Assessment and Modeling of Surface Water Quality Dynamics in Awash River basin, Ethiopia

A Dissertation

by

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Abstract

Awash River has the most important economic values in Ethiopia. However, it has been recognized as being impaired by high amount of various pollutants owing to waste released from different socio-economic activities in its basin since the basin encompasses the main urban, industrial and agricultural centers of the nation. However, investigation of pollution level of the basin is necessary for decision makers to safeguard Awash River and its end users, which has not been addressed yet. This research was therefore aimed at evaluating the status, assessing the spatial-temporal dynamics and modeling surface water quality dynamics in relation to different land use scenarios in Awash River basin.

Status of water quality of Awash River was evaluated with respect to drinking and irrigation water uses by choosing 17 sample sites along the River based on accessibility and land use severity and sampling was done twice in each of the dry and wet seasons. Then both onsite and offsite water quality analyses were undertaken following standard procedures. After comparing different water quality indices in use todate, Canadian council of ministers of environment water quality index was applied to compute the water quality indices. The drinking and irrigation water quality indices of the upper basin were 34.79 and 46.39 respectively, which were in the poor and marginal categories of the Canadian water quality ranking. Similarly, the respective indices for the middle/lower basin, which were 32.25 and 62.78, lie in the same ranges of the ranking. Although the difference in the used dataset of the two cases and natural purification in the course of the River might contribute to the difference in WQI, it is generally conceivable that the water quality of the River is below the fair rank.

To assess the spatial and temporal variation of water quality in the basin, means of the 9 years' (2005-2013) water quality dataset of 19 parameters from 10 stations in the basin were used. After validating, normalizing and checking the sampling adequacy and internal consistency of the data, principal component analysis was computed and four principal components were generated. Factor loadings, correlations between variables and the principal factors as well as between sites and the principal factors were tabulated. Agglomerative hierarchical clustering done on the dataset resulted in four clusters based on similarity of water quality characteristics. The Mann-Kendall's two tailed trend test detected temporal trends for total hardness in February over all sites and for most parameters in the basin in the 9 years period. Spatial analysis of the 14 sampling sites of the basin showed that as one moves from upper to lower parts of the basin, electrical conductivity, total hardness and chloride levels decrease in

the dry season. However, total hardness slightly increases and total dissolved solids, chloride, and sulfate content decrease in the rainy season. Cl^- and EC/TDS/SO_4^- are maximized respectively at before Beseka and Beseka in both seasons and Beseka, before Beseka and Sodere spring are found to be important sites responsible for the spatial variation.

To see the relation between land use/land cover (LULC) and water quality in the basin, LULC dynamics was assessed by using cloud-free LS 5 and 7 TM imageries of 1994, 2000 and 2014. The images were captured from EROS center of USGS GloVis viewer and classified by supervised classification coupled with maximum likelihood algorithm in ERDAS Imagine. The dominant LULC of the eight identified land use types were agriculture, barren land, and shrub-land in the 3 years' period. Built-up and water bodies were found to have increased and decreased respectively by about 147% and 63% as one goes from 1994 to 2014.

Moreover, in line with the changes in land use specifically of urbanization and agricultural intensification from 2000 to 2014, around which water quality have been analyzed, the parameters EC, TDS, Alkalinity, TH, SO_4^{2-}, Na^+, Cl^-, K^+, and NH_3 were found to increase monotonically. Mean values of water quality indicators such as EC, nitrate, and some anions have been compared in the agriculture-dominated, industry-dominated and urban-dominated land uses. As a result, EC within the urban and industrial land uses was found to be maximized. Nitrate, on the contrary, is observed to be higher in agriculture-dominated land uses and higher concentration of anions (bicarbonates and chlorides) and hardness have been generated from urbanized areas.

This study also evaluated performance of the Soil and Water Assessment Tool (SWAT) by modeling nitrate and phosphate at the basin scale. First, the model was set up using digital elevation model (DEM), climate, soil, and land use data. Thereafter, overall performance of the model was assessed by linking its outputs to the Sequential Uncertainty FItting Version 2 (SUFI2) procedure of the SWAT Calibration and Uncertainty Program (SWAT-CUP). The most sensitive parameters for the flow and nutrients were identified using t-stat and p-values from global sensitivity analysis of the SWAT-CUP. The goodness-of-fit of the monthly calibration measured by coefficient of determination (R^2), Nash-Sutcliffe Efficiency (NSE), and root mean square error-observations standard deviation ratio (RSR) were respectively 0.79, 0.64 and 0.60 for flow; 0.73, 0.71 and 0.54 for nitrate and 0.77, 0.76 and 0.49 for phosphate. During validation, R^2, NSE and RSR were respectively 0.81, 0.52 and 0.70 for flow; 0.68, 0.63

and 0.61 for nitrate and 0.82, 0.81 and 0.44 for phosphate. The results suggested that the model is promising to predict nutrients in the basin.

From the modeling, concentrations of nutrients were found to be both seasonally and spatially variable. Sub-basins 4, 8, 13, 21 and 39 were hotspots both in 1994 and 2014 with respect to exporting higher amounts TN and TP. From the temporal investigation of nutrients' monthly averages in the period from 1997 to 2014 of sub-basin 3, the rainy months (March, July and August) export higher amounts. Basin-wide comparison of the monthly averages of nitrate, phosphate, TN and TP losses from the model simulations with the 2000 and 2014 LU's indicate that the respective values were generally greater in 2014 than in 2000. From the trends of TN and TP for each of the 53 sub-basins in 1994, 2000 and 2014, slight reduction was observed for the year 2000 as compared to that in 1994. However, since the increment from 2000 to 2014 was significant, the overall trend from 1994 to 2014 was found to be positive (increasing).

Results of the study have applications of filling the existing knowledge gap, facilitating informed decision making, using as a customizable framework for similar studies in other river basins of the nation.

Keywords: Agglomerative hierarchical clustering, Awash River basin, CCME WQI, Drinking, Ethiopia, Irrigation, Land use/Land cover, Mann-Kendall's trend, model, nutrients, principal component analysis, spatial and temporal, SUFI2 algorithm, SWAT-CUP, Water quality.

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Publications

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b. Keraga, A. S., Kiflie, Z., & Engida, A. N. (2017). Spatial and temporal water quality dynamics of Awash River using multivariate statistical techniques. *African Journal of Environmental Science and Technology*, *11*(11), 565-577.

c. Keraga, A. S., Kiflie, Z., & Engida, A. N. (2019). Evaluation of SWAT performance in modeling nutrients of Awash River basin, Ethiopia. *Modeling Earth Systems and Environment*, 5(1), 275- 289.

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Preface

This study was part of the AAU Thematic Research titled "*Development of Dynamic and Integrated Water Resources Management System for River Basins of Ethiopia*". The project hosted various MSc and other components. The overall project goal was to integrate water quality, hydrology, demand, supply and the general governance to highlight the interdependencies between policies, activities and aspirations in order to identify constraints and explore mutually acceptable alternatives. The water quality part, carried out by the PhD candidate in this document, is owned by the school of Civil and Environmental Engineering and school of Chemical and Bio-Engineering, AAIT of AAU bound by a Memorandum of Understanding (MoU). The information provided in this study, shared by the two parties, could aid in customizing governance of Ethiopian river basins in general and Awash River Basin in particular: a critical but severely threatened part of all the national river basins.

Chapter 1 Introduction

1.1 Background

Water is a factor within the economic, social and environmental pillars of sustainable development (Marseille, 2012). "Water is an essential element of life, and a satisfactory (adequate, safe and accessible) supply must be available to all since diseases related to contamination of drinking-water impose a major burden on human health" and it is impossible for a single life to exist without it (WHO, 2008; Degefu *et al*., 2013 & WHO, 2006). However, shortage of water and sanitation persist in every corner of the globe and tackling such water challenges have become a global topic for the 21^{st} century (WWC and WWFS, 2005) and therefore watershed and wellhead protection regulations should be a primary consideration (Nemerow *et al*., 2009).

The ecological and human crises resulting from inadequate access to, and the inappropriate management of, freshwater resources are numerous. These include destruction of aquatic ecosystems and extinction of species, millions of deaths from water-related illnesses, and a growing risk of regional and international conflicts over water supplies. Hence, a sustainable, which is a long-term water planning and management are required by national and international water experts and organizations (Gleick, 1998).

Recently water demand has increased in response to the increase in the global population, industrialization, urbanization, and development which led to a more utilization of water (Aweng-Eh, 2010). This has resulted in the generation and discharge of high amount of wastewater either treated, partially treated, or untreated into the water bodies. Consequently, water resources have been deteriorated, and water has become a more vulnerable natural resource in both quality and quantity. A unified and holistic approach is therefore required for the sustainable management of these vulnerable resources (Ekdal *et al*., 2011).

Like that of ensuring supply of sufficient quantity of water to society, water quality is equally imperative to be addressed for an integrated management of water resources, which in turn will enhance an effective social, economic and ecological development thereby promoting sustainable development (Worako, 2015). Although the term ‘water quality’, whether related to surface or groundwater, is extremely broad, it is effectively the sum of different physical, chemical and biological properties. These properties of concern in a given water often vary depending on the purpose for which the water is used (Haygarth and Jarvis, 2002; Chin, 2013; Wang, 2001). It is also a measure of the condition of water relative to its impact on one or more of the intended uses (Rock and Rivera, 2014). Moreover, the presence, diversity, abundance and distribution of aquatic species in surface waters are dependent upon a myriad of physico-chemical factors, such as temperature, suspended solids, pH, nutrients, chemicals, and in-stream and riparian habitats (Wang, 2001).

