlement with in the vicinity of the river. Despite suggesting the mitigation approaches, detailed study of the pollutants dynamics and the pollution load carried by the LAR is not explicitly estimated. Moreover, pollution hotspots are not identified and river water quality constituents are not effectively characterized making the water quality management decision-making process unsustainable.

1.4. Statement of the Problem

Despite the huge potential of water resource which can have significant impact on the country's economy, the water quality of many of the surface water resources in Ethiopia is yet unsolved and the water quality management and pollution control has remained unsuccessful. In addition, owing to the release of unregulated waste from numerous sources, Ethiopia's urban rivers are now becoming a pollution hotspot. Among these, LAR is the most heavily polluted and threatened river, more than any other urban rivers in the country, due to the release of point sources such as wastewater treatment plant effluents, industrial wastewater, untreated domestic waste, and nonpoint sources mainly from urban runoff, agricultural land and animal breeding, washouts from urban gardens and ground water intrusion during critical period (Abegaz, 2005; Aschale et al., 2016; Beyene et al., 2009; Gebre & Rooijen, 2009). Previous pollution management strategies have created unsustainable wastewater management system which causes serious water environmental degradation in the city, leaving aquatic life completely at risk (Feven Solomon, 2007). The city's daily wastewater production rate has now reached about 400,000 m^3, with more than 92 percent of it ending up in drains and surrounding rivers (Yilma et al., 2019). This is rising at an unprecedented rate, posing a threat to the city's surface water sources long-term management.

Despite the ongoing and unwavering efforts to monitor the impacts of point source load on rivers in Addis Ababa in general and LAR in particular, little has been done to quantify, identify and manage nonpoint pollution sources and devise its controlling mechanism. Although the Ethiopian government has initiated a river side protection program through river buffer zoning and drafted a document in 2016 for the rivers in Addis Ababa (MoUDH, 2016), the implementation is not yet fully realized. This has resulted in excess transport of pollution from various land uses to the nearby rivers and augmented the pollution load in the LAR. The waste load from the nonpoint sources, mainly due to the contribution of various land uses have never been quantified in the study area primarily due to data limitation and technical knowledge incapability.

The main challenges of pollution management in countries like Ethiopia is not only in estimating the waste load from various pollution sources but also in determining the clear distinction between point and diffuse sources (Ongley et al., 2010), thus complicating the impacts of the pollutants to the river. The experience from studies on other watersheds suggest that the impact of nonpoint source on surface water quality is significant and if due attention is not given, the aquatic environment could easily be endangered (Amaya et al., 2012; Brezonik & Stadelmann, 2002; Yuhong et al., 2010). In this regard, poor urban land use management and improper waste handling are contributing for the high diffuse source pollutants load in the catchment. The poor nonpoint source pollution management in LAR arises from two indispensable factors. First, lack of scientific study that explicitly investigate the prime causes of the waste from diffuse sources is making the practitioners to underestimate the impact of the diffuse source load. Second, a general attitude towards nonpoint sources relative to the point source load is insignificant, despite its high impact. This could be due to the fact that point sources can be addressed more easily while the nonpoint sources lead to the problem of not existing or insufficient sanitation structures demand much more effort for being established. The implementation of best waste management practices (from point and diffuse sources) supported by verified scientific researches could solve the possible impacts of the nonpoint sources on surface water resources (Jamwal et al., 2011; Schaffner et al., 2009).

Despite few initiations to study the on-time pollution status determination in the LAR by analyzing the physical, chemical, bacteriological, and heavy metals concentration, none of the studies have so far explicitly determined the quantity of each pollution sources contribution for individual constituent making the water quality management approach unsustainable. The decisions on LAR water quality management and pollution control are often based on the snap-monitoring campaigns that end up correlating the cause-effect in pollution management. However, accurate determination of the pollutants load originating from point and nonpoint sources is often achieved by integrating the event-based pollutant concentration and watershed and hydrological models which has remained the major gap in the study area is the main reason for the development of incomplete and unsustainable water quality management and pollution control system in LAR.

Water quality management and pollution reduction approaches development in LAR often lacks the best understanding of the river system. Process-based modeling in this regard are considered as a better option to solve water environmental problems such as river pollution management (Bui et al., 2019; Zhang et al., 2012; Zhu et al., 2015). In this regard, the water quality models have gained advantages recently in water quality management for two basic reasons. First, they can give a relative estimate on rivers response to various waste releases. Second, the models can be used as a tool to select a better approach among available pollution management options. At the very least, the water quality models can be used for environmental control, planning, and the creation of insights into the characteristics of river pollutants. However, the application of water quality models in Ethiopia is not familiar and decision making for the environmental problems is often based on simple analysis, personal judgement and experience. Based on the complexity of the chemical characteristics of the LAR constituents, model-based management approach could play paramount benefit in developing best pollution management alternatives.

Generally, there is no single, accurate, and magic bullet approach that solves and address the numerous water quality problems (Biswas & Tortajada, 2011). However, in light of the above facts and figures, the LAR water quality management and pollution control system need to be improved in order for the river to be used for the intended purposes. Comprehensive study on the spatio-temporal constituent variability, dynamics and transport, detailed determination of multi-sourced pollutants loads in the catchment integrated with water quality modeling could assist in solving such complex water environmental problems in the LAR catchment.

1.5. Objectives of the Study

1.5.1. Main Objective

The main objective of the research is to develop an easy-to-use and working better water quality management and pollution control strategy in the LAR by monitoring and determining the spatio-temporal water quality constituents' dynamics and water quality modelling.

1.5.2. Specific objectives

- To assess the spatio-temporal dynamics, source apportionment and quantification of the pollution source contribution of LAR constituents based on conjunctive application of multivariate statistical techniques and multivariate receptor model.
- To quantify pollutants load originating from point and nonpoint pollution sources using the integral application of chemical mass balance (CMB) and watershed nonpoint sources model, PLOAD.
- To simulate water quality constituents in LAR using modified stream water quality model, QUAL2Kw for better water quality management.

- To develop and evaluate various source-based targeted pollution reduction scenarios in QUAL2Kw and ultimately select an optimum water quality management and pollution load reduction options in the LAR.

1.6. Research questions

This study is specifically intended to explore approaches that can help for the better management of Little Akaki River pollution. More specifically, it is intended to answer the following specific questions.

- How is water quality in the Little Akaki River characterized spatially and temporally and what is the contribution of each pollution source for individual constituents in the river? What are the various environmental factors that affect the pollution in the river?
- How efficient is integral application of chemical mass balance and watershed models in quantifying diffuse pollution load in data scarce urban catchments?
- How is the temporal and spatial water quality constituents transport represented by an instream water quality model in LAR? How the Little Akaki River responds for the changing environmental factors?
- Which in-steam and pollution source-based targeted individual or integrated scenario is feasible option for better water quality management and pollution load reduction in LAR?

1.7. Significance of the study

This study is specifically intended to explore approaches that can help for the better pollution management of Little Akaki River. It explicitly investigated the various physico-chemical, nutrient and heavy metal pollutants dynamics, fate and transport in the river. Besides, it identified the various environmental and anthropogenic factors that triggered the pollution in the river. Despite the unwavering effort of the government in alleviating the pollution problems, the study identified the main management gaps and system bottlenecks that hinder effective pollution management in the LAR watershed. The existing state of the city's water resources in general and the LAR pollution management in particular was explored in detail and better management directions forwarded. Moreover, despite the high desire of the city administration and the government (EEPA) to control the pollution in the river, the efficacy of the management system was explicitly evaluated on catchment perspective. Despite few success stories in achieving better pollution management in the urban rivers in the country elsewhere, the overall management was found to have failed to achieve the intended goal in the LAR. This has created a non-conducive environment for the communities residing with the LAR's vicinity and the river peripheries.

This research evaluated the complex relationships between the LAR water quality and associated environmental factors. Much has been assessed to investigate the response of the river for the changing pollution types, loads and land uses. In doing so, it highlighted the need to find new methods and techniques for efficient management of the pollution in the river and search for approaches of compliance with nature. The mismatch between the existing LAR water pollution management system and fast water quality degradation in the river was examined so that the management policy framework could be adjusted in a way that it would holistically respond to sustainable LAR catchment pollution management.

Theoretically, the study investigated an overview of pollution management alternatives specifically diffuse sources in data scarce catchments. It explored the major sources, dynamics of pollutants and driving factors for the transport of the contaminants in the urban land use dominated and environmentally complex watershed. The research thus would give an insight in to the pollution management processes of poor urban catchments and forwarded the ways that change the existing theoretical works in developing countries.

Empirically, the study established a baseline empirical evidence of pollution load quantification and management in the research area based on the explicit study in the watershed creating opportunities for future researches in the area and elsewhere. Besides, new and applicable research questions were developed and areas of possible future research areas were identified.

Methodologically, the study used process-based yet simple and economical tools to assess the quantity and quality of pollutants in the LAR. Besides, the output from nonpoint sources was integrated in the water quality models to better understand the transport and fate of pollutants in the river to better manage it. This integration of models and incorporation of nonpoint sources in the pollution management process in developing countries is often missing in many of the previous studies making the management system ineffective. This study has thus familiarized a user-friendly analytic tool that enabled local policy makers to holistically examine the system.

furthermore, it introduced a better approach for the decision makers to design an integrated response to cover all dimensions of the system.

Summarizing, scientific communities would be benefited from this research study because it in-depth explored the peculiarities of urban river pollution and better management options in a developing African nation. It will also largely assist and serve as a basis for policy makers and practitioners who wish to analyze pollutant processes, transport and fate in the LAR catchment in a different perspective. Moreover, it also indicated prospective research areas for future researchers and scientists.

1.8. Limitations of the study

The study suffered from inherent limitations of monitored water quality and hydrologic data at required temporal and spatial scale. This has led to the change in methodological approaches which was conducted in limited time and resource. Some of the techniques were dependent on the researcher's decision that may later hamper some of the qualities of the conclusions and generalizations from the research output. Regarding the data reliability, some of the water quality and quantity data from industries nearby the LAR and in the catchment were confidential and hence depended on third party and informal sources. Moreover, due to congested nature of the city's roads for traffic, delay in delivery of sample water to the laboratory could also be one of the major constraints for this research. In addition, inaccessibility of roads for hydraulic data collection that in part was due to predominance of informal settlements has resulted in collection of a smaller number of data than initially expected.

1.9. Layout of the Thesis

All the chapters in this thesis are structured in a way to explain the outcomes of the research specific objectives under study. **Chapter 1** discusses the general introduction and state-of-the-art river pollution in global perspective and water quality management in urban rivers of specifically developing countries. It explicitly discusses state-of-the-art river pollution management and clarifies and criticizes the major issues related with pollution management approaches in Ethiopia and the study area (LAR) such as policy, management strategy, and implementation approaches, justifications and problem rationalization, and summarizes the research specific and general objectives. Chapters 2, 3, and 4 are research outcomes of all specific objectives and are based on the three articles published on peer reviewed and reputable international journals.

Chapter 2 explains the main findings of the assessment of spatio-temporal variation of water quality constituents in the study area which tried to evaluate the water quality constituent variability based on statistical interpretation. Besides, quantification of pollution sources contribution and composition on individual constituents by integrating the multivariate statistical techniques with multivariate receptor models based on the predefined source profile in factor analysis was discussed in detail. Moreover, spatial clustering and pollution hotspots identification in the study area is discussed in detail. The chapter is based on the following publication;

Angello, Z. A., Tränckner, J., & Behailu, B. M. (2021). Spatio-temporal evaluation and quantification of pollutant source contribution in Little Akaki River, Ethiopia: conjunctive application of Factor Analysis and multivariate receptor model. Polish Journal of Environmental Studies, 30(1), 23-34. https://doi.org/10.15244/pjoes/119098.

Chapter 3 exclusively presents the quantification of pollutants load contributed by point and nonpoint pollution sources based on the integral application of watershed nonpoint sources model (PLOAD) through export coefficient method and chemical mass balance analysis. It mainly investigates and quantifies the diffuse sources load contributed by various land uses. Besides, local pollutants export coefficient was developed for selected water quality constituents in the study area. This chapter consists of the following publication;

Angello, Z. A., Behailu, B. M., & Tränckner, J. (2020). Integral Application of Chemical Mass Balance and Watershed Model to Estimate Point and Nonpoint Source Pollutant Loads in Data-Scarce Little Akaki River, Ethiopia. Sustainability, 12(17), 7084. https://doi.org/10.3390/su12177084

Chapter 4 explicitly presents the evaluation of various water quality management and pollution reduction options based on a well-simulated water quality model. Based on the pre-developed targeted pollution reduction approaches, QUAL2Kw was used to evaluate and ultimately select the optimum pollution reduction options. This chapter consists the following publication;

Angello, Z. A., Behailu, B. M., & Tränckner, J. (2021). Selection of Optimum Pollution Load Reduction and Water Quality Improvement Approaches Using Scenario Based Water Quality

Modeling in Little Akaki River, Ethiopia. Water, 13(5), 584. https://doi.org/10.3390/w13050584.

Finally, **chapter 5** discusses about the general synthesis of the study (discussion based on the major findings), recommendation and prospective (future) research directions.

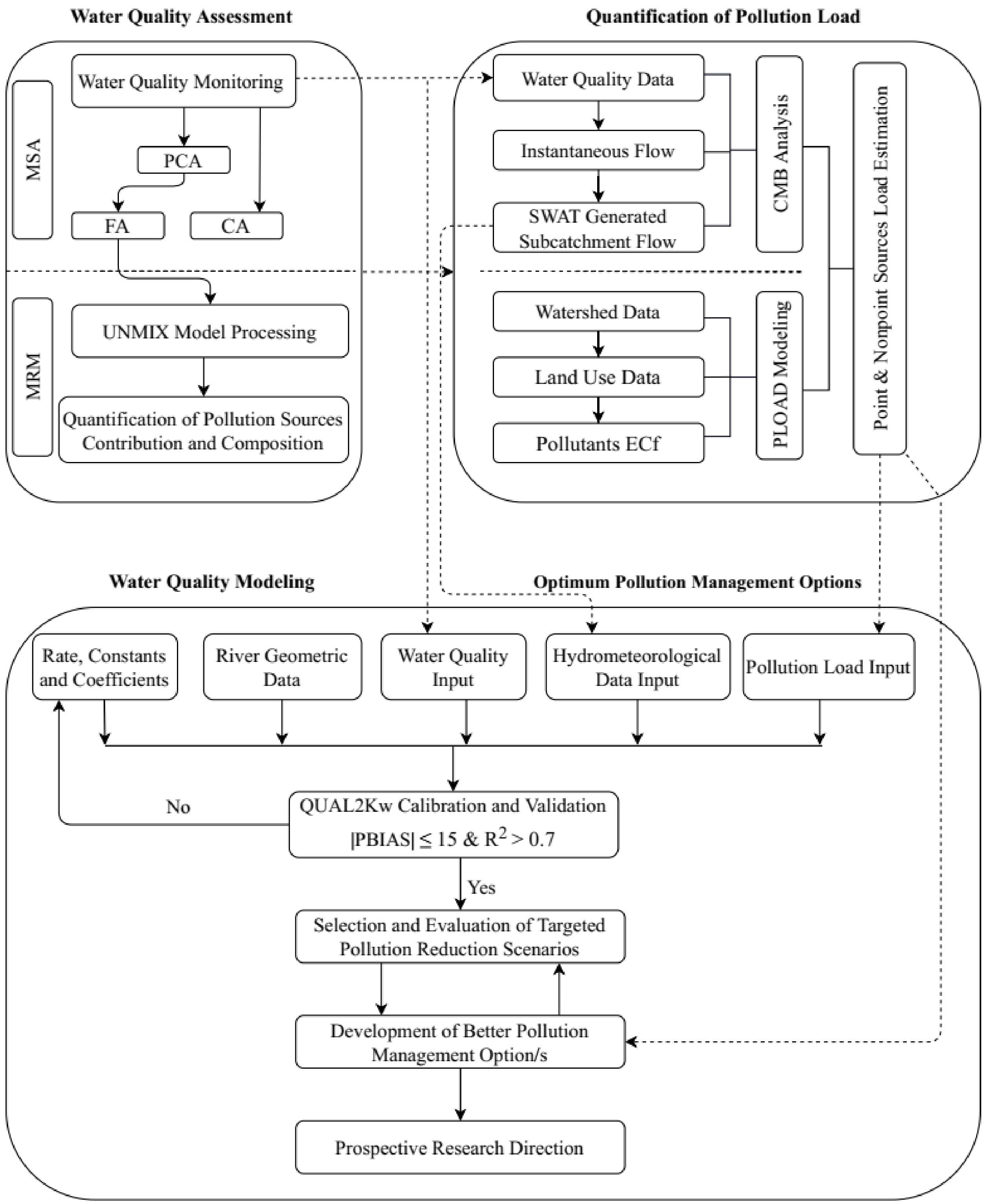

Figure 1.3: Work flow diagram and structure of the thesis

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2. Pollutants Characterization and Pollution Source Apportionment

This chapter exclusively discussed the physico-chemical characteristics of the LAR and its catchment based on continuously monitored water quality samples. Besides, it explored the contribution and composition of the various pollution sources on individual water quality constituents based on the identified source profile using multivariate receptor model.

This chapter is based on the following journal article:

Angello, Z. A., **Tränckner, J.**, & **Behailu, B. M.** (2021). Spatio-temporal evaluation and quantification of pollutant source contribution in Little Akaki River, Ethiopia: conjunctive application of Factor Analysis and multivariate receptor model. Polish Journal of Environmental Studies, 30(1), 23-34. DOI: https://doi.org/10.15244/pjoes/119098

Abstract: Little Akaki River (LAR) is among the heavily polluted urban rivers in Ethiopia. A bimonthly physico-chemical and heavy metals water quality analysis was conducted aimed at assessing the spatio-temporal characteristics and quantifying sources contributing to the pollution during dry and wet season at 22 monitoring stations. Accordingly, laboratory analysis results indicated that most of the constituents deviated from the national and international guideline limits and the river is critically polluted at the middle and downstream segments. Factor Analysis (FA) was used to qualitatively determine the possible sources contributing to the pollution of LAR where three factors are identified that determine the pollution level during wet and dry season explaining 79.26 % and 79.47 % of the total variance respectively. Agricultural and urban runoff (nonpoint pollution sources), industrial and domestic waste were the three dominant factors that contribute to pollution in LAR. On the other hand, pollution sources of heavy metals in LAR were mostly dominated by industrial release whereas urban washouts from garages and automobile oil spills were other possible sources. Cluster Analysis spatially grouped all 22 monitoring stations into four and three clusters during the dry and wet season respectively. USEPA's receptor model, UNMIX, was used to quantify the composition and contribution of LAR constituents. The model predicted quite well with a minimum Signal to Noise ratio (S/N) of 2.71 and 2.16>2 and R^2 of 0.91 and 0.88>0.8 for the dry and wet season respectively. The UNMIX model effectively predicted the water quality source composition with a model predicted to measured ratio (P:M) of 1.04 and 1.16 during the dry season and wet season with an average percentage error of 1.38 % and 17.13 % respectively. LAR water quality management approach incorporating all the three pollution sources could be feasible.

Keywords: LAR, spatio-temporal assessment, FA, UNMIX, source composition

2.1. Introduction

Urban rivers of developing countries are often considered as carriers of toxic heavy metals, nutrients, organic and inorganic pollutants, and are becoming a threat to community wellbeing (Su et al., 2011). The rivers are serving as a hotspot where waste from various sources are dumped (Kausar et al., 2019). Due to the complex and dynamic characteristics of waste released to the rivers, it is becoming extremely difficult to accurately characterize the water quality constituents of these rivers thereby making water quality management more challenging. Hence assessment of spatio-temporal variation of a river water quality is becoming vital in characterizing the different constituents of the river water through routine water quality monitoring programs (Singh et al., 2005; Korkanç et al., 2017).

The spatio-temporal assessment of water quality based on a short duration monitoring campaign will give an erratic result which is difficult to draw concrete water quality management plan (Cid et al., 2011). Nowadays, multivariate statistical techniques (MSTs) such as Factor (FA) and cluster analysis (CA) are becoming a way to effectively evaluate this spatio-temporal variability in a watershed identification of the possible pollution sources (Huang et al., 2010) where they are applied and found to be successful in evaluating river water quality in South America (Cid et al., 2011), Asia (Huang et al., 2010; Wang et al., 2012), North America (Hajigholizadeh & Melesse, 2017), Africa (Barakat et al., 2016; Kilonzo et al., 2014), and Europe (Uncumusaoğlu & Akkan, 2017). Though MSTs, specifically FA, is effective in the qualitative estimation of the type of pollution sources, they have weaknesses in quantifying sources contributing to the pollution of a water environmental constituents (Gulgundi & Shetty, 2016). Hence, multivariate receptor models (MRMs) have the tendency to fill the gap and they become a tool that can effectively quantify the sources contributing to river pollution. Studies conducted using MRMs such as Absolute Principal Component Score-Multiple Linear Regression (APCS-MLR) (Gulgundi &

Shetty, 2016), UNMIX (Sun, 2015), and Positive Matrix Factorization (PMF) (Huang et al., 2018) have proved effective in estimating the contribution of each source to individual constituents.

In Ethiopia, urban river pollution is often associated with the high and unplanned expansion of cities, uncontrolled agricultural and urban runoff, and improper domestic and industrial waste release. Moreover, waste generated from different sources in urban areas is released to the nearby rivers without or minimal treatment making the rivers a primary pollution hotspot (Yohannes & Elias, 2017). Due to the lack of continuously monitored water quality data, few studies have been conducted on Little Akaki River (LAR) water quality. The study conducted by Abegaz (2005) with two sampling campaigns showed that the distribution of pollutants and heavy metals in LAR deviated from the Ethiopian and international guideline standards. In addition, based on the land use type of the study area, Yilma et al. (2019) classified the LAR in three pollution zones (low, medium, and high). Therefore, it is time to carefully look at the main causes that control the spatial and temporal water quality dynamics in LAR. Hence, the objectives of this study were; evaluating the LAR physico-chemical and heavy metal water quality characteristics during dry and wet seasons; determining the possible pollution sources contributing to the LAR pollution and classifying the pollution based on their spatial similarity; quantifying the contribution and composition of the identified pollution source using USEPA's UNMIX model

2.2. Materials and Methods

2.2.1. The Study Area

LAR is located in Addis Ababa, the capital and the largest city of Ethiopia. Geographically, the study area is bounded between 9.06°N and 38.69°E to 8.89°N and 38.75°E (Figure 2.1). The climate of the area is mostly warm temperate to humid and subhumid with an altitude ranging from 2200 m to 2600 m above sea level. The main dry season in the study area ranges from October to May whereas the wet season ranges from June to September. The rainy season in the study area is characterized by rainfall of short duration with an annual depth of 1400 mm. There are three major rivers in the city (Kebena, LAR and Tiliku Akaki River) all originating near the foothills of Entoto. LAR is one of the heavily polluted rivers in the country (Aschale et al., 2016; Beyene et al., 2009) due to the release of industrial, agricultural, and domestic waste into the river with no or minimal treatment.

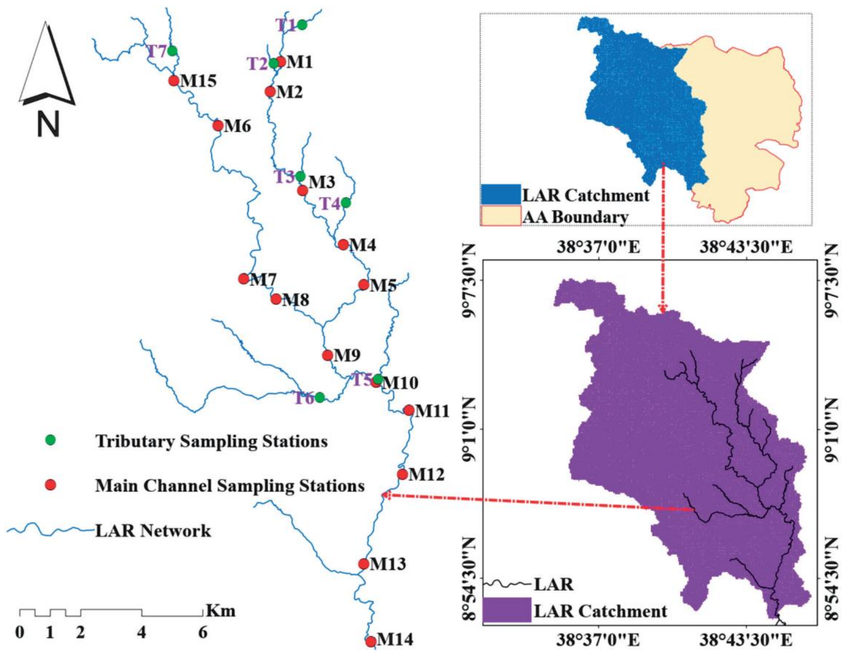

Figure 2.1: The study area and monitoring stations

Nearly 52% of the country's large-scale industries are located in Addis Ababa where most of them discharge their wastewater directly to the river (Beyene et al., 2009). Moreover, the river is highly impacted by the release of household and agricultural waste. On the other hand, the study conducted by Ghebretekle (2015) showed there are a total of six large-scale tanning facilities near LAR only that directly discharge their industrial waste to the river. LAR receives a lot of waste from households, tanneries, shoe factories, detergent and oil industries, abattoir, marble factories, hospitals and schools, soft drink industries and brewery factories. This study generally comprises upstream from the outlet of Gefersa dam and downstream to Aba Samuel Lake inlet which stretches for about 43 km.

2.2.2. Sampling

Water sample in LAR was collected bi-monthly for physico-chemical and heavy metal constituents from April 2018 to March 2019 during dry and wet seasons. The sample collection for the wet season was event-based where samples were collected following the rainfall. A total of 22 monitoring stations were selected (Figure 2.1); 15 on the main river channel and 7 from tributaries (LART). The sample site selection was purposive based on the factors such as availability of point and nonpoint sources, land use type, nature of anthropogenic influences, accessibility, level of disturbance and type of settlement. Sample collection, handling, preservation, and treatment were according to (APHA, 1999). A 1.5 L PE bottle was used to collect water for physico-chemical analysis. The bottles were washed by deionized water 24 hours prior to sample collection and rinsed three times by sample water during collection. Once collected, the samples were preserved, put in the cooler box (Mobicool v30 AC/DC, Germany) and transported immediately to the laboratory for analysis.

2.2.3. Analytical Methods

The collected samples were analyzed for 11 physico-chemical parameters, namely, pH, Electrical Conductivity (EC), Total Dissolved Solids (TDS), Water Temperature (T), Dissolved Oxygen (DO), 5-days Biochemical Oxygen Demand (BOD5), Chemical Oxygen Demand (COD), Total Kjeldahl Nitrogen (TKN), Nitrate (NO_3-N), Nitrite (NO_2-N), Orthophosphate (PO_4-P) and heavy metals such as Manganese (Mn), Chromium (Cr), Lead (Pb), Zinc (Zn), Copper (Cu), and Cadmium (Cd). All the analytical procedures (Table 2.1) for the determination of physicochemical and heavy metals constituents of the LAR are according to (APHA, 1999; HACH, 2007).

Table 2.1: Analyzed physico-chemical and heavy metal parameters and analytical methods

No.	Parameter	Measurement Location	Analytical Method	Instrument
1	pH	On site	Digital Multi-parameter analyzer	HQ40d, USA
2	DO	On site	Digital Multi-parameter analyzer	HQ40d, USA
3	EC	On site	Digital Multi-parameter analyzer	HQ40d, USA
4	TDS	On site	Digital Multi-parameter analyzer	HQ40d, USA
5	Temperature	On site	Digital Multi-parameter analyzer	HQ40d, USA
6	BOD	Laboratory	Modified Winkler	
7	COD	Laboratory	Open Reflex	
8	Orthophosphate	Laboratory	Spectrophotometer	DR2800 (HACH)
9	TKN	Laboratory	Kjeldahl	Kjeldahl
10	Nitrate	Laboratory	Spectrophotometer	India
11	Nitrite	Laboratory	Spectrophotometer	DR2800 (HACH)
12	Heavy Metals	Laboratory	GFAAS	

All units in mg/L except pH (pH unit), Temp (°C), EC (µS/cm)

2.2.4. Statistical Analysis

Data treatment needs to be performed for water quality constituents with non-detects, outliers, retaining, and deletion, and exclusion of monitored water quality data prior to the implementation of MSTs during water quality interpretation. For effective interpretation of water quality variables by MSTs such as FA, redundant parameters need also be excluded so that the information explained by PCA/FA will not be distorted (Olsen et al., 2012). In addition, data normalization and standardization are also prerequisites during MST analysis so as to control bias during evaluation (Wang et al., 2013). Accordingly, In LAR, the raw water quality data were tested for normality and checked for outliers. The variables were further Z-scale standardized to have standard deviation of one and a mean of zero. With Z-standardization, some parameters with different measurement units will have similar weight to others and the impact of parameters with unjustified influence will be avoided (Özdemir, 2016; Singh et al., 2004). Besides, a parametric test, one-way ANOVA, was performed on raw data to check the availability of a significant difference between the sample means.

In LAR, FA was used to qualitatively determine the type of source contributing for LAR pollution where data quality plays a vital role while analyzing the water quality constituents. Hence, prior to FA, the suitability of the collected samples for FA was checked using the parameters suitability test: Kaiser-Meyer-Olkin (KMO), a measure of sampling adequacy and Bartlett's test of sphericity that on the other hand examines whether the available data are independent or not. A KMO value close to unity would generally mean the correlations are compacted and hence the sampling and the samples are highly suitable for FA whereas smaller values would generally mean that the variables in consideration have very little in common (Wang et al., 2013). Though KMO greater than 0.5 is considered adequate (Ogwueleka, 2015; A. Uncumusaoğlu & Mutlu, 2019), higher values are often recommended. On the other hand, CA was used to group all the monitoring station according to their spatial similarity were Hierarchical Cluster Analysis (HCA) was used to classify the monitoring stations based on the similarity between constituents through Ward's method. The statistical analysis in this study was performed integrally by R (v3.5.3), PAST, and Microsoft Excel (2016).

2.2.5. Multivariate Receptor Model (UNMIX) and Its Application in LAR

Although MSTs are nowadays gaining advantages as they can predict the type of source contributing to river pollution, quantifying constituent contribution is often difficult (Gulgundi & Shetty, 2016). MRMs, developed based on the mathematical procedure in consideration of sources contribution of constituents, have now become successful to fill this gap. Many studies were conducted by integrating MRMs such as PMF and UNMIX (Huang et al., 2018), APCS-MLR and PMF (Gholizadeh et al., 2016; Salim et al., 2019) or used individual model such as UNMIX (Sun, 2015), APCS-MLR (Gulgundi & Shetty, 2016; Juahir et al., 2011) to estimate the contribution of a certain pollution source to each individual constituent based on the identified source profile. EPA's UNMIX model has become popular MRM in recent days to review environmental sample data such as air, water quality and sediment analysis (Sun, 2017). The UNMIX model primarily assumes the constituent concentration has a linear relationship with a certain source of unknown number and contribution where both remain positive (Norris et al., 2007). Whereas the source contribution explains the share of each source for individual constituents, the source type is determined based on the constituents' source profile (Sun, 2017).

2.3. Results and Discussion

2.3.1. Evaluation of Spatio-Temporal Variation of Water Quality in LAR

Descriptive statistics for physico-chemical characteristics of LAR for the dry season is shown on Table 2.2. A physical water quality parameter, pH, in LAR during the wet season has shown few irregularities across the monitoring stations. The monitored pH on LAR ranged from 7.1-7.97 were the minimum pH of 7.1 was recorded at two of the tributaries; T1 and T4, where both receive domestic waste including raw sewage and feces from residential areas. Though deviation of pH from the recommended standard limit could have impact on the aquatic environment (Korkanç et al., 2017), the observed pH in LAR was within the national standard (EEPA, 2003). On the other hand, maximum pH was recorded at M13 with 7.97 where the effluent released from the wastewater treatment plant upstream of the monitoring station could be a contributing factor for the rise in pH. Unlike the wet season, the pH recorded during the dry season showed deviation from the guideline standard at M3. The lower pH at station M3 (5.7) could be due to the presence of acidic waste released from the most polluted segment of the river originating from densely populated urban commercial center, Merkato.