The problems are visualized by the annual death of over three million people, mostly children, from water-related diseases in addition to subtle or indirect adverse health effects such as weakened and physically stunted children by frequent diarrhea episodes, permanent cognitive damage, and the immune-compromised people imposing significant social and economic burdens. This has implications of difficulty to achieve poverty alleviation and the other millennium development goals without improvements in water quality (UNICEF, 2008; Tebbutt, 1998).

Water quality problems are caused by various factors, which can broadly be divided into natural and anthropogenic (UNEP and WHO, 1996; Harrison, 2001). The most important of the natural influences are geological, hydrological and climatic, since these affect both the quantity and the quality of water available. Their influence is magnified especially when the available water quantity is low and maximum use is expected to be made of the limited resource. This is exemplified by the frequent high salinity problem in arid and coastal areas where water scarcity is observed like that of Awash River basin. Additionally, even if water may be available in adequate quantities, its unsuitable quality limits the uses that can be made of it. Even though the natural ecosystem is in harmony with natural water quality, any significant changes to water quality will usually be disruptive to the ecosystem and vice versa (UNEP and WHO, 1996).

The impact of human activities on water quality is versatile in the degree to which it disrupts the ecosystem and restricts its use. One way through which human activities can usually affect quality of a water body in a watershed is by point sources (discrete, localized, and often readily measurable discharges of chemicals) such as runoff and leachate from waste disposal sites; runoff and infiltration from animal feedlots; runoff from mines, oil fields, un-sewered industrial sites; storm sewer outfalls from cities; overflows of combined storm and sanitary sewers; runoff from construction sites.

The other way is through non-point sources (diffuse, and typically distributed over large areas) such as agriculture runoff and irrigation return flow; runoff from pasture and range; urban runoff; septic tank leachate and runoff from failed septic systems; runoff from construction sites; runoff from abandoned mines; atmospheric deposition over a water surface; activities on land that generate contaminants (Carpenter *et al*., 1998; Hemond & Fechner, 2015). One of such effects comes from human feces. Fecal pollution may occur because there are no community facilities for waste disposal, collection and treatment facilities are inadequate or improperly operated, or on-site sanitation facilities drain directly into water bodies. Eutrophication, for instance, results not only from point sources, such as wastewater discharges with high nutrient loads, but also from diffuse sources such as run-off from livestock feedlots or agricultural land fertilized with organic and inorganic fertilizers (Wang, 2001; UNEP and WHO, 1996).

The problem of water quality degradation and its spatial and temporal variability in developing countries like Ethiopia is becoming a threat to human, animals and the natural water resources. This is because of the rapid increase in population, climate change, industrialization, and the associated land use dynamics in the countries (Kithiia, 2012; Abbaspour, 2011; Davies and Simonovic, 2011). Surface water quality and its spatial variation is governed by both natural processes and anthropogenic activities such as climatic variables, types of soils and soil erosion, rocks, hydrology and surfaces through which it moves, agricultural land use, and sewage discharge (Bu *et al*., 2010; Pejman *et al*., 2009).

Though there is no detailed study of water quality done at the basin level, a number of researches have been conducted on water quality at the sub-basin levels of Awash River Basin (ARB) especially where some sorts of developments are undertaken. Salinity, which is expressed by EC and sodium hazard (SAR) is found to be the main determinant for water to be used for irrigation. Basin wise, salinity of water has been increasing progressively from the upper basin where it is low to the middle where it is moderate and then to the lower basin at which it is highest (Taddese *et al*., 2003; Halcrow, 1989). On the other hand, sodium hazard is found to be low in the upper and middle basins and become moderate in the lower basin. The possible causes for this increase in salinity were suggested to be irrigation return flows and hot springs. Temporally, there were indications of water quality being generally deteriorating in the low flow season certainly because of the decrease in dilution as abstractions for irrigation increase and low rainfall (Halcrow, 1989). The study by Halcrow (1989), also evidently showed that the pollution level in the upper part of the basin was worse owing to the Little and Great Akaki tributaries, which satisfy neither the physico-chemical nor the bacteriological requirements for water supply and contact even. In the meantime, these streams have been used for livestock watering, domestic, irrigation and washing.

According to Taddese *et al*. (2003), nitrate, mean concentration of heavy metals including manganese, chromium, nickel, lead, arsenic (As) and zinc (Zn) are reported to be higher in soils irrigated by the Akaki River. The authors found out that salinity problems are recognized throughout the Lower Awash Valley. Another common problem in drained marshes and swamps is that soils become infertile and acidic. They added that there is a development of persistent shallow saline groundwater due to large scale irrigation projects without functional drainage system and appropriate water management practices in the middle awash region, capillary rise. There is also a reduction of NO_3, Fe, Zn and Cu. Discharge to the groundwater by surplus irrigation water has caused a rise in the water table in middle awash irrigated field and problems with secondary salinity in surface and sub - surface soil horizons (Taddese *et al*., 2003).

1.2 Statement and justification of the problem

Ethiopia is endowed with a number of large rivers and lakes which have a potential of providing immense values to the overall socio-economic development. In fact, the nation has 12 main rivers in the 12 basins, 11 fresh water lakes, 9 saline lakes, 4 creator lakes and more than 12 major swamps and wetlands (Worako, 2015). From these resources, the country produces about 124.4 billion cubic meter (BCM) of river water, 70 BCM lake water (totally 194.4 BCM surface water potential), and 30 BCM of groundwater resources. It has a potential of developing 3.8 million ha of irrigation and 45,000 MW hydropower production (Melesse *et al*., 2014). However, despite these potential, adequacy and quality of water reaching to the society is being threatened (Worako, 2015).

Lakes and rivers in the Ethiopian rift, which pass through valleys of the study area, are means for mechanized irrigation, soda abstraction, commercial fishery, recreation and support a wide variety of endemic birds and wild animals. Such an intensive utilization of water resources is found to endanger the resource nowadays (Ayenew, 2007). Improper management of water resources in the region is seen by the shrinkage of lake Abjiata due to excessive abstraction of water and expansion of Lake Beseka due to increased surface runoff and groundwater flux from percolated over-irrigated fields and active tectonism. Apart from these quantitative challenges, the water bodies are also facing water quality problems as a result of these and the natural factors as climate and geology (Ayenew, 2007).

River water pollution in developing countries, including Ethiopia, is a growing challenge and needs urgent action to implement inter-sectoral collaboration for water resource management that will ultimately lead to integrated watershed management (Awoke *et al*., 2016). There is a downside of the water sector with regard to water quality monitoring and surveillance in Ethiopia. The root cause for this is the less focus given to water quality monitoring compared to provision of access and coverage. Absence of organized and well equipped central water quality monitoring laboratory, lack of sufficient capacity to monitor water quality, weak community-based awareness raising activities in the area of drinking water quality and absence of fully functional data management system are other factors inhibiting water quality nationally (MoH, 2011).

Despite the fact that the water quality variation is assessed at the global scale, the type and magnitude of quality degradation and impacts of the determining factors for the dynamics at a river basin scale is not investigated in most part of Ethiopia. Furthermore, implementation gap of water quality management being observed in Ethiopia at a basin scale is witnessing not to see the required quality level for intended water uses (Romilly and Gebremichael, 2011). The water quality of most rift valley lakes is also very poor in most water quality parameters especially in salinity and alkalinity and hence not suitable for irrigation, domestic or industrial purposes. There is also a spatial difference in water quality between the lakes (Tiruneh, 2005; HGL and GIRDC, 2009).

Among the major Ethiopian rivers, Awash has the most important economic value to the nation. However, it has special water quality problems to which attention needs to be paid. Since much of the wastewater (domestic, agricultural and industrial) produced in the basin reaches the Awash River untreated, the River is prone to various types of serious pollution. The exposure is due to the fact that the river serves as a major water supply source for domestic and large to small-scale irrigation schemes and as a sink for the basin-wide urban, industrial and rural wastes. On the other hand, there are no significant treatment systems corresponding to the wastewater generated in response to the water use. Though the then water of the Awash River was reported to be quite suitable for irrigation, water from the saline springs and wells or from lakes fed by saline springs of the basin was recommended not to be used (UNFAO, 1965) but the situation even of the river is changing currently.

Extensive and diverse socio-economic activities such as urbanization, agricultural activities, industrialization, and deforestation are being expanded at an alarming rate recently in the ARB. Particularly, the upper part of the basin is relatively more mountainous, populated and humid than the lower part. As a result, the nature and concentration of the pollutants entering into the river from tributaries originating from the two parts were observably quite different. These differences in sub-basin characteristics such as topography, population density and regional climate may account for the high indices of flow variability. This would contribute to the seasonal variability of inflow in these regions, which may in turn magnify the loading differences of nutrients.

Nowadays, like that of other basins in the nation where agricultural-led industrialization is being implemented, there are a number of small, medium and large scale industries booming in the basin. Most of Ethiopian chemical, printing, metal machinery, and equipment manufaturing industries in addition to the leather, food, cotton, non-metallic mineral and textile industries are concentrated along the tributaries mainly in Addis Ababa, Alem Gena, Dukem, Bishoftu, Mojo and Adama. The practice of these industrial, urban and comercial centers to discharge their liquid waste into open areas, the river stream, or its tributaries has caused the basin's water resources to become highly polluted (Kloos & Legesse, 2010).

Moreover, the contaminated surface and ground water around Addis Ababa metropolitan area is used widely for domestic, hyegiene, medicinal purposes (holy springs) and for production of vegetables by irrigation. This is because most industrial firms and urban centers within the basin do not have the required treatment mechanism for their waste. These industries if continued at present trend, one way or another, will have potentially adverse impacts on the quality of Awash River. Irrigation schemes of different scales (sugarcane plantations) as Wonji, Wonji-showa and Metahara sugar estate and subsistence farms also contribute to the water pollution in Awash valley. One example of which is application of agro-chemicals such as fertilizers and pesticides (insecticides, herbicides, fungicides and rodenticides) (Kloos & Legesse, 2010).

It has also been reported by Akele (2011) that there is an inadequate participation of stakeholders in the management and usage of water parallel to the various development activities that have been intensively carried out in the basin. Subsequently, the river receives back the untreated domestic and agricultural wastewater from the catchment area and effluents from industries directly during its course. The polluted river from the uncontrolled waste serves again in the downstream as water supply source of domestic, hydropower, industrial, irrigation, and disposal of wastewater (Belay, 2009; Alemayehu, 2001; AwBA, 2014).

On the other hand, developing water quality criteria, guidelines and standards for all intended water uses as well as formulating receiving water quality standards and legal limits for pollutants for the control and protection of indiscriminate discharges of effluents into natural water courses are crucial for the end users. But these are specific cases of the general national policy of ensuring water resources management, development and utilization is compatible and integrated with overall socio-economic development framework and other natural resources as well as river basin development plans. Since the Ethiopian water sector policy focuses mainly on river basins as fundamental planning unit and water resources management domain, the research is believed to contribute to the realization of these issues. The research also addresses the specific water quality management included in the national policy of developing appropriate water pollution prevention and control strategies in the Ethiopian context. That is related to one of the national general water resource policy of recognizing that water supply and sanitation, watershed management, water resources development, protection, conservation and related activities need integration and addressing in unison (MoWIE, 1999).

The majority of people living in the rural parts of Ethiopia rely on water from unprotected sources such as rivers, lakes and springs which are unsafe to drink, and Awash River basin (ARB) is no exception. As a result, nationally more than half a million people die every year of water borne and water related diseases, mostly infants and children below 5 years of age though different ministries and regional authorities concerned with water quality have been involved in water quality monitoring to safeguard the quality of drinking water (HGL and GIRD, 2008) and hence water related diseases are the major causes of morbidity and mortality in rural areas of Ethiopia. Natural water constituents such as fluorides and inputs of socio-economic activities such as pesticides, herbicides and heavy metals and pollution from industrial effluents, domestic wastes are also threats to the water resources nationally (HGL and GIRD, 2009). To that end, assessment of spatio-temporal variability of water quality parameters due to land use variation is of great importance in the conservation of water with respect to quality basin wide (Li et al., 2008).

Communication of the status of quality of a water body between water quality professionals, general public and the policy makers is needed to curb the quality problem thereby to safeguard the public health and the environment in general. One of the strategies by which this can be realized is by having an evaluation result of the water quality variables. Such an evaluation is effected by developing some water quality indices, which provide a broad overview of environmental performance rather than detailed information. These indices provide water resource experts the ability to represent measurements of different variables in a single number, the ability to combine various measurements in a variety of different measurement units in a single metric, and the facilitation of communication of the results (Hambright et al., 2000; Cude, 2001).

1.3 Research questions

- What is the status of water quality of Awash River (in ARB)?
- How is water quality of Awash River vary spatially and temporally?
- What is the effect of changes in land use/land cover on water quality of ARB?
- Which methods are suitable to look at the spatial and temporal dynamics of water quality in ARB?
    - Which multivariate statistical tools can show the dynamics?
    - How can hydrologic/water quality models be prioritized to model nutrients?
        - ✓ How strong is the SWAT model in simulating nutrients in the basin?

1.4 Objectives

1.4.1 Main objective

The general objective of the study was to undertake the analysis and modeling of water quality dynamics in Awash River Basin (ARB) and look for its nexus with land use/land cover.

1.4.2 Specific objectives

The specific objectives were to:

a. Evaluate water quality of Awash River using water quality index,
b. Investigate the spatial and temporal water quality variation (and trends) of Awash River,
c. Assess the land use/land cover (LU/LC) dynamics of the basin and assess the effect of change in the LU/LC on water quality,
d. Model nutrients of ARB and identify hotspots of the basin w.r.t nutrient loss.

1.5 Significance of the Study

Basin-wide dealing with water quality status of Awash River parallel to its exhaustive usage for different activities, its spatial and temporal dynamics, and relationship of the quality with land use in the basin is non-existent to the best of our knowledge. But such a study has a scientific and practical significance in that it fills the existing knowledge gap and establishes a water quality database. This insight, which provided on the spatio-temporal water quality dynamics, facilitates informed decision making and implementation of sound management options. It is also used for fair water allocation by figuring out the exact amount of usable water to be supplied to consumers. It contributes towards quantification and understanding (the status of the river's water by figuring out exactly which of the parameters and sites are showing deviations from standards) of the status of the river basin's water quality at different locations in terms of relevant water quality parameters. Ultimately, it enables decision makers to have ample information on the status so as to suggest if the water is suitable for intended use in the downstream. Establishment of water conservation strategies robust enough to accommodate the quality changes which could possibly occur due to anthropogenic changes can also be realized only if the status of the basin water is assessed well.

1.6 Structure of the thesis

The chapters in the manuscript are outlined in such a way that the idea is well built. The first chapter introduces the general background, rationalizes the problems and states the main and specific objectives of the research. The second chapter reviews literatures related to water quality. Current status of water pollution (quality) is reviewed from the global, regional, and national perspectives together with previous water quality studies in the ARB. Water quality management as a tool for integrated water resources management, spatio-temporal water quality dynamics in river basins**,** causes and observable effects of water quality degradation in ARB**,** characterization and assessment of water quality, factors affecting water quality and its variation in river basins are some of the issues addressed here. Next, the general materials and methods are briefly described in the third chapter. Here location, topography, climate (rainfall, temperature of the basin), hydrology, and basin ecosystem structure of the study area are described. The main methodologies used to meet the objectives are sequentially stated in this chapter. Chapter 4 explains the main findings of the study by starting with evaluation of water quality in the basin. Then, spatial and temporal variations of water quality of the river are assessed using long-term water quality data. Modeling results relating land use and water quality in ARB are also highlighted here. It also discusses the results with respect to literatures already reviewed on the study area. Finally, chapter 5 closes up the whole chapters by concluding and recommending all the necessary and possible solutions for the betterment of the basin water quality.

Chapter 2 Literature Review

2.1 Global surface water pollution

As a result of fast population growth, increasing resources' utilization and industrial development, water is becoming a very scarce and valuable resource. Due to the scarcity of water and its quality related problems, the ability of developing countries specially to supply their population with water and to satisfy their future water demand for the economic and environmental needs have already been affected. In a country sustainable development is possible only if water resources of the country are managed and utilized properly. Proper utilization of water resources requires knowledge, basic understanding of the hydrologic system and the processes influencing them both spatially and temporally (Chekol *et al*., 2007). Therefore, literatures conducted on the global, regional and local status of water pollution, its determinants (causes) and effects, the nexus that quality has with management, the modeling philosophy and studies in line with the study objective done in different spatial and temporal extents were reviewed according to Randolph, (2009).

The main environmental and public health dimensions of the global freshwater quality problem are: five million people die annually from water-borne diseases; ecosystem dysfunction and loss of biodiversity; contamination of marine ecosystems from land-based activities; contamination of groundwater resources and global contamination by persistent organic pollutants (Ongley, 1996). Furthermore, Ongley (1996) added that freshwater quality would become the principal limitation for sustainable development in many countries early in this century since pollution can no longer be remedied by dilution and this has global implications as: declining in sustainable food resources due to pollution, cumulative effect of poor water resource management decisions because of inadequate water quality data in many countries, many countries can no longer manage pollution by dilution leading to higher levels of aquatic pollution and escalating cost of remediation and potential loss of creditworthiness.

A variety of land uses resulting from different human activities such as agriculture, urban and industrial development, mining and recreation potentially and significantly alter the water quality differently (Li *et al*., 2008; Tong and Chen, 2002; Abbaspour *et al*., 2007). This is because of the fact that these various land use types produce runoff enriched with different kinds of contaminants or that they can modify the land surface characteristics, water balance, hydrologic cycle, and the surface water temperature. For example, while runoff from agricultural lands may be enriched with nutrients, sediments and pesticides; runoff from highly developed urban areas may be enriched with rubber fragments, heavy metals, hydrocarbons, chlorides as well as sodium and sulfate from road deicers (Tong and Chen, 2002; Abbaspour *et. al*., 2007). As a result, the physico-chemical and biological processes in the receiving water bodies are being affected in recent years and the cause for the declining availability of usable freshwater is such an unsustainable land use practices (Tong and Chen, 2002). Major water quality issues in rivers include changes in physical characteristics (such as temperature, turbidity and TSS), fecal contamination, organic matter, river eutrophication, salinization, acidification, trace elements, nitrate pollution in rivers, and organic micro-pollutants (Chapman & WHO, 1996).