The DO concentration in river is the major controlling factor for the existence of aquatic life (Gurjar & Tare, 2019). In LAR, DO concentration rises during the wet season due to increased flow and physical aeration by the river wave action. The DO trend in the LAR monitoring stations during the wet season was found that the concentration in the upstream segment of the river had few deviations from the standard guideline relative to the middle and downstream catchment. This could primarily be due to the availability of fewer industries and relatively less anthropogenic influence. On the other hand, LAR tributaries, mostly in the middle catchment, have shown high DO deterioration where 0.79 mg/L is recorded at T3, the most polluted tributary of the LAR. The higher DO concentration was recorded at M15 (7.07) and M7 (7.06) mg/L respectively. Both stations are located at the upstream and less disturbed section of the LAR catchment, the later found at a closer range downstream from a waterfall that initiate the re-oxygenation. The average DO concentration in LAR tributaries during the wet season was nearly 3.88 mg/L whereas in the main channel is about 5.39 mg/L. The overall mean DO in the LAR during the rainy season was 4.91 mg/L. Though DO is considered very essential in sustaining aquatic life, its concentration in LAR revealed that the river is severely polluted so that it is not suitable for any purpose during the dry season. The middle catchment of LAR is highly impacted by this low flow and hence had high DO deterioration. Almost all of the stations didn't meet either the Ethiopian or international standards for aquatic life. The study conducted on similar area by Yilma et al. (2019) also showed that nearly 89% of the monitored stations analyzed on LAR during the dry season had DO concentration less than 4 mg/L whereas the current assessment showed 82% indicating the river is severely polluted.

The EC, a proxy measure of salt concentration, was found very high in LAR with a mean value of 660.4 (±282.25) μS/cm recorded during the wet season indicating the severity of the river pollution. The TDS in the river, on the other hand, was found in high amount with a mean value of 325.3 (±141.48) mg/L. The high standard deviation in both parameters could imply that the characteristics of both constituents vary spatially (Yilma et al., 2019) and seasonally (Barakat et al., 2016). Both EC and TDS were recorded highest in the LAR tributaries located in the highly polluted segment of the river that could be attributed due to the presence of inorganic salts

(Korkanç et al., 2017). EC during the wet season has shown strong positive correlation with BOD ($r = 0.87$), negative with DO ($r = -0.83$), and positive with PO_4-P ($r = 0.70$) at a significance level $p<0.01$. Unlike the wet season, EC and TDS during the dry season recorded high in almost all monitoring stations in general and LART in particular, with a mean value of 1142.5 µS/cm and 565.7 mg/L respectively.

Table 2.2: Descriptive statistics of spatial variation of LAR main channel physico-chemical constituents during the dry season: mean and standard deviation *(italics)*.

St.	PO_4-P	NO_2-N	COD	BOD	DO	pH	TDS	Temp	TKN	NO_3-N	EC
M1	5.5	0.06	1146	101.2	1.53	7.2	502	12.8	28.2	0.35	1022
	1.3	*0.02*	*106*	*80.9*	*0.3*	*0.1*	*74*	*0.5*	*4.8*	*0.09*	*133*
M2	4.5	0.07	912	110.8	3.2	7.3	440.8	12.9	40.8	0.23	899.8
	0.03	*0.03*	*308*	*30.5*	*0.44*	*0*	*39.5*	*0.4*	*6.2*	*0.17*	*56*
M3	3.02	0.08	1477	582.3	0.25	5.6	699.75	18.7	61.6	0.74	1415
	2	*0.004*	*250*	*10.3*	*0.02*	*0.5*	*93*	*0.22*	*16.4*	*0.5*	*203*
M4	5.2	0.11	1036	316.4	0.12	7.2	638.2	19.8	42.2	0.92	1293.3
	0.23	*0.01*	*357*	*98.1*	*0.01*	*0.1*	*52.4*	*0.06*	*3.9*	*0.23*	*85.7*
M5	7.8	0.11	1442	389.2	0.11	7.2	724.2	19.7	44.6	0.72	1464
	1.62	*0.02*	*355*	*35.9*	*0.01*	*0.2*	*38.8*	*0.08*	*2.4*	*0.22*	*42.5*
M6	5.5	0.06	1260	481	2.06	6.9	481.8	16.2	84.1	0.4	984
	0.6	*0.02*	*409*	*104*	*0.53*	*0.2*	*31.3*	*0.21*	*12.1*	*0.12*	*29.3*
M7	3.96	0.03	771	180.4	4.8	7.5	514.5	15.8	40.6	0.37	1046.8
	1	*0.02*	*344*	*104*	*0.84*	*0.4*	*80.7*	*0.13*	*5.4*	*0.06*	*142*
M8	1.2	0.01	1078	139.2	2.9	6.8	634.5	21.1	27.6	1.8	1286
	0.1	*0.001*	*403*	*10.1*	*0.43*	*0.1*	*117*	*0.77*	*1.6*	*0.43*	*218*
M9	3.9	0.04	1467	284.8	0.14	6.9	677.8	20.7	43.8	0.94	1380
	0.2	*0.02*	*554*	*98.8*	*0.03*	*0.1*	*84.2*	*1.02*	*1.4*	*0.33*	*164*
M10	4.99	0.07	1112	161.4	0.36	7.2	641.5	19.2	55.4	1.33	1300.3
	0.7	*0.01*	*515*	*71*	*0.02*	*0.2*	*51.4*	*0.42*	*13.5*	*0.68*	*93.2*
M11	5.3	0.03	988	117.1	0.2	7.3	638.2	19.4	85	1.3	1294.3
	0.2	*0.006*	*332*	*7.9*	*0.1*	*0.2*	*46.1*	*0.7*	*21.6*	*0.41*	*79.9*
M12	6.3	0.27	1056	129.7	0.1	7.6	665.8	20.5	50	0.95	1347.5
	1.7	*0.22*	*402*	*38.9*	*0.04*	*0.1*	*26.8*	*0.8*	*8.3*	*0.1*	*20.4*
M13	6.7	0.084	1011	117.1	1.02	7.6	685.5	19.8	38.8	0.82	1387.5
	1.4	*0*	*488*	*12.9*	*0.23*	*0*	*57.4*	*0.33*	*1.35*	*0.22*	*81.9*
M14	6.63	0.05	1076	63.3	0.8	7.5	692.5	21.4	43.3	1.05	1401.5
	1.1	*0.02*	*427*	*25.9*	*0.4*	*0*	*80.9*	*0.21*	*3.1*	*0.35*	*129*
M15	0.36	0.3	594	60.1	5.8	7.6	224.6	13.1	12.5	0.2	464.8
	0.1	*0.08*	*290*	*10*	*0.8*	*0.1*	*37.3*	*0.26*	*0.96*	*0.09*	*52.5*

All units in mg/L except pH (pH unit), Temp (°C), EC (µS/cm), M=Main Channel, T=Tributary, St.=Station (code)

In most of the monitoring stations of LAR, the water temperature has shown slight increment from upstream to the downstream of the river, though there were few irregularities at some monitoring stations during the wet season. The mean temperature in the LAR was found to be 19±2.18ºC. The minimum and maximum temperatures were recorded at M2 and T4 respectively. In general, the LAR tributaries recorded the highest temperature than the main channel. The temperature in LAR has a very weak correlation with other parameters except for TKN (r = 0.57). The trend in water temperature during the dry season has shown nearly similar distribution across the river stretch where the lowest was recorded at station M1 and maximum at T6.

Table 2.3: Descriptive statistics of spatial variation of LAR tributaries physico-chemical constituents during the dry season: mean and standard deviation *(in bracket)* †.

St.	PO_4-P	NO_2-N	COD	BOD	DO	pH	TDS	Temp	TKN	NO3	EC
T2	2.09	0.33	506.8	70.8	5.2	7.7	358.3	18.6	26.1	0.27	749.8
	1.9	*0.27*	*154*	*75.2*	*0.72*	*0.32*	*71.1*	*0.91*	*15.7*	*0.02*	*131*
T4	8.7	0.08	1167	518	0.14	7.2	877	24	70.5	0.17	1704.7
	6.3	*0.03*	*280*	*150*	*0.04*	*0.15*	*138*	*0.83*	*23.5*	*0.13*	*253*
T3	14.5	0.15	1697	520	0.14	7	821.3	20.8	129	0.1	1601.7
	2.9	*0.03*	*502*	*126*	*0.05*	*0.18*	*115*	*0.93*	*32.4*	*0.08*	*212*
T7	1.37	0.35	310.5	82.3	3.54	7.2	364.8	19.1	30.3	0.03	761.7
	0.7	*0.46*	*187*	*50.9*	*1.27*	*0.25*	*41.9*	*1.11*	*8.5*	*0.01*	*77.1*
T1	4.76	0.07	656.5	127.7	1.35	7.1	412.8	16.9	42.9	0.17	850.1
	2	*0.05*	*460*	*97.7*	*1.11*	*0.2*	*36.1*	*0.95*	*16*	*0.15*	*66.4*
T5	5.2	0.09	497.3	94.5	0.95	7.4	496	23.7	33.1	0.16	1003.2
	0.9	*0.04*	*222*	*104*	*0.98*	*0.18*	*57.2*	*1.49*	*3.26*	*0.14*	*105*
T6	4	0.08	440.3	112.4	0.22	7.7	584.8	24.8	96.6	0.24	1166.5
	1.4	*0.01*	*150*	*78.5*	*0.06*	*0.21*	*51.3*	*1.42*	*64.6*	*0.09*	*94.4*

All units in mg/L except pH (pH. u), Temp (°C), EC (µS/cm), M=Main Channel, T=Tributary, St.=Station (code); †this table is part of Table 2.2.

COD and BOD measures the organic contamination load and indicates the pollution level in a river (Barakat et al., 2016). During the wet season, the LAR main channel has nearly similar trend of BOD5 across the monitoring stations, whereas the variation in concentration among the monitoring stations in LART was significantly high. The mean BOD5 concentration in LAR was 46.79 mg/L where minimum and maximum BOD5 concentration of 2.5 mg/L and 130.324 mg/L were recorded at T7 and M3 respectively. Similarly, the mean COD concentration of LAR for the wet season was 266.9 mg/L with the highest recorded at two of the LARTs: T4 and T3 with a mean concentration of 552 and 520 mg/L respectively. Both BOD and COD concentration has shown high deviation from Ethiopian (EEPA, 2003) guideline for aquatic life on some of the stations and have strong positive correlation during the rainy season ($r = 0.76$) and dry season ($r = 0.81$). The highest BOD5 and COD concentration recorded during the dry season was due to the reduced flow in the river that minimizes the dilution and self-purification of LAR.

Apart from the organic and inorganic pollutants, nutrients contribute pollution load to the LAR. A nitrate concentration up to 10 mg/L in natural water bodies where the concentration in excess amount may affect the river ecology (Barakat et al., 2016). However, nitrate concentration in LAR during the rainy season was within the guideline standard of Ethiopia (EEPA, 2003). The mean concentration of NO_3-N in the LAR main channel and tributaries respectively are 0.424 mg/L and 0.856 mg/L, the tributary exceeding the main channel two folds. On the other hand, mean nitrite concentration in the seven monitored LARTs (0.441 mg/L) is slightly lower than the concentration in the main channel (0.892 mg/L). On the other hand, the mean concentration of TKN in the tributaries during wet season was 32.4 mg/L where the monitoring station at T6 has recorded the highest (61.2 mg/L). The stations downstream of M4 and near M13 downstream of Addis Ababa wastewater treatment plant have the highest TKN concentration with a mean value of 32.2 mg/L each. The TKN during the dry season has shown an increasing trend relative to the wet season. The station M3 (129.3 mg/L) has shown the highest concentration of TKN. The phosphate during the wet season has recorded the highest on LARTs. Less variation of phosphate concentration was observed across the monitoring stations. The maximum concentration of phosphate was recorded at T5 where the river receives waste from the slaughterhouse where the animal bone and small scale urban agricultural washouts remain the major source of phosphate in the area. The phosphate concentration during the dry season has shown an increasing trend where the middle of LART at T3 recorded the maximum phosphate concentration at 15.65 mg/L. Phosphate concentration at M5 could suggest that the wastewater released from the slaughterhouse was the possible source for the high concentration.

Heavy metal concentrations in LAR and LART has shown much higher concentration than the national (EEPA, 2003) and international guideline values for industrial release to a water body at most of the monitoring stations. Analysis of Ni in LAR has shown 67% and 100% of non-detects during the rainy and dry seasons respectively. Among the trace metals analyzed during the monitoring campaign for the rainy and dry season, Cr has shown the maximum concentration relative to other metals with a mean concentration of 2.175 mg/L and 1.17 mg/L respectively. This could be due to the presence of most tanneries and textile industries near the river. The maximum Cr concentration during the rainy season was recorded downstream of M12 (2.175 mg/L). The highest Mn concentration was observed at the station near M13 (0.93 mg/L) followed by the monitoring station at M11 (0.87 mg/L). The distribution of Zn concentration along the LAR has shown slight irregularity across the monitoring stations during both seasons. LAR monitoring station M1 (0.62 mg/L) and T3 (0.42 mg/L) were found to be the highest Zn concentration during the rainy and dry season respectively. The mean concentration of Zn is found to be 0.227 mg/L. Cd, which originates mostly from anthropogenic activities through the application of phosphate fertilizer, has shown almost a constant trend across the monitoring stations. The mean concentration of Cd during the rainy season and the dry season is found to be 0.0093 mg/L and 0.116 mg/L respectively. The concentration of heavy metals during the wet season in the order of Cr>Mn>Cu>Pb>Zn>Cd whereas in the dry season the order was Cr>Mn>Cu>Zn>Pb>Cd.

2.3.2. Factor Analysis and Seasonal Source Apportionment in LAR

Factor Analysis has long been widely used in water quality assessment for identifying the most influential and significant parameter from a set of constituents by minimizing the constituents' dimensions without much loss of information contained in the original data (Yilma et al., 2019). In order to interpret water quality data using the PCA/FA, the data collected need to be checked for suitability for FA. Accordingly, the adequacy of the collected sample for interpretation by PCA/FA in LAR was tested based on the KMO, where it is recommended to be greater than 0.5. In LAR, however, the KMO was found to be 0.728 and 0.725 for the wet and dry seasons respectively ($p<0.05$) showing the suitability of FA for interpreting LAR water quality.

For the FA in LAR, extraction was done by principal components using correlation matrix analysis based on eigenvalues greater than one and varimax rotation. The Kaiser normalization was used for maximizing the variance and extraction of underlining factors called varifactors. A similar approach was followed by (Najafpour et al., 2008; Ogwueleka, 2015). The loading by constituents of the principal components (PCs) extracted by the FA determines the weight of the respective parameter for the component and would generally indicate the correlation between the variable and the component. According to Cid et al. (2011) and Kilonzo et al. (2014), component loadings >0.75, 0.5-0.75 and 0.3-0.5 are classified as strong, moderate, and weak loading respectively. Accordingly, the FA in LAR extracted three factors by retaining the PCs through varimax rotation that explained 79.26% of total variance for the wet season. The first factor that explained 37.9% of total variance after the varimax rotation had strong positive loading for COD (0.96), BOD (0.844), EC (0.775) and TDS (0.767) and moderate loading for DO, PO_4-P, and NO_3-N. The strong loading of COD, BOD, EC, and TDS in PC1 indicate that the possible source of pollution could be due to the combined effect of anthropogenic factors such as the release of untreated urban sewage (Juahir et al., 2011; Su et al., 2011) and the presence of organic pollutant constituents from food, detergent, and beverage industries (Yilma et al., 2019). In addition, high TDS (325.3 mg/l) and EC (660.4 μS/cm) in LAR could be due to the impact of urban runoff (Barakat et al., 2016) and natural effects such as the dissolution of soil constituents (Singh et al., 2005). Therefore, the factor contributing to the first principal component may be named as a combined domestic and unrecognized nonpoint source, generally a combined anthropogenic factor. The factor is more dominant in the middle catchment and monitoring stations such as M3, M4, T3, and T4 where domestic waste prevails.

The second principal component (PC2) showed strong loading on temperature (0.9) and TKN (0.79) and moderate negative loading for DO (-0.645) and moderate positive loading for TDS (0.578) explaining 27.5% of the total variation. The high loadings of Nitrogen on the PC2 suggest that the sources could be nonpoint sources such as agricultural land use, urban drainage, and residential lawns during the rainy season (Salim et al., 2019; Su et al., 2011). Therefore, the component could be named agricultural factor. The last PC, PC3, has strong positive loadings on pH (0.946) and strong negative loadings on NO_3-N (-0.716) explaining the remaining variance of 13.85%. The strong loading on pH could be due to the prevalence of physical processes and reactions by aquatic plants (Parinet et al., 2004) and acidity impact from different sources (Marcello Benedini, 2001). It can be clearly seen that PC3 is more influenced by industrial sources and may be named the acidity factor. This acidity factor is more dominant in the central and downstream of middle section of the LAR where industrial land use setup prevails.

The FA in LAR for the dry season has extracted three principal components explaining a total variance of 79.47% and retained three factors. Accordingly, the first factor explained 36.87% of total variation and has strong loadings on PO_4-P, TKN, TDS, and EC with a component loading of 0.851, 0.773, 0.796 and 0.778 respectively, indicating dominance of non-point sources such as washouts from agricultural fields and urban land use and can be named agricultural and urban runoff factor. The component has also moderate positive loading on Temperature (0.71) and negative loading on DO (-0.745) that could imply the impact of seasonal variation. Similarly, the second component which is responsible for 23.1% of the variation during the dry season has a strong negative loading on pH (-0.86) and strong positive loading on BOD (0.813) and COD (0.762), suggesting biodegradation of organic and inorganic nutrients are negatively impacted by the acidity of the river. The component is more explained by industrial impact and hence can be named industrial (acidity) factor. The third principal component explaining 19.5% of total variation has strong positive loading on nitrate (0.926) and negative moderate loading on nitrite (-0.58). Though the source of nitrate could be various in type, the role of domestic waste is high and hence this component can be best explained by domestic waste source.

The concentrations of heavy metals have shown a very high seasonal variation during both where the major source remains industry. Most of the industries within the vicinity of the river are tannery industries known for their Cr effluent. The tannery industries nearby the LAR release their wastewater to the river with no or minimal treatment. During the dry season, the FA has extracted two factors that explain a total variance of 68.62%. Pb (0.93) and Cr (0.85) in the first component loaded strongly suggesting that sources of heavy metal pollution in LAR is contributed by more than one source. The probable source of Cr is tannery industries where most of these industries are located near LAR and are discharging their raw waste to the river directly. On the other hand, the location of many garages and heavy machinery maintenance workshops near LAR could initiate the level of Pb concentration in the river. Hence factor one could be defined by both industrial and lead-acid battery. On the other hand, the second component is composed of two heavy metals: Mn and Zn where Zn loaded negatively that explains 26.47% of the total variation.

2.3.3. Spatial Water Quality Analysis of LAR Using Cluster Analysis

The CA in MSTs is used to classify monitoring stations with similar characteristics into the same group (Ling et al., 2017; Ogwueleka, 2015). In LAR, before the CA, raw data was Z-scale standardized and tested for normality of data distribution. The dendrogram showing the grouping of all 22 monitoring stations for the wet and dry seasons in LAR and LART is shown in Figure 2.2. The CA grouped all 22 monitoring stations in three significant clusters for the wet season in LAR (Figure 2.2b). Accordingly, the first cluster (Cluster 1) grouped monitoring stations at the downstream and middle section of LAR in one cluster. The stations in this cluster are characterized by relatively moderate to heavily polluted and consist of 13 monitoring sites: M3-M6, M8-M14, T5, and T6. The physical location of all the stations in cluster 1 in a similar area suggests that the clustering is reasonably fair.

Cluster 2 consists of seven monitoring stations that are located at the most upstream section of the river and hence are relatively less polluted. The monitoring stations grouped in this cluster are T1, T2, T7, M1, M2, M7, and M15. The last significant cluster, cluster3, is composed of two highly polluted tributaries: T4 and T3. Similarly, the CA on LAR identified four significant clusters during the dry season. Cluster 1 grouped monitoring stations downstream of the middle section of LAR consisting of stations such as M4, M5, M8-M14. Cluster 2, however, grouped monitoring stations at the most polluted river section: T3, T4, M3, and M6. Cluster 3 is composed of tributaries from the most upstream section with monitoring stations T2, T7 and M15 in the group which are characterized by less anthropogenic influence. Finally, cluster 4 is composed of upstream monitoring stations: M1, M2, M7, T1, T5, and T6.

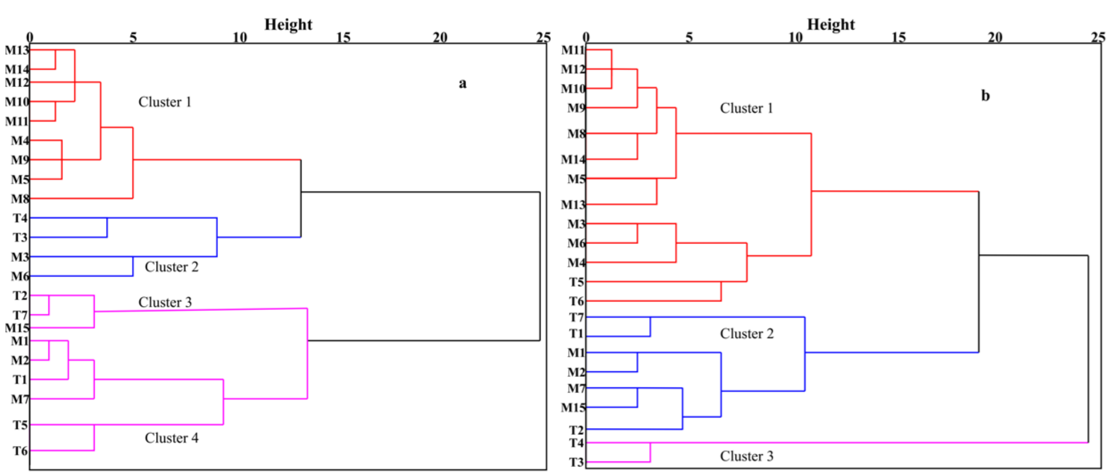

Figure 2.2: Dendrogram showing clustering of LAR monitoring stations for dry (a) and wet season (b)

2.3.4. Quantification of Source Composition and Contribution in LAR

For the estimation of pollution contribution and composition of various sources in LAR, we used the UNMIX model for both dry and wet season. In our study, we have performed manual inclusion and exclusion of parameters in UNMIX until parameters with high error became excluded from modeling (Norris et al., 2007). As a basic requirement, the UNMIX was run by checking the Noise-to-Signal (N/S) ratio and overall minimum recommended R^2 value. The R^2 is meant to express the variance explained by the determined source for each constituent (Huang et al., 2018). Accordingly, Minimum S/N ratio>2 and R^2>0.8 was adopted and the UNMIX model for LAR has fulfilled the minimum requirements with S/N of 2.71 and R^2 of 0.91 for the dry season. With this, 91% of the variance of each constituent can be explained by three sources namely uncharacterized nonpoint (mainly agricultural and urban runoff), domestic (residential and commercial) and industrial. Similarly, the model output for the rainy season showed S/N of 2.16 and R^2 of 0.88 explained by three factors: domestic, industrial, and agricultural (nonpoint) pollution. Source composition by UNMIX in LAR constituents during the dry season has quantified for the three possible sources identified by FA. Table 2.4 shows percentage source composition and distribution during the wet and dry season calculated by the UNMIX model.

Table 2.4: Source composition and contribution (%, bracket) of LAR constituents for the dry and wet season.

Par.	Season	Source1(S1)	Source2 (S2)	Source3 (S3)	P	M	P/M	e (%)
PO_4-P	Dry	0.419 (8.4%)	1.4 (28.1%)	3.17 (63.5%)	4.989	5.02	0.994	-0.62
	Wet	0.83 (35.5%)	0.06 (2.5%)	1.45 (61.96%)	2.34	1.93	1.2	21.2
COD	Dry	78.8 (8%)	464 (47.1%)	443 (44.9%)	985.8	986	0.99	-0.02
	Wet	62.2 (18.9%)	27 (8.2%)	240 (72.9%)	329.2	266.9	1.23	23.3
BOD	Dry	0.26 (0.11%)	53.3 (24.2%)	167 (75.7%)	220.6	216.4	1.1	1.9
	Wet	12.4 (20.3%)	20.2 (33.06%)	28.5 (46.6%)	61.1	48.48	1.26	26.03
DO	Dry	0.11 (7.1%)	0.535 (34.3%)	0.914 (58.6%)	1.56	1.59	0.98	-1.89
	Wet	0.2 (3.42%)	0.51 (8.7%)	5.14 (87.9%)	5.85	4.91	1.2	19.9
pH	Dry	1.93 (27.6%)	2.86 (40.9%)	2.2 (31.5%)	6.99	7.22	0.97	-3.2
	Wet	0.48 (6.4%)	0.36 (4.84%)	6.6 (88.7%)	7.44	7.61	0.98	2.2
TDS	Dry	70.4 (12.2%)	271 (46.9%)	236 (40.9%)	577.4	580.7	0.99	-0.57
	Wet	122 (33.3%)	22 (6.01%)	222 (60.65%)	366	325.3	1.12	12.5

Temp	Dry	4.25 (22.75%)	8.01 (42.9%)	6.42 (34.4%)	18.68	19	0.98	-1.7
	Wet	2.35 (12.6%)	1.05 (5.6%)	15.3 (81.82%)	18.7	19	0.98	-1.6
TKN	Dry	5 (2.37%)	15.3 (25.3%)	30 (72.3%)	50.3	50.4	1	-0.2
	Wet	13.2 (62%)	2.06 (9.7%)	6.02 (28.28%)	21.28	21	1.01	1.3
NO_3-N	Dry	0.007 (1.07%)	0.599 (96.83%)	0.013 (2.1%)	0.619	0.602	1.03	2.8
	Wet	0.11 (15.8%)	0.451 (64.6%)	0.134 (19.6%)	0.698	0.561	1.24	24.4
EC	Dry	148 (12.7%)	552 (47.3%)	467 (40%)	1167	1173.5	0.99	-0.55
	Wet	289 (38.74%)	16 (2.14%)	441 (59.11%)	746	660.4	1.13	12.96
NO_2-N	Dry	0.095(79.8%)	0.0031 (2.6%)	0.021 (17.6%)	0.119	0.117	1.02	1.71
	Wet	0.024 (2.2%)	0.11 (10.3%)	0.942 (87.5%)	1.073	0.75	1.43	43.1

All units are in mg/L except pH (pH units), Temp (°c), EC (µS/cm), P=predicted, M=measured, e=error

S1=Agricultural and urban non-point, S2=Domestic waste, S3=Industrial waste pollution, wet season

S1=Nonpoint source, S2=Domestic waste, S3= Industrial and bio-chemical pollution for the dry season

In LAR, UNMIX model has effectively predicted the constituents contained in the model with an overall R^2 of 99.8% between the model predicted and observed values, with an average predicted to measured (P/M) ratio of 1.01 during the dry season and 99.88% and 1.06 for the wet season. The maximum coefficient of variation (CV) on the constituents was 16.84% with a mean of 4.78%<25% showing that the prediction was reasonably good and can be interpreted well. Moreover, the model performance during the dry season is much better than the corresponding rainy season with an average absolute error of 1.38% when compared to the rainy season (17.13%). The model accuracy for individual parameter estimation ranges from good to very good with an R^2 value ranging from 0.66 to 0.98 (an example of NO_3-N with R^2 of 0.96 is shown on Figure 2.3). The model was relatively weak to capture source contribution for NO_2-N during the rainy season generating 43.1% error calculated between the predicted and observed concentrations.

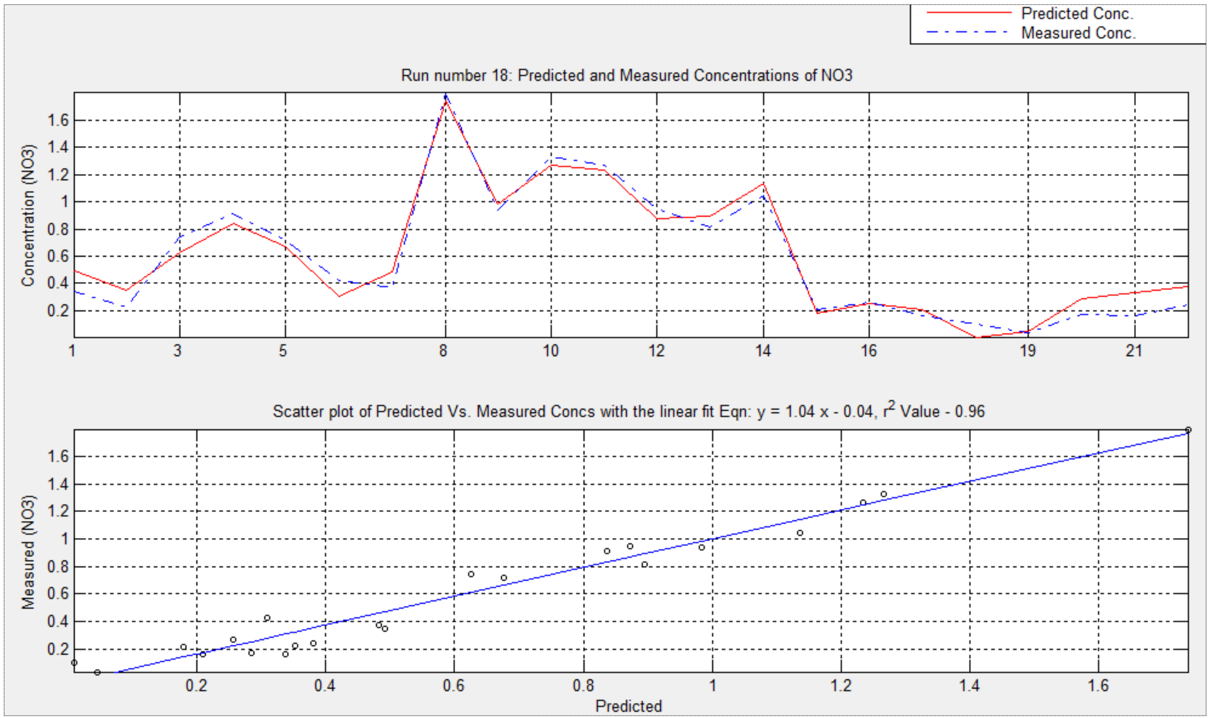

Figure 2.3: Model predicted vs. measured graph and scatter plot of NO_3-N for the dry season (R^2=0.96, e=2.8%)

From Table 2.4, it can be clearly seen that the contribution of source 1 (uncharacterized non-point source) for individual constituents was relatively weak during the dry season. The UNMIX showed that source 1 has the highest loading of NO_2-N and relatively weak on others indicating the source contribution is insignificant during the dry season. On the other hand, the source 1 contribution during the wet season is significant on constituents such as PO_4-P, TDS, TKN and EC where the highest loading on EC could imply the prevalence of nonpoint source by runoff from different land uses. During the dry season, nonpoint source loading on NO_3-N (96.83%) is very high whereas moderate loading on COD (47.1%), EC (47.3%) and TDS (46.9%) could indicate the dominance of domestic waste and hence the contribution for the constituents is from domestic waste.

2.4. Conclusion

The output from this research in the study area revealed that the status of LAR is heavily polluted during both seasons. Poor waste management system coupled with uncontrolled waste release from industries, institutions, households, and other point and nonpoint sources such as agriculture and urban runoff is contributing to the river pollution. Accordingly, the most upstream section of LAR is relatively less polluted than the middle and downstream segment in which LAR increases the pollution level in its course downstream. But due to the self-purification of the river at the most downstream section, the water quality level recovers to some extent but insignificantly. According to the assessment made across different monitoring stations during both dry and wet seasons on LAR, most of the physical water quality constituents were within the guideline standard whereas most of the organic and inorganic pollutants, nutrients and heavy metals have exceeded the limit. The concentration of the constituents during the dry season has shown deterioration due to reduced flow and physical aeration in the river and tributaries.

FA in the area has revealed that three significant sources are responsible for LAR pollution, both during dry and wet seasons: Industrial, non-point source (agricultural and urban runoff), and domestic waste. On the other hand, the CA conducted on the LAR monitoring stations grouped the stations based on their chemical similarity. Accordingly, the rainy season produced a dendrogram with three clusters where the downstream and middle section of the main river showed similar characteristics and hence are grouped together. Stations at the most upstream and highly polluted tributaries in the middle of the catchment are grouped under clusters 2 and 3 respectively. On the other hand, the CA during the dry season classified the monitoring station into four clusters, unlike the rainy season clustering where tributaries are grouped in one.

In most cases, specifically in developing countries, it is often difficult to quantify the contribution of certain pollution source for individual constituents. This is primarily due to the unavailability of continuously monitored data that in turn is due to financial constraints. Moreover, the fast-changing characteristics of the urban river water quality hinder the accurate quantification of pollution source contribution and composition in a river system. In LAR, however, the USEPA's UNMIX model was used to fill this gap. With the continuous and year-long monitored data, UNMIX gave a reliable and accurate result where the minimum requirement by the model was satisfied. Accordingly, min S/N and R^2 values were predicted and measured values are found to be greater than 2 and 0.8 respectively for both seasons. The model accurately predicted the source contribution and composition of all constituents. An average error between model-predicted and measured data was 1.38% and 17.13% during dry and wet season respectively. The contribution of domestic and industrial waste for the pollution of LAR was found very high during both seasons whereas the nonpoint source contribution prevails during the wet season. Controlling point source pollution could greatly improve the water quality. Implementation of local oxygenation techniques such as the use of weir at critical locations would help improve water quality. Additionally, nonpoint source pollution reduction strategies through land use management such as growing grass strips, terracing and filtering and treatment structures at selected locations would greatly help improve the pollution in LAR.

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3. Quantification of Point and Nonpoint Sources Pollution Load

This chapter briefly introduced process-based modeling approaches for quantification of pollution loads in data scarce areas. It described the input data processing and model integration techniques for the determination of the pollution loads in the LAR catchment. Besides, it described techniques on localization of pollutants export coefficient from export coefficients of catchments elsewhere with similar or nearly similar characteristics.

This chapter is based on the following journal article:

Angello, Z. A., Behailu, B. M., & Tränckner, J. (2020). Integral Application of Chemical Mass Balance and Watershed Model to Estimate Point and Nonpoint Source Pollutant Loads in Data-Scarce Little Akaki River, Ethiopia. Sustainability, 12(17), 7084. https://doi.org/10.3390/su12177084

Abstract: The quality of Little Akaki River in Addis Ababa (Ethiopia) is deteriorating significantly due to uncontrolled waste released from point and diffuse sources. In this study, pollution load from these sources was quantified by integrating chemical mass balance analysis (CMB) and the watershed model of pollution load (PLOAD) for chemical oxygen demand, biochemical oxygen demand, total dissolved solid, total nitrogen, nitrate, and phosphate. Water samples monitored bimonthly at 15 main channel monitoring stations and 11-point sources were used for estimation of pollutant load using FLUX32 software in which the flow from the soil and water assessment tool (SWAT) model calibration, measured instantaneous flow, and constituent concentration were used as input. The SWAT simulated the flow quite well with a coefficient of determination (R^2) of 0.78 and 0.82 and Nash-Sutcliff (NSE) of 0.76 and 0.80 during calibration and validation, respectively. The uncharacterized nonpoint source load calculated by integrating CMB and PLOAD showed that the contribution of nonpoint source prevailed at the middle and downstream segments of the river. Maximum chemical oxygen demand (COD) load from uncharacterized nonpoint sources was calculated at the monitoring station located below the confluence of two rivers (near German Square). On the other hand, high organic pollution load, biochemical oxygen demand (BOD) load, was calculated at a station upstream of Aba Samuel Lake, whereas annual maximum total dissolved solid (TDS), total nitrogen (TN), and phosphate load (PO_4-P) from the nonpoint source in Little Akaki River (LAR) were found at a river section near Kality Bridge and maximum NO_X load was calculated at station near German Square. The

integration of the CMB and PLOAD model in this study revealed that the use of area-specific pollutant export coefficients would give relatively accurate results than the use of mean and median ECf values of each land use.

Keywords: Chemical Mass Balance; Pollution Load (PLOAD); Nonpoint Sources; Export Coefficient; FLUX32

3.1. Introduction

Nowadays, urban rivers of developing countries are heavily polluted due to the release of pollutants from the point and nonpoint sources where the determination of accurate pollution load to a river is often difficult due to combined factors of financial, data quality and availability, and technical capability making the river water quality management more challenging (Zinabu et al., 2017). In one way, not only is the determination of waste load from various sources, such as diffuse sources, difficult to quantify as a result of complexity in the generation and uneven distribution of wastewater from various sources (Gurung et al., 2013) but also as a result of the lack of clear distinction between urban point and diffuse pollution sources (Ongley et al., 2010). On the other hand, pollutants released from point sources such as industries and institutions to the rivers are becoming a threat to the aquatic life arising from poor waste load allocation and monitoring systems, and most importantly, monitoring all the point sources in a watershed is quite difficult due to economic and time limitations (D. Chen et al., 2013). Despite the wide range of challenges for the estimation of pollutant loads on different watersheds, scientists have tried to develop different approaches and come up with various best pollution management practices. The most common approaches for pollutants load estimation is based on watershed models that require extensive data, which were reported in the works of (Hao et al., 2020; Huiliang et al., 2015; Y. Liu et al., 2020; Wu et al., 2016). Similarly, the application of the land use-based pollutant export coefficient method (Wu et al., 2015) and the modified mass balance approach (Y. Chen et al., 2019) are also alternative pollutant load estimation techniques. Researchers often recommend the study of pollutant loads rather than the concentration could ease the river pollution and pollutant load management in a river system (S. Shrestha et al., 2008).

When the data required for the estimation of pollutant loads are limited, it is often necessary to explore simple approaches that estimate the transport of loads from various land uses to water (Zinabu et al., 2017). Various researchers have hence used different techniques to estimate pollutant loads from diffuse sources. One such approach, which has been widely used is through the determination of pollutant flux based on the base flow separation (Waseem et al., 2018). However, such an approach could not be feasible for data-scarce areas like Ethiopia, which have limited hydro-meteorological and water quality data. Availability of monitored water quality and hydrological data is central for the accurate determination of the pollutant load that hence hinders the urban water quality management and pollution load estimation, specifically in developing worlds. In that case, an indirect approach, such as chemical mass balance (CMB) analysis, which is often considered as an economical and viable way, is used as a means of preliminary load estimation. Waseem et al. (2020) suggested the use and importance of detailed information of water and chemical mass balance analysis approach for the establishment of efficient surface and ground water management. However, the CMB approach for pollutant load estimation is more accurate if the time of travel between the river segments of monitoring stations is small and the river is assumed to be completely mixed. Many studies have been conducted to estimate the pollutant loads in a river using the CMB analysis globally. The application of CMB was used by Raj et al. (2007) to determine the subsurface flow contribution to a river where the load difference between the monitoring stations nearby was that contributed by the flow from a subsurface source. Besides, the method was also used for the estimation of internal processes in rivers, sediments, and chemical resuspension (Berndtsson, 1990), where bottom sediment usually plays a key role by acting as both source/sink during mass flux and CMB analysis (Morris et al., 1995). The approach was also used as a means of preliminary pollutant lateral load estimation in different watersheds such as in India (C.K. Jain et al., 1998), North America (Dolan & El-Sharawi, 1989), and Europe (Berndtsson, 1990).

In Ethiopia, due to combined limitations of finance, monitoring data, and commitment, it is nowadays becoming difficult to estimate loads from point and nonpoint sources, and hence river water quality management is neglected. However, the recent initiation of the government to reduce the point source pollution has led the nonpoint source pollution to be recognized, and it has ultimately become the primary focus area. It is apparent that pollutant load estimation specifically originating from nonpoint sources in data-scarce catchments like Ethiopia is challenging. Thus, the use of less complex, effective, economical, and reliable watershed models is highly important for better pollutant load estimation in river water quality management. Therefore, the objectives of this research were: quantification of annual pollutant loads contributions from point and nonpoint sources to the Little Akaki River (LAR), to identify the possible pollution load hotspots, and calibration of pollutant export coefficient for the study area by integrating CMB analysis and catchment nonpoint source model of pollution load (PLOAD).

3.2. Materials and Methods

3.2.1. The Study Area

Addis Ababa is the sprawling city and capital, economic, and political center of Ethiopia, found on the border of the greater rift valley at the foothill of the Entoto mountain, with a total land area of 520 square kilometers and population of more than 3 million (Feyisa et al., 2014). The study area Figure 3.1 is characterized by a subtropical highland climate with a mean annual maximum and minimum temperature of 24°C and 12°C, respectively, and a mean monthly rainfall of 260 mm (Arsiso et al., 2017). The main surface water sources of the city consist of three rivers: Kebena River, Big Akaki River (BAR), and Little Akaki River (LAR), all originating at the foothills of Entoto and draining down to Aba Samuel Lake.

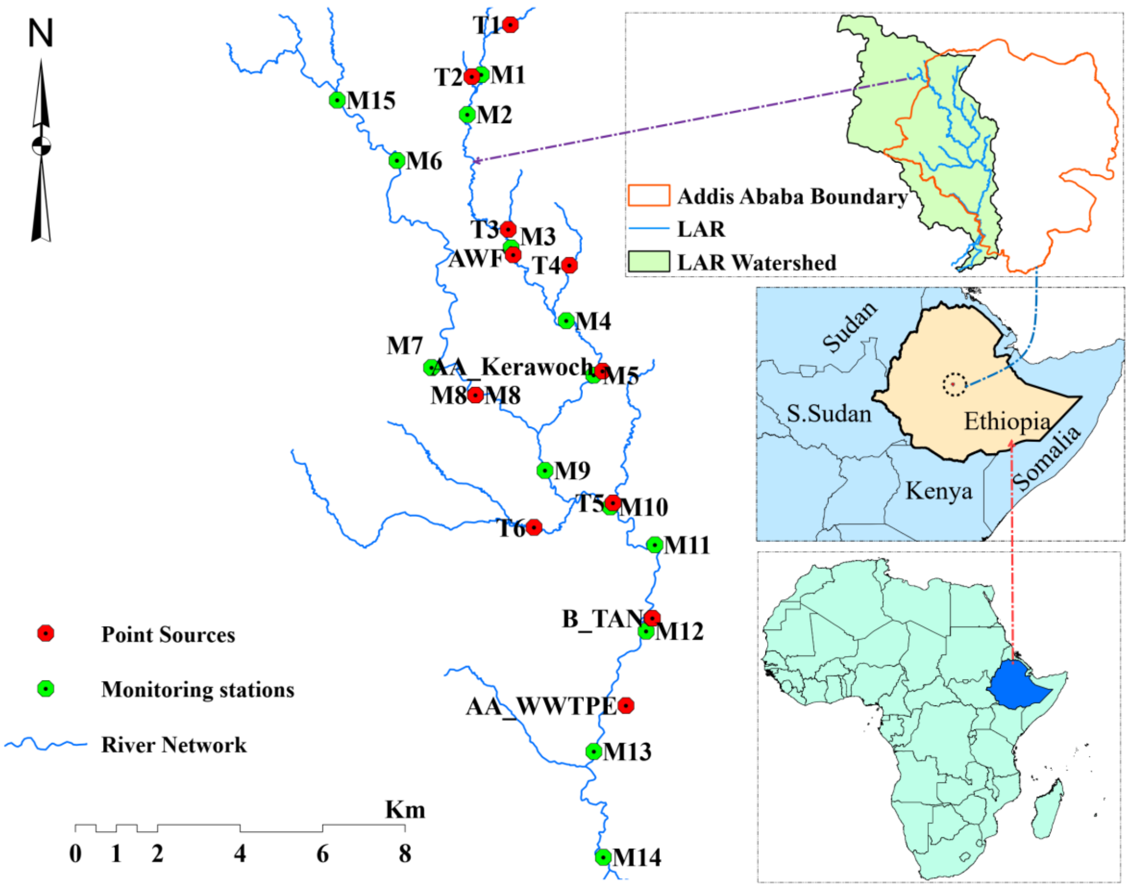

Figure 3.1: The Little Akaki River (LAR) water quality monitoring stations and point source locations.

The LAR flows from the northwest of the city to the most southern Addis Ababa, before joining the BAR at Aba Samuel Lake, and has a total length of 43 km. The LAR consists of several highly polluted tributaries, mainly located in the middle of the catchment where untreated household waste, including raw sewage, and industrial waste that increases pollution load in the river are discharged. Nearly 65% of the country's industries, ranging from small-scale to large-scale, are concentrated in and around Addis Ababa (Yohannes & Elias, 2017), including food and beverage, textiles, tanneries, rubber, and paper products.

The location of most large-scale industries within the vicinity of the LAR that are releasing their wastewater directly to the river without prior treatment (more than 90%) has augmented the pollution load, making the river's water quality unmanageable easily (Aschale et al., 2016). The river is serving as a natural sewer line for waste originating from various sources, such as domestic, industrial, institutional, and residential areas (Beyene et al., 2009). Besides, the study area is characterized by trachytes, rhyolites, basalts, and several episodes of pyroclastic materials of older volcanic rocks, specifically prevailing in the upper catchments, whereas the western, southwestern, and eastern parts of Addis Ababa are characterized by younger volcanic of trachy-basalt.

3.2.2. Water Quality Sampling and Flow

A bimonthly water sample was collected for selected constituents in LAR from April 2018 to March 2019 during dry and wet seasons. A total of 11 physico-chemical parameters were collected and analyzed where dissolved oxygen (DO), water temperature, pH, total dissolved solids (TDS), and conductivity were determined onsite. For the estimation of pollutant load in LAR, water samples were collected from 15 main channel monitoring stations (Table 3.1) and 11 tributaries and point sources (Figure 3.1 and Table 3.2). The samples were collected using a 1.5 L polyethylene bottle, 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 3.3. All the analytical methods were done according to the standard methods for the examination of water and wastewater (APHA, 1999).

Table 3.1: Main channel monitoring stations and locations in LAR.

Code	Station Name	Longitude	Latitude	Area (ha)
M1	LAR at Medhanealem Square	38°43′14″	9°03′10.1″	277.15
M2	LAR near Kolfe Atena Tera Taiwan Sefer	38°43′3.1″	9°02′38.3″	74.31
M3	LAR at the Back of Coca Cola SC	38°43′38″	9°00′53.1″	437.14
M4	LAR downstream of AACRA	38°44′21″	8°59′55.5″	343.59
M5	LAR near Kera Beg Tera	38°44′44″	8°59′12.7″	400.42
M6	LAR Downstream of Likuanda Bridge	38°42′7.1″	9°02′2.13″	1202.13
M7	LAR Upstream of Alert Hospital at Augusta	38°42′35″	8°59′18.5″	461.62
M9	LAR at German Square	38°44′5.1″	8°57′57.3″	826.42
M10	LAR Upstream of Biheretsige Park	38°44′57″	8°57′28.6″	476.48
M11	LAR Downstream of Biheretsige Park	38°45′32″	8°56′58.7″	294.63
M12	LAR Downstream of Batu Tannery	38°45′45″	8°55′50.1″	777.23
M13	LAR at Kality Bridge	38°44′44″	8°54′15.4″	869.91
M14	LAR Upstream of Aba Samuel Lake	38°44′53″	8°52′51.8″	1870.96
M15	LAR Downstream of Addis Ababa Tannery	38°41′20″	9°02′19.7″	9795.4

On the other hand, instantaneous flow in LAR was measured at the time of sample collection using the current meter (Dentan CM-1AX, Tokyo, Japan), and the gauge data for soil and water assessment tool (SWAT) model calibration were collected from the Ministry of Water, Irrigation, and Electricity.

Table 3.2: Identified point sources near LAR, station locations, flow rates, and characteristics.

PS †	Longitude	Latitude	Q	Characteristics
T2	38°43′6.6″	9°3′8.11″	172.8	A tributary with wastewater from Ethio-marble industry
T3	38°43′35″	9°1′7.81″	259.2	A tributary receive waste mainly from domestic source
AWF	38°43′39″	9°0′47.4″	95.01	Wastewater originating from wine factory
T4	38°44′24″	9°0′39.6″	518.4	A tributary carrying hospital and tobacco factory waste
AA*	38°44′51″	8°59′16″	362.9	Receive wastewater effluent from abattoirs
T6	38°43′56″	8°57′12″	18144	A tributary carrying agricultural and industrial waste
T5	38°44′59″	8°57′32″	363.04	Small but heavily polluted Kera stream
W_TAN	38°45′30″	8°56′0.6″	181.4	Waste effluent from tannery factory
B_TAN	38°45′30″	8°56′0.6″	267.8	Waste effluent from tannery factory
AAW	38°45′9.5″	8°54′51″	4542.4	Addis Ababa waste water treatment plant effluent
M8	38°43′9.6″	8°58′57″	22982.6	Major tributary load
T1	38°43′37″	9°3′49.2″	86.3	Very small but highly polluted tributary

† Point source; Q is the mean flow rate (m^3/d); AA=AA_Kerawoch; AAW=AA_WTPE on Figure 3.1

The SWAT model calibrated on Big Akaki River (BAR) outlet was used to simulate and generate flow at each of the sub-catchment outlets (monitoring stations) and later used for pollutant load calculation at monitoring stations, along with the instantaneous flow and constituent concentration. The flow generated by SWAT for each subcatchment outlet was later input to the FLUX32 software for load estimation at each monitoring station.

Table 3.3: Analytical techniques used for the analysis of selected constituents in LAR.

No	Parameter	Analytical Method	Apparatus/Equipment
1	BOD	Modified Winklers Method	BOD Incubator
2	TDS	Digital Multiparameter	HQ40d
3	COD	Titrimetric	COD Digester, Heating Block
4	PO_4-P	Spectrophotometric	HACH DR-2800
5	NOx	Spectrophotometric	UV-VIS Spectrophotometer
6	TKN	Kjeldahl Method	Kjeldahl

3.2.3. CMB Analysis and Uncharacterized Nonpoint Source Load

In urban rivers of developing countries, the nonpoint source load estimation is a bit challenging due to uncontrolled and irregular waste release rates and unknown and uneven distribution of diffuse sources entry points (Falconer et al., 2018; Han et al., 2011; Jamwal et al., 2011; Lai et al., 2011). To overcome such complexities, various software nowadays is developed to estimate the pollutant loads in a river by taking advantage of simple mathematical equations, from where the diffuse source loads are estimated. FLUX32 is one such software system, developed by the Minnesota Pollution Control Agency (MPCA) to estimate the pollutant loads carried by tributaries and streams. The software requires two data sets: event-based pollutant concentration and respective instantaneous flow and historical gauge recording or model output of the river flow for the specified period (Zinabu et al., 2017). The software uses six different methods to calculate the pollutant load/flux and the choice of each method depends on the sampling approach and variability of flow and concentration (Walker, 1999). Accordingly, method six (regression applied to individual daily flows) was selected for load calculation in LAR Equation (1).

$$W_i = \sum \exp[a + (b+1)\ln(Q_i) + \frac{SE^2}{2}] \qquad (1)$$

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 q is instantaneous flow (m^3/s), Wi = pollutant load/flux (kg/yr).

In LAR, point source load, such as from industries, was calculated by the product of the average discharge rate of wastewater effluents and the mean concentration, where similar approach was used by Amaya et al. (2012), whereas the load from tributaries was calculated by using FLUX32. This is partly because the point source load is often assumed stable and insignificant change occurs seasonally (Albek, 2003; X. Xin et al., 2017). On the other hand, estimation of nonpoint source loads from available monitored water quality data is quite complex and in LAR it was calculated by using upstream–downstream CMB analysis integrating with the watershed model, PLOAD. Since it was difficult to explicitly estimate the nonpoint source load in LAR directly, the term uncharacterized nonpoint source load was used instead, which might include unidentified point source and unrecognized nonpoint source load, where a similar description was used by Jain et al. (1998). A simple upstream–downstream mass balance approach could be used as an initial estimation of pollution load from lateral sources (C.K. Jain et al., 2007). Accordingly;

$$\sum Q_D C_D - \sum Q_{Ui} C_{Ui} + \sum \text{Losses} = \sum L_i \quad (2)$$

Where Q_D = river flow at the downstream station, C_D = downstream constituent concentration, Q_{Ui} = flow of a river at a river section upstream, C_{Ui} = upstream constituent concentration, ΣLosses = the sum of all losses in the stream, L_i = is the net load.

The above simple approach was used in LAR lateral diffuse pollutant load (differential load) estimation for two basic reasons. First, the span length between the monitoring stations is very small, indicating that the loss is minimum and hence neglected. Second, the river constituents are assumed completely mixed. In the above simple mathematical mass balance equation (Equation (2)), the term ΣLi does not mean it is only contributed from nonpoint source loads and is not the exact net load at a point, but the combination of all loads and the losses and/or generations (Sekhar & Sreenivasulu, 2003), which could be due to settlement, resuspension, and decay and the generation due to reaction.

3.2.4. Watershed Model Selection

The study of pollutant loads contributing to the pollution of a river is vital for better water quality management. Sekhar & Sreenivasulu (2003) suggested that the catchment pollution management plan should follow a complete study of three components: point sources, nonpoint (background) sources, and natural processes. Though the estimation of point source load is relatively easy, it is challenging to quantify diffuse source loads, specifically in developing countries, where the estimation is often based on simple empirical equations with limited hydro-meteorological and water quality data. To fill such gaps, many watershed models have been developed and studies were conducted to determine pollutant loads from diffuse sources at catchment scale such as the hydrological simulation program—FORTRAN (HSPF) (Z. Li et al., 2017), agricultural nonpoint source pollution model (AGNPS) (Xingwei Wang et al., 2016), pollution load (PLOAD) (Kipyego & Ouma, 2018), soil and water assessment tool (SWAT) (Santhi et al., 2001), and storm water management model (SWMM) (Lai et al., 2011). However, most of the models developed so far are complex and require a large number of data, and hence are not feasible for data-scarce areas like Ethiopia. However, watershed level nonpoint source pollution management could be achieved by using a simple but reliable and relatively accurate model with a reasonable and limited budget. In LAR, hence, we used the PLOAD model due to its versatility, simple data usage, and ease of applicability for the study area (Zinabu et al., 2017), integrating with the CMB analysis approach based on monitored water quality data. Most researchers prefer the use of PLOAD due to its cheaper and faster water pollution management of water bodies (Gurung et al., 2013) and the capability and adaptability of the model in different watersheds (Z. Shen et al., 2011). On the other hand, Zinabu et al. (2017) recommended the use of the PLOAD model in Ethiopia for nonpoint source pollution management.

The PLOAD is a BASINS (better assessment science integrating point and nonpoint sources) model plugin used to estimate nonpoint source load at catchment level interpreted as an annual load (USEPA, 2001). The model integrates point source and GIS-based land-use data to estimate the nonpoint sources' load contribution from each land use using two approaches: the export coefficient and simple method. Both approaches can be applied based on the data availability and applicability on a watershed, but generally the simple method is used in smaller watersheds, usually less than 1 square mile, while the export coefficient method is used in a mixed land uses (Lin, 2004) for the estimation of constituents such as total suspended solid (TSS), TDS, BOD, COD, NOx (nitrate + nitrite), total Kjeldahl Nitrogen (TKN), ammonia, fecal coliforms (FC), lead, and zinc (USEPA, 2001). In LAR, we used the export coefficient approach where pollutant loads in PLOAD are calculated by;

$$L_P = \sum_P (L_{PU} \times A_U) \quad (3)$$

where Lp = pollutant load (kg/yr), LPU = pollutant export coefficient for each land use (kg/ha/yr), AU = area by certain land use, ha.

3.2.5. Pollutant Export Coefficient

The export coefficient (ECf) is the total amount of pollutant load transported from certain land use per unit area over a specified period of time (Ma et al., 2011). When estimating catchment nonpoint source contribution by ECf, each land use is assumed to contribute to the pollutant load per land area and is hence expressed in kg/ha/yr. The watershed shape file was delineated by using ArcSWAT, where the land use in the study area is mostly dominated by urban and agricultural set-ups where informal settlements prevail. Accordingly, urban land use has the highest percentage coverage with 51.8%, followed by agricultural land (25.72%), forest (10.18%), rangeland (7.2%), bare land (4.63%), and water (0.46%).

Mathematically, the pollutant load using export coefficient with an inclusion of precipitation induced pollution can be expressed by;

$$L_{i,j}=\sum_{k=1}^{n}(E_{k,i}\times A_{k,j}+P_{i,j}) \tag{4}$$

Where $L_{i,j}$ is calculated load of constituent i at the sub-catchment outlet j (kg/yr); 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/yr); $A_{k,j}$ is the 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). $P_{i,j}$ is assumed negligible in LAR.

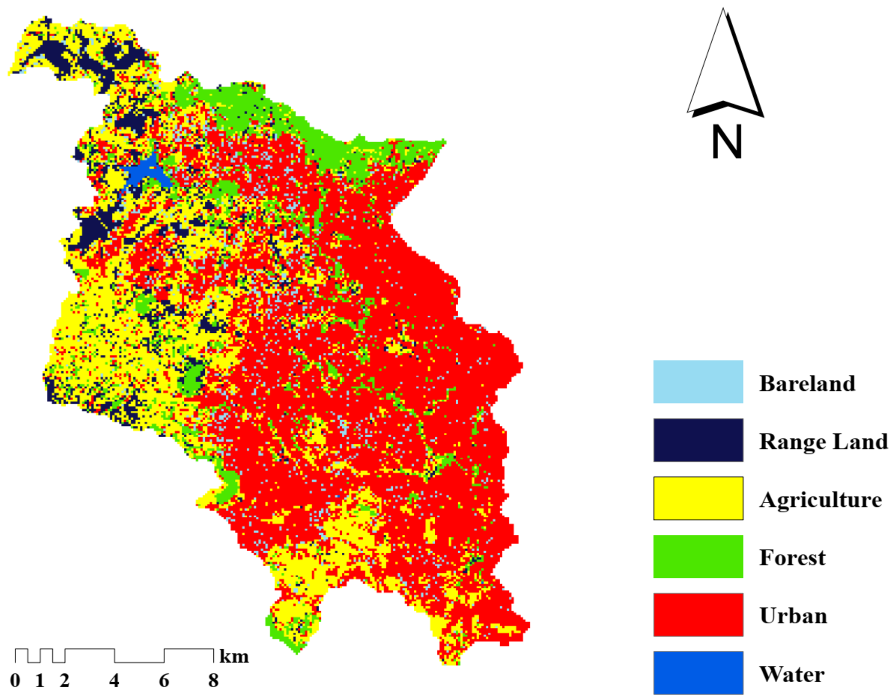

Figure 3.2: Land use map of the study area.

Availability of the local pollutant export coefficient is a prerequisite for accurate determination of pollutants loads in a watershed. However, the study area did not have an established pollutant ECf and determination for LAR depends on the data on another watershed elsewhere with nearly similar hydrological, topographical, land use, and climatic set-up. To account for catchment variability and to select appropriate ECf values, we evaluated coefficients globally (Table 3.4). For pollutant ECf in PLOAD, we reviewed literature values from Ethiopia (Zinabu et al., 2017), Canada (Jeje, 2016), USA (Lin, 2004), China (Han et al., 2011), Taiwan (Chang et al., 2001), New Zealand (Alexander et al., 2002), Philippines (Amaya et al., 2012), Egypt (Fleifle et al., 2014), Lithuania (Povilaitis Arvydas, 2010), and Japan (S. Shrestha et al., 2008). Table 3.4 summarizes the ECf for pollutants and nutrients in literature and selected for LAR for preliminary estimation.

Table 3.4: Export coefficient from literature (kg/ha/yr) selected for pollution load (PLOAD) calibration in LAR.

Land Use	ECf of Different Land Uses from Literature, kg/ha/yr					
	TN	TDS	BOD	COD	NO_x†	PO_4-P
Urban	4.38–36.86[a]	292–2263[a]	2199.6[e]	2343.4[e]	91.44[e]	1.73[s]
Agriculture	2.1–79.6[d]	2280[e]	68.4[e]	90.9[p]	34.32[e]	9[r]
Forest	0.9–38[s]	250[j]	50[n]	50[n]	2.12[s]	0.71[s]
Bare land	0.51–6[b]	100[n]	3.46[q,o]	1–5*	67.29[r]	4.81[r]
Water	21.96–73.45[h]	10–150[n]	50[n]	50[n]	0.46[s]	10.11[r]
Rangeland	3.2–14[b]	24.02–100.99[j]	0.5[s,g]	0.5[s,g]	0.46[s]	2[r,g]
	Export coefficients selected for PLOAD calibration in LAR, kg/ha/yr					
	TN	TDS	BOD	COD	NO_x†	PO_4-P
Urban	36	2260	2195	2340	91	1.7
Agriculture	79	2250	68	90	34	9
Forest	38	250	50	50	2	0.7
Bare land	6	100	3.4	5	67	4.8
Water	73	150	50	50	0.45	10
Rangeland	14	100	0.5	0.5	0.45	2

[a](Haith et al., 1992); [e](Fleifle et al., 2014); [s](S. Shrestha et al., 2008); [p](Povilaitis Arvydas, 2010); [b](Zinabu et al., 2017); [h](Han et al., 2011); [j](Jeje, 2016); [r](Wali et al., 2011); [q](USEPA, 2001); *Approximated from PLOAD user guide for BOD (USEPA, 2001); [d] (Lin, 2004); [n](Amaya et al., 2012); †reported in literature as $NO_3 + NO_2$; [r,g]estimated from grassland value (Wali et al., 2011); [s,g]estimated from grassland value (S. Shrestha et al., 2008); [q,o]value taken for open land from PLOAD user guide (USEPA, 2001).

3.2.6. Calibration and Validation of PLOAD

PLOAD uses GIS-based input data such as land use, watershed boundary, pollutant loading rate (ECf), rainfall depth and optional best management practices (BMPs), terrain imperviousness, and point sources load based on the type of the approach used for estimation. In PLOAD, nonpoint sources from each land use were calculated based on the ECf for each land use. In LAR, once the ECf for each land use was assigned, the PLOAD was calibrated by using the uncharacterized nonpoint source load calculated by CMB analysis and validated using another set of data using an optimized ECf and measured nonpoint load through CMB. The PLOAD model performance was then evaluated by comparing the measured pollutant load (CMB analysis) with the model output until the total percentage error between the measured and model-predicted value became zero or close to zero. Since the model has no direct calibration option, an Excel (2016)-based optimization on Excel Solver was used. In the Excel Solver, the objective to be optimized was set to minimize the percentage total relative error with a possibility of zero value. We selected a GRG nonlinear optimization in Solver due to its faster performance, which uses the local optimum solution. Accordingly, the performance of the model was checked by;

$$\%\ ES=\frac{MPL - PPL}{MPL} \tag{5}$$

where ES is an error of estimation, MPL is measured pollutant load, PPL is PLOAD predicted load.

3.3. Results and Discussion

The results in this section are presented in a way that the pollutant load for selected segments of the LAR and monitoring stations of the catchment outlets are represented. The discussion mainly focuses on the major pollution hotspots in the watershed and the pollutant contribution of various land uses were quantified.

3.3.1. Point Sources Load in LAR

The pollutant load from point sources in LAR was much smaller than the tributaries load due to the relatively higher flow rate and pollution level of the tributaries than the point sources. However, stations M3 to M11 (Figure 3.1) were heavily loaded by point source pollution that contributes significant pollutant loads to LAR including, the soft drink industry, wine industry, abattoir, tobacco factory, and hospitals. Similarly, the heavily polluted Mesalemya stream that joins the main river upstream of outlet M3 and a tributary that crosses densely populated urban center, Merkato, and receives many wastewaters from industries joining the main river at M4 have highly augmented the pollutant load in LAR. Besides, the load contributed by the Addis Ababa Abattoir near Kera Beg Tera (M5) was found to be very high due to significantly higher water consumption from the slaughterhouse that generates wastewater with a higher flow rate. Table 3.5 summarizes the load contributed by point sources to the LAR. Almost all of the point sources near LAR discharging the wastewater directly to the river have either no treatment plant or couldn't fully operate. From the point source load summary on Table 3.5, it can be apparently seen that the contribution of stations T6, AA_Kerawoch, AA_WWTPE, and M8 were quite significant for the LAR organic and nutrient pollution.

Table 3.5: Summary of point source loads of selected physico-chemical constituents in LAR (t/yr).

		Constituents Load in LAR (t/yr)					
Point Source	MS†	COD	BOD	NOx	PO_4-P	TDS	TN
T2	M2	37.73	8.32	0.017	0.312	26.52	2.48
T3	M3	185.74	59.89	0.013	1.388	89.75	14.74
AWF	M4	13.69	6.39	0.12	0.447	33.76	0.585
T4	M4	189.45	98.28	0.056	1.18	178.36	10.18
AA_Kerawoch	M5	821.2	105.96	0.073	3.338	306.68	5.298
T6	M10	2867.46	1005.59	1.39	26.2	3185.59	342.65
T5	M10	341.95	98.13	0.115	3.999	358.87	22.07
W_TAN	M12	60.75	3.48	0.74	0.616	49.42	7.076
B_TAN	M12	27.32	14.53	1.912	1.767	103.46	7.617
AA_WWTPE	M13	622.17	217.12	1.005	8.137	440.96	147.26
M8	M9	11661.75	1052.19	16.35	15.5	5874.3	223.04
T1	M1	82.624	19.99	0.023	0.584	42.69	5.275

MS† is downstream monitoring station where the point source load is contributing; T=tributary; AA=Addis Ababa; WWTPE=wastewater treatment plant effluent; M=main channel.