2.2 Factors affecting water quality and its variation in river basins

There are various factors that have either direct or indirect impacts on water quality. Such factors as demography, economy, policy changes, current spatial pattern of houses and land use are generalized as of either natural or anthropogenic causes (**Figure 2-1**) (Bartram & Ballance, 1996; Khatri & Tyagi, 2015; Harrison, 2001). The specific factors governing water quality at a given river station include: a) the proportion of surface run-off and groundwater, b) reactions within the river system governed by internal processes, c) the mixing of water from tributaries of different quality, and d) inputs of pollutants. The chemical weathering of surficial rocks; volcanic fallout; recycled oceanic aerosols; continental Aeolian erosion; decay of vegetation; leaching of organic soils; atmospheric inputs are the particular processes adding elements to a river water (Lintern et al., 2018; Chapman & WHO, 1996).

Chaudhry and Malik (2017) suggested that precipitation, climate, soil type, vegetation, geology, flow conditions, ground water and human activities such as industries, mining, urban development and agriculture, generate non-point sources of pollution (including nutrients, sediments and toxic contaminants), but the biggest cause of all are industrialization and increase in population (Chaudhry and Malik, 2017). In the assessment of effects of land use, topography and socio-economic factors on river water quality of agricultural watershed; TN, pH and temperature were found to generally be higher in the rainy season, whereas BOD_5, DO and turbidity were higher in the dry season. Spatial variations were found to be related to numerous anthropogenic and natural factors (Chen & Lu, 2014).

2.2.1 Natural water quality determinants

Naturally, water quality varies due to catchment characteristics such as the type of bedrock (geological), soil, meteorological (climate change), topographical, hydrological, biological and population growth (driving increased social and economic development, globalization, and urbanization), rainfall, and vegetation (Cosgrove & Loucks, 2015; Zimmerman et al., 2008; Bartram & Ballance, 1996). It is also affected by biochemical processes such as denitrification in aquatic and terrestrial ecosystems through the amount of nitrogen in water. On top of that, surface water-groundwater interaction (ground-water discharge) also determines the quality in either of them (Gedion, 2009; Varanka, 2016). Torrential rainfall and hurricanes as natural factors may also lead to excessive erosion and landslides (Bartram & Ballance, 1996). The occurrence of highly soluble or easily weathered minerals of which the order of weathering is halite > gypsum > calcite > dolomite > pyrite > olivine; the distance to the coastline; the precipitation/river run-off ratio; the occurrence of peat bogs, wetlands and marshes which release large quantities of dissolved organic matter; ambient temperature; thickness of weathered rocks; and organic soil cover are other factors (Chapman & WHO, 1996).

2.2.2 Anthropogenic water quality determinants

Human activities have changed the nature of most rivers in the world by controlling their floods, constructing large impoundments, overexploiting their living and non-living resources and by using rivers for disposal of wastes. Threatening rivers and riverine resources these ways have often led to serious decline in river water quality, which in turn led to impairing their use for agricultural, drinking, recreational and other purposes and causing serious implications on human health and the environment (Carpenter *et al.*, 1998). Anthropogenic activities are found to be more detrimental than the natural ones in affecting water quality (Khatri & Tyagi, 2015; Bartram & Ballance, 1996). For instance, effects of anthropogenic activities on water quality of rivers was identified in Taihu watershed of china and they are found to have had significant effects on quality of the rivers. The rivers strongly influenced by household wastewater presented the highest concentrations of nutrients (TN and TP), while agriculture was proved to put less pressure on the case in the rivers. Rivers in the vicinity of cities presented serious negative feedback of water pollution due to their low DO level, while those flowing through the countryside, especially through hilly areas, were found to have high DO content (Wang *et. al*., 2007). The main factor in the tropical countries like Ethiopia is found to be a combination of human, geology, warm climate, and physiographic factors such as rugged terrain. These impair water bodies qualitatively through increasing the rate of mineralization, soil erosion and transport of particulates and solutes (Zinabu et al., 2002; Khatri & Tyagi, 2015).

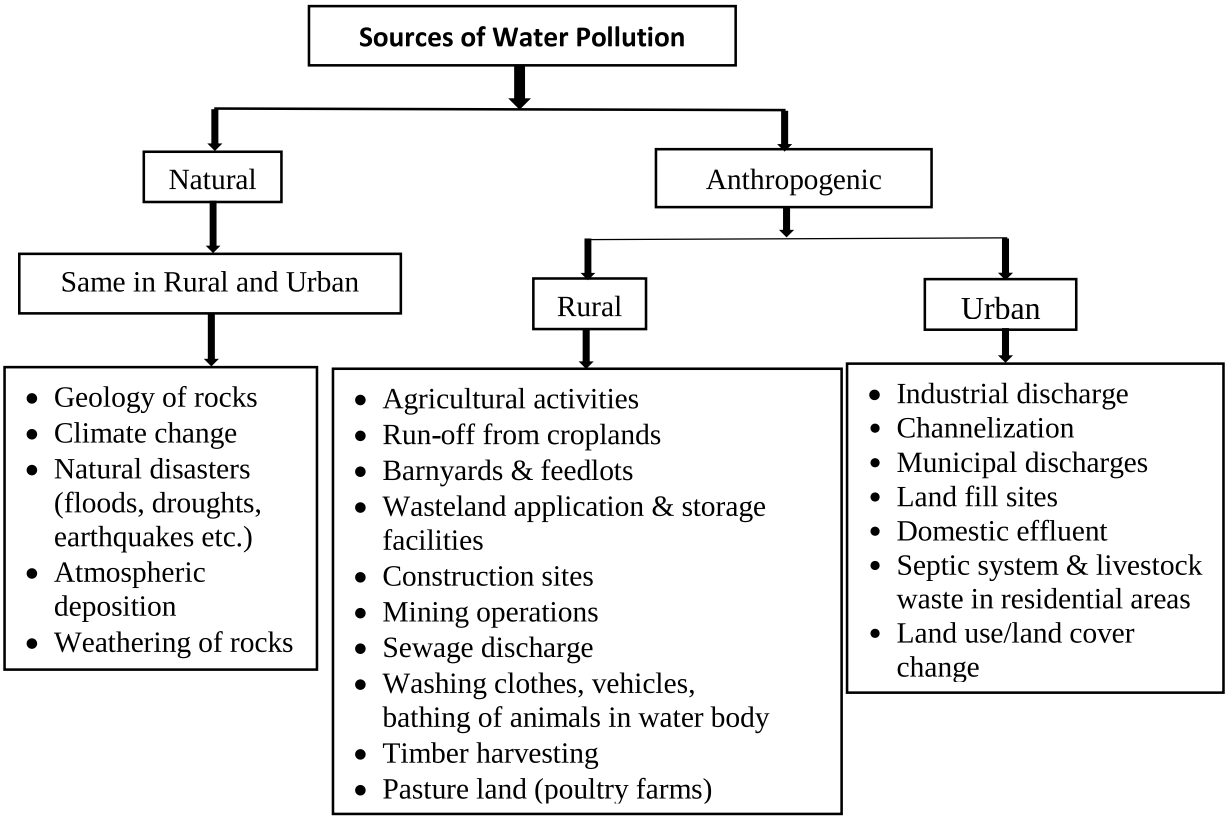


Figure 2-1 Classification of factors affecting water quality

Some of the socio-economic factors include: economic factors (industrialization, agricultural intensification), climate change, urbanization (demographic-population growth), technology (exemplified as commercial farming and dam construction relocate communities against their will and induce land degradation), level of affluence, political structures, attitudes and values (Briassoulis, 2009)- all causing change in land use and land cover. But discharge/flow is another cause resulting from land use change. Other factors having no cause-effect relationship with land uses include, but not limited to, soil, geology, topography and other natural ones. The formation, chemistry, morphology, and type of soil contribute to a greater extent to the quality of surface water. Water quality changes are seen by fluctuation and/or change in the amount/type of waste resulting from change (s) in these factors.

2.2.2.1 Impacts of land use on water quality

Specially in recent years, there is a rapid declining availability of usable freshwater in terms of water quality due to unsustainable land use practices since quality components such as sediments and nutrients are highly linked to land use and land cover in a catchment (Li et al., 2008; Maidment, 1993). The impact of land use on water quality, which should be assessed as part of water resource management, should take into consideration: land cover modification; extraction activities; construction/modification of waterways; application of fertilizers, herbicides, pesticides and other chemicals; livestock density and application of manure; road construction, maintenance and use; various forms of recreation; urban or rural residential development, with particular attention to excreta disposal, sanitation, landfill and waste disposal; and other potentially polluting human activities, such as industry, military sites, etc (WHO, 2006). The change in water quality could generally be elaborated in terms of manifestations of land use change in the form of urbanization (Kasarda & Crenshaw, 1991; Pugh, 1995; Teng, et al., 2011; Giri & Singh, 2013; Tegenu, 2010; Adeba et al., 2015; CIA, 2008), agriculture (Ongley, 1996), and industrialization (Ademe and Alemayehu, 2014; Kloos & Legesse, 2010).

2.2.2.2 Discharge and water quality

Understanding discharge of a river is very important to the interpretation of water quality measurements (e.g suspended sediment) as water quality is highly dependent on river flow conditions. Discharge of a river is a function of the catchment characteristics such as climate, meteorology, topography, hydrology, vegetation, geology, and geography. The discharge regime of, specifically, a tropical river is largely determined by the annual cycle of wet and dry seasons. Erosion, which is a cause for sediment (a carrier of water quality determinants) is a function of the amount and pattern of rainfall and resultant river regime, slope of the land, extent of destruction and regeneration of vegetation, soil type and resistance to the effects of temperature changes (Bartram & Ballance, 1996). River flow affects its water quality by altering dilution, residence time, mixing, and erosion (Ji, 2008).

There are also a number of other studies relating river discharge (which is largely determined by climate) and water quality. Aweng-Eh (2010), for instance, found out that there is a negative relationship between values of water quality variables (pH, DO, EC and temperature) and discharge. Variability in water quality is also found, by Chapman & WHO (1996), to depend on the hydrological regime of the river (water discharge variability), the number of floods per year and their importance. Different origins of the water: surface and sub-surface run-off, and groundwater discharge during flood periods show significant variations of water quality. Surface run-off is usually highly turbid and carries large amounts of total suspended solids (including particulate organic carbon (POC)). Sub-surface run-off, on the other hand, leaches dissolved organic carbon and nutrients (N and P) from soils, whereas groundwater provide most of the elements resulting from rock weathering (SiO_2, Ca^{2+}, Mg^{2+}, Na^+, K^+) (Chapman & WHO, 1996).

2.2.2.3 Effect of topography on water quality

Topographical factors played important roles in explaining spatial variations in river water quality in a river basin. Most studies are said to have shown that higher catchment slope or elevation lead to higher erosion rates, which subsequently increase the rate at which particulate matter enters a water body and hence the pollution loads on surface water bodies is greater there due to higher discharge though inverse relation may be seen when sloppy areas are occupied by forests and flatty ones are used for crop production (Chen & Lu, 2014). Water quality in rivers is also reported to be strongly related to land use and topography (Ye et al., 2009).

2.3 Water quality management as a tool for integrated water resources management (WQM-IWRM Nexus)

Recent socio-economic development and climate change demand multi-viewpoint and/or multi-criteria on river basin for a sustainable resource utilization in it. This needs incorporation and optimization of all components one way or another affecting water quantity, quality, and the ecosystem (Kojiri, 2008). Integrated Water Resources Management (IWRM) is a process of promoting the coordinated development and management of water, land and related resources, to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems (Tessema, 2011). IWRM is an important issue nowadays since the global environment is being threatened by factors such as climate change, regional development and population growth (Kojiri, 2008). IWRM needs communicative participation among multi-stakeholders, political commitment from the government side, capacity building, awareness raising and experience sharing among the participants, which can step-by-step be effective in Ethiopia (Jembere, 2009).

According to the Global Water Partnership (2000) guiding principles, successful implementation of IWRM relies on: an enabling legislative and policy environment; an appropriate institutional framework composed of a mixture of central, local, river basin specific and public/private organizations, which provides the governance arrangements for administration; and a set of management instruments for gathering data and information, assessing resource availability and needs, and allocating resources (enabling environment, institutional roles and management instruments) (GWP, 2000).

Water quality management is a discipline that integrates the technical and management activities as well as decision needed for effective maintenance of a guaranteed supply of water of suitable quality for the intended uses. A fundamental principle on dynamic water quality management for sustainable development embraces the inseparable concepts of increasing productivity in all its forms while concurrently protecting and conserving water quality and quantity as well as the environment in general (MoWIE, 2010). The best approach to manage water resources therefore links the environmental aspects of water quality directly to social and economic factors (Palmer *et al*., 2004).

Integrated River Basin Management (IRBM), which embraces IWRM, involves all management issues related to the supply, use, pollution, protection and rehabilitation in a river basin. Integrated implies that relations between the abiotic and the biotic part of the various water systems, between the ecological and economic factors and between the various stakeholder interests are taken into consideration in decision process (Matthies *et al*., 2003). Therefore, water quality management is a major instrument and critical component for integrated water resources management (Loucks and Beek, 2005). Specifically, maintenance of the quality and quantity of freshwater has a long-term ecological, health, and economic implications as it is an essential and integral parts of the natural resource (Ferrier et al., 2001)

2.4 Water quality dynamics

Variation in water quality can be dealt in terms of dfferent spatial and temporal scales. This is because of the fact that every unique point of catchment areas is exposed to and endowed with physiography and natural and anthropogenic attributes differently. Even a single point of a place may attain different climatic and physiographic features, which directy or indirectly, are determining causes for water quality dynamics.

2.4.1 Water quality dynamics in Ethiopia

Ethiopia parallel to its economic development, is showing an increasing rate of release of pollutants into water bodies. In recent years, increasing amounts of sewage originating from domestic and industrial sources in Ethiopia are being discharged to rivers and agricultural lands with only low-level or even no treatment. Additionally, other factors such as climate change, soil type and topography are found to be causes for Ethiopian water quality deterioration. Nationally, a number of scholars have conducted studies on assessment of water quality at different spatial and temporal scales. For instance, water resources and specifically the rift-valley lakes in Ethiopia are in the vicinity of fast growing cities and agricultural lands. As a result, they are usually exposed to water quality changes due to land use modification, irrigation, waste disposal, and other practices associated with population and socio-economic growth (Zinabu et al., 2002).

Infact, sources of specifically organic water pollution have been identified using autoregressive, dynamic and distributed lag model for time series data taking into account exogenous variables (previous year water pollution, gross capital formation, industrial growth, agricultural value added), inflation, Foreign Direct Investment (FDI), and dependent population number. Among the exogenous variables it is only the industrial growth that has a direct relation with water pollution while the rest all (previous year water pollution, gross capital formation, and agricultural value added) have an inverse relation. Others which directly affect water pollution are found to be inflation and dependent population number but FDI has an inverse impact (Ademe and Alemayehu, 2014).

Moreover, many rivers in Ethiopia showed water quality deterioration as well as showing variation of this problem spatially and temporally (Degefu et al., 2013; HGL and GIRDC, 2009). The Ethiopian river basins show large variations in their seasonal rainfall patterns and total rainfall amounts (Romilly and Gebremichael, 2011), which is an indication of the spatial variation of water quality. An overall long-term change in some water quality parameters of most Ethiopian rift-valley lakes has been identified despite differences in the analytical methods and ways of handling samples. Since 1960s, for instance salinity of the lakes increased in lakes Abijata and Chamo, decreased in Awassa and Langano, and was maintained as it is in lakes Abaya, Shalla and Ziway (Zinabu et al., 2002).

In the characterization of the spatial and temporal variability of water quality parameters and sediment distribution in Lake Abaya, Gebremariam (2007) came up with a result that water temperature, pH, conductivity, dissolved oxygen (DO), total suspended solids (TSS), and total dissolved solids (TDS) at fixed stations in the lake varied respectively from 21.9 to 30°C; 8.8 to 9.3, 861 to 1162 µScm-1, 5.4 to 7.9 mg. L^{-1}, 4 to 404 mg. L^{-1}, and 618 to 1206 mg. L^{-1}.

Fitsum Merid (2005) has forwarded a baseline report assessing the dataset of three Ethiopian river basins [Blue Nile (Abay), Baro-Akobo (Sobat) and Tekeze (Atbara)], which are sub-basins of the Nile basin. In his report, values for Abay basin of pH (10.9%), EC (19%), TDS (0.7%), Nitrate (2.4%), fluoride (1.6%), sulfate (0%) and iron (25.3%) were found not to comply with the Ethiopian guideline values for drinking water quality. The high nitrate concentration (up to 145 mg/l) could be ascribed to the poor solid and liquid waste management practices around towns and the water quality problems with regard to pH, TDS, fluoride, sulfate and iron could possibly be associated with the natural geological formation of the Basin. Though the proportion of surface water samples from the collected and analyzed ones of Tekeze basin is not representative, exceptionally high EC values were recorded in the rivers located in Tigray Region. These unusual values could be attributed either to pollution of domestic waste around towns or to sample taking during low flow conditions. On the other hand, for Baro-Akobo (Sobat) River basin, Turbidity (65 FTU), Color (342 TCU), Iron (1.05mg/l) and Manganese (0.5mg/l) were found to exceed the standards while pH, SAR, TDS, EC, Nitrate and Nitrite were found to be within the acceptable range (Fitsum Merid, 2005).

In addition to urban and industrial wastes, agricultural activities such as those associated with processing of agricultural products in Ethiopia such as coffee and food processing discharge usually to water courses directly (Kloos & Legesse, 2010). On the other hand, except in lakes Abaya and Hawassa, chlorophyll *a* concentrations showed an overall increase in all the lakes when concentrations measured during 1990 - 2000 are compared to values recorded during the 1960s and 1980s (Zinabu et al., 2002).