3.3.2. Flow Simulation and Pollutants Flux in LAR

The SWAT calibrated at BAR was used to generate flow in LAR sub-catchment outlets where the model output along with the instantaneous flow and constituent concentration was used in FLUX32 software to calculate the pollutant flux (load). Accordingly, the SWAT simulated the flow quite well as shown on Figure 3.3 and Figure 3.4 with an R^2, NSE, and RSR value of 0.78, 0.76, and 0.49 during calibration and 0.82, 0.8, and 0.45 during validation, respectively. The model performance indicators above (R^2, NSE and RSR) were good enough to interpret the model output for any purpose. From Figure 3.3, it can be seen that there is slight deviation between the SWAT model simulated and observed peaks. This could primarily be due to the model performance. The hydrological model performance determined by the Nash-Sutcliff (NSE) was found to be 0.76 and 0.78 during calibration and validation in the study area, which is good enough to interpret the model output (Moriasi et al., 2007) and the deviation between the observed and simulated flow is interpreted by the error. Similar results were reported elsewhere with similar trends between the model simulation and observation in the works of Abbaspour et al. (2015), Rostamian et al. (2008), and Shawul et al. (2019). Sometimes the time lag between the small rainfall event and the main rain event could dictate the variation between the model simulation and observed values. This explanation is supported by the study conducted by Li et al. (2017), who used hydrological and water quality model, HSPF, where a similar trend with this study between the model simulated and observed flow was observed. The spatial location of rain meters and the heterogeneity among rainfall stations could also determine the deviation. Though there was deviation between model simulated and observed values at some peak points, the model performance indicators (specifically the Nash-Sutcliff) could suggest that the model output can be interpreted with a good accuracy. The SWAT-generated subcatchment outlet flow was used to calculate the load in FLUX32. Accordingly, the flow-weighted concentration calculated by method 6 (Equation (1)) was < ±20% of all other methods in FLUX32.

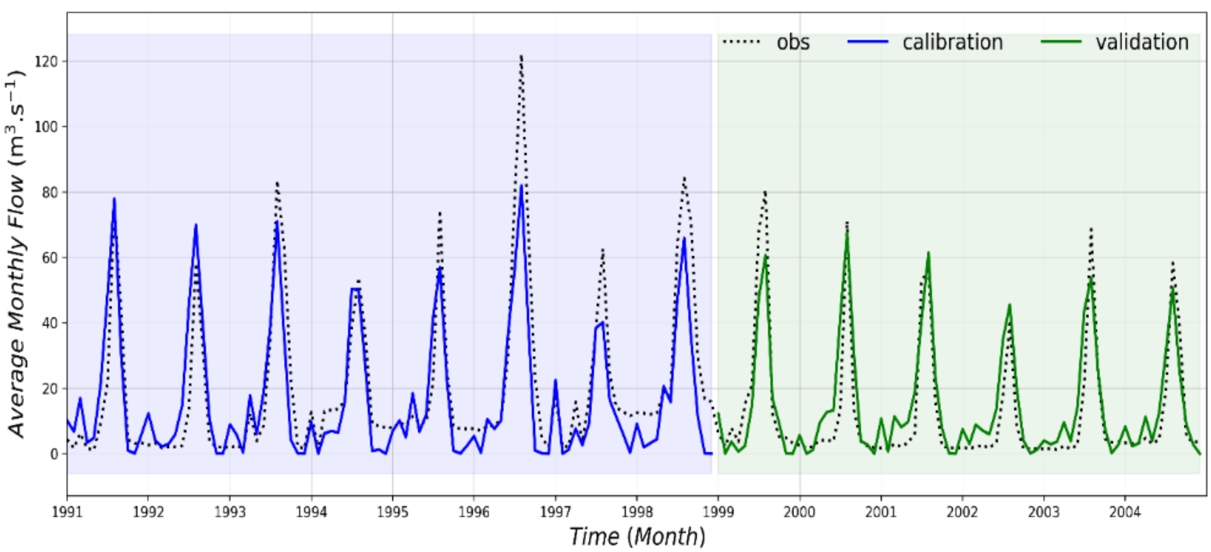

Figure 3.3: Soil and water assessment tool (SWAT) simulation for flow at Big Akaki River (BAR) (calibration and validation).

The residual plot of bias (as slope) for flow, date, and month at each catchment outlet in LAR was in the range of 0–0.05, which is quite acceptable. Similarly, the plot of slope significance was in the range of 0.88–0.99 ≈ 1. The coefficient of variation (CV) is recommended to be in the range of 0–0.2 during flow-weighted load calculation and in LAR, the CV has resulted in the range of 0.03–0.101, which is quite good. During pollutant load calculation in LAR using FLUX32, the presence of the outlier was checked statistically by testing the significance level, $p \leq 0.05$.

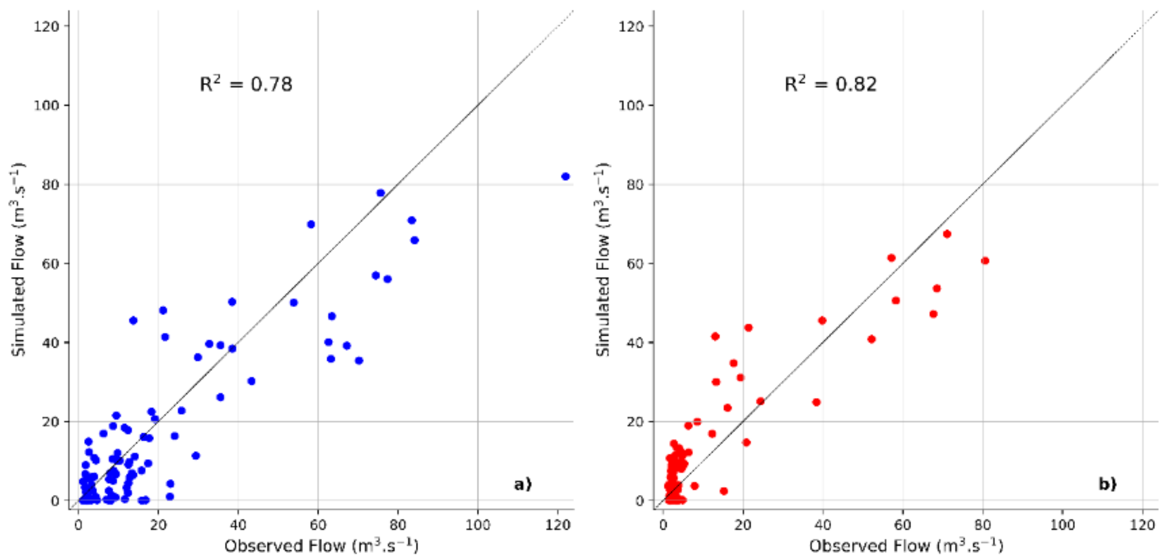

Figure 3.4: Plot of SWAT simulated versus observed flow in BAR (a) calibration and (b) validation (black diagonal line is a one to one (equality) line).

3.3.3. Chemical Mass Balance and Pollutants Differential Load in LAR

Once the loads were calculated at each of the sub-catchment outlets by FLUX32, a CMB analysis was performed following an upstream–downstream mass balance approach (Equation (2)) to determine the differential load. A similar approach was also followed by (C. K. Jain, 2000; C.K. Jain et al., 2007; Sekhar & Sreenivasulu, 2003). From the calculated CMB analysis at each monitoring station (Table 3.6), we found that the prevalence of differential uncharacterized nonpoint source load at the middle and downstream segment of the LAR with highest calculated differential load were BOD, COD, and TDS, which had shown highest loads at segment outlets M9, M10, M12, M13, and M14, and the influence of uncharacterized nonpoint sources were found to be significantly high. The areas were dominated by urban set-ups (industrial with both large and small scale), residential settlement (usually informal), and agricultural (predominantly small scale) land uses.

Table 3.6: Uncharacterized (differential) nonpoint source pollutants load at LAR monitoring stations, chemical mass balance (CMB) analysis.

	Catchment Outlet Differential Load, t/yr										
Pa	M1	M2	M3	M4	M5	M9	M10	M11	M12	M13	M14
BOD	27.8	12.7†	269.7	94.15†	51.9	1833.2	1867.5†	738.49	395.15	157.6†	1007.8†
COD	181.6	87.7	471.9	108.8	65.5	5588.7	1859.5	3228.6†	2306.9	3217.2	192.12
NO_x	0.05	0.04†	0.61	0.18	0.04	6.05†	15.11	2.15†	10.59†	0.17	6.1
PO4	0.72	0.12†	0.43	0.24	1.99	12.43	13.92	7.46	23.63	11.79	7.82†
TDS	80.7	6.6	162.2	54.06	36.8	581.9	59.67†	558.85	730.78	1916.2	389.62
TN	1.77	5.39	10.22	11.38†	15.92	157.2	674.79	97.02	708.88†	227.6†	76.82

Pa = parameters; differential load = incremental load of the downstream station relative to the upstream station/s; NO_x = reported as NO_3+NO_2; †deficit (sink).

The organic pollution contribution from the nonpoint sources prevailed in the study area where the maximum calculated differential BOD load was observed at M9 with 1833.2 t/yr, where the station is located downstream of two highly polluted but large streams make a confluence. On the other hand, the maximum COD differential load from the nonpoint source was observed at the same station with a calculated load of 5588.7 t/yr contributed by the sub-catchment having an area of 826.419 ha, followed by M13, M12, and M10, having annual load of 3217.2 t, 2306.9 t, and 1859.55 t, respectively. Similarly, high BOD depletion was observed at downstream stations M10 (1867.49 t/yr), M11 (738.49 t/yr), and M14 (1007.76 t/yr), where the impacts of nonpoint sources were assumed to be insignificant, showing that the river is going through a high rate of recovery, possibly due to morphometric effects and the improved self-purification capacity of the river (Setiawan et al., 2018).

High PO_4-P differential load was calculated at most downstream stations characterized by small-scale urban agricultural activities prevailing at M12 (23.63 t/yr), followed by M10 (12.92 t/yr) and M9 (12.42 t/yr). Besides, the area is characterized by large number of small-scale industries, dumping sites for informal solid waste including bio-waste, wastewater treatment plant effluent, and animal remains. On the other hand, from Table 3.6, it can be seen that high differential TN load from uncharacterized nonpoint source was calculated at monitoring stations M9 (157.2 t/yr), M10 (674.79 t/yr), and M11 (97.02 t/yr), whereas stations M4, M12, and M13 were identified as areas with TN sink. COD, BOD, TDS, and TN were found to be dominant nonpoint source load contributions and were found in large quantities prevailing in the middle and downstream segments, indicating the increased impact of washouts from agricultural and urban land uses. The CMB analysis in LAR revealed that most of the organic waste load were concentrated at the middle segment of the river, whereas the sink for these pollutants was found far downstream. The CMB analysis in LAR also showed that NOx, TN, and BOD had sinks at most of the LAR monitoring stations calculated at outlets. Stations M9–M14 are the recognized sink areas for organic pollutants and nutrients located in the middle and downstream segments of LAR. A similar finding was reported by Elósegui et al. (1995), where most of the nutrient load in river Agüera in Northern Spain was retained in the middle of the river. The station M11 is a place where the organic pollutants are highly degraded and hence the area was identified as a major nutrient sink. It is a place where public protected park (Biheretsige Park) is located, which could reduce the impact of nonpoint source load contributions. Relative to the downstream and middle catchments, the upstream segments have low nonpoint source load contributions, where a similar result was also found by Jain et al. (2007) on Hindon River, India. This could be due to relatively low flow, less anthropogenic influence in the area, and the presence of buffer zones such as grass strips and urban forests.

From the CMB analysis (Figure 3.5), it can be seen that most of the constituents in the upstream section of the LAR (M1–M5) had minimum differential load, showing reduced impact of nonpoint source pollution. Conversely, differential loads of BOD, TN, and NOx have shown most of the sinks were observed at the middle and downstream segment of LAR, where riversides are protected by grasses and plants, predominantly at M10 and M11. Maximum loads of nutrients, such as TN, NOx, and PO_4-P, were recorded at M10, which was also identified as a major sink for BOD. Similarly, M14 was found as an area where both TN and NOx have shown a positive differential load. The station is found downstream of the discharge point of wastewater treatment plant effluent and is also characterized by small-scale urban agriculture.

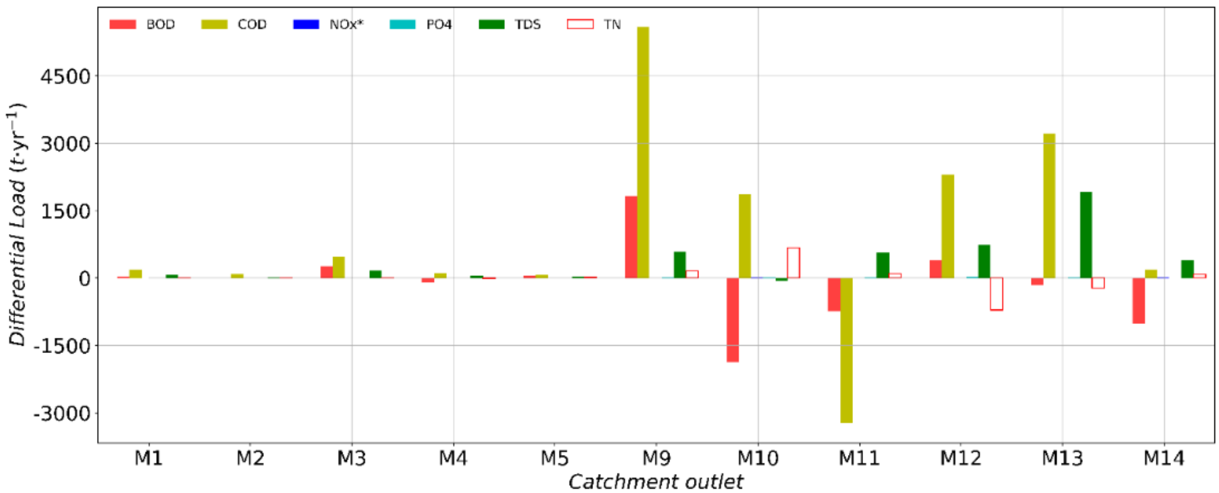

Figure 3.5: Differential pollutants load calculated at selected monitoring stations in LAR (t/yr).

3.3.4. Integration of CMB-PLOAD and Uncharacterized Nonpoint Source Load

Loads calculated at selected LAR subcatchment outlets (monitoring stations) by CMB were used for PLOAD calibration and the selected ECf for LAR was used as an initial estimation for calibration. During the calibration of PLOAD in Excel Solver, the ECf were used as independent variables and the ranges were constraints by setting the upper and lower bounds of the ECf based on the literature for optimization. At the initial stage of calibration and pre-optimization, the total percentage error between the model-predicted and measured load at all monitoring stations for COD, BOD, TDS, NO_X, PO_4-P, and TN were 3680.6%, 2965.64%, 767.97%, 446.8%, 750.40%, and 899.36% respectively. After the optimization of the ECf in Solver, the average percentage relative error dropped to 12.16%, 3.98%, 0.53%, 26.86%, 8.9%, and 29.22%, respectively. On the other hand, the sum of errors in COD was found to be higher than BOD, which resulted in a total sum of error at 3680.6% pre-optimization, where much was attributed by station M5, at which point the PLOAD underestimated both constituents at the station.

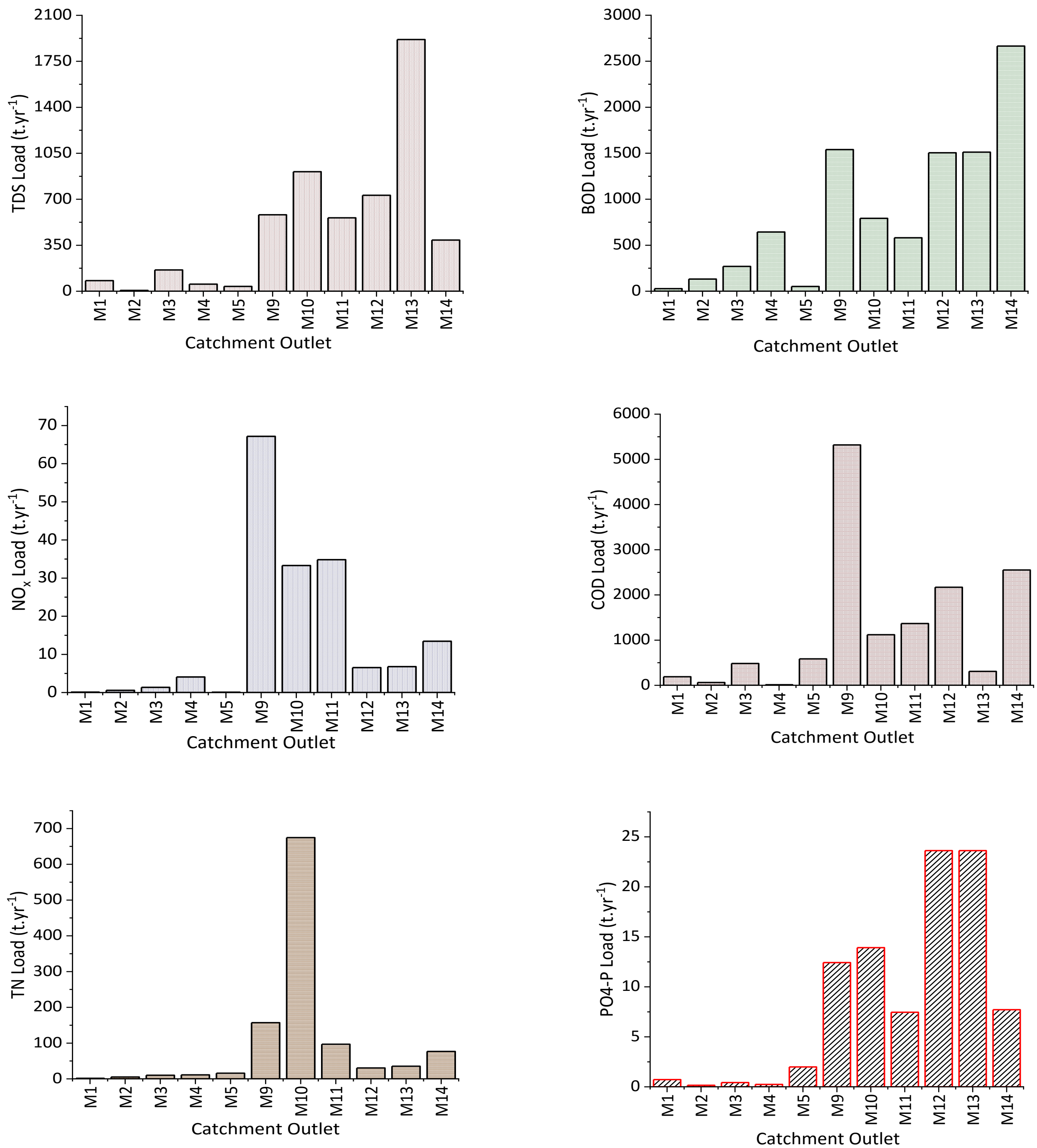

Figure 3.6: Nonpoint source pollutant loads at selected catchment outlets of LAR (t/yr).

The PLOAD prediction for TDS was relatively accurate, where the total relative error at all monitoring stations before optimization was found to be 767.97%, which sharply dropped to 0.53% after optimization. Unlike other parameters, the PLOAD model has overestimated the TDS load in the upstream section of the LAR (M1–M5, and M9), whereas the model underestimated the PO_4-P load in LAR at the downstream segment of the river. High total errors were recorded at smaller catchments of LAR than the bigger catchments, and Zinabu et al. (2017) also came up with a similar finding in Kombolcha catchment, Ethiopia. From the optimized ECf, we found that urban and agricultural land use ECf varies greatly with varying urban land-use types and has shown a significant variation spatially. The water body land-use showed minimum change over the loading of constituents across the monitoring stations, which could be due to less area coverage in the watershed.

Table 3.7: Uncharacterized nonpoint source load in LAR by integrating CMB and PLOAD, t/y.

R‡	TDS	BOD	COD	PO_4-P	TN	NO_X
M1	80.77	27.82	189.96	0.72	1.768	0.102
M2	6.56	132.0†	62.432	0.155†	5.391	0.572†
M3	162.18	269.69	482.89	0.431	10.217	1.352
M4	54.055	644.28†	14.31	0.243	11.232†	4.063
M5	36.76	51.91	585.64	1.993	15.913	0.083
M9	581.95	1540.12	5319.119	12.428	157.242	67.168†
M10	910.12†	792.22	1119.375	13.921	674.791	33.304
M11	558.85	581.51†	1367.92†	7.46	97.018	34.825†
M12	730.78	1504.80†	2170.24	23.627	30.462†	6.529†
M13	1916.16	1511.69†	308.91	23.628	35.453†	6.791†
M14	389.72	2664.75†	2551.43	7.717†	76.825	13.454

†Loads where the deficit was calculated by CMB analysis but PLOAD estimated the value from nearby sub-catchment ECf; ‡catchment outlet where PLOAD was calibrated, and hence represents catchment nonpoint source load contribution.

The PLOAD was rerun using the median and mean value of the optimized and calibrated ECf. Though the median ECf gave minimum total percentage error relative to the mean value, high variation in the ranges of the ECf made the load to vary greatly, and hence the loads calculated by both mean and median ECf were not acceptable. The optimized ECf values revealed that the use of mean and median value resulted in an underestimation of pollutant load at some catchment outlets, whereas overestimation on others. Thus, the use of area-specific ECf was relatively acceptable and was found effective in better estimation of pollutant loads in LAR. The study conducted by Shrestha et al. (2008) also recommended the use of area-specific and development of local ECf for effective pollutant load estimations. The optimized values can then be interpreted well for LAR and used for the management of the nonpoint source pollution load in the catchment. Similarly, the PLOAD was validated for a different data set without changing the optimized export coefficient and the error calculated from the model was acceptable for further interpretation. Accordingly, the percentage error between the PLOAD predicted and measured values for COD, BOD, TDS, NOx, PO_4-P, and TN during validation were found to be 16.41%, 7.06%, 1.77%, 13.23%, 5.4%, and 18.83%, respectively.

The calibrated pollutant ECf showed that the urban land uses had significantly varying export coefficients. Accordingly, the pollutant loading rate for urban land use ranged from 42.1–2083 kg/ha/yr, 63.3–2012 kg/ha/yr, and 0.49–1.6 kg/ha/yr for COD, TDS, and PO_4-P, respectively, varying with the subtype of urban land use (such as residential, commercial, industrial) and location. The urban land uses dominated by residential settlements and industries do have high loading rates, whereas other urban land uses have relatively lesser rates. Similarly, the urban land use pollutant ECf for BOD and NOx also vary greatly, ranging from 120–1950.55 kg/ha/yr and 0.1–47.32 kg/ha/yr respectively. The high variation in ECf spatially is due to the high difference in the impact of nonpoint sources among various urban land uses. The upstream urban land uses have less pollutant loading than the middle and downstream catchments (Table 3.7). The agricultural land use for all the constituents was sensitive in controlling the impact of the pollutants load on the LAR. Though the contribution of agricultural land for nonpoint COD load was quite constant with a range of 79.64–81 kg/ha/yr, an appreciable magnitude of ECf for TDS with 76.4–2005 kg/ha/yr would suggest that the agricultural land use varies spatially in contributing the TDS loading rate. Similarly, PO_4-P, NOx, and BOD have an annual loading rate of 7.72–8.1 kg/ha, 0.1–30.16 kg/ha, and 60.25–60.8 kg/ha/yr from the agricultural land use.

3.4. Conclusions

In this study, conjunctive application of chemical mass balance and watershed model, PLOAD, was used to estimate the nonpoint source load in the data-scarce Little Akaki River, Ethiopia, which was found effective. The approach proved to be more efficient in the study area, which ultimately focused on the determination of organic pollutants and nutrient loads based on a continuously monitored water quality data in the river. The following major conclusions were drawn from the research findings.

- The impact of nonpoint sources in the upstream segment of the LAR catchment was relatively less than the downstream and middle segments, primarily due to the reduced impacts of unrecognized point sources, less urban settlements, better land-use protection and management. Moreover, lesser flow rate in the upper segment of the river could be playing a critical role for the lower diffuse source load in the area.
- The integration of CMB and catchment nonpoint source pollution models such as PLOAD could be an effective and alternative pollutant load estimation approach in data scarce areas.
- The nonpoint source pollutant load was found to be very high in areas where urban land uses prevail, followed by agricultural and barren land uses, indicating the nonpoint source pollution management focus areas. Mitigation measures involving these land uses is recommended.
- Area-specific (local) pollutant export coefficients were found to be more effective and accurate load estimation approach than the use of mean and median export coefficients, which ultimately give a lower error during pollutants load calculation. Despite higher accuracy of CMB for the estimation of differential uncharacterized nonpoint source load estimation, integrating with a simple watershed model was found to be a good alternative for a more accurate representation of the diffuse source load.
- Under- and overestimation of the PLOAD for pollutant load estimation was observed at some catchment outlets, which when integrated with CMB analysis gave a promising result. But adaptation of global export coefficient to the local condition with different hydro-climatic setup is the limitation of the integral modeling approach.
- The pollutant and nutrient export coefficients developed in LAR catchment could be transferred to other catchment elsewhere in the country for similar application for preliminary nonpoint source pollutant load management. The accuracy and effectiveness of the CMB for nonpoint source load estimation highly depends on a number of factors, such as frequency of data collection, distance between the monitoring stations, and identification of the major point sources to the river.

In conclusion, the integral application of chemical mass balance and watershed models such as PLOAD could be a better option for the estimation of nonpoint source pollutant loads in areas with few monitored water quality data. Future studies incorporating the vast and long-term monitoring program at larger catchment scale would be helpful for better pollution load management in the river.

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4. Water Quality Modeling and Selection of Optimum Pollution Management Options

This chapter explored about water quality modeling pre- and post-processing techniques, inputs and variables. It investigated the applicability of water quality models for data scarce areas. Moreover, the role of water quality model (QUAL2Kw) in the river pollution management and selection of optimum control techniques based on development of targeted scenario was also discussed in detail.

This chapter is based on the following journal article:

Angello, Z. A., **Behailu, B. M.**, & **Tränckner, J.** (2021). Selection of Optimum Pollution Load Reduction and Water Quality Improvement Approaches Using Scenario Based Water Quality Modeling in Little Akaki River, Ethiopia. Water, 13(5), 584. https://doi.org/10.3390/w13050584

Abstract: The collective impacts of rapid urbanization, poor pollution management practices and insufficient sanitation infrastructure have driven the water quality deterioration in Little Akaki River (LAR), Ethiopia. Water quality modeling using QUAL2Kw was conducted in the LAR aimed at selecting the optimal water quality improvement and pollution load reduction approaches based on the evaluation of five scenarios: modification of point sources (PS) load (S1), modification of nonpoint sources (NPS) load (S2), simultaneous modification of PS and NPS load (S3), application of local oxygenators and fish passages using cascaded rock ramps (S4), and an integrated scenario (S5). Despite the evaluation of S1 resulting in an average load reduction of Biochemical Oxygen Demand (BOD) (17.72%), PO_4-P (37.47%), NO_3-N (19.63%), the water quality objective (WQO) in LAR could not be attained. Similarly, though significant improvement of pollution load was found by S2 and S3 evaluation, it did not secure the permissible BOD and PO4-P pollution load in the LAR. Besides, as part of an instream measure, a scenario evaluated using the application of rock ramps (S4) resulted in significant reduction of BOD load. All the individual scenarios were not successful and hence an integration of scenarios (S5) was evaluated in LAR that gave a relatively higher pollutant load reduction rate and ultimately was found a better approach to improve pollution loads in the river. In conclusion, pollution load management and control strategy integrally incorporating the use of source-based

wastewater treatment, control of diffuse pollution sources through the application of best management practices and the application of instream measures such as the use of cascaded rock ramps could be a feasible approach for better river water quality management, pollution reduction, aquatic life protection and secure sustainable development in the LAR catchment.

Keywords: QUAL2Kw, pollution reduction Scenario, Pollution Load; Little Akaki River, WQO

4.1. Introduction

Urbanization is greatly impacting the river water quality of developing countries driven by factors such as lack of proper sanitation infrastructure and urban drainage networks, poor land use management, the knowledge gap in environmental systems, and managerial incapability (McGrane, 2016; T. Ouyang et al., 2006; Qin et al., 2014). Nowadays, the beginnings can be seen, though slowly, of urban river pollution becoming a core focus area due to the threats it poses for the water environment through a wide range of physical, chemical, and biological processes (Jiabiao Wang et al., 2018). Primarily, the wastewater released from various sources such as industry, household, agricultural and urban land use has augmented the pollution load in the rivers which heavily degrades the aquatic environment (J. Wang et al., 2012). Moreover, the release of nutrients from agricultural land to the surface water resources promotes eutrophication which ultimately depletes the dissolved oxygen concentration (D. T. Mekonnen et al., 2020; Waseem et al., 2018). Despite the high impact of pollution originating from the point and nonpoint sources on urban rivers of developing countries, pollution management and control has remained unsuccessful mainly due to the direct adaptation of management policies from developed worlds without customization to the local conditions (Awoke et al., 2016).

Owing to a lack of better mitigation and remediation steps as part of the management strategy, most of the river water quality management and pollution control policies in developing countries remain unsustainable. Researchers recommend that sustainable urban river pollution management should incorporate practical remediation approaches. In line with this, water quality models are gaining the advantage in predicting surface water quality pollution management and hence are used in the decision-making process and implementation of the mitigation measures (Oliveira et al., 2012). The conventional way of using these water quality models in pollution management is to link the upstream pollution source with the downstream consequences. The water quality management strategies hence involve a complex set of interdisciplinary decisions based on the changing water quality characteristics where the determination of the complex relationship between the surface water pollution sources and associated water qualities can best be represented by water quality models (Raj et al., 2007). The water quality models are also used in wider water quality management applications such as determination of the impact of point and nonpoint source loads on surface water quality (Chong-hua et al., 2015; León et al., 2001), the determination of the fate and transport of agricultural waste on river water quality (Luo & Zhang, 2009), and the development of pollutant load reduction strategies and allocation techniques (Desai et al., 2011).

To date, several water quality models have been developed to solve complex water environmental and pollution management problems. Various researchers used different water quality models and the integration of models to solve such water environmental problems. Yuceer & Coskun (2016) used a continuous stirred tank reactor approach to model the water quality constituent dynamics where a good agreement was found between the model predicted and measured values recommending the use of the approach for further pollution management. An integrated model between water quality, hydrological and watershed models such as River Water Quality Model No. 1 (RWQM1), SWAT, and SWMM were evaluated on the Zenne river, Belgium where the modeling output showed that the integrated models can effectively simulate the water quality constituents very well (N. K. Shrestha et al., 2016). Despite the development of various water quality models that have wider applications in water environmental management, most of them remain complex, requiring a large set of data which is the bottle-neck, particularly in developing countries with a high hydro-meteorological and water quality data scarcity (Gao & Li, 2014). Hence, the use of a less complex but relatively accurate water quality model would be a feasible technique for pollution management in urban rivers. In this regard, the QUAL2Kw model is often used for water environmental management and is suggested by many water quality modelers not only due to its simplicity but also its adaptability to various type of catchments, affordable data demand, and effective simulation of constituent dynamics, fate, and transport (Holguin-Gonzalez et al., 2013; Reza et al., 2015; Vieira et al., 2013; R. Zhang, Qian, Yuan, et al., 2012).

In Ethiopia, urbanization has largely triggered the expansion of medium and large-scale industries. In particular, most surface water resources in the capital Addis Ababa are polluted by waste water released from different sources. Industrial waste, which directly discharges waste water with little to no treatment, is one of the major pollution sources. Today, there are over 2000 industries in the city, most of them founded near rivers (Gebre & Rooijen, 2009). Wastewater from households (Angello et al., 2021) and human excreta and feces wash-outs from open fields (Abebe & Tucho, 2020) contribute a large quantity of waste load to the Little Akaki River (LAR). Runoff through urban drainage is discharging a significant quantity of pollutants at different locations along the length of the river (Abegaz, 2005; Aschale et al., 2016). Urban small-scale agricultural activities within the vicinity of the river banks contribute a significant quantity of pollutants washed off from agricultural fields to the LAR (A. Mekonnen, 2007). Despite the ratification of the wastewater management plan of Addis Ababa city in 2017 (MoWIE, 2017) and the development of the charge-per-pollution (CPP) program in 2018 (Awash Basin Authority, 2018) which serves as an economic instrument that provides an incentive to reduce dis-charges of polluting effluents from point sources, the river's water quality is deteriorating and hence needs a clear, working and scientifically sound management strategy. The objectives of this research, therefore, were to simulate pollutant transport and dynamics using a modified stream water quality model (QUAL2Kw) in the LAR, to develop a scenario-based water quality management strategy and ultimately select the optimal water quality improvement and pollutant load reduction approaches in the study area.

4.2. Materials and Methods

4.2.1. The Study Area

Addis Ababa, located in the central highlands of Ethiopia, is the country's capital and largest city. Due to high rate of urbanization, the city's solid and liquid waste generation rate is increasing alarmingly where the rivers are serving as an "open sewer". The city has three major rivers: Kebena River, Big Akaki River (BAR) and LAR all originating at the foothills of Entoto mountain and drains down to Aba Samuel Lake. The LAR, one of the Awash River tributaries, flows from the northwest of the city to the most southern Addis Ababa before joining the BAR at Aba Samuel Lake. The LAR consists of a number of heavily polluted tributaries mainly by untreated household waste including raw sewage and industrial waste that increases the pollution load in the river. The location of large-scale industries within the vicinity of the river that are discharging their wastewater directly to the river without or minimum treatment have also augmented the pollution load in the river. Details of all the monitoring stations are presented on Figure 4.1.

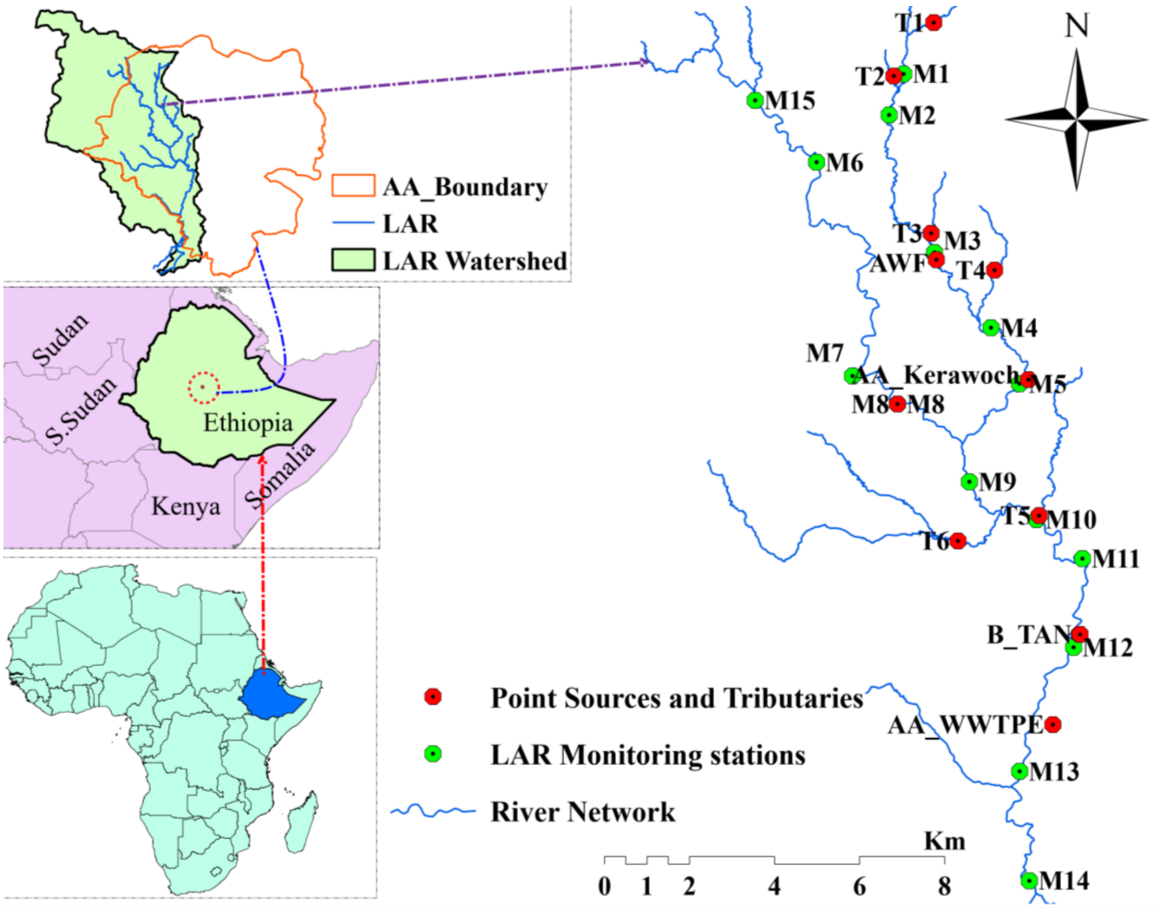


Figure 4.1: The LAR water quality monitoring stations and point source locations (AA=Addis Ababa)

4.2.2. Sampling and Analysis

A bimonthly water sample collection from April 2018 to March 2019 was con-ducted at 22 monitoring stations on LAR. All the analytical methods are shown in Table 4.1 and the analysis was conducted according to (APHA, 1999).

Table 4.1: Analytical methods used for the analysis of water quality constituents

Parameter	Analytical Method	Apparatus/Equipment
BOD	Modified Winklers Method	BOD Incubator
TDS	TDS Probe	HQ40d
COD	Titrimetric	COD Digester, Heating Block
NO_2-N	Spectrophotometric	HACH DR-2800
PO_4-P	Spectrophotometric	HACH DR-2800
NO_3-N	Spectrophotometric	UV-VIS Spectrophotometer
TKN	Kjeldahl Method	Kjeldahl Distillation
TP	Stannous Chloride Method	UV-VIS Spectrophotometer
NH_3-N	Titrimetric	Kjeldahl Distillation

4.2.3. The QUAL2Kw Model

Water quality models are nowadays becoming efficient in water environmental management, primarily developed to predict the fate and transport of contaminants in water bodies (Gao & Li, 2014). They are used in many water resource applications such as environmental impact assessment, pollution management and remediation (Q. Wang et al., 2013), determination of nutrient load, transport and dynamics (Brito et al., 2019), nutrient control and eutrophication (Mamani Larico & Zúñiga Medina, 2019), and waste load allocations (Tsegaye, 2019). The QUAL2Kw is one of such models, a one dimensional, steady-state model for water quality modeling of rivers, estuaries, and well-mixed lakes (Mateus et al., 2018). The model simulates constituents in surface water using the advective−dispersive approach through a mass balance approach. The model can simulate up to 16 water quality constituents in any combination (Marcello Benedini and George Tsakiris, 2013) including DO, BOD (fast and slow), T, pH, EC, suspended solids, alkalinity, total inorganic carbon, TN, ammonia/ammonium, NO_3-N, NO_2-N, organic and inorganic phosphorus, chlorophyll a, coliform bacteria, one nonconservative constituent (arbitrary), and three conservative constituents (G. Pelletier & Chapra, 2008). In QUAL2Kw, the dissolved organic nitrogen increases due to detritus dissolution whereas the ammonium nitrogen is gained due to dissolved organic nitrogen hydrolysis and plant respiration and lost due to nitrification and plant photosynthesis. Similarly, organic phosphorus increases due to plant death and is lost via hydrolysis and settling whereas inorganic phosphorus increases due to organic phosphorus hydrolysis and phytoplankton respiration.

The QUAL2Kw uses two forms of carbonaceous BOD; slowly oxidizing BOD (sBOD) and fast oxidizing BOD (fBOD) where denitrification is modeled as a first-order reaction when low oxygen concentrations are limiting aerobic BOD degradation (Kannel et al., 2011). The sBOD is gained due to the detritus dissolution which on the one hand is lost due to oxidation and hydrolysis. On the other hand, fBOD increases hydrolysis of sBOD and is lost due to oxidation and denitrification. Nitrification of ammonia causes an increase in nitrate nitrogen that on the other hand is lost through denitrification and photosynthesis. The detailed water quality state variables interaction is shown in Figure 4.2. The model simulates the transport of conventional water quality constituents assuming the river as a one-dimensional channel having steady and nonuniform flow. Whereas the flow in QUAL2Kw is assumed as steady, the water quality constituents are calculated by diel water quality kinetics and heat budget dynamically in which the impacts of both point and nonpoint source loads are simulated (G. J. Pelletier et al., 2005). The model has the ability to simulate the fate and transport of constituents except the conversion of algal death to BOD (Kannel et al., 2011). The model calculation is based on a general mass balance equation (Equation (1)) that governs the simulation process (Raj et al., 2007).

$$\frac{dc_i}{dt}=\frac{Q_{i-1}}{V_i}C_{i-1}-\frac{Q_i}{V_i}C_i-\frac{Q_{ab,i}}{V_i}C_i+\frac{E_{i-1}}{V_i}(C_{i-1}-C_i)+\frac{E_i}{V_i}(C_{i+1}-C_i)+\frac{W_i}{V_i}+S_i \qquad (6)$$

Where Q_i is flow at reach i, $Q_{ab,i}$ is the abstraction from reach i, V_i is volume of reach i, W_i is the external load of constituent to reach i, Si is the source and sink of the constituent due to reaction and transfer, E_i is bulk dispersion coefficient.

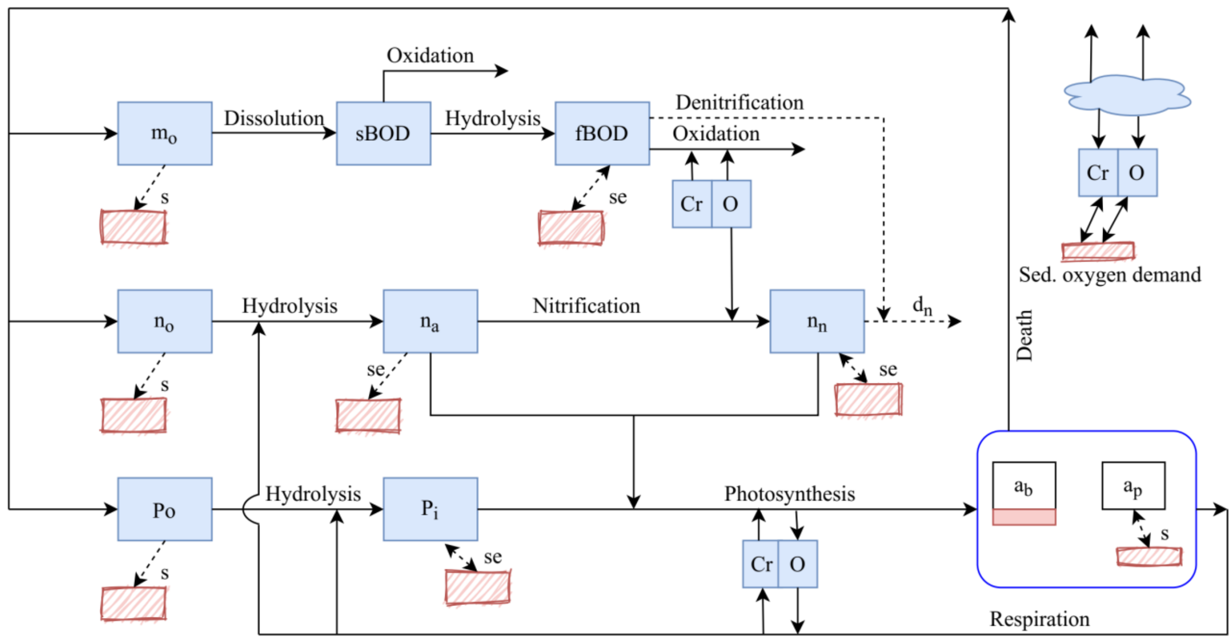
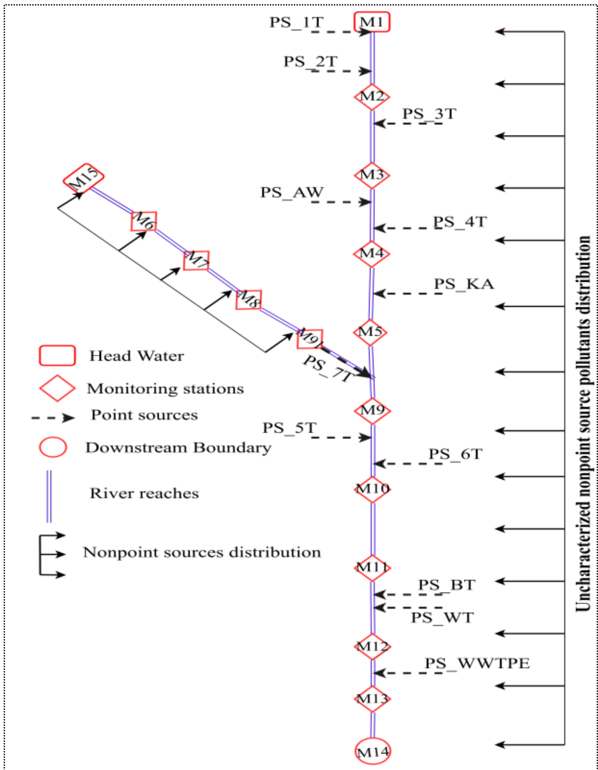


Figure 4.2: Schematic diagram of interacting water quality state variables in QUAL2Kw (a_b: bottom algae, a_p: phytoplankton, m_o: detritus, sBOD: slow CBOD, fBOD: fast CBOD, se: sediment exchange, d_n: denitrification, Cr: inorganic carbon, DO: dissolved oxygen, n_o: organic nitrogen, n_a: ammonia nitrogen, n_n: nitrate nitrogen, po: organic phosphorus and pi: inorganic phosphorus).

4.2.4. LAR Segmentation, Labeling and Discretization in QUAL2Kw

The QUAL2Kw is suitable for both straight and dendritic rivers where it considers a river without tributaries as a series of reaches (R. Zhang et al., 2014). The reaches are hence grouped according to their hydraulic and hydro-geometric properties which should hold the same characteristics (Goktas & Aksoy, 2007). In QUAL2Kw, the river reaches play an important role that in turn is classified into several computational elements (CEs) (G. Pelletier & Chapra, 2008). The reach numbering in QUAL2Kw starts with a 1 beginning from the headwater reach until it reaches the junction with a tributary where another numbering starting with 1 from the tributary headwater. Accordingly, the LAR was divided into 16 reaches (5 in segment 1 and 11 in segment 2) which then are divided into 48 computational elements (15 in segment 1 and 33 in segment 2) based on their hydro-geometric similarity. The nonpoint source was assumed to be uniformly distributed across the river stretch (Figure 4.3a) (Z. Xin et al., 2019).



(a)

Station		Reach Label	Length (km)	CEs	Description
From	To				
T1	M1	Medhanealem	0.11	1	The head water segment
M1	M2	Kolfe Taiwan	1.33	2	The upstream reach
M2	M3	Mercato	5.45	4	Highly polluted river section
M3	M4	Mexico	4.64	5	Highly polluted river section
M4	M5	Kerawoch	2.14	2	polluted from waste from abattoirs
M5	M9	German Menged	3.48	3	Confluences of two major rivers
M9	M10	Biheretsige Maryam	2.82	3	High nonpoint source impact
M10	M11	Biheretsige Park	2.72	3	High nonpoint source impact
M11	M12	Industry Zone	2.86	3	Receptor of many industrial waste
M12	M13	Kality Fisash	3.77	4	Receives WWTPE
M13	M14	Aba Samuel	4.32	4	Dominated by agricultural waste
T7	M15	Addis Ababa Koda	1.298	2	Head water reach for segment 1
M15	M6	Ashewa Meda	3.114	3	Influenced by agriculture
M6	M7	Yeshi Debele	8.398	8	Relatively undisturbed
M7	M8	Augusta Maryam	1.998	2	Relatively undisturbed
M8	M91	Qore Menged	2.11	2	Outlet to the main River

(b)

Figure 4.3: Segmentation (a) and labeling (b) of LAR for QUAL2Kw modeling (WWTPE = wastewater treatment plant effluent).

4.2.5. Calibration, Validation, and Performance Evaluation of QUAL2Kw

QUAL2Kw The QUAL2Kw model in LAR was run until the system parameters were properly adjusted and a reasonable agreement between model predicted and actual measurements was achieved. For the constituent simulation in LAR, the calculation time step was chosen 5.625 min so that the model could be simulated with the assumption that the steady-state was maintained and instability was controlled (Kannel et al., 2007). The integral solution used in QUAL2Kw calibration for LAR was based on Euler's method. In LAR, the QUAL2Kw was calibrated by adjusting and minimizing the error between the observed and model-predicted value (Turner & Pelletier, 2009) using a monitored water quality constituent and flow by adjusting the parameters that controlled the pollutants and nutrient dynamics. The detritus, inorganic suspended solids, phytoplankton, and pathogens were not simulated due to data limitations and a default value of 100 mg/L was used as alkalinity as calcium carbonate. The reaction rates, heat constants, and hydraulic parameters were used for calibration where the rate and constants were estimated from the literature (USEPA, 1985). In order to assess the ability of the calibrated model to predict water quality constituents, the model was rerun using different data without changing the calibrated parameters. Manual and autocalibration were performed to closely observe the changes in the model parameters through the embedded autocalibration genetic algorithm (GA) by setting the goodness of fit formula (Equation (7). Accordingly, the weighted mean inverse Root Mean Square Error (RMSE) method was chosen as a method of fitness criteria. The individual parameters in the modeling were given weight according to the impact of the parameter on the LAR. The GA control for auto-calibration recommended by the QUAL2Kw, PIKAIA, was used by adjusting to the local condition. The autocalibration uses GA to find the best fit between a set of paired parameters by comparing the model predicted and measured water quality constituents.

$$f(x)=\left[\sum_{i=1}^{q} W_i\right]\left[\sum_{i=1}^{q}\frac{1}{W_i}\left[\frac{\frac{\sum_{j=1}^{m} O_{i,j}}{m}}{\left[\frac{\sum_{j=1}^{m}(P_{i,j}-O_{i,j})^2}{m}\right]^{1/2}}\right]\right] \quad (7)$$

Where: $O_{i,j}$ =Observed value, $P_{i,j}$ =Predicted value, m=number of pairs of predicted and Observed values, Wi=waiting factor, q= the number of variables used in the reciprocal of weighted normalized RMSE

The sensitivity analysis was performed in the LAR by applying a ±50% variation on calibrated parameters and analyzing the disturbance and ultimately selecting the most influential parameters. The most influential parameters hence were used as a means to develop a pollution reduction scenario. During the calibration of water quality models, although there are many statistical measures to evaluate the model performance, the performance indicators such as percentage bias or error (PBIAS), coefficient of determination (R^2), and Nash−Sutcliff (NSE) are often used. According to Bui et al. (2019), if |PBAIS| < 25% the model simulation is considered “very good”, “good” if 25% ≤ |PBAIS| < 40%, “satisfactory” if 40% ≤ |PBAIS| < 70%, and “unsatisfactory” if |PBAIS| ≥ 70%. Different water quality modelers use different performance evaluation approaches but the recommended methods are |PBIAS| < 25% (Keraga, 2019), R^2 > 0.5 (Chong-hua et al., 2015), and NSE > 0.5 (Moriasi et al., 2015). However, it is often challenging to find all three criteria satisfying at the same time. Bui et al. (2019) recommended the use of PBIAS over any other evaluation methods in water quality modeling. In the LAR, however, R^2 (Equation (8) and PBAIS (Equation (9) were used interchangeably to evaluate the QUAL2Kw model performance and the acceptable ranges are shown in Table 4.2.

Table 4.2: General performance ratings of the recommended statistics for a monthly time step

Measure	Output response	Performance Rating				Reference
		Very Good	Good	Satisfactory	Unsatisfactory	
R^2	Nutrient	> 0.70	$0.60 < R^2 \leq 0.70$	$0.30 < R^2 \leq 0.60$	≤ 0.30	(Keraga, 2019)
	Flow	>0.80	$0.70 \leq R^2 \leq 0.80$	$0.50 < R^2 < 0.70$	≤0.50	
PBIAS	Nutrient	≤±15	±15 < PBIAS < ±20	±20 ≤ PBIAS < ±30	≥±30	(Moriasi et al., 2015)
	Flow	≤±5	±5 < PBIAS < ±10	±10 ≤ PBIAS ≤ ±15	>±15	

$$R^2=\left[\frac{\sum_{i=1}^{n}(Oi-\bar{O})(Pi-\bar{P})}{\sqrt{\sum_{i=1}^{n}(Oi-\bar{O})^2}\sqrt{\sum_{i=1}^{n}(Pi-\bar{P})^2}}\right]^2 \tag{8}$$

$$PBIAS=\frac{\sum_{i=1}^{n} Oi-Pi}{\sum_{i=1}^{n} Oi}*100 \tag{9}$$

Where O and P are observed and predicted values respectively.

4.2.6. Input Data and Parameter Estimation for QUAL2Kw

Data play a key role in the accurate determination of pollutant fate and transport in surface water quality simulation (Marcello Benedini and George Tsakiris, 2013). In the LAR, however, certain parameters were not available and hence the determination depends on the estimation of the values from the literature and other secondary data sources. Accordingly, meteorological data were derived from five weather stations located near the study area and analyzed as per the requirement of the QUAL2Kw model. Hourly wind speed and air temperature data from Bole Observatory station were used for modeling since finer data for other stations nearby were missing. The dew temperature for the study area was calculated using the tool dew01 that uses daily maximum and minimum temperatures and daily average humidity and was calculated by a monthly time step whereas other parameters such as shade and cloud cover were assumed based on the local conditions. In the absence of available data, the sediment oxygen demand (SOD) was estimated from the literature. Previous studies in the study area by Hamda, (2007) showed that the SOD in the LAR ranged from 5–10 g/m2/d, varying with the depth of the river, and hence in the LAR, SOD was assumed to range from 2–10 g/m2/d during calibration. The sediment thermal conductivity and diffusivity were assumed as 1.82 W/m/°C and 0.048 cm^2/s, respectively. All other parameters were defaults taken from Chapra and Pelletier (Chapra & Pelletier, 2003) and rates and constants were adopted from USEPA (USEPA, 1985). Due to the scar-city of monitored data, the value of Manning's roughness coefficient was based on the SWAT calibration result which also agreed with the previous literature in the study area ranging from 0.02−0.045 that varied from upstream to downstream. The oxygen reaeration model selected was internal where the result highly depended on the hydraulic parameters. All other rate parameters and constants such as the reaction rate, decay rate, reaeration rate, death rate, settling velocity, nitrification and denitrification rate, oxidation rate, hydrolysis rate, and temperature correction were all calibrated based on the literature and user manual (G. Pelletier & Chapra, 2008).

4.2.7. Development and Evaluation of Pollution Reduction Scenarios

Different studies reveal that the use of pollution reduction scenarios integrated with water quality models could help in the development of better water quality management programs and assist the decision-making process (Kannel et al., 2007; R. Zhang, Qian, Yuan, et al., 2012; R. Zhang et al., 2014; Zhu et al., 2015). The conventional approach of using this mathematical model in pollution management is usually based on the principle of linking the upstream pollution sources with the downstream responses (consequences). However, most water pollution management programs in developing countries fail due to lack of clear policy and strategy where widespread evidence of water environment destruction associated with the uncontrolled human and industrial waste discharge prevails (FAO, 2000). In this regard, it is often imperative that reduction of pollution load emitted from the point and diffuse sources to the rivers are prioritized during water quality management. However, despite the availability of environmental laws, waste release control, mainly from industry and urban land use is increasing in many developing countries hindering the implementation of sustainable river water quality management and pollution control. Strong environmental law that limits the discharge of industrial wastewater, such as through the use of advanced wastewater treatment plants could greatly reduce the pollution load released to the rivers. Equally important but neglected is the role of the diffuse source load where a significant pollution load is contributed by various land uses and remains the major pollution source in developing countries (Cho & Lee, 2019; Jabbar & Grote, 2019). Reduction of the pollution load from diffuse sources by implementing best management practices and catchment protection such as the creation of a riverside buffer zone would be a better option for ecological restoration (Yu Wang et al., 2019). In-stream measures such as the use of cascaded rock ramps or, if integrated with a weir, often named ramped weirs (Amaral et al., 2019), can support the self-cleaning efficiency and improve the ambient water quality by creating water head that initiates the supply of oxygen. Besides, the structures can also restore natural ecology and create a safe environment for aquatic organisms such as fish by allowing free passage between upstream and downstream even during critical times (Mooney et al., 2007). The instream measures would not be sufficient, however, without reducing the incoming loads from pollution sources and sustainable water quality management and pollution control could not be maintained. Ecological restoration of a polluted water environment therefore needs integrated management of all the pollution sources and instream measures. A successful river water ecological restoration program hence is based on the mitigation and remediation approaches incorporating all the source-based pollution management options and instream measures. However, most water quality management programs in developing countries are not successful due to inappropriate, poorly articulated, and narrowly focused mitigation measures. The water quality remediation techniques need to be incorporated as part of the pollution management programs which involve assessing the relative significance of available point and nonpoint sources, determining the specific remediation objectives, and assessing various management options in cost-benefit terms for pollution source reduction (Ongley & Booty, 1999).

In the LAR, five hypothetical scenarios were evaluated for the development of pollution control and management strategy and to ultimately select the optimal pollution reduction scenario or a combination of scenarios. The scenarios were evaluated on selected and most common pollutants identified by the respective government office of Ethiopia, based on factors such as the pollutant’s toxicity, the threats they pose to water bodies and most importantly the cost of measuring the concentrations and volumes accurately (Awash Basin Authority, 2018). Hence, the scenarios were evaluated based on the modification of organic pollutant (BOD), and nutrient (NO_3-N and PO_4-P) load from the point and non-point sources. Besides, instream measures, such as a cascaded rock ramp making a head difference of 2 m were evaluated as part of the pollution reduction and ecological restoration approach. Once all the scenarios were evaluated individually and integrally, an optimum scenario that best satisfied the water quality objective (WQO) for the parameters was selected and the best combination of the individual constituent reduction rates was determined based on an iterative and trial and error calibration on QUAL2Kw. Since it is difficult to fully meet the standard limits for the constituents in developing countries like Ethiopia, a value close to the permissible limits was used as a WQO. Accordingly, the WQOs for the parameters BOD (10 mg/L), PO_4-P (1 mg/L), and NO_3-N (50 mg/L) were determined in QUAL2Kw until the simulated constituents load fell under the standard guideline (WQO).

4.2.7.1. Scenario 1: Modification of Point Sources Load

The first scenario (S1) was developed in consideration that nearly all of the point sources in the study area have no treatment plants (Aschale et al., 2016; UNEP/ESTC/ECPC, 2005). Accordingly, the scenario evaluation was based on the average removal rate of pollutants in a wastewater treatment plant that put the LAR water quality within the WQO. Hence, the scenario applied for the three selected parameters (BOD, PO_4-P, NO_3-N) was based on the average wastewater treatment plant removal efficiency. Different kinds of literature found different pollutant removal efficiencies in wastewater treatment plants. For example, a horizontal surface flow constructed wetland efficiency tested in a brewery factory in Addis Ababa, Ethiopia, has resulted in more than 87% BOD removal rate (Worku et al., 2018). Similarly, BOD removal using an activated sludge plant in South Africa was found to have an efficiency of 90–95% (Iloms et al., 2020) whereas the BOD removal rate using activated carbon on palm waste was found to have more than 92%. On the other hand, the study performed on the dairy industry in Ethiopia using horizontal subsurface flow constructed wetland had a BOD removal efficiency of 65.2 to 84.2% (Ali, 2013) whereas a slaughterhouse BOD removal showed 91.6% efficiency (Alayu & Yirgu, 2018). Similarly, the removal efficiency of treatment plants for NO_3-N using chemical treatment may range from 10% to 98% based on the type of chemical used (Aghapour et al., 2016), whereas the integrated biological-chemical treatment of PO_4-P was found to have an efficiency of 60–70% (Ruzhitskaya & Gogina, 2017). Studies in Ethiopia showed that the nutrient removal rate was lower than the organic pollutant removal rate (Alayu & Yirgu, 2018). In general, the studies revealed the BOD removal rate ranged from 65% to 95% and the nutrient removal rate ranged from 10% to 98%. Hence scenario 1 was evaluated using an assumed average removal rate of BOD (70%), NO_3-N (50%), and PO_4-P (50%) and was assigned as S1 (0.7BOD + 0.5NO_3-N + 0.5PO_4-P) to represent their respective removal rates in a treatment plant.

4.2.7.2. Scenario 2: Modification of Nonpoint Sources Load

The nonpoint source loads are the dominant loads in the LAR catchment that contribute the highest pollution load to the river (Angello et al., 2020) and the proportion is seen even more than 69% in Korea (S. Lee et al., 2012). For effective management of water quality and pollution control in the river, the determination of nonpoint source load is necessary (Yohannes & Elias, 2017). Hence, the second scenario (S2) evaluation was based on the modification of nonpoint source load. Many studies suggest varying removal efficiencies for BOD, PO_4-P, and NO_3-N using best management practices. Wang et al. (2019) studied the nitrogen and phosphorus removal efficiency of buffer strips and found a reduction rate of 12.12% to 70.54% and 14.38% to 73.3%, respectively. Similarly, the integration of constructed wetlands, retention ponds, grassed waterways, and buffer strips applied on Wuliangsuhai watershed, China, for the same parameters showed the reduction rates of nitrogen and phosphorus were found to be 40–80% and 50–90%, respectively (Shi et al., 2012). On the other hand, the use of an infiltration trench was found to have a removal efficiency of BOD (91.1%), nitrogen (87.1%), and phosphorus (91.2%) (S. Lee et al., 2012). Hence in consideration of the best management practices' adaptability to the local conditions, the S2 was evaluated using an assumed average nonpoint sources load reduction of BOD (80%), NO_3-N (60%), and PO_4-P (60%). The scenario was designated as S2 (0.8BOD + 0.6NO_3-N + 0.6PO_4-P).

4.2.7.3. Scenario 3: Simultaneous Modification of Point Source and Nonpoint Sources Load

In a country where both point and nonpoint sources, individually and collectively, significantly affect the water environment, a sufficient change in the water quality and the development of a better management system due to the modification of one of the pollution sources is highly unlikely. For that reason, S3 combines the measures of S1 and S2 simultaneously.

4.2.7.4. Scenario 4: Application of Local Oxygenators: - Instream Measures

For effective water quality management and ecological restoration, source-based pollution control should be supported by instream measures providing ecological niches, improved physical aeration, ecological passability, etc. For example, the application of local oxygenation techniques through the use of structures such as cascaded rock ramps at critical pollution locations could significantly reduce the pollution load in a river and allow free movement of aquatic organisms such as fish (Armstrong et al., 2010). In principle, the flow of polluted water over such structures creates head and initiates oxygenation and hence reduces the pollutant load in a river and the amount of oxygen to be added to the river depends on the height and type of the structure to be applied (Chapra & Pelletier, 2003). Even though priority should better be given to the reduction of emissions from the point and nonpoint sources, instream measures, such as the application of cascaded rock ramps create not only a smooth transition of aquatic life between upstream and downstream but also bring substantial benefits to the ecology of the catchment (NSW Department of Primary Industries, 2006). It is also one of the widely used approaches for ecological restoration nowadays. Scenario 4 (S4) was hence based on the application of cascaded rock ramps creating a total head difference of 2 m and width varying with the width of the LAR with a gentle slope for the free passage of fish and other aquatic organisms at selected critical pollution locations which could also enhance oxygenation in the river. In contrast to S5 (see below) S4 is applied solely, i.e., without source-based pollution control.

4.2.7.5. Scenario 5: Integrated Scenario

Scenario 5 (S5) is the combination of all scenarios (integrated scenarios). All hypothetical scenarios were individually and integrally evaluated and optimum combination was selected in LAR. Finally, the selection of optimum pollution reduction approach and the reduction rate was based on the iterative simulation in the QUAL2Kw.

4.3. Results and Discussion

4.3.1. Point and Nonpoint Source Loads in LAR

The point and nonpoint source pollutants load is one of the major inputs of the QUAL2Kw. In LAR, eleven-point sources were used including highly polluted tributaries. The Kality wastewater treatment plant effluent is one that contributes a significant quantity of pollution load in LAR. Similarly, highly polluted tributaries of the river also carry a large quantity of pollutants load to the LAR, most of them carrying high domestic and industrial wastewater. On the other hand, the nonpoint source load used in QUAL2Kw was estimated by integrating chemical mass balance (CMB) and watershed model, PLOAD, based on the export coefficient of pollutants, and the detailed approach was summarized in the previous work of the authors (Angello et al., 2020). The summary of point and nonpoint source load in the study area is shown in Table 4.3.