2.4.2 Water quality in Awash River basin

Nowadays, improper utilization of water resources especially in the Main Ethiopian Rift (MER) lakes and feeder rivers by, for instance, direct water abstraction for irrigation, soda ash abstraction, commercial fish farming, recreation, domestic and industrial purposes is being observed. This resulted in lake level decreasing change for almost all lakes including lake Abiyata (except lake Beseka), increase in the supply of nutrients to the water bodies, the change in the chemistry of the water resource, disappearance of aquatic flora and fauna, water supply scarcity for the population at large (Ayenew, 2007). Lake Beseka, on the contrary, is drastically expanding due to the enhanced groundwater recharge caused by very high infiltration from nearby over-irrigated fields. This results in threatening the passage from the central part of the country to the east and the harbor. On top of that, mixing of the lake with Awash River affects hydrochemistry of the river thereby the aquatic ecosystem downstream is affected. The highly saline nature of the lake water is challenging to the irrigation schemes and water users downstream (Alemayehu et al., 2006; Ayenew, 2006).

Recently, Dinka (2017) analyzed the temporal water quality dynamics of Lake Baseka of the basin. This study showed that lake Beseka was so saline (EC ~ 6.3 dS/m), alkaline (Residual Sodium Carbonate (RSC)) ~ 80, pH ~ 9.5) and sodic (SAR ~ 300) that it was hardly usable for irrigation and drinking purposes. It also indicated that Na, K, Cl, and HCO_3 contents were dominant and the recent trend of Na, Mg, Ca, Cl, and SO_4 were increasing and the causes were attributed to be natural (weathering of rocks, soil erosion, sediment loading, deposition of animal and plant debris, and solution of minerals in the basin) and anthropogenic (discharges from factory, domestic sewage, and farming activities which introduce ions and metals from agro-chemicals (fertilizers, herbicides, fungicides, etc)) factors. However, ionic concentration was found to be decreasing as expected since the volume of the lake was increasing (Dinka et al., 2015; Dinka, 2017).

The presence of high concentration of natural inorganic constituents as F, Li, Sr, Cu, Pb, and Hg is found to result from the volcanic and tectonic activities in the basin as they can’t increase in the surface water by runoff. This is because of the fact that these activities, with the help of high temperature of the area, favor removal of toxic contaminants from volcanic rocks and make ground water to be full of the chemicals, which in turn are imparted to surface water that consequently is deteriorated by these constituents (Alemayehu, 2000). Particularly, F in the MER could possibly originate from chemical weathering, magmatic emissions, atmospheric dust from continental sources and industrial pollution. The main reason for the bicarbonate in the area is reported to be the high rate of carbon dioxide outgassing. This, combined with acid volcanics, geothermal heating, high subsurface CO_2 pressure, low Ca and low salinity, is also one of the causes of high fluoride in the active volcanic zone of the East African Rift (Gizaw, 1996).

Expansion of new industries and disposal of industrial and domestic wastes to the Awash River with high nitrate and phosphate contents enrich the biological growth and degrade the quality of fresh water. This leads to raising suspended solids, nitrates, chlorides, eutrophication, BOD and coliforms (when the flow rate of these streams is very low) and this is reported to be of great concern to the nation (Taddese, 2001).

The main sources of pollution that enters surface water bodies are untreated effluent and wastewater from industries, households and institutions, municipal solid waste and oily wastes from garages and fuel stations. Most of the registered industries (over 2,000) in Addis Ababa are located along the river banks. According to Gebre & Van Rooijen, (2009), 90% of all these industries lack facilities for onsite treatment, and subsequently discharge any effluents into adjacent streams. More than 25% of the uncollected, un-composted and un-recycled solid waste is being dumped into open spaces, ditches and water bodies. In addition to solid waste, domestic wastewater is a major contributor to water pollution in the basin. Due to lack of any form of sanitation facility dwellers use open spaces and river banks to relieve themselves (Gebre & Van Rooijen, 2009).

Since Awash River is being used by Jile, Kereyu, Arsi Oromo, the most Afar pastoralists and subsistent farmers for all domestic (bathing, washing clothes, watering livestock, cooking, and drinking), and irrigation purposes, acute illnesses and occasional deaths associated with pesticide poisoning were reported (Kloos & Legesse, 2010). Surface water - groundwater interactions can be one cause for water quality change. The effect of this can be observed by quality change of the mixing of Beseka lake with Awash River. Agro-chemicals and wastes from large and small scale irrigation activities and industries such as leather and food processing industries in the basin are some of the causes (Gedion 2009; Belay, 2009). Additionally, population growth and the associated land use dynamics, climate change, soil type and topography are unforgettable causes for WQD which needs a further study of identification and prioritization among the factors.

The river water in most part of the basin is being used for drinking (both for human and animals), domestic consumption and industrial purpose. The observable resulting effects are direct water borne diseases to animals and human being, indirect concentration of heavy metals on plant and vegetables and coliforms. Water pollution is also likely to have contributed to the disappearance of aquatic species (Gebre & Van Rooijen, 2009).

In addition to direct water-borne diseases to animals and human beings, indirect concentration of heavy metals on vegetables grown by irrigating the river and coliforms in the river are observed. Heavy bacteriological and helminths pollution load, as well as toxicity level and the slight to moderate salinity effects of the irrigation waters made the little Akaki River, which is a tributary of Awash River, unfit for any intended use. Though high fluoride concentration is especially apparent in the Rift Valley Lakes basin, the problem is also observed to have a negative impact on public health in the Awash Basin too. This is proved by the well documented fact that there were incidences of dental and skeletal fluorosis from huge concentration of fluoride in its valleys (Reimann *et al*., 2003). Few investigations conducted in the basin showed that nitrate levels are above 10 mg/l in the surface water, and according to Taddese *et al*. (2003), mean concentration of heavy metals including manganese, chromium, nickel, lead, arsenic and zinc in Addis Ababa catchments are higher in the soils irrigated by Akaki River. The irrigation water’s heavy metal content is shown to exceed the irrigation water quality standard (Mekonnen, 2007).

In assessing the pollution level of Awash River, Benti et al., (2014) came up to the conclusion that attention need to be paid in using the river for fear of public health effects. This was confirmed by examining the bacteriological contaminant level of leafy vegetables in Melka Hida and Wonji Gefersa farms around Adama town that is grown with Awash River and finding heavy pollution loads on the vegetables (Benti et al., 2014).

2.5 Assessment of irrigation and drinking water quality parameters

Selection of variables in a water quality assessment must be related to the objectives of the program (Chapman & WHO, 1996). There are basically two forms of assessments in a catchment: use-oriented and impact-oriented. While the use-oriented one tests whether water quality is satisfactory for specific purposes (for drinking, industries or irrigation), impact-oriented one is governed by knowledge of the pollution sources and the expected impacts on the receiving water body (Chapman & WHO, 1996).

Chemical water quality for irrigation in the study area is of particular importance since lots of irrigation schemes are found in the area. Irrigaton water quality depends on a number of factors as: soil type, crop growth, climatic conditions, irrigation methods used, drainage condition of the area, type and amount of fertilizer used, and farm management practices. However, the main determinants are permeability, salinity and toxicity (Hussain et al., 2010; Bauder et al., 2011). Permeability affects infiltration rate of water into the soil and is determined by the relative concentrations of EC and sodicity. Sodicity is a measure of the relative amount of sodium to calcium and magnesium and gives an indication of the level at which the exchangeable sodium percentage of the soil will stabilize after prolonged irrigation (Holmes, 1996). Soil sodicity, which is expressed by a ratio called Sodium Adsorption Ratio (SAR), can be calculated from the major cations and anions studied for the criteria of irrigation water quality and suitability for irrigation.

Salinity, expressed by EC and TDS, affects crop water availability. Usually it is severely restricted for irrigation use if their concentration exceeds 3dS/m and 2000mg/l respectively. Even so; pH, alkalinity and some other specific ions such as chloride, sulfate, boron, nitrate and bicarbonate, the toxicity of which severely affects sensitive crops if their concentration is above the tolerable limit, are also issues of considaration to some extent.

The (drinking) water quality determinants (parameters) are broadly classified as of physical, microbiological and chemical properties. The physical water quality parameters are taste, odor, color, turbidity, temperature, flow, bed substrate, instream and riparian habitat, specific weight, viscosity, surface tension, enthalpy and others (Chin, 2013; Maidment, 1993). The microbial factors include waterborne microorganisms such as bacteria, viruses, protozoa, helminths, schistosoma, helicobacter pylori, tsukamurella, iso-spora belli and cryptosporidium parvum and microsporidia, hazardous cyanobacteria (algae) and indicator organisms listed as total coliform bacteria, Escherichia coli, thermos-tolerant coliform bacteria, heterotrophic plate counts, intestinal enterococci, clostridium perfringens, coliphages, bacteroides fragilis phages, and enteric viruses.

The chemical factors that are of health concern include: BOD, COD, DO, SS, fluoride (which causes mottling of teeth and in severe cases results in crippling skeleton). Presence of arsenic implicates the risk of cancer and skin lesions. Nitrate and nitrite cause methaemoglobinaemia. Lead can have adverse neurological effects, mainly in areas with acidic waters and where it is used for pipes, fittings and solder. Its accumulation in the bloodstream has effects including anemia, kidney damage, elevated blood pressure, and central nervous system effects, such as mental retardation. pH can control the solubility and reaction rates of most metal species. Iron, lead, copper, calcium (in the form of silicates, aluminates and lime), magnesium, brass and nickel added into water sources have aesthetically unpleasant properties. High-calcium water suppresses parathyroid hormone both acutely and chronically relative to low-calcium water (WHO, 2009). Manganese can cause an undesirable taste as well as staining laundry when it exceeds 0.1 mg/L. Total dissolved solids, EC, and low pH levels can enhance corrosive characteristics (WHO, 2011; Amenu, 2014).