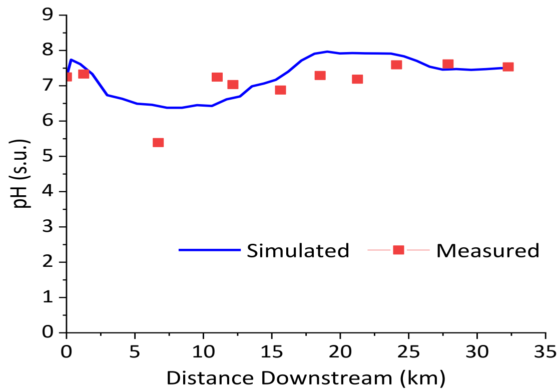
Table 4.3: Summary of annual point and nonpoint source load for selected constituents in LAR*

		Point[n] and Nonpoint Source Load for selected constituents in LAR, t/yr					
P†	R‡	TDS	BOD	COD	PO_4-P	TN	NO_3-N
T2	M1	80.76 (*26.52*)	27.82 (*8.32*)	189.96 (*37.73*)	0.72 (*0.31*)	1.77 (*2.48*)	0.102 (*0.02*)
T3	M2	6.56 (*89.75*)	132.09 (*59.89*)	62.43 (*185.74*)	0.15 (*1.39*)	5.39 (*14.74*)	0.57 (*0.013*)
A	M3	162.2 (*33.76*)	269.68 (*6.39*)	482.88 (*13.69*)	0.43 (*0.45*)	10.22 (*0.58*)	1.35 (*0.122*)
T4	M4	54.05 (*178.36*)	644.27 (*98.28*)	14.31 (*189.45*)	0.24 (*1.18*)	11.23 (*10.18*)	4.06 (*0.056*)
K	M5	36.8 (*306.68*)	51.9 (*105.96*)	585.63 (*821.2*)	1.99 (*3.34*)	15.91 (*5.3*)	0.083 (*0.74*)
T6	M9	581.9 (*3185.59*)	1540.12 (*1005.59*)	5319.12 (*2867.5*)	12.43 (*26.2*)	157.24 (*342.6*)	67.17 (*1.39*)
T5	M10	910.12 (*358.87*)	792.22 (*98.13*)	1119.37 (*341.95*)	13.92 (*4*)	674.79 (*22.07*)	33.3 (*0.115*)
W	M11	558.85 (*49.42*)	581.5 (*3.48*)	1367.92 (*60.74*)	7.46 (*0.62*)	97.02 (*7.076*)	34.82 (*0.74*)
B	M12	730.78 (*103.46*)	1504.8 (*14.53*)	2170.24 (*27.32*)	23.63 (*1.77*)	30.46 (*7.617*)	6.53 (*1.912*)
M	M13	1916.16 (*440.96*)	1511.68 (*217.12*)	308.91 (*622.17*)	23.63 (*8.14*)	35.45 (*147.26*)	6.79 (*1.005*)
M8	M14	389.71 (*5874.3*)	2664.75 (*1052.19*)	2551.43 (*11661.7*)	7.72 (*15.5*)	76.82 (*223.04*)	13.45 (*16.33*)
T1		(42.69)	(19.993)	(82.624)	(0.584)	(5.275)	(0.0234)

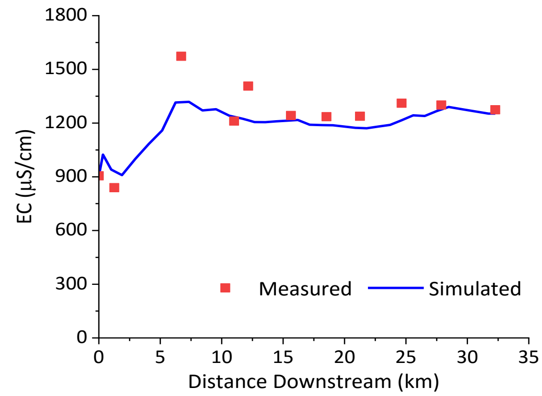
†Point source monitoring stations where A represents (AWF), K represents (AA_Kerawoch), W represents (W_TAN), B is for (B_TAN) and M is for (AA_WWTPE) on Figure 4.1; ‡Catchment outlet which represents the river segment (reach) between two nearby monitoring stations for nonpoint source load estimation; [n]Point source loads (values in bracket, italics); *Summarized from previous work of the authors (Angello et al., 2020).

4.3.2. Calibration and Validation of QUAL2Kw in LAR

The QUAL2Kw model performance during simulation of water quality in LAR varies with constituents. The spatial assessment of DO in the LAR has revealed deterioration from upstream to downstream as reported by Angello et al. (2021) and was better simulated by QUAL2Kw (Figure 4.4c). The calibration result in the river showed that the water quality did not meet the minimum requirement of DO concentration of 4 mg/L in the river. During calibration, the DO dropped sharply after monitoring station M2 (after 4.98 km) due to the release of highly polluted tributary waste near Mesalemya that collects domestic waste, including raw sewage from Mercato area, the largest market place and densely populated urban center in the country with no wastewater collection and treatment facility. Besides, the middle segment of the river has shown high DO deterioration during calibration mainly attributed to a high presence of point and nonpoint source loads predominantly from urban land uses.



(a)



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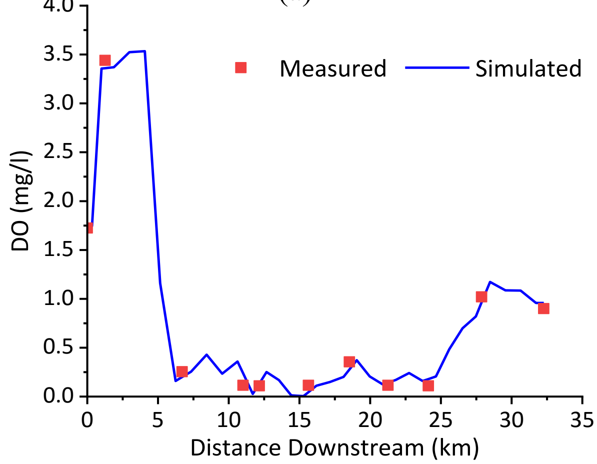

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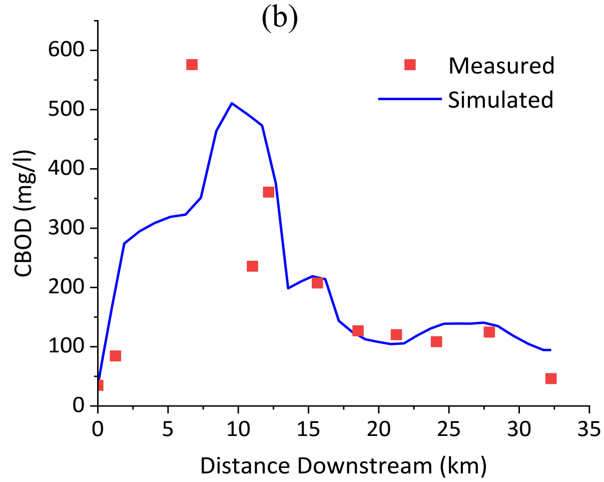

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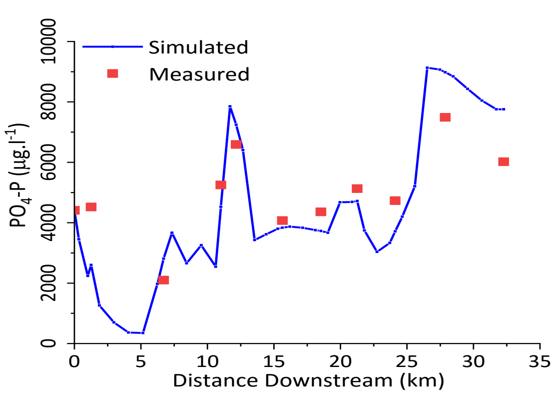
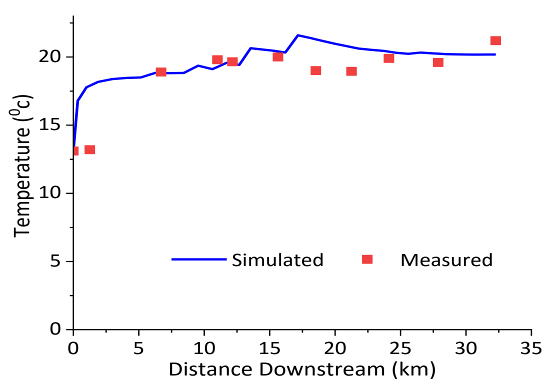


(e)



(f)

Figure 4.4: Simulation of QUAL2Kw for selected water-quality constituents in LAR (calibration): (a) pH, (b) Electrical Conductivity (EC) (µs/cm), (c) Dissolved Oxygen (DO) (mg/l), (d) Carbonaceous Biochemical Oxygen Demand (CBOD) (mg/L), (e) Phosphate (PO_4-P), (f) Temperature (°C).

The DO sag was noticeable in this segment of the LAR and had concentrations <1 mg/L due to the release of industrial waste from an abattoir, soft drinks, wine, and tannery factories. The DO started to recover near 25.5 km, though insignificantly, due to the reduced impact of point sources and less human interference due to dispersed settlement. Moreover, the consumption of easily degradable organic waste contributed to less consumption of oxygen and hence leads to the DO recovery. The coefficient of determination (R^2) be-tween model-simulated and measured DO in LAR of 0.99 and |PBAIS| of 0.57% during calibration and 0.98 and 11.8% during validation has revealed that the model is good enough to interpret the DO dynamics in the river.

The QUAL2Kw simulation for BOD during calibration (Figure 4.4d) showed that the model could not sufficiently simulate the constituent dynamics near monitoring station M3 (7.35 km) where the station was characterized by frequent constituent chemical variabilities observed during field monitoring and analysis. This deviation was partly due to the noninclusion of a small but highly polluted tributary upstream of the station. Moreover, underestimation of the pollution load of the Mesalemya stream that contributes high pollution load to the LAR could also be a contributing factor for the deviation of the BOD at the monitoring station. This deviation of BOD simulation was more pronounced at the upstream part of the middle segment of the LAR (near Lideta) and can be explained by the presence of multisource pollutants, including an unrecognized pollution source in the area which is dominated by informal settlements with no sanitation infrastructure. BOD often undergoes a complex chemical process in the river and attaining a good simulation result can be challenging. The |PBAIS| of BOD during the model calibration was 13.2% and 9.4% during validation which is acceptable for developing countries with high hydro-meteorological and water quality data limitations (Tsegaye, 2019). Beyond the M3 monitoring station, the model simulation for BOD was quite good due to the correct inclusion and assignment of the available pollution sources. Mainly due to the improved self-purification efficiency of the LAR, the BOD showed significant reduction far downstream, which was associated with oxygen recovery. Despite many limitations, the model gave quite a good result to interpret the water quality for further decision making in the study area.

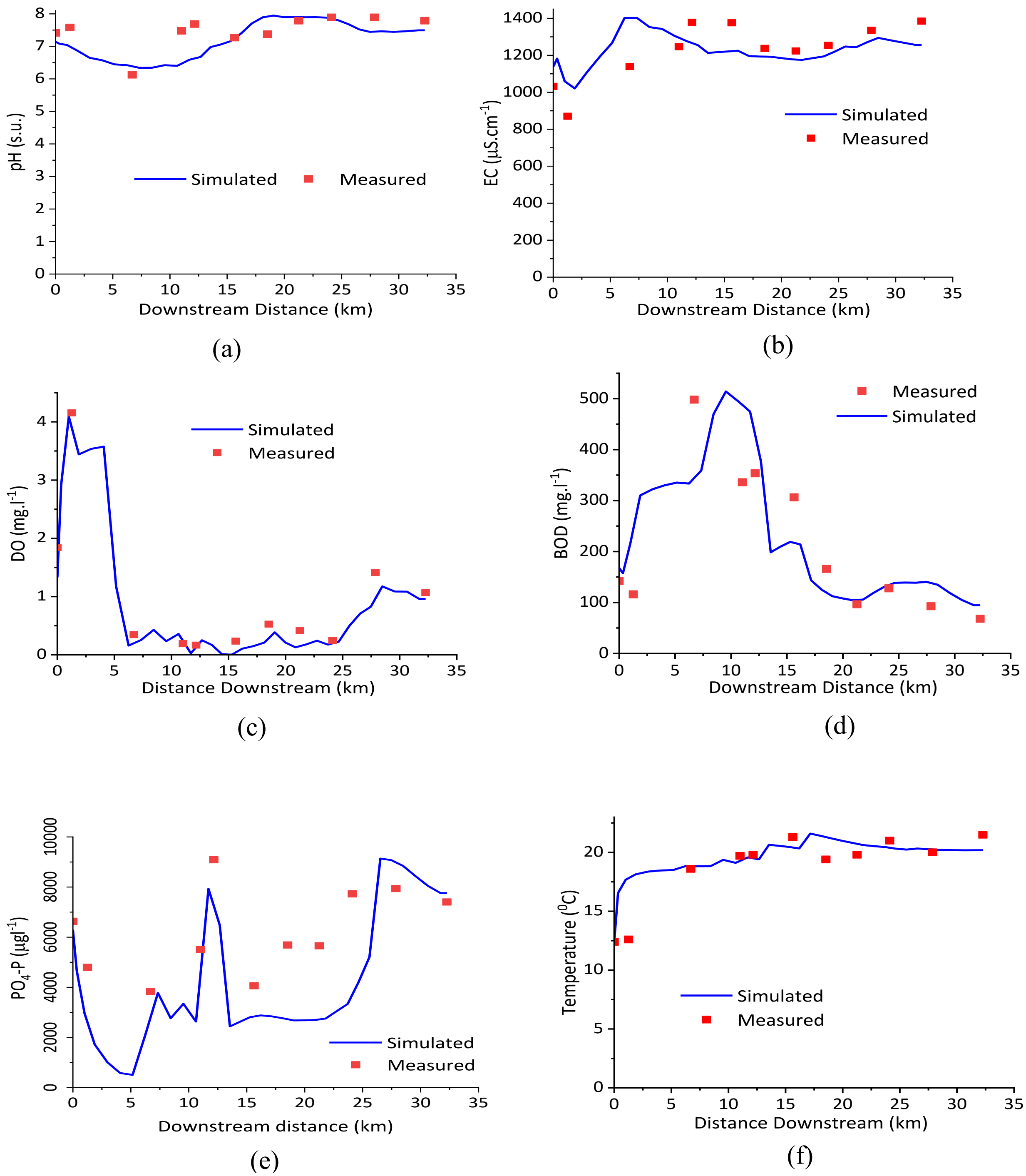


Figure 4.5: Simulation of QUAL2kw for selected water quality constituents in LAR (validation): (a) pH, (b) Electrical Conductivity (EC) (µs/cm), (c) Dissolved Oxygen (DO) (mg/L), (d) Carbonaceous Biochemical Oxygen Demand (CBOD) (mg/L), (e) Phosphate (PO_4-P), (f) Temperature (°C).

Other parameters such as water temperature, EC and pH were all well simulated by QUAL2Kw in LAR both during calibration and validation with a |PBIAS| (R^2) of 3.2% (0.51), 5.1% (0.90) and 0.33% (0.62) during calibration and 1.3% (0.63), 10.31% (0.54) and 0.32% (0.56) during validation, respectively. Monitoring station M2 to M3 has shown an observable deviation between the measured and simulated for some water quality constituents indicating the presence of unrecognized or missed pollution sources in the area. The QUAL2Kw did not sufficiently simulate the water temperature near station M2 (1.33 km), upstream of which the tributary carrying wastewater from the Ethio-marble factory joins the river and the segment between 18.3 km (M10) and 24.1 km (M11). These middle segment areas are characterized by the presence of large-scale industry, such as a tannery factory, from which the release of wastewater at the unrecognized place could be contributing. The model simulated the water temperature quite well on most of the monitoring stations with an overall |PBAIS| of 3.2% and 1.3% during calibration and validation, respectively. Similarly, the model simulation for EC showed deviation near monitoring stations M3 and M5 where the QUAL2Kw underestimated EC at both stations. The pH at monitoring station M3 had deviated from the measured value upstream which was the release point of wastewater treatment plant effluent from a Coca Cola soft drinks factory and the highly polluted Mesalemya tributary joins the river upstream of the monitoring station. The spatial PO_4-P variation in the study area showed some irregularity across the monitoring stations and was relatively better represented by the model. Far upstream and downstream of the river segment showed high PO_4-P deviation where the areas were characterized by small scale urban agriculture. In general, the QUAL2Kw model simulated the water quality constituents with an R^2 ranging from 0.51 to 0.99 (Figure 4.4 a-f) which could be enough to interpret the model output for the development of water quality management programs and pollution control in LAR.

4.3.3. Sensitivity Analysis

The sensitivity analysis conducted on QUAL2Kw in LAR (Table 4.4) was performed varying the parameters by ±50%. The sensitivity analysis result revealed that five parameters were identified highly influential. Among the selected parameters and rates, the point source flow and Manning's roughness coefficient highly influence the DO and BOD concentration. A 50% reduction in point source flow has resulted in nearly 47% disturbance in DO concentration whereas augmentation of the same amount in the flow of the point source has improved the DO concentration by 18.9%.

The high sensitivity of point source flow on the DO concentration was also reported by Raj et al. (2007) on Bagmati River, Nepal. Similarly, the Manning's roughness coefficient has a vital contribution that plays a significant role which can disturb nearly 50% of the DO concentration, where similar finding was reported by Oliveira et al. (2012) on Cértima River, Portugal. On the other hand, slow BOD hydrolysis rate, sediment denitrification transfer coefficient, and inorganic phosphorus settling velocity also play critical roles that impact the BOD, nitrate, and phosphate concentration in the LAR, respectively.

Table 4.4: Sensitivity analysis results for selected parameters in LAR

		Disturbance on parameter (%) ‡			
Parameter	Variation (%)	DO	BOD	PO_4-P	NO_3-N
Point source flow†	50	18.87	6.31	10	5.86
	-50	46.93	14.84	11.8	3.84
Headwater Flow†	50	3.85	3.78	0.37	1.34
	-50	3.56	5.22	0.01	1.92
Manning's Roughness Coefficient†	50	41.59	19.5	1.25	4.33
	-50	49.96	19.08	2.72	11.14
Slow BOD hydrolysis†	50	1.12	20.01	0.09	0.037
	-50	0.9	35.26	0.14	0.32
Slow BOD oxidation rate	50	0.68	1.12	0.36	0.27
	-50	5.9	1.2	0.42	0.28
Organic nitrogen hydrolysis rate	50	1.17	0.02	0.16	6.74
	-50	4.82	0.05	0.00	5.95
Organic nitrogen settling velocity	50	1.09	0.01	0.05	6.41
	-50	6.79	0.06	0.06	5.71
Ammonium nitrification rate	50	2.15	0.01	0.12	0.19
	-50	1.12	0.01	0.07	0.41
Sediment denitrification transfer coefficient†	50	0.32	0.01	0.17	19.73
	-50	1.45	0.01	0.11	35.95
Organic phosphorus hydrolysis	50	0.01	0.00	0.03	0.019
	-50	0.00	0.00	0.04	0.008
Inorganic phosphorus settling velocity†	50	1.26	0.01	11.78	0.22
	-50	0.26	0.00	17.36	0.37

† Most influential parameters; ‡ The percentage disturbance is in absolute value of the number

4.3.4. Scenario Evaluation and Selection of Optimum Pollution Load Reduction Approach

In the first scenario (S1), despite the reduction of point source loads of BOD, phosphate, and nitrate, by a factor of 0.7, 0.5, and 0.5, respectively, it did not meet the required BOD and PO_4-P concentration, but the NO_3-N concentration was in the recommended range in LAR set by Ethiopian environmental standards for aquatic life (EEPA, 2003). Although the reduction of BOD load was observed in the downstream segment of the LAR, no noticeable change was seen between monitoring stations M1 to M3 (downstream distance 0.00 km to 4.06 km) and an overall average improvement of 17.7% was found in the river (Figure 4.6a). Although the modification of the point source constituent load (S1) has brought an average reduction of 17.7% in the overall BOD load in LAR, the minimum requirement of WQO was not met at all monitoring stations. On the other hand, the PO_4-P load showed an average reduction of 37.5% where the change was pronounced in the middle and downstream segments (after 5 km) relative to the upstream segments of the river. The modification of the point source load has significantly changed the PO_4-P load in the river but slightly deviated from the maximum permissible value in the river. In general, despite a visible change in the overall reduction of the pollution load in the LAR, the scenario could not satisfy the permissible WQO in the river.

Though it is difficult to achieve the WQO due to the heavy pollution in the LAR, the S2 was evaluated based on the modification of BOD, PO_4-P, and NO_3-N loads from diffuse sources. Accordingly, the response of the LAR for the S2 revealed that though the BOD load was significantly reduced, the minimum requirement in the river was not satisfied (Figure 4.6b). Relative to the S1, the S2 was found effective in reducing the BOD, PO_4-P, and NO_3-N load in the LAR. This is strong indication that the nonpoint source in the study area is the dominant pollution source for the LAR water quality deterioration. It also signals intensive land use management and best management practices should be prioritized for effective water quality management by controlling the diffuse source loads (Pegram & Bath, 1995). The average reduction rate of each constituent due to the modification of the nonpoint source load was found to be 58.7%, 51.06%, and 30.9%, for BOD, NO_3-N, and PO_4-P, respectively. From the reduction rate of constituents, it can easily be seen that the role of nonpoint sources for water quality management and pollution control is significant. Despite a significant reduction of the pollution load, the S2 evaluation showed a reduction rate of the nonpoint sources BOD, PO_4-P, and NO_3-N load by factors of 0.8, 0.6, and 0.6, it was not enough to meet the WQO in LAR.

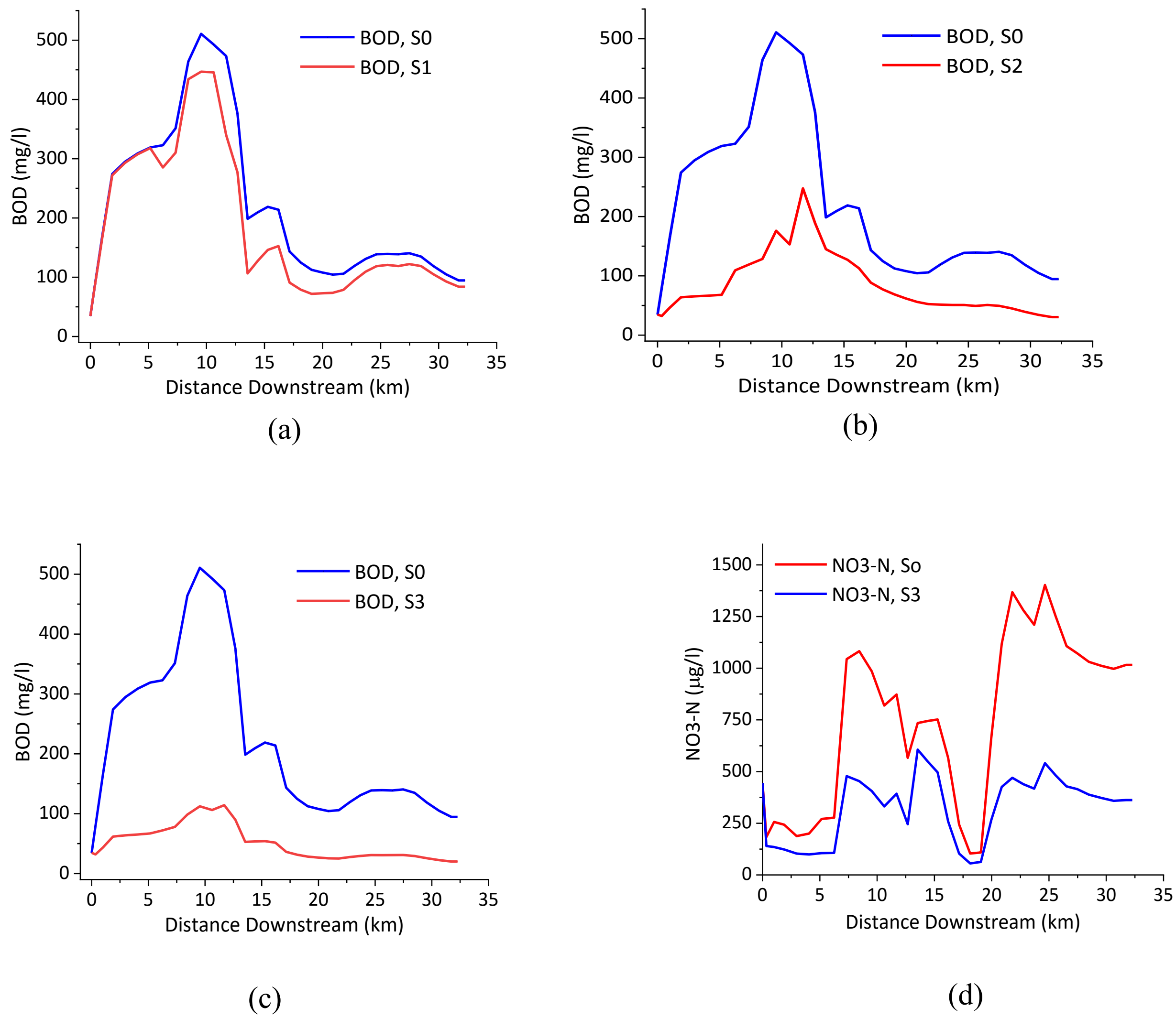


Figure 4.6: Evaluation of S1, S2 and S3 for BOD and NO_3-N relative to the base scenario (S0)

The simultaneous modifications of point and nonpoint source load (S3) have highly reduced the organic waste load (BOD) by 76.4% where significant change was seen across the whole stretch of the LAR (Figure 4.6c). Though the minimum requirement of BOD load in the river was not met, the reduction was significantly high. Moreover, the NO_3-N and PO_4-P (Figure 4.7a) pollution load were more highly improved than the previous individual scenarios (S1 and S2), which ultimately dropped the PO_4-P slightly near to the WQO. Significant PO_4-P (49.3%) and NO_3-N (54.1%) loads were reduced at the middle and downstream segments of the river where the area is characterized by urban land use and small-scale urban agricultural setup. Moreover, a high nonpoint source load was observed in the area and hence modification on the diffuse source load could be contributing to the high change in the pollutant load. The S3 evaluation results also reveal that source-based pollution management is vital for better water quality management and pollution control in the river.

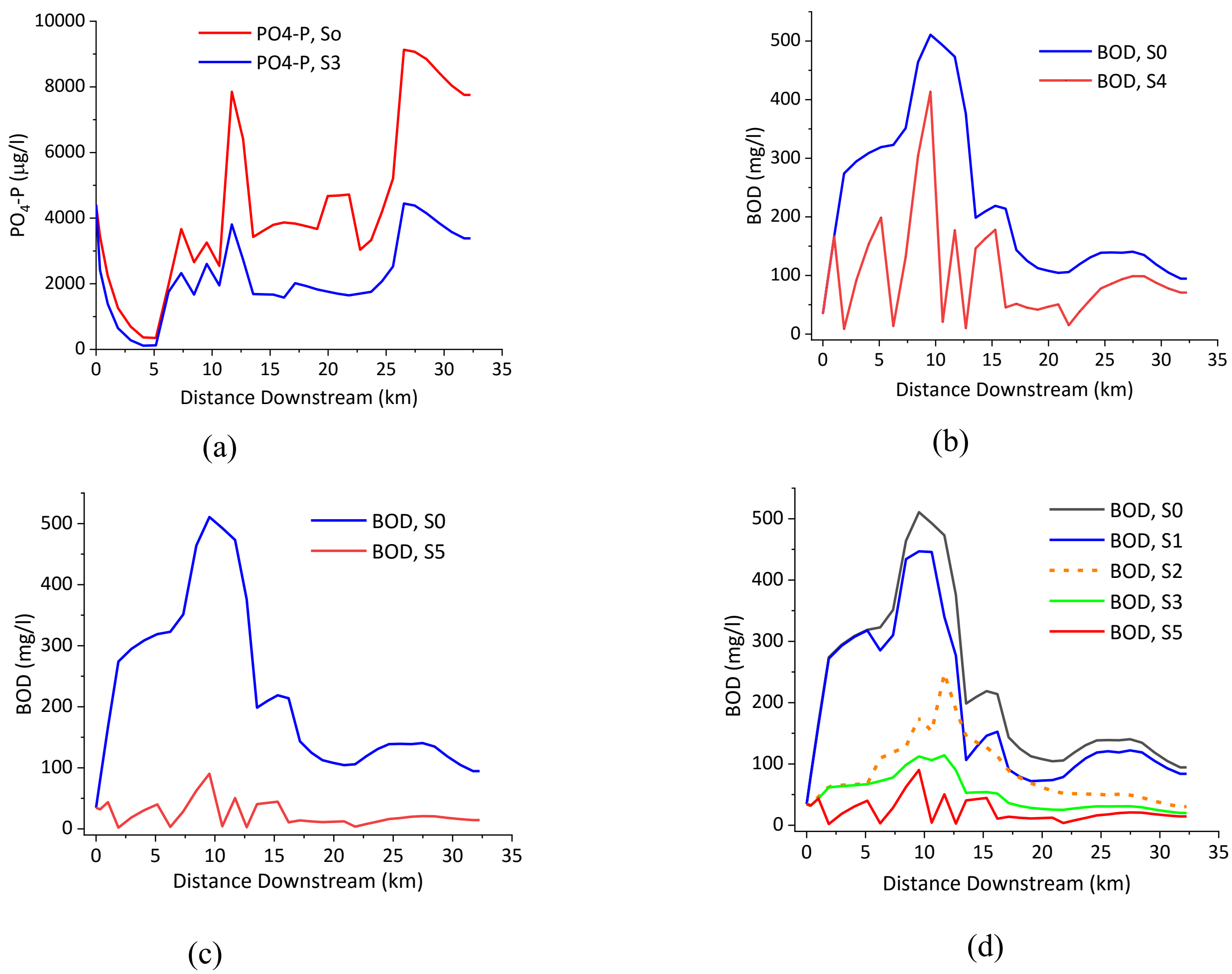


Figure 4.7: Comparison of various hypothetical scenarios evaluated for the pollutant load reduction in LAR for S4 and S5 (S0 is the base scenario)

Hydraulic structures such as cascaded rock ramps and weirs are used as local oxygen suppliers and used to manage the pollution load in a stream when placed at critical pollution locations (Campolo et al., 2002). However, weirs do not allow the free passage of aquatic organisms like fish. In the LAR, a cascaded rock ramp which can create a total head of 2 m and gentle slope was evaluated at five critical pollution locations (6.78, 11.43, 13.57, 17.05, 22.59 km). The BOD reduction due to the rock ramp application showed that there was a high improvement with an average 51.51% reduction relative to the baseload, despite some deviation from the standard values. From Figure 4.7b, it can be seen that the BOD load upstream of the structures had a surge, though reduced relative to the base value, due to the head created upstream of the structures that increased the water depth and reduced aeration, hence raising BOD. The implementation of rock ramps on the LAR has revealed that there are still other critical pollution locations that need further improvement. Such instream measures are often applied for initiating the self-cleansing efficiency of the river thereby allowing the supply of atmospheric oxygen.

Table 4.5: Average percentage constituent improvement for various hypothetical pollution reduction scenarios in LAR

		Average percentage improvement		
Scenario	Description	BOD	PO_4-P	NO_3-N
S1	Modification of point source load	17.72	37.47	19.63
S2	Modification of diffuse source load	58.69	30.96	51.07
S3	Simultaneous modification of point and diffuse load	76.41	49.28	54.15
S4	Application of local oxygenation techniques (cascaded rock ramp)	51.51	5.80	10.90
S5	Integrated scenarios (S1+ S2+S3+S4)	87.78	53.72	55.6

From the previous scenario evaluations on LAR, it is evident that none of the individual scenarios have fully met the required environmental quality standards (with respect to organic and nutrient pollutants) though they were quite effective in overall pollution load reduction. To satisfy the basic aquatic life water quality requirements, there was a need for the integration of scenarios and hence the scenarios integrally made up relatively good pollution reduction approaches in LAR with an overall reduction rate of BOD (87.8%), NO_3-N (55.6%), and PO_4-P (53.7%). However, even the integrated scenarios applied to the LAR could not satisfy the minimum requirements of the WQOs with the specified reduction rates from the point and nonpoint sources (Figure 4.7d). The S5 evaluation also showed that the scenario was relatively more effective in improving the organic waste pollution load (such as BOD) than the nutrient (such as PO_4-P and NO_3-N) load. Relative to other evaluated scenarios, the integrated approach was found very effective in reducing the organic pollutant and nutrient loads in the river. Table 4.5 summarizes all scenarios and the average improvement rate in percent.

4.3.5. Optimum Pollution Load Reduction Approach and Rate

River pollution load is highly affected by the emission rate from the point and nonpoint sources and hence the determination of the optimum load (water environ-mental capacity) in the river was based relative to the standard guidelines. Based on the evaluation of the individual scenarios, the source-based (point and nonpoint) scenarios could not bring all the constituents to the intended guideline standards in the LAR. However, it is often difficult to meet these guidelines specifically in developing countries due to the financial constraints, poor pollution management system, and lack of sanitation infrastructure. The optimum pollution reduction rate in the LAR was evaluated iteratively with trial and error using QUAL2Kw until the load in the river came under the WQO. Accordingly, none of the iterations conducted based on the modification of point source load (up to 100%) was found to be effective in meeting the intended WQO in LAR for BOD and PO_4-P on the entire river section. On the other hand, the NO_3-N load was within the WQO with minimum modification of the point source pollution load. Similarly, the iterative modification on the nonpoint source load on QUAL2Kw revealed that a reduction rate of nonpoint source load of BOD (0.8), PO_4-P (0.6), and NO_3-N (0.6) brought the NO_3-N load to the WQO but could not guarantee the PO_4-P and BOD load in LAR. From the evaluation of the scenarios, we can see that the point and the nonpoint sources could not individually satisfy the permissible pollution load in the LAR for BOD and PO_4-P and it requires an integrated point and nonpoint sources pollution modification along with the application of cascaded rock ramps which ultimately have an economic implication. Accordingly, to meet the WQO in the LAR, at least an average removal rate of 85%, 80%, and 76% from each considered point source and 92%, 83%, and 83% from all contributing nonpoint source loads for BOD, PO_4-P, and NO_3-N, respectively, and cascaded rock ramps creating head differences of 2 m with a gentle slope at critical pollution zones are necessary.

4.4. Conclusion

Urban river water quality management in countries like Ethiopia with a high scarcity of monitored water quality and hydrologic data is very challenging and needs an integrated and coordinated approach. In this study, a modified water quality model, QUAL2Kw, was evaluated in LAR to select the optimum pollution load reduction approach and rate using five targeted scenarios. The simulation of the QUAL2Kw for flow and constituents has shown that the model is sufficient for the interpretation of water quality in the river. The QUAL2Kw simulated the water quality constituents with relatively good accuracy having an R2 ranging from 0.51 to 0.99 and |PBAIS| from 0.33% to 13.2%. Hence, the model is applicable to assess the effect of various pollution controls and supporting instream measures on key water quality parameters. The hypothetical scenarios were evaluated relative to the base scenario (S0). None of the individual source-based scenarios and instream measures fully satisfied the mini-mum requirement for the pollution load-carrying capacity of the LAR, though a significant reduction of pollution load was found in the river. We generally believe that this study has laid the foundations for the future development of a water quality management strategy and initiation of best management practices in the study area. Besides, addressing the water quality problems in LAR is deemed crucial to safeguard the existence of aquatic life and protection of the ecosystem of the basin. However, achieving well-defined pollution control and water quality management requires collecting multispatial and temporal data at a higher resolution. The following conclusions are drawn from the finding.

- The water quality model, QUAL2Kw, is a quite effective tool for pollution management of urban rivers of specifically developing countries with high hydro-meteorological and water quality data scarcity. The output can be effectively interpreted for preliminary water quality management and pollution control programs. Moreover, the model is capable of providing decision-making support to design, execute and manage projects for river improvement in the study area.
- The QUAL2Kw model-based scenario evaluation revealed that the impact of nonpoint sources pollution load on the LAR was much higher than the point source pollution load. An integrated approach on point and nonpoint source pollution control is highly recommended for sustainable water quality management in the study area.
- Despite the rather ambitious source-based pollution load reduction scenarios applied in this study, the intended goal of reducing the pollutants load in the LAR was still not achieved. Hence additional pollution control mechanisms are required for better water quality and pollution management in the catchment.
- Combining pollution reduction with instream measures to improve reaeration can have clear synergistic effects. Since a fast dramatic pollution reduction is hardly achievable in

developing and emerging countries, those integrative approaches are cost-efficient mitigation options.

In conclusion, the scenarios evaluated on LAR were hypothetical and can be ap-plied for the development of a river pollution management program and decision-making process. For a targeted improvement of the ambient water quality, the model can be used to iteratively develop and allocate a set of cost-efficient measures.

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5. Synthesis, Recommendation and Prospective Research Directions

5.1. Overview

The LAR is among the heavily polluted urban rivers in Ethiopia where a coordinated, comprehensive and integrated water quality management is needed urgently. However, due to the financial constraints, technical incapability and lack of commitment, the river's water quality management and pollution control has remained neglected. Therefore, this study is conducted with the main aim of developing better water quality management and pollution control strategy in the LAR by determining the spatial and temporal dynamics of pollutants and quantifying the constituents' load. Furthermore, targeted scenarios were developed and evaluated in a water quality model, QUAL2Kw, to determine the response of the river for the changing scenarios and ultimately selecting a better option among the available alternatives and are discussed under chapter two to four. The intention of this chapter (chapter 5) is therefore to integrate all the outcomes from each specific objective and to discuss in detail and come-up with a better water quality management option in the LAR.

The chemical characterization of constituents in LAR was discussed exclusively in chapter 2 (Angello et al., 2021) where the possible pollution sources and spatial and temporal constituent variability in the watershed are determined. The spatio-temporal characterization of physicochemical constituents was based on continuous river water monitoring in areas where hydro-meteorological and water quality data are limited. The monitored water quality data were further analyzed and used to determine the spatial pollution hotspots and seasonal effects on the river, as well as qualitatively determining the pollution sources in the LAR, using MSA interpretations. Accordingly, the study identified three major pollution sources in the LAR: domestic, industrial, nonpoint sources (agricultural and urban). Besides, the contribution of each pollution source to each water quality constituent was determined using MRMs based on the identified source profile.

One of the most difficult issues that developing countries frequently face when implementing river pollution management, particularly in urban areas, is the quantification of nonpoint source load, which has become a major component of river pollution in many watersheds (Li et al., 2011).

In this study, the nonpoint source load in the study area was found to contribute more than half of the pollution contributed by other sources to the river. Poor urban land use management, lack of sanitation infrastructures, poor sanitation best management practices and lack of river side protection mechanisms are contributing for the excess presence and intensification of diffuse sources constituents load in the LAR. The research findings will have a significant contribution on identifying the major nonpoint pollution hotspots and, ultimately, quantifying the contribution of each land use which further pinpoints better pollution management options. As a result, the middle and downstream segments of the LAR were found to carry significant amount of nonpoint source load, and they have been designated as the future water quality management focus area. The pollution management plan based on the research output will hence assist policymakers for comprehensive pollution management plan studies in Ethiopia.

This study also presents the generation of local pollutants export coefficient (ECf) based on the calibration of the global export coefficients in PLOAD-a nonpoint sources pollution model (Angello et al., 2020). Studies reveal that developing local pollutants ECf is crucial for accurate determination of diffuse sources pollutants load (Shrestha et al., 2008). In this regard, ECf for the study area was developed from ECf of other catchments. The ECf generated was used for estimation of nonpoint sources load in the study area. The determination of nonpoint sources load in LAR contributed by each land use in the catchment holds double advantages. First, based on the quantified pollution source contribution, a preliminary nonpoint source load management mechanism was developed, thereby suggesting best pollution management practices. Second, it provided a detailed input to process-based water quality modeling, which will be further investigated and used to generate an optimum water quality management and pollution control plan. Nowadays, river water quality management in Ethiopia is often based solely on the determination of point sources load, with the impact of nonpoint sources load usually ignored. Water quality models are thus found to be effective in filling this gap by incorporating the impacts of both pollution sources, allowing pollution management and associated remediation measures to be justified. However, due to factors such as lack of monitored hydro-meteorological data, technical capability, and know-how on modeling tools, this approach is almost entirely ignored in Ethiopia.

5.2. Synthesis

The role of land uses on the distribution and intensification of nonpoint sources load in the LAR catchment

Several studies reveal that the impact of nonpoint sources in a watershed is highly associated with the type of land use type and planning techniques (Kim et al., 2018; Lee et al., 2012; Wang et al., 2005). Therefore, the type, nature and planning of the land use plays key role in the urban river pollution management (Ding et al., 2015). However, urban land use planning and management in Ethiopia in general and Addis Ababa in particular is poor resulting in significant river pollution. Consequently, many of surface water resources in the city are highly polluted by organic, inorganic and nutrients pollutants, intensifying eutrophication in the rivers. As a result, nutrient loads from nonpoint sources in Ethiopian highlands are becoming threat to surface water quality, owing primarily to poor land use management causing erosion and runoff (Moges et al., 2018). The study of nonpoint sources in the LAR discussed in Chapter 3 (Angello et al., 2020) supports these findings and revealed that more than 50% of the load in the study area was contributed by nonpoint source pollution. This is significantly higher than the corresponding point source load and is more pronounced in the middle and downstream segments of the river (Figure 5.1, Zone 2 and Zone 3). According to the study area land use classification and ground monitoring, the area is dominated by urban land use, with informal settlements, dense population, and industrial establishments predominating. Besides, most of the domestic waste from the residential areas are dumped in the nearby river or urban drainage infrastructures where they usually end up to the rivers and the river often serves as an “open sewer”.

The organic pollution load, such as BOD, and the excess presence of nutrients, which initiate eutrophication, were found to increase from upstream to downstream in the LAR. The organic waste load intensity was found to be more congested in the central part of the catchment, where more urban land use configurations predominate. Furthermore, organic pollution load in the study area was notable with the prevalence of residential and industrial land uses whereas the nutrient pollution was more prominent in the areas where the residential and agricultural land uses dominate. The upstream segment of the LAR catchment is relatively protected and has less anthropogenic interference and hence the nonpoint sources loads are relatively low (Figure 5.1

Zone 1). Furthermore, the presence of forests and public parks has significantly aided in reducing the impact of diffuse sources. The study by Kuai et al. (2015) on Xizhi River watershed, Guangdong, China, also supports this interpretation where best land use planning could be a better approach to control the impacts of nonpoint sources load.

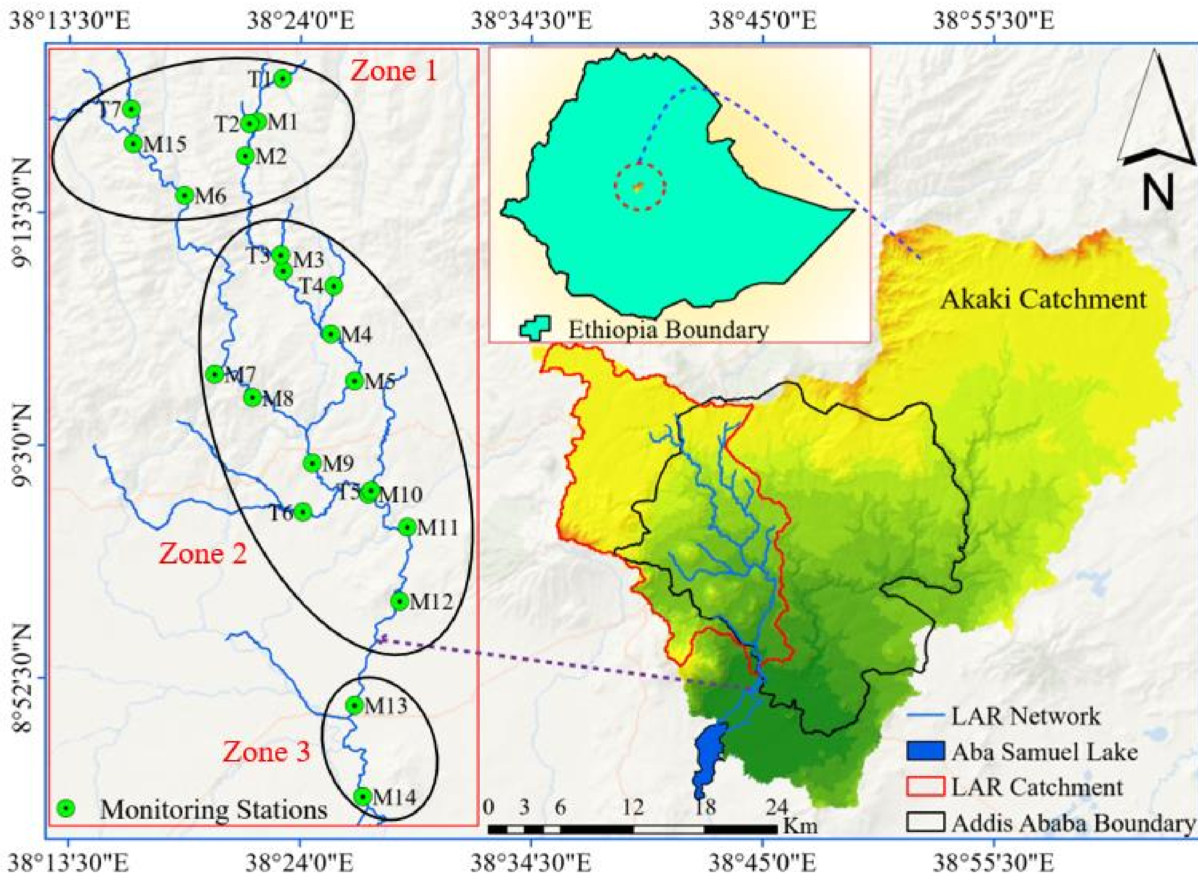

Figure 5.1: Pollution hotspots zoning in LAR (classification based on this study pollution analysis)

The intensity of organic pollution load in the LAR and its catchment was found to be significantly high in the most urbanized land use areas, where commercial and industrial activities predominate. Similar finding was also reported in Dongjiang river basin, Southeastern China (Ding et al., 2015). In these areas, nutrient pollution and accumulation was also found significantly high and eutrophication has intensified due to land use alteration. Open spaces and runoff drainage infrastructures are often considered as a dumping ground for liquid and solid waste in the LAR catchment. Furthermore, urban small-scale agricultural activities in the study area are usually carried out on small plots of land at the household level where agricultural waste is dumped in the river or in the field which is later washed-off by rainfall and runoff. This collective impact is more pronounced in the middle and downstream segments of the LAR catchment (Figure 5.1, Zone 2 and Zone 3). Hence, a coordinated land use management could significantly reduce the waste load in the river, as stipulated in chapter 3 (Angello et al., 2020) and chapter 4 (Angello et al., 2021b) of this study and findings of other literatures (Xu et al., 2013; Yang et al., 2014).

Given the alarmingly high increase in pollution load in the LAR, the government is currently implementing riverside protection measures such as buffer zoning and urban land use conservation and protections (MoUDH, 2016). Although the project's inception appears to be a positive step forward for water environmental protection, it has yet to be implemented in the study area. One of the nonpoint source management and reduction mechanisms proposed in chapter 4 of this study was the restoration of LAR water quality using buffer conservation. The implementation of this river buffer zoning will significantly improve the water quality in LAR by reducing silt load, maintaining water quality, stabilizing river banks, trapping nonpoint sources (primarily nutrient pollutants), enhancing river buffer aesthetic value, and maintaining the LAR water environmental quality.

Impact of nonpoint sources load on the pollution management of the LAR: The neglected component

As discussed qualitatively in chapter 2 (Angello et al., 2021) and quantitatively in chapter 3 (Angello et al., 2020), the nonpoint sources load contribution for the pollution of the LAR was found to be significantly high. Despite the fact that global data (Jabbar & Grote, 2019; Lee et al., 2012) and this study's findings show that nonpoint source pollution is the prime cause of river pollution, little is being worked so far. Most importantly, because of its complexities in determination, a basin-wide and careful determination of nonpoint source load is critical (Falconer et al., 2018; Jamwal et al., 2011). Despite the high contribution of urban land uses for the diffuse sources load, many studies often focus on determining nonpoint source pollution from agricultural land uses only (El-Nakib et al., 2020; León et al., 2001). However, this study on chapter 3 (Angello et al., 2020) is evident enough that the urban land uses carry significantly high pollution load than any other land uses.

Many studies suggest incorporating the role of diffuse source as part of water quality management based on strict implementation of best pollution management practices (Yuhong et al., 2010) and strong environmental policy intervention (Jain & Singh, 2019). However, despite a significant deterioration in water quality due to nonpoint source pollution, the management system and the emphasis placed on diffuse source pollution are insignificant in the study area. More emphasis was given to the point source by limiting the discharge rate, followed by irregular inspection of wastewater release from these sources. However, the government and other stakeholders' attitude on diffuse sources pollution impact, contribution and role on the river pollution is poor. Global experience has shown that most researchers focus solely on specific types of nonpoint source pollution sources, such as agricultural and urban, rendering the diffuse source load study ineffective (Wang et al., 2020). However, with the advancement of computer models and software, the inclusion of nonpoint sources as an important component of water quality management study has been eased. Despite the advancement of sciences, water quality management and pollution control strategy in the country lack the best understanding of this scientific approach, the management system is often based on traditional techniques and hence is unsuccessful.

Essentially, the lack of sustainable water quality management system in the study area emanates from two basic problems. First, the difficulty of identifying a clear distinction between point and diffuse sources is becoming a major challenge when a number of sources of pollution with an unidentifiable point of origin are entering the LAR. As a result, the nonpoint source load study and river pollution management should take into account by identifying all potential background sources. Second, due to lack of understanding on the extent and impact of diffuse sources, the country's surface water pollution controlling office (FDRE-EPA) has almost ignored the role of nonpoint pollution sources making the water quality management incomplete. The high presence and dominance of diffuse sources over point sources in the LAR catchment could be interpreted by a number of factors such as poor urban sanitation infrastructures, lack of coordinated land use management and less understanding of the impacts of nonpoint sources load and most importantly the less attitude towards the nonpoint sources impact. In order to have a successful nonpoint sources management system, an awareness creation plan should be established in parallel to the improvement of the sanitation infrastructures. However, no nonpoint source management and control approach has yet been established in any relevant government departments (such as FDRE-EPA, MoWIE, AAWSA, MoH), nor has it been recommended by private organizations in the country. It is extremely concerning that the impacts of nonpoint source pollution have been overlooked in the study area during management of urban river water quality.

The influence of high LAR tributary pollution load on the ecological status of the LAR

Tributaries often carry large amounts of pollutants and contribute to the pollution of the main river, and studies suggest that it should be prioritized during development of river pollution management plan (Zhang et al., 2015). In the study area, the monitoring stations on the LAR tributaries carry high pollution loads than any of the corresponding point sources in the area. This is partly because most of the domestic (including raw sewage) and industrial wastes (mostly untreated), are released to the tributaries than the main river. The tributaries usually have a higher flow rate than the point sources and hence contribute, despite generally lower concentrations, large pollutants load to the main river. Most of the tributaries originate from the densely populated urban areas with informal settlements. However, previous studies in the river often focus on the main river segment undermining the dominant influence of the LAR tributaries pollution load. Accordingly, the so made water quality management decisions will only be partly successful and not sustainable.

The findings from chapter 2 of this study (Angello et al., 2021) revealed that organic and inorganic, nutrient and heavy metals pollution in the LAR showed a surge in the middle segment of the river near Mercato, a highly congested market place in the city. The Mesalemya, Jemo and Kera streams were among the heavily polluted tributaries that change the ecological status of the river downstream of their confluence with the main river. Besides, the water quality simulation in the LAR (Angello et al., 2021b) showed that the trend in most of the monitoring station was deteriorating the water quality at the point where these highly polluted tributaries are joining the main river. This study thus suggests pollution reduction management strategy should consider the prioritization of tributaries pollution management.

Many studies agree that, for better water quality management and pollution control, tributary management plays critical role (Anawar & Chowdhury, 2020). In support to this, for example, a study on the Nakdong River basin pollution in Korea was found that tributaries are among the highest pollution load contributing agents for main river pollution, indicating the need for prioritization during water quality management (Lee et al., 2018). Similarly, the impact of tributaries load on the main river is exclusively studied by Kim et al. (2008) and recommended that mass load-based analysis of the tributaries will significantly enhance understanding of the pollution levels in the tributaries, allowing decision-making process easier. Besides, prioritization of pollution zones in the study area is required, with tributary pollution management being as important as the study of point and nonpoint sources. The tributaries of the study area specifically located in the middle segment of the LAR (Figure 5.1 Zone 2) need clear and effective management direction and strong action plan in order to restore the natural ecology of the river. Studies also recommend the flow augmentation by allowing additional external water source in the tributaries so as to dilute the pollution in the main river (Raj et al., 2007). However, this approach could lead to hydrological disturbance of other watersheds and hence could not be a good pollution management option for the study area.

The impact of organic and nutrient pollution on the LAR water environment

Organic waste are usually contained in municipal and industrial wastewater and are the main source of water environmental degradation (Karpińska & Kotowska, 2019; Wen et al., 2017). Similarly, excessive nutrients presence and massive production of algae could lead to eutrophication in the river (Kanownik et al., 2019). The combined organic and nutrient pollution such as due to intensification of agricultural productions (Parris, 2011), land use alteration (Rodríguez-Romero et al., 2018) and insufficient industrial and domestic wastewater treatment (Wang & Yang, 2016) are often the major cause for the natural water environmental degradation and threatens aquatic life. As exclusively described in Chapter 4 (Angello et al., 2021b), the evaluation of organic pollutants and nutrients in QUAL2Kw by modifying point and nonpoint sources load in the river resulted in high pollution load reduction in the LAR. Accordingly, this study revealed that nearly a half reduction on these pollutants loads from point and diffuse sources significantly improved the LAR water quality. Previously, the river pollution management is based on the inspection of wastewater (effluent) quality at few point sources releasing institutions only followed by issuing a warning letter to construct wastewater treatment plant. However, this has had little effect on water quality and is, in reality, not bringing much change on the pollution load over time due to non-inclusion of diffuse sources pollutants during water quality management. Despite the large amount of waste emitted from point sources, controlling organic and nutrient contaminants from point sources alone was not enough to meet the intended water quality objectives and hence the excess presence is triggering the intensification of eutrophication in the LAR. Similarly, lack of better pollution management practices in the study area is heavily impacting the organic and nutrient pollution to be intensified. A scenario evaluation based on the modification of BOD, PO_4-P and NO_3-N on the LAR, for example, revealed that the control of the three constituents would greatly improve the water quality and sustains ecological wellbeing of the river mainly in controlling the eutrophication. Eutrophication is intensified in the Addis Ababa Rivers in general and LAR in particular where reduction mechanisms are critically needed. Simultaneous controlling of the organic and nutrient pollution incorporated from point and nonpoint source would greatly contain this problem.

Economic implication of the water quality restoration and pollution control options and the role of central wastewater treatment plant on the LAR water quality

River water pollution is one of the major concerns of developing nations, with the majority of surface water resources are contaminated to the level that it is very difficult to be used for any purpose (Anawar & Chowdhury, 2020). In order to sustain the intended purpose of the urban rivers, a comprehensive river remediation approach (both instream and catchment wide pollution sources control) is vital. The goal of urban river restoration is to improve the ecological status of water bodies, including physico-chemical, biological, and hydro-morphological quality. However, owing to the extreme depletion of river water quality in the urban rivers of developing countries, ecological restoration has typically remained challenging. In this regard, despite the difficulty of river water environmental restoration, a number of studies globally proposed different river pollution remediation and mitigation techniques. For instance, according to Wang et al. (2012), a biological-ecological remediation technology based on advances of river remediation was found a better approach in river pollution control than the physical and chemical remediation. Similarly, Cao et al. (2012) evaluated a bioremediation technique using biofilm on filamentous bamboo and found it relatively effective. Anawar & Chowdhury (2020), on the other hand, recommended integrating the engineering structures with biological and ecological engineering to restore the river ecology. However, none of these river restoration and mitigation approaches are applied in the study area and hence the management and restoration program was ineffective. For efficient water quality management and pollution control, while implementing river remediation measures, priority should be given to measures aimed at reducing water pollution and land reclamation, reactivating fluvial spaces, and rebalancing geomorphological dynamics and the hydrological regime (Gusmaroli et al., 2011). However, appropriate economic analysis should be developed as part of the decision-making process, and reasonable alternatives should be thoroughly evaluated.

In this study, much was discussed about the level of pollution, source contributing for the river pollution, factors associated with pollution and techniques to control and remediate the pollution in the LAR. Accordingly, source-based pollution management strategies coupled with application of instream measures were found relatively effective in reducing the pollution load in the river and were efficient mitigation options. An integrated instream measures and pollution source control approach was found that pollutants from point sources and nonpoint sources need to be reduced by more than 75% from their existing load. Moreover, a rock ramp creating water head with gentle slope could be placed at very critical pollution locations, specifically middle segment (Figure 5.1, Zone 2) of the LAR in order to improve physical aeration and restore the natural ecology of the LAR and protection of aquatic life such as fish. However, the economic implication of simultaneous application of the three approaches for a river like LAR extending long distance and for a country with high financial shortage is challenging. But, in the perspective of the public health, implementation of the approach could be very vital. The approach is also essential to recover valuable nutrients such as phosphorus.

Most of the pollution load to the LAR is contributed from the middle segment of the LAR catchment located between Mesalemya to upstream of the Kality Bridge (Figure 5.1 from monitoring station T3 to M13). Among the investigated targeted scenarios is reduction of point sources pollution load by installing a central wastewater treatment plant incorporating these areas and was found one of the efficient option for the LAR water quality restoration. Accordingly, the government of Ethiopia has proposed the expansion and rehabilitation of the existing wastewater treatment plants in Addis Ababa including some part of the study area. The implementation of the newly proposed sewer network and wastewater treatment system expansion in the LAR catchment could reduce the pollution load in the river. Despite the origin and contribution of the high pollution load from the central catchment, the non-inclusion of the major pollution areas near Mercato raises concerns that the river's water quality management will remain ineffective. Simultaneous treatment of the nonpoint pollution, domestic and industrial wastewater is suggested to effectively and sustainably manage the LAR water quality and restore the natural ecology of the river. However, this approach requires high financial readiness, resource mobilization, property relocation, community participation and detailed investigation of the implementation routes. Furthermore, the newly proposed expansion and rehabilitation project has not given emphasis for the storm water collection and treatment options. However, a separate system for the collection and treatment of nonpoint source through implementation of storm water system could be a feasible option in this regard (see the options of storm water management systems below). A decentralized wastewater treatment plant implementation for selected critical pollution areas like Mercato, Kolfe and Kera could be used as an alternative option in consideration of financial constraints.

The existing wastewater treatment plant serving the city was initially designed with a capacity of 7,500 m^3/d of wastewater with a population equivalent of 75,000. The newly proposed treatment plant, on the other hand, is designed to receive a daily wastewater flow rate of about 100,000 m^3 covering Bole, Kirkos, Akaki-Kality, and Nefas Silk-Lafto sub-cities (some part of Zone 2 and Zone 3, Figure 5.1). However, many of the high pollution areas of the Zone 2 in the study area catchment (Figure 5.1) were not included leaving the decentralized wastewater treatment system as a primary option. However, for an area with a very dense population, like Mercato, where implementation of sanitation infrastructures is not feasible due to site inaccessibility, implementation of a decentralized treatment system is a better alternative. This approach holds double advantage. First, the capital investment required for the decentralized system is much less than the conventional (centralized) treatment system. Second, it will increase responsiveness and belongingness of the local community (Parkinson & Tayler, 2003). As far as environmental pollution and river ecological restorations is concerned, an economical, separate and decentralized wastewater treatment system is feasible for the Mercato areas (at some informal and congested residential areas), but must be accompanied by a sustainable operation. Areas on Zone 3 of the waste-watershed is better connected to the central wastewater treatment system. Most importantly, separate industrial and institutional wastewater treatment and reuse could be a feasible option for efficient implementation of the restoration programs (Figure 5.2, Zone 2-upper).

Concerns over the increasing industrial and municipal (liquid and solid) waste pollution and relaxed law enforcement on industrial pollution in the LAR

Improperly treated industrial wastewater is one of the major pollution source in urban rivers of developing countries (Bougherira et al., 2014; Zhao et al., 2020). Similarly, surface water pollution mainly by industrial wastewater has remained the prime challenge and worrisome phenomenon in Ethiopia. As discussed under chapter 2 of this study (Angello et al., 2021), one of the major pollution sources in LAR is the industrial wastewater. Most of the industries in the city and in the LAR catchment in particular are established near the river banks (Ademe, 2017) where nearly all of the industries are discharging their wastewater (effluent) directly to the rivers (Aschale et al., 2016). During the study period, it was discovered that the majority of industrial wastewater is discharged directly into rivers, exposing the extent to which factories are neglectful of water environmental safety. Most importantly, many of the industries' wastewater discharge points were observable enough for the respective regulating agency (such as FDRE-EPA) to take the appropriate steps, but none had been enforced yet. This has clearly augmented the pollution load in the river.

Similarly, most industries' solid waste management was poor, which may have contributed to the high nonpoint source pollution in the watershed. Despite high volume of solid waste released to the environment including the water bodies, large portion of it is uncollected. Today, 20-30% of the solid waste generated in the city are left uncollected (Tilaye & Dijk, 2014). The Addis Ababa Municipality is in charge of solid waste collection where collection is often made by small and medium enterprises and the payment is based on the volume of the solid waste collected. The municipality is also in charge of transporting the collected solid wastes to the dumping site. However, despite the high efforts of the government to control the solid waste in the city, the management system is still insufficient (Gelan, 2021). The poor solid waste management in the study area is partly due to lack of public awareness, financial constraints, illegal dumping, and lack of private and community participation (Regassa et al., 2011). Pollutants associated with the solid waste accumulations are usually intensified with flooding during the rainy season washed from various land uses and open spaces (Manfredi et al., 2010) and unless necessary management and corrective measures are not taken, the impact would be overwhelming in the study area.

Despite the large quantity of physico-chemical, nutrient and heavy metal pollution from industrial sources, the monitoring and legal inspection on the implementation of liquid and solid waste management policies were much less evident. During data collection for this study, it was observed that the reports by the EEPA, which is in charge of the industrial waste release management and control in the country, stating the deviation of most of the constituent concentration from the national guideline standards for selected industries in the catchment. The breach of the legal release of the industrial wastewater in the study area emanate from a number of factors such as poor inspection program, relaxed law enforcement, ignorance and lack of commitment. The lack of continuous monitoring and inspection of industrial waste release (both liquid and solid) followed by legal enforcement is contributing for an ever-increasing pollution load in the river. This could primarily be due to the overlapping of responsibilities among the key controlling institutions in the country, as reported in the work of (Awoke et al., 2016). In Ethiopia, the Ethiopian Quality Control Authority (EQCA) is authorized to develop standards and guidelines related to environment including the release of contaminants to the rivers. However, the Ethiopian Environmental Protection Authority (EEPA) has set its guideline standard the pollutants concentration to be released to the rivers without considering the permissible level to safeguard the fate of aquatic life. This research points out that both the miscommunication between the government institutions to control the industrial waste pollution and lack of interest of the industries to treat the wastewater before releasing to the nearby rivers is aggravating the LAR water pollution.

5.3. Recommendations

In this study, it is tried to investigate the existing water quality status of the LAR and approaches for better pollution control based on the selected monitoring stations, identify the possible pollution sources and quantify the contribution of each pollution sources in the river thereby delineating the pollution hotspots in the study area. Moreover, the study has established pollution management plan based on evaluation of water quality improvement and pollution control options on QUAL2Kw model. Besides, the research provided further evidences on the pollution level of the LAR and strengthens the findings of other researches that the water quality of the river has deteriorated heavily and cannot be used for any purpose unless efficient physical, chemical and ecological restoration mechanisms are framed. As characterized under chapter 2 and quantified under chapter 3, the pollution of the river has exceeded the maximum organic and nutrients pollution load carrying capacity of the river. But chapter 4 of this study has investigated some of the approaches that could restore the natural water environment and the possible mitigation and restoration measures for sustainable water quality management and pollution control in the river. In line with this, the study points out the following key improvement areas that need urgent action plan in order to come-up with a sustainable water quality management and pollution control system in the LAR and the watershed at large.

Improved water quality monitoring programs

The grim reality now days is that water quality of surface water resources is depleting than ever requiring urgent actions on water environmental management (Kilonzo et al., 2014; Silva et al., 2017). However, in developing countries like Ethiopia, water quality and quantity information are often missing and the water and sediment management are still ineffective. In those countries, where shortage of well-trained professionals is common and monitored hydro-meteorological and water quality data are unavailable, decision-making process becomes complicated making the water quality management even more challenging. In the absence of these data, the water quality management decisions made are incomplete. For example, as discussed under chapter 3 of this study, nonpoint source models, such as PLOAD are recommended for data scarce areas like Ethiopia for preliminary nonpoint sources management in consideration of the data shortage. If monitored water quality data with better quality are available, the use of more complex models is feasible. Besides, detailed water quality management plan couldn't be achieved with limited monitoring data. This study therefore suggests adopting economical monitoring programs, institutional capacity building, training more skilled manpower and alternative use of the recent remote sensing devices and approaches.

In its current ambition towards sustainable and integrated water resources management and development, Ethiopia should pay due attention to strengthen the institutions with the water quality and hydrological monitoring infrastructures, human capital and experts. In this regard, water quality and watershed models are identified as a supporting tool for water environmental management where they often rely on the available data (Tsakiris & Alexakis, 2012). But in the study area, the models used were more linked to developing a preliminary pollution management strategy. A more detailed investigation on the pollution characteristics and comprehensive pollution management strategy based on complex water quality model and ground control points require a large set of data, which also has an economic implication. Besides, the general public (FDRE-EPA, MoH, MoWIE) and private institutions (private consultants, research institutions) are encouraged to engage, actively participate, and form partnerships in order to fill the monitoring instrumentation gap in the government's effort to control river pollution.