Phosphate, zinc, chloride, sulphate, cadmium, chromium, *Mercury and Synthetic organic chemicals* are some others determining potable water quality (Chin, 2013; Sorlini et al., 2013).

Cadmium causes high blood pressure and kidney damage and is a probable human carcinogen. Though *Chromium* in Cr^{+3} oxidation state is an essential trace element in human diets, Cr^{+4} causes a variety of adverse health effects, including liver and kidney damage, internal hemorrhage, respiratory disorders, and cancer. *Mercury* is a metal of particular concern in surface waters, where the biological magnification of mercury in freshwater food fish is a significant hazard to human health. *Synthetic organic chemicals*, including pesticides, PCBs, industrial solvents, petroleum hydrocarbons, surfactants, organometallic compounds, and phenols are hazardous to human in relatively small concentrations (Chin, 2013).

These chemical ones are categorized either as inorganic or organic contaminants. While the inorganic contaminants include: lead, nitrate, aluminum, fluoride, arsenic, water hardness, and other contaminants, the organic ones are listed as: disinfection by-products, pesticides, endocrine disrupters, Polycyclic Aromatic Hydrocarbons (PAH), tri- and tetra-chloroethene (Harrison, 2001).

2.6 Watershed hydrology and significance of modeling

Watershed hydrology deals with interaction of water with the bio-physical environment, transport of sediment and pollutant constituents as well as various phases in the hydrologic cycle (Edwards et al., 2015; Han, 2010; Raghunath, 2006). Watershed hydrology is determined by watershed characteristics including: landscape topographic and geomorphological factors (such as area, length, slope, shape, topographic contours, aspect, streamlines, land use and soil characteristics, vegetation, channel geomorphology and its spatial variation, drainage density, climate characteristics and its spatial variation, population and its distribution); subsurface characteristics; aquatic features including rivers and streams, lakes and inland seas, oceans, seas, and estuaries and wetlands; as well as sources of streamflow such as precipitation, interflow and base flow of the watershed (Wainwright and Mulligan, 2004). Alteration of one or more of the catchment characteristics result in a change in the catchment hydrology and in turn in the pollution loads from the catchments since the main media for pollutant transport from a point to another is water.

Overland hydrologic processes (runoff, infiltration, and evapo-transpiration), soil erosion, and nutrient/pesticide wash-off and leaching processes are represented in sufficient detail in watershed models (Narasimhan *et al*., 2010). Simulation models of watershed hydrology and accompanying pollutants are extensively used for water resources planning and management (Leon and George, 2011; Loucks and Beek, 2005). Understanding the hydrology of a watershed and modeling different hydrological processes within a watershed is very important for assessing the environmental and economic well-being of the watershed. This can be visualized by understanding the basic mathematical equations governing surface runoff, overland flow, ground water discharge, and infiltration capacity. In other words, the complex relationships between waste loads from different sources and the resulting water qualities of the receiving waters are best described with mathematical models (Kannel et al., 2007). Additionally, the types of land uses, soil texture, intensity and frequency of rainfall help to estimate the upcoming point and non-point sources (Leon and George, 2011). Hence hydrological modeling is crucial to examine the pollution dynamics in a catchment.

2.7 Hydrological (water quality) modeling and classification of models

Water quality is defined by physical, biological and chemical parameters and its deterioration is controlled mainly by the geological structure and lithology of watersheds/aquifers, the chemical reactions as well as the type of land uses and anthropogenic activities taking place in these watersheds/aquifers (Tsakiris & Alexakis, 2012). The complex relationships between waste loads from different sources and the resulting water quality of receiving water bodies are best described with mathematical models (Gao & Li, 2014). Measured data alone are usually insufficient to make informed decisions on water quality, especially when it comes to large and complex waterbodies. This is because data errors can result in ambiguous interpretation and misunderstanding of the real physico-chemical and biological processes. Hence, modeling is crucial as it develops tools capable of realistically representing surface waters, which enable better understand the physical, chemical, and biological processes involved; and as it plays a critical role in advancing the state - of - the - art of hydrodynamics, sediment transport, water quality, and of water resources management (Ji, 2008).

Surface water quality models have become important tools to identify water pollution, to simulate and predict the fate and behaviors of pollutants in the water environment (Wang *et al*., 2013). Watershed hydrologic models are basic to water resources management, development, assessment and planning by analyzing, for instance, the quality of streams since monitoring of water quality continuously is expensive and impractical in mixed land uses. This can subsequently control pollution by developing TMDL through simulating loads/waste to receiving water bodies under various BMPs (Santhi *et al*., 2001; Gao & Li, 2014; Chu *et al*., 2004). They are used to understand the natural processes, as well as to find solutions for problems, while assessing the environmental conditions on a watershed scale (Qi et al., 2017). Watershed models are usually used to estimate the long–term effects of individual management practices and can account for long-term weather, soil, land use/cover and topography variability (Santhi *et al*., 2001).

Models can be classified according to the: type of approach (physically based, conceptual, empirical); pollution item (nutrient, sediment, salt, etc); area of application (catchment, ground-water, river system, coastal water, integrated); nature (Deterministic, stochastic); state analyzed (Steady state or dynamic simulation); spatial analysis (lumped, distributed); dimension (1-d, 2-d or 3-d); and data requirement (extensive database, minimum requirement) (Khandan, 2002; Tsakiris & Alexakis, 2012; Aral, 2010) and are briefly given by **Figure 2-2**.

Models containing elements of randomness, to account for uncertainty associated with the model input variables and parameter values and model structure, are called stochastic. Thus, stochastic models generate a range of values (rather than a single one) as model output. If the model contains no elements of randomness, or does not comprise uncertainty, or its output is a single value, then it is a deterministic one. A deterministic model can further be divided into white-box (mechanistic), grey-box and black-box models. White-box (mechanistic) models are based on physical, chemical and biological principles, whereas the black-box ones are those models that are not based on any physico-chemical or biological laws; rather they are based on a data driven transfer function. If a model contains elements of both the white-box and the black-box model, the model is called grey-box (Deksissa, 2004). On the basis of the level of representation, the mechanistic models are divided into very simple (lumped models) and relatively complex (distributed models). In the lumped models, several processes may be combined and expressed as one, whereas in the distributed model, the model attempts to represent every significant process (Deksissa, 2004).

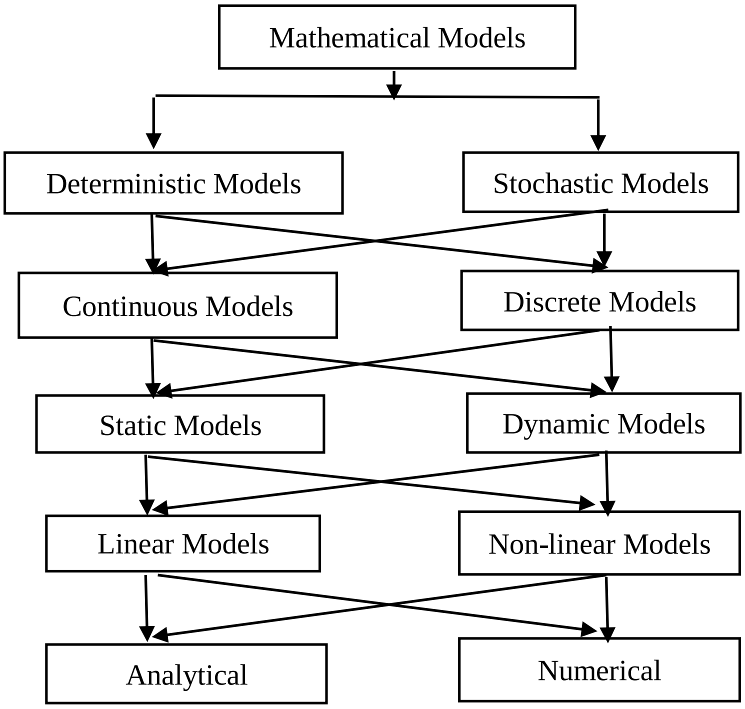


Figure 2-2 Classification of mathematical models (Source: Aral, 2010)

2.8 Overview of available watershed and water quality models

A number of watershed and water quality models have been developed and used by different scholars since 1925 when Streeter and Phelps built the first water quality model to control river pollution (Wang *et al*., 2013; Ekdal *et al*., 2011). Water quality models for catchments are becoming more and more complex because of landscape and riverine processes as well as transport and transformartion processes for reactive substances. There are a number of water quality models of different complexity in use to date. To mention some: AGNPS/AnnAGNPS, ANSWERS, AQUATOX, EFDC, GLEAMS/CREAMS, QUALs (e.g. QUAL2K), HSPF, SWAT, GWLF, WASP, AquaChem, BASINS, AGWA, TMDL Toolbox, and others. However, scholars have reported that an increase in model complexity doesn't increase model performance for a number of investigated cases (Qi et al., 2017). Evaluation of some watershed and receiving water quality models based on their features, level of experience required, time needed for application, data needed, support availability, software tools affecting their application as well as their simulation capabilities of quality parameters is described below and shown in **Table 2-1**, **Table 2-2**, **Table 2-3**, and **Table 2-4** which enable one decide which model to choose.

AGricultural Non-Point Source (AGNPS) pollution model is an event-based model that simulates runoff, sediment, and nutrient transport from agricultural watersheds. It is a tool used for evaluating the effect of management practices on water, sediment and chemical loadings within a watershed system. The nutrients considered include nitrogen and phosphorus, both essential plant nutrients and major contributors to surface water pollution. Basic model components include hydrology, erosion, and sediment and chemical transport. In addition, the model considers point sources of sediment from gullies and inputs of water, sediment, nutrients, and chemical oxygen demand from animal feedlots, springs, and other point sources (Young et al., 1989). Outputs related to soluble & attached nutrients (nitrogen, phosphorus, & organic carbon) and any number of pesticides is provided. Water and sediment yield by particle size class and source are calculated. Nutrient concentrations from feedlots and other point sources are modelled as well (Young et al., 1995).

Aerial Nonpoint-Source Watershed Environmental Response Simulation (ANSWERS) is used to simulate the effects that various combinations of land uses, management schemes, and conservation practices could have on the hydrologic and erosion responses of a watershed. ANSWERS is a public domain, GIS-based, distributed parameter, physically-based, continuous simulation, farm or watershed scale, upland planning model developed for evaluating the effectiveness of agricultural and urban BMPs in reducing sediment and nutrient delivery to streams in surface runoff and leaching of nitrogen through the root zone. The model is intended for use by planners on ungagged watersheds where data for model calibration is not available. The model simulates interception; surface retention/detention; infiltration; percolation; sediment detachment and transport of mixed particle size classes; crop growth; plant uptake of nutrients; N and P dynamics in the soil; nitrate leaching; and losses of nitrate, ammonium, total nitrogen, and P in surface runoff as affected by soil, nutrient, cover and hydrologic conditions (Beasley et al., 1980).

Aquatic ecosystems simulation model (AQUATOX) is a one-dimensional and ecosystem model that predicts the fate of nutrients and organic chemicals in water bodies by simulating multiple environmental stressors as well as their direct and indirect effects on the resident organisms in the ecology unlike many other models (Shoemaker et al., 2005). AQUATOX simulates the transfer of biomass and chemicals from one compartment of the ecosystem to another by simultaneously computing important chemical and biological processes over time. It simulates multiple environmental stressors (including nutrients, organic loadings, sediments, toxic chemicals, and temperature) and their effects on the algal, macrophyte, invertebrate, and fish communities. It can represent a variety of aquatic ecosystems, including vertically stratified lakes, reservoirs and ponds, rivers and streams, and estuaries (Shoemaker et al., 2005).

Environmental Fluid Dynamic Code (EFDC) is single-source-code 3-D modeling system having hydrodynamic, water quality-eutrophication, sediment transport, and toxic contaminant transport components transparently linked together (Shoemaker et al., 2005). EFDC can simulate water and water quality constituent transport in geometrically and dynamically complex water bodies, such as rivers, stratified estuaries, lakes, and coastal seas. The code solves the three-dimensional primitive variable vertically hydrostatic equations of motion for turbulent flow in a coordinate system which is curvilinear and orthogonal in the horizontal plane and stretched to follow bottom topography and free surface displacement in the vertical direction that is aligned with the gravitational vector. A second moment turbulence closure scheme relates turbulent viscosity and diffusivity to the turbulence intensity and a turbulence length scale. Transport equations for the turbulence intensity and length scale as well as transport equations for salinity, temperature, suspended cohesive and non-cohesive sediment, dissolved and adsorbed contaminants, and a dye tracer are also solved. An equation of state relates density to pressure, salinity, temperature and suspended sediment concentration (Shoemaker et al., 2005).

Hydrological Simulation Program - FORTRAN (HSPF) is a comprehensive package for simulation of watershed hydrology and water quality for both conventional and toxic organic pollutants. HSPF incorporates watershed-scale ARM and NPS models into a basin-scale analysis framework that includes fate and transport in one dimensional stream channels. It is the only comprehensive model of watershed hydrology and water quality that allows the integrated simulation of land and soil contaminant runoff processes with in-stream hydraulic and sediment-chemical interactions. The result of this simulation is a time history of the runoff flow rate, sediment load, and nutrient and pesticide concentrations, along with a time history of water quantity and quality at any point in a watershed. HSPF simulates three sediment types (sand, silt, and clay) in addition to a single organic chemical and transformation product of that chemical. Although HSPF simulates water quality and hydrology components with a slightly better accuracy, HSPF is less user-friendly than SWAT with relatively high data need due to numerous parameters to control and represent hydrologic cycle, sediment and nutrients transport (Mostaghimi, 2003, July; Im et al., 2007).

River and stream water quality model (QUAL2's) is a widely used mathematical model for conventional pollutant impact evaluation though it has inadequacies of providing information for conversion of algal death to carbonaceous biochemical oxygen demand. Then it is modified and developed into QUAL2K, which included the addition of new water quality interactions, such as conversion of algal death to BOD, denitrification, and DO change caused by fixed plants. Currently, this is also further developed into QUAL2Kw. QUAL2Kw is a one-dimensional, steady flow stream water quality model and thus its application is limited to steady state flow condition. It includes DO interaction with fixed plants, conversion of algal death to CBOD, reduction of amount of CBOD due to denitrification, and auto-calibration system. It can simulate a number of constituents such as temperature, pH, carbonaceous biochemical demand, sediment oxygen demand, dissolved oxygen, organic nitrogen, ammonia nitrogen, nitrite and nitrate nitrogen, organic phosphorus, inorganic phosphorus, total nitrogen, total phosphorus, phytoplankton and bottom algae along a river and its tributaries and is useful in data limited conditions and is freely available (Kannel et al., 2007; Park & Lee, 2002). It doesn't offer a room to link water quality with land use as it is a receiving water quality model.

Generalized Watershed Loading Function (GWLF) is a mid-range watershed loading model developed to simulate nonpoint sources of mixed land use watersheds to evaluate the effect of different land use practices on flow (runoff) and downstream loads of sediment and nutrients. It is typically used to evaluate long-term loadings from urban and rural watersheds. As a loading function model, it simulates runoff and sediment delivery using the Curve Number (CN) and Universal Soil Loss Equation (USLE), combined with average nutrient concentration, based on land use. It has also algorithms for calculating septic system loads, and allows for the inclusion of point source discharge data. GWLF is considered to be a combined distributed/lumped parameter watershed model, which is based on a combination of simple runoff, sediment, and groundwater relationships and empirical chemical parameters (Shoemaker *et al*., 2005). GWLF is similar with SWAT model in that both are continuous, pollutant-loading models that operate with a daily time step (though the outputs are only given monthly because of lack of detail in predictions and stream routing) (Qi et al., 2017). It differs from SWAT in that it requires fewer data to set up, less time to run, and is easier to be used than SWAT. However, it is not suitable for application in large catchments and cannot reflect spatial variations. SWAT simulates with higher accuracy and offers advantage than GWLF when measured data are scarce. Additionally, SWAT performed more dependably and robust in sediment and total nitrogen (Qi et al., 2017).

Water Quality Analysis Simulation Program (WASP5,6,7) is a dynamic and general-purpose compartment-modelling program to simulate the fate and transport of conventional and toxic contaminants in surface water bodies. It interprets, analyzes and predicts water quality responses to natural phenomena and man-made pollution in such diverse water bodies as ponds, streams, lakes, reservoirs, rivers, estuaries, and coastal waters for various pollution management decisions. WASP can also be linked with hydrodynamic and sediment transport models that can provide flows, depths velocities, temperature, salinity and sediment fluxes (Paul *et al*., 2010). Hence, it is one of the most widely used water quality models throughout the world in the development of Total Maximum Daily Loads (TMDL). The model is based on the concept of flexible compartmentalization and simulates conservation of mass both spatially and temporally which is accounted using fluid dynamics equation for each segment. The basic program includes time-varying processes of transport, loading, and transformation are simulated using advection, dispersion, kinetic transformation, point and diffuse mass loading and boundary exchange. It can be applied in 1D, 2D and 3D on a water body and according to Sharma & Kansal, (2013). WASP7, unlike the previous versions, included additional sub-models like advanced EUTRO simulating benthic algae and multiple phytoplankton classes (named periphyton), mercury and heat. The model has a user-friendly windows-based interface with a pre-processor; sub-model processors and a graphical post-processor though it is not a watershed model to associate land use with water quality.

AquaChem is a software package which features a fully customizable database of physical and chemical parameters and a comprehensive selection of analysis, calculation, modeling and graphing tools for water quality data (Lukas and Waterloo, 2017). AquaChem's data analysis capabilities cover a wide range of functionalities and calculations including, statistical summaries, trend analysis, unit conversions, charge balances, sample comparison and mixing. AquaChem also has a customizable database of water quality standards with up to three different action levels for each parameter. Any samples exceeding the selected standard are automatically highlighted with the appropriate action level color for easily identifying and qualifying potential problems. Additionally, AquaChem features a built-in link to the popular geochemical modeling program PHREEQC for calculating equilibrium concentrations (or activities) of chemical species in solution and saturation indices of solid phases in equilibrium with a solution. It is ideally suited for ground water quality analysis