Nowadays, network based, automatic and real-time water quality monitoring systems have gained a wide range of benefits in water resources management (Mamun et al., 2019). However, such types of automated monitoring stations are missing in the study area. While the LAR has the potential to provide numerous economic and social benefits if used wisely, little research is being conducted on it due to lack of water quality monitoring stations measuring water quality and quantity data. Moreover, with the advancement of the current science, the use of sensors will have a paramount benefit for the water quality monitoring. However, an effective and extensive water quantity and quality data monitoring country wide is highly expensive and logistically challenging for the country. Equally important is that the large water quality data collected need to be analyzed meaningfully and promptly presented to all stakeholders which requires much skilled man power. The automatic water quality and quantity monitoring stations need to be installed at least for the three sub-geographical clusters of the LAR catchment (upper, middle and downstream) segments. Moreover, trained man power should analyze the collected data, tabulate and register and send it to the authorized offices. Summarizing, the study strongly recommends the following key focus areas (but not limited to);

- Implementation of a more economical water quality monitoring approach such as adaptation of mobile water quality monitoring station.
- Devising a fast-monitoring mechanism through grab sampling.
- Incorporating a hydraulic monitoring as part of a water quality monitoring program.
- Enabling manpower for data logging, registering, analysis, interpretation and preparation of databases.
- The required data need to be managed and assessed in a process-oriented way and the

implementation of consistent digital data management system by the responsible authorities.

Empowerment of environmental pollution policy

Despite the workability of many legislations, environmental policies such as emission reduction may not always work as seen in China by only setting the target objective of total pollution reduction (Shen & Yang, 2017). However, it needs commitment, continuous inspection and tighter policy implementations. One of the major polluting factors in the LAR is the industrial wastewater in which most industries near the LAR discharge their wastewater without or minimum treatment (Aschale et al., 2016). This study, however, revealed that the inspection mechanisms are not adequate nor targeted making the implementation of the environmental policy unproductive. The law enforcement is seen to be underperforming, despite the fact that the policies drafted are well documented in such a way that the water environment is protected. Despite the community's repeated and ongoing complaints about certain industries dumping waste into LAR, the respective government offices are often hesitant.

Though the Ethiopian ambient environmental standards guideline document (EEPA, 2003) is relatively good at controlling the environmental pollution, the implementation and legal enforcement is poor and much is still needed to improve the environmental quality standards. The majority of the standards are taken directly from the developed world and thus necessitate some adaptation to local conditions, such as the release of wastewater containing heavy metals, PAH, and pharmaceuticals, where large amounts are released to the LAR. Despite having many strong components, the Ethiopian ambient environmental quality standard is not well documented in such a way that specific guideline limits can be identified, and the environmental quality standards are not uniform across institutions, resulting in discrepancies. This study hence proposes two policy empowerment approaches; first, with the help of the recent information technology advancement, creating a dynamic wastewater quality monitoring database from respective institutions and industries that enforces regular reporting. Besides, the respective offices (FDRE-EPA, MoH and MoWIE) should hold irregular monitoring and arbitrary inspection programs. Moreover, these institutions should clear their overlapping gap so as to smoothen the pollution control process. Second, involving the community in the control mechanisms and policy implementation programs in which the government takes the lead. In general, key recommendations from this study towards empowerment of environmental policy are:

- The government should uphold its firm and strong commitment on water environmental pollution and amend the environmental guideline standards by customizing to the local conditions.
- The respective environmental pollution controlling authorities and offices should take a hardline attitude towards the implementation of the environmental policies and laws.
- Preparing strong and systematic intervention, implementation and enforcement mechanisms on the environmental quality guidelines and policies.
- Adaptation of pay-per-pollution policy for all wastewater generating industries in the watershed based on their emission level.

River pollution management prioritization

Ethiopia mainly experiences two distinct seasons: the dry and wet season. The LAR become severely polluted during the dry season when the flow in the river decreases from its natural flow. Because of the low flow, combined with the high rate of pollution release from various sources in the catchment, primarily industries and nonpoint sources, the pollution load in the river increases in its course downstream. On the other hand, during the high flow in the LAR (the wet season), which lasts nearly 4 months, the pollution of the river become relatively better than during the dry season. The spatio-temporal water quality assessment on the LAR (Angello et al., 2021) revealed that the physico-chemical pollution load becomes high during the driest months of December–March during when the river's color turns nearly black mainly contributed by industrial wastewater discharge and domestic pollution sources. The management plan should therefore consider prioritization of pollution control mechanisms during the dry season than the wet season. In support to this, the study conducted by Fan et al. (2012) on Pearl River Delta, China, recommended a water quality management and pollution control in consideration of seasonal variation. Despite high wash-off from various land uses into the river during the rainy season, the high flow may initiate self-purification and dilution of pollutants, resulting in a relatively lower pollution load than during the dry season.

Water quality management during the seasonal variation has to be prioritized for critical seasons.

Much emphasis should be given to the dry seasons since the pollution load are expected to rise, where similar conclusion was also drawn by (Fan et al., 2012). In this regard, this study suggests 2 major tasks to be executed while implementing water quality management during the critical period, dry season. First, the wastewater release from industries needs to be carefully controlled during the dry season than the rainy season. Even though, the contribution of the point sources load is less than the diffuses sources load in the study area, significant quantity of pollution could be controlled by better managing the point sources. More stricter rules should be imposed on the release rate of the industrial wastewater effluents. This could also be achieved by recycling the water from treatment plant effluents. Second, creating public awareness on environmental management should be given high priority.

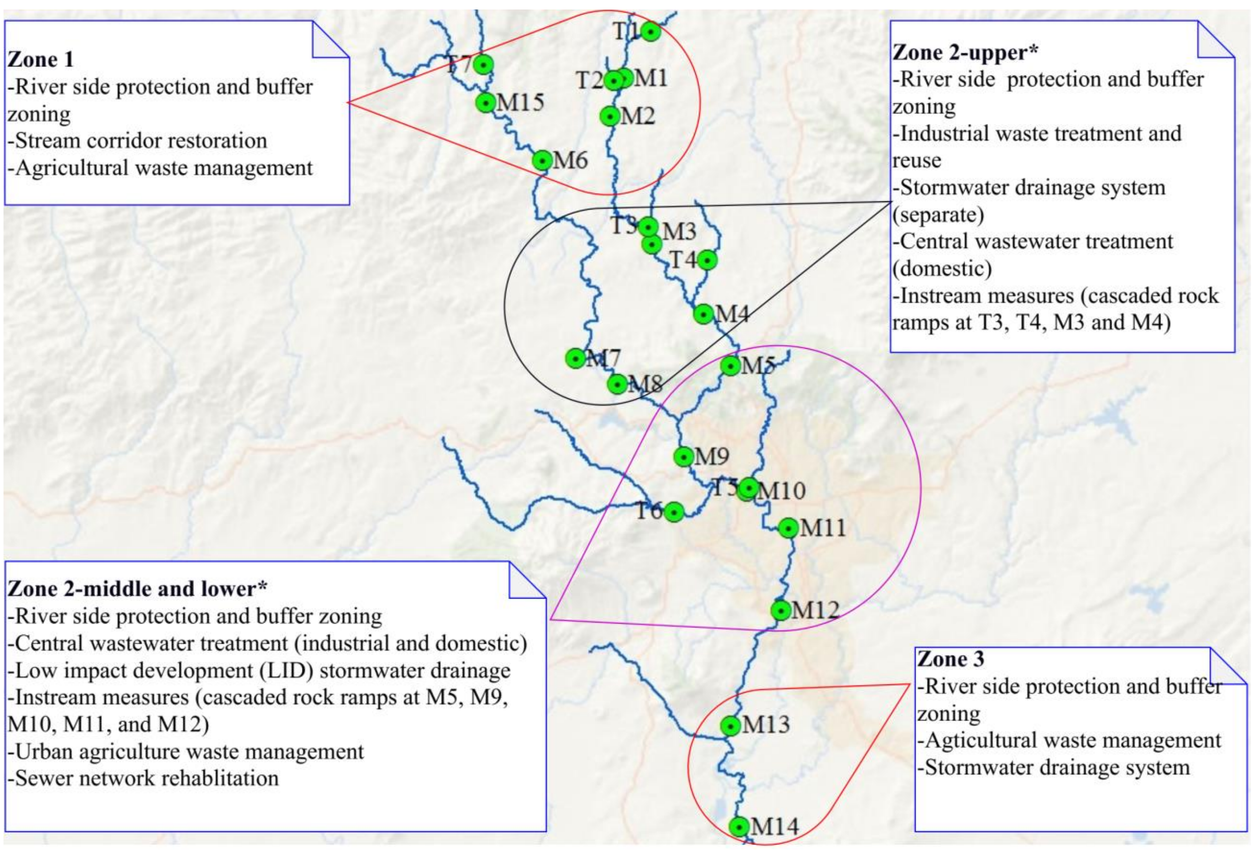

Figure 5.2: Water quality improvement and pollution reduction measures at selected pollution zones of the LAR (upper*, middle* and lower* are meant to denote the relative spatial location of the monitoring stations at Zone 2).

Apart from the temporal variation among chemical constituents, high spatial variation is also worryingly becoming the major challenge for the water quality management in the LAR. The middle and downstream segment of the LAR (Zone 2 and Zone 3 of Figure 5.2) predominantly carry high organic and nutrient pollution load than the upstream segment of the river. As a result, water quality management must be prioritized in these areas because the river's ecology is heavily influenced by the waste load carried by this river segment. The recommendations for the dry season suggested above are recommended to be implemented for spatial pollution management priority in the watershed. Figure 5.2 summarizes the better management options to be adopted in to the respective pollution hotspots (zones). The most upstream (Zone 1) and downstream (zone 3) segments of the LAR are mainly characterized by agricultural pollution and management of waste originating from agricultural fields and buffer zoning/stream corridor restoration could be a feasible option (Figure 5.2). On the other hand, for the heavily polluted LAR segment, a more advanced waste management such as industrial and domestic wastewater treatment plant, implementation of low impact development (LID) storm water drainage (Zone 2-middle* and lower) and instream measures using cascaded rock ramps (Zone 2) is highly recommended.

Integrated land use management, planning and catchment protection

Effective water quality management is strongly linked to better understanding of the correlation between land use and surface water quality (Ding et al., 2015). However, in LAR, better land use planning and management are missing, and stream corridor restoration evaluation is limited and often omitted from most river restoration programs. The nonpoint sources load contribution was found to be substantial in the study area due to poor land use management. As a result, the urban land use dominates the LAR catchment, contributing the largest proportion of organic and nutrient pollution to the river as nonpoint sources. Land use planning is thus linked to the management of nonpoint source pollutants, necessitating a clear and functional strategic action plan in the study area. The land use management should focus on the larger perspective of a wider catchment scale. Moreover, prioritizing the urban land uses than other land uses in the catchment could make the management process more focused. This study, therefore, recommends the following key improvement areas.

- Identification and implementation of river buffer zones.
- Insuring active community participation on the land use management, protection and

planning.

- Adopting the riparian vegetation in the urban areas.
- Rehabilitation of public sanitation infrastructures such as leaking sewer networks and nonfunctional septic systems.
- Adapting ecological sanitation options in areas where informal settlements prevail and the sewer systems doesn't exist.
- Implementation of wastewater conveyance and treatment systems in urban land use dominated areas aiming at controlling both sewage and storm water.

Need for attitude change on the impact of nonpoint sources: Modification of the existing pollution management approach

In water quality management, despite the high impacts of nonpoint sources load on surface water resources, nearly all the efforts are directed to the point sources load (Li et al., 2011). In Ethiopia, nonpoint sources are not yet considered as a major polluting agent in the urban river pollution management and hence were neglected from previous water quality management programs. This could be due in part to poor understanding of the potential impacts of nonpoint source pollution, lack of capital budget, and lack of attitude, less focus and underestimation of diffuse source pollution. Previously, no study was conducted on the quantification and impacts of nonpoint sources load in the study area nor the country has a nonpoint source pollution and management guideline and plan. In contrary, studies on nonpoint sources globally showed that the pollution load carried by the diffuse sources is significantly high and are included in the water quality management and pollution control plan (Li et al., 2011).

Until today, there is no single approach that is used to accurately determine the nonpoint sources load. Therefore, the only option should focus on the development of a system to estimate it. The problem is more acute in developing countries such as Ethiopia where quantification of diffuse sources often based on the personal judgement and experience. However, in Ethiopia, the government's focus is more of point sources centered. This approach has led to unsuccessful system in the country's urban rivers pollution management. The study finding revealed that the most common diffuse pollution sources in the LAR catchment are washouts from urban land uses (urban storm water), agricultural waste, runoff from construction sites and garages, and solid waste dumping site wash-outs. As discussed under chapter 3 of this study, the washouts from urban land uses were quantified and is more pronounced during the rain events. This can best be interpreted as the combined effects of rainfall and runoff. Despite the significant contribution of nonpoint source pollution, the attitude toward diffuse pollution is insignificant, leaving the LAR more polluted than ever. This study, therefore, recommends the following major change areas in the country's ambition to combat the impacts of nonpoint sources load and water quality management in the LAR.

- Reviewing the available guidelines on nonpoint sources pollution load and customizing to the local condition.
- Developing an area specific nonpoint sources quantification and management options.
- Developing and implementing the best nonpoint source management practices and customizing to the LAR catchment.
- Adopting a river side protection mechanism such as buffer zoning practices along the stretch of the river.
- Implementing a successful land use management and planning at the selected critical catchment areas (mainly middle and downstream segment of the catchment).
- Devising a mechanism for efficient solid waste management plan to reduce the pollution load to the river by the rainfall and runoff.

Rehabilitation and expansion of the existing sanitation infrastructures and urban drainage networks

The LAR catchment is mainly dominated by urban land use with informal settlements and poor sanitation infrastructures. The existing wastewater treatment plant in the catchment that is serving some parts of Kaliti sub-catchment such as Bole, Lideta, Old Airport, some part of Mekanisa and Kera is serving below its operating capacity. The expansion and rehabilitation work (currently underway) would have a positive impact where the project encompasses the largest treatment plant in the catchment, Kaliti wastewater treatment plant. However, the most urbanized areas of the LAR catchment that contribute largest pollution load were not part of the project. Maintenance of the broken sewer pipes where the wastewater is being released to the LAR is part of the expansion and rehabilitation work. In chapter 2, it is discussed that wastewater from a broken sewer system and septic tanks were among the major pollution sources to the river and the execution of the project will largely reduce the river pollution.

Despite the wider benefit of the centralized wastewater treatment plant by enhancing the water environmental quality of the LAR, it is still a concern that the project doesn't fully cover the middle segment of the LAR catchment near Mercato, where highly polluted tributaries carry large quantity of pollutants (Figure 5.2, Zone 2-upper*). The area is mostly characterized by the release of wastewater including raw sewage and toilet wastes to the open ditches, nearby river and LAR tributaries. Moreover, the LAR main channel also crosses densely populated urban centers where most segment of it is not part of the rehabilitation program. Furthermore, under chapter 2 of this study, domestic waste contributes significant quantity of pollution load where household liquid wastes such as raw sewage, toilet feces and solid wastes are dumped to the river. Beside the domestic and urban wastewater leakage, the storm water wash-off from urban land uses are discharged to the river. This is partly because the storm water infrastructures are either broken or clogged by solid waste dumped in the structures. This creates extra load to the LAR which is pronounced during the wet season. Accordingly, the following key recommendations are forwarded:

- Expansion of the current wastewater treatment system to the most affected and densely populated areas like Mercato so that the wastewater released to the LAR will be ultimately reduced.
- Maintenance of urban drainage networks and connecting to the treatment plants (or constructing a separate collection and treatment system-see option 2 below).
- Adapting a small decentralized wastewater collection and treatment plant as an alternative collection and treatment mechanism.
- Implementing a pay-per-pollution strategy for the wastewater released either through irregular dumping to the river and through the urban drainage infrastructures.

Planning separate storm water management system

Drainage problems are common in urban areas of developing countries, causing flooding that disrupt numerous environmental issues by damaging built environments and receiving water bodies. These problems are expected to be intensified partly due to fluctuating rainfall patterns as a result of climate change, aging infrastructures, and the nonstop densification of cities, where impervious surfaces are increasingly replacing permeable surfaces (Bohman et al., 2020). Despite the environmental degradation associated with poor storm water drainage systems, urban storm water management is generally inadequate or non-existent in developing countries like Ethiopia.

In Ethiopia, particularly Addis Ababa, few of the available storm water collection systems are mainly concentrated at the central part of the city which due to aging they are at extremely poor conditions. During heavy rains, the storm water is contained in the natural ravines and river channels carrying pollutants. Many factors are responsible for the poor urban drainage management that ultimately degrade water environment such as densification of urban areas, degradation of plant cover, inadequate infrastructures, lack of city-wide drainage master plan, weak enforcement on solid and liquid waste dumping into drains, and overlap between storm water, wastewater and solid waste. However, the traditional urban drainage management system in the city that collects the storm water and conveys to the nearby rivers has exacerbated the pollutant concentrations and hydrologic disturbance in the rivers (Adugna et al., 2019).

In the central and downstream segment of the LAR catchment constituting Mercato, Kera and Lafto, many of the urban drainage networks are diverted to the river and hence nonpoint sources from urban areas are washed off to the river. However, this has clearly augmented the pollution load in the river degrading the water quality in LAR. This study therefore recommends the following points in order to control the river pollution associated with storm water wash-offs.

- Implementing a separate storm water collection system for Zone 2-upper (Figure 5.2).
- Developing a low impact development (LID) storm water management approach for Zone 2-middle and lower and Zone 3 segments of the river (Kidist, 2018).
- Incorporating an alternative and optional use of integrating other sustainable storm water management system such as rainwater harvesting, retention and detention-based solutions (Adugna et al., 2019)
- Rehabilitation of the existing urban drainage networks.
- Shifting the urban drainage infrastructure problem corrective measures from complaints based to system-based approach.

5.4. Prospective Research Directions

This study tried to establish water quality management and pollution control mechanisms in LAR by characterizing pollutants in the river, estimating preliminary pollution loads in the watershed, and developing optimum pollution management options. However, the complete study and assessment of the pollution level, ecological restoration mechanisms and development of pollution management strategies largely depend on the monitoring of long-term data. In chapter 3 of this study, the pollutants characterization was based on the water quality monitoring of bimonthly sampling event over a one-year period. Even though it could be feasible for preliminary studies, design of frequent collection programs is recommended for future studies. Less frequency monitored water quality data might lead to under- and overestimation of pollution load by creating wrong, biased and erratic conclusion. However, most constituent concentration data from industries in Ethiopia are confidential and often rely on third-party data. Without the input from point sources, river water quality management could not be successful. It is therefore recommended that future studies focus on the continuous monitoring of water quality and quantity with high frequency sample collection design.

During the study of nonpoint sources load estimation based on the conjunctive application of chemical mass balance and watershed nonpoint source model, 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. In order to overcome this challenge, it is recommended to conduct direct estimation of nonpoint sources load by dividing the study area in to more classified land uses. This approach holds double advantage: First, the estimation of pollutants load is more accurate and the contribution from each land use can be explicitly determined. Second, a site-specific pollutants and nutrients export coefficient can be developed which could be used on another watershed diffuse source load estimation. The study of the nonpoint sources at each land use should also consider event variability. The data collection based on multiple rain events with continuous sampling and extreme dry seasons are highly advised. Another challenge when estimating the nonpoint sources pollution load in a river is difficulty in identifying the clear distinction between point and nonpoint sources load. Future studies should incorporate a detailed investigation of these pollution sources and clearly define the potential entry points for effective management of the LAR water quality. In addition, the studies should also include the impacts of ground water contribution, atmospheric deposition and other background pollution sources and flow.

River water quality studies in Ethiopia are often based on the determination of pollution cause-effect and assessment of on-spot pollution status of the water resources. Despite the fact that determining this cause-effect has significant impact on river pollution management, it does not explicitly investigate the root causes nor propose sustainable pollution management options and thus reliable techniques need to be devised. In LAR, the quantification of the point and nonpoint sources load was based on the integrated application of the chemical mass balance and a watershed nonpoint sources load model (PLOAD). Both methods are relatively simple but require accurate water quality and hydrologic data. The earlier approach requires water quality data collected at a closer range whereas the later uses the pollutants export coefficient for each reclassified land use. The estimation used in this study was based on the data at relatively closer range but the pollutants export coefficient data was estimated from literature elsewhere making the approach to be used for relatively accurate load estimation. This study therefore recommends collection of water quality samples at closer range, development of local export coefficients based on the detailed study of individual land uses, periodic characterization of the watershed with continuous monitoring and study, monitoring and inspection of the land use changes, preparation of databases for fertilizer applications and uses.

Hydro-meteorological data plays key role in water quality modeling, pollutants load estimation and catchment characterization. It has, however, remained a bottleneck in the LAR, rendering water quality management and pollution control ineffective. Due to the lack of flow measuring station in the LAR catchment at an appropriate location for determining pollution load, hydrological data inputs in this study were partly focused on hydrological model output. When estimating pollutants load in data-scarce regions, entirely depending on hydrological model outputs has a number of drawbacks. The transfer of flow from gauged to ungauged catchment is influenced by the catchment characteristics, land use and soil type and climatic factors. This in turn creates processing error and coupled with limited water quality data could lead to wrong conclusion. Accordingly, the primary gauge flow data is preferred over the hydrological model output where a correlation between river flow and pollutants load can easily be determined. This study therefore recommends deployment of automatic and manual river flow gauging stations at selected and critical locations in the river. Furthermore, the installed gauge recorders should be used to log the sediment load at stations in order to characterize sediment pollution emission and pollutants holding capacity.

In Ethiopia, due to lack of continuously monitored data, most of the point sources constituent concentrations and flow are assumed uniform. However, this method often yields a crude estimation of the pollution load released from point sources, which may result in an inaccurate quantification of the pollution load. On the one side, industrial water use varies with demand and production capability of the plant, resulting in high wastewater discharge. Furthermore, some plants may be unable to operate for a period of time, especially if the market condition decline to the point where water consumption and wastewater discharge are at an all-time low. Thus, this study recommends the respective industries and institutions to monitor the wastewater flow rate and the constituent quality during high and low flow periods. In order to check accountability, the respective government offices (FDRE-EEPA, AAEPA) need to inspect and follow-up the performance and prepare the database for the industrial wastewater and hydraulic characteristics. Besides, the industries and institutions need to be open to any research data requests. As a consequence, future studies on the constituent characteristics of industrial wastewater should be based on long-term data rather than average values or simple estimation and direct measurement of wastewater flow could be feasible for accurate determination of the pollution load from the point pollution sources.

Finally, the study under chapter 4 revealed that the optimum pollution reduction techniques selected are simultaneous application of source-based treatment of pollutants from point and nonpoint sources and instream measures such as the use of rock ramps. However, the implementation of such pollution reduction approaches simultaneously has an economic implication in a country where financial constraints are prevailing. Future research in this field should explore other economical pollution reduction solutions when designing the best water quality management and pollution control systems, taking into account the economic consequences of the chosen approaches.

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Appendix A: Original Published Paper 1

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Original Research

Spatio-Temporal Evaluation and Quantification of Pollutant Source Contribution in Little Akaki River, Ethiopia: Conjunctive Application of Factor Analysis and Multivariate Receptor Model

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Abstract

Little Akaki River (LAR) is among the heavily polluted urban rivers in Ethiopia. A bimonthly physico-chemical and heavy metals water quality analysis was conducted aimed at assessing the spatio-temporal characteristics and quantifying sources contributing to the pollution during dry and wet season at 22 montoring stations. Accordingly, laboratory analysis results indicated that most of the constituents deviated from the national and international guideline limits and the river is critically polluted at the middle and downstream segment. Factor Analysis (FA) was used to qualitatively determine the possible sources contributing to the pollution of LAR where three factors are identified that determine the pollution level during wet and dry season explaining 79.26 % and 79.47 % of the total variance respectively. Agricultural and urban runoff (nonpoint pollution sources), industrial and domestic waste are the three dominant factors that contribute to pollution in LAR. On the other hand, pollution sources of heavy metals in LAR are mostly dominated by industrial release whereas urban washouts from garages and automobile oil spills are other possible sources. Cluster Analysis spatially grouped all 22 monitoring stations into four and three clusters during the dry and wet season respectively. USEPA's receptor model, UNMIX, was used to quantify the composition and contribution of LAR constituents. The model predicted quite well with a minimum Signal to Noise ratio (S/N) of 2.71 and 2.16>2 and R^2 of 0.91 and 0.88>0.8 for the dry and wet season respectively. The UNMIX model effectively predicted the water quality source composition with a model predicted to measured ratio (P:M) of 1.04 and 1.16 during the dry season and wet season with an average percentage error of 1.38 % and 17.13 % respectively. LAR water quality management approach incorporating all the three pollution sources could be feasible.

Keywords: LAR, spatio-temporal assessment, FA, UNMIX, source composition

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Appendix B: Original Published Paper 2

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Article

Integral Application of Chemical Mass Balance and Watershed Model to Estimate Point and Nonpoint Source Pollutant Loads in Data-Scarce Little Akaki River, Ethiopia

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Abstract: The quality of Little Akaki River in Addis Ababa (Ethiopia) is deteriorating significantly due to uncontrolled waste released from point and diffuse sources. In this study, pollution load from these sources was quantified by integrating chemical mass balance analysis (CMB) and the watershed model of pollution load (PLOAD) for chemical oxygen demand, biochemical oxygen demand, total dissolved solid, total nitrogen, nitrate, and phosphate. Water samples monitored bimonthly at 15 main channel monitoring stations and 11-point sources were used for estimation of pollutant load using FLUX32 software in which the flow from the soil and water assessment tool (SWAT) model calibration, measured instantaneous flow, and constituent concentration were used as input. The SWAT simulated the flow quite well with a coefficient of determination (R^2) of 0.78 and 0.82 and Nash-Sutcliff (NSE) of 0.76 and 0.80 during calibration and validation, respectively. The uncharacterized nonpoint source load calculated by integrating CMB and PLOAD showed that the contribution of nonpoint source prevails at the middle and downstream segments of the river. Maximum chemical oxygen demand (COD) load from uncharacterized nonpoint sources was calculated at the monitoring station located below the confluence of two rivers (near German Square). On the other hand, high organic pollution load, biochemical oxygen demand (BOD) load, was calculated at a station upstream of Aba Samuel Lake, whereas annual maximum total dissolved solid (TDS), total nitrogen (TN), and phosphate load (PO_4-P) from the nonpoint source in Little Akaki River (LAR) were found at a river section near Kality Bridge and maximum NO_X load was calculated at station near German Square. The integration of the CMB and PLOAD model in this study revealed that the use of area-specific pollutant export coefficients would give relatively accurate results than the use of mean and median ECf values of each land use.

Keywords: chemical mass balance; pollution load (PLOAD); nonpoint sources; export coefficient; FLUX32

1. Introduction

Nowadays, urban rivers of developing countries are heavily polluted due to the release of pollutants from the point and nonpoint sources where the determination of accurate pollution load to a river is often difficult due to combined factors of financial, data quality and availability, and technical capability making the river water quality management more challenging [1]. In one way, not only is the determination of waste load from various sources, such as diffuse sources, difficult to quantify as a result of complexity in the generation and uneven distribution of wastewater from various sources [2],

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Appendix C: Original Published Paper 3

water

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Article

Selection of Optimum Pollution Load Reduction and Water Quality Improvement Approaches Using Scenario Based Water Quality Modeling in Little Akaki River, Ethiopia

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Abstract: The collective impacts of rapid urbanization, poor pollution management practices and insufficient sanitation infrastructure have driven the water quality deterioration in Little Akaki River (LAR), Ethiopia. Water quality modeling using QUAL2Kw was conducted in the LAR aimed at selecting the optimal water quality improvement and pollution load reduction approaches based on the evaluation of five scenarios: modification of point sources (PS) load (S1), modification of nonpoint sources (NPS) load (S2), simultaneous modification of PS and NPS load (S3), application of local oxygenators and fish passages using cascaded rock ramps (S4), and an integrated scenario (S5). Despite the evaluation of S1 resulting in an average load reduction of Biochemical Oxygen Demand (BOD) (17.72%), PO_4-P (37.47%), NO_3-N (19.63%), the water quality objective (WQO) in LAR could not be attained. Similarly, though significant improvement of pollution load was found by S2 and S3 evaluation, it did not secure the permissible BOD and PO_4-P pollution load in the LAR. Besides, as part of an instream measure, a scenario evaluated using the application of rock ramps (S4) resulted in significant reduction of BOD load. All the individual scenarios were not successful and hence an integration of scenarios (S5) was evaluated in LAR that gave a relatively higher pollutant load reduction rate and ultimately was found a better approach to improve pollution loads in the river. In conclusion, pollution load management and control strategy integrally incorporating the use of source-based wastewater treatment, control of diffuse pollution sources through the application of best management practices and the application of instream measures such as the use of cascaded rock ramps could be a feasible approach for better river water quality management, pollution reduction, aquatic life protection and secure sustainable development in the LAR catchment.

Keywords: QUAL2Kw; pollution reduction scenario; pollution load; Little Akaki River; WQO

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1. Introduction

Urbanization is greatly impacting the river water quality of developing countries driven by factors such as lack of proper sanitation infrastructure and urban drainage networks, poor land use management, the knowledge gap in environmental systems, and managerial incapability [1–3]. Nowadays, the beginnings can be seen, though slowly, of urban river pollution becoming a core focus area due to the threats it poses for the water environment through a wide range of physical, chemical, and biological processes [4]. Primarily, the wastewater released from various sources such as industry, household, agricultural and urban land use has augmented the pollution load in the rivers which heavily degrades the aquatic environment [5]. Moreover, the release of nutrients from agricultural land to the surface water resources promotes eutrophication which ultimately depletes the dissolved oxygen concentration [6,7]. Despite the high impact of pollution originating from the point and nonpoint sources on urban rivers of developing countries,

Curriculum Vitae

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Date of Birth: February 24, 1986

Place of birth: Masha/Ethiopia

Sex: Male

Marital Status: Single

Nationality: Ethiopian

Passport No.: EP4465369

Summary

Graduate of Water Supply and Environmental Engineering who has integrated academic achievement with administrative skills and capable of motivating and organizing others for research works with good interpersonal communication skills. Concrete practical and theoretical foundation supported by MSc in Hydraulic Engineering from Addis Ababa University.

Software and Skills

WaterCAD, SewerCAD, Microsoft Office (Basic), ArcGIS, HEC-HMS, QUAL2Kw, UNMIX, PLOAD, SPSS, R (Basic), SWAT.

Education

University of Rostock, Rostock, Germany (2017-onwards)

PhD candidate, Department of Water Management, faculty of Agriculture and Environmental Sciences.

Research area: Water/Quality Management, Pollution Control, Environmental Remediation

Addis Ababa University, Addis Ababa, Ethiopia (2010– 2012)

MSc in Hydraulic Engineering

MSc thesis title: Flood Mapping and Modeling on Fogera Flood Plain: Case Study of Ribb River

Arba Minch University, Arba Minch, Ethiopia (2005– 2008)

BSc in Water Supply and Environmental Engineering

Final year project title**:** Design of waste stabilization pond for Arba Minch University.

Employment History

Lecturer, Faculty of Water Supply and Environmental Engineering, Arba Minch University, Arba Minch, Ethiopia

Achievements and responsibilities:

- Instructed different courses on water supply engineering, hydrology, sanitation and design of hydraulic structures.
- Project advisor for undergraduate as part of the BSc curriculum for the final year thesis
- Research co-supervisor for postgraduate students in the area of water supply and sanitation engineering.
- Acted as university industry linkage and technology transfer officer under the Arba Minch Water Technology Institute of Arba Minch University, Ethiopia.
- Guided the revision and development of each curriculum, manuals and teaching materials
- Monitored and followed up the progress and evaluation of teaching, research and community service activities within the department and across the faculty as deemed necessary.

Projects and researches

- Preliminary design engineer and construction supervisor of water treatment plant for pond water in pastoralist areas of Borena, Oromia, Ethiopia-Funded by AFD.
- Primary investigator of sanitation option for Arba Minch Town, base line study editor and water supply technology assessor for Arba Minch town, February-May 2013, a project funded by CLARA.
- Office Engineer at Addis Ababa Water and Sewerage Authority.
- Team leader, Kulfo Grand Project: Professional contributions in two sub project teams including Hydrometeorological investigation and Land use planning & watershed management, a project initiated by Arba Minch University, Ethiopia.

Trainings and Workshops

- International Training of Trainers-Integrated Water Resources Management from Basin Perspective" organized by Wageningen University-UR, Center for Development Innovation, May 27, 2013-June 14, 2013, the Netherlands.
- Development of Mini-hydropower for Rural Electrification and Energy Shortage in Rural and Semi-Urban Areas of Ethiopia", December 23-29, 2012, Arba Minch, Ethiopia
- Capacity Building Training on "operation, maintenance and management of water supply schemes", 13th-17th November 2015, Ara Minch University, Arba Minch, Ethiopia.

Publications and conferences

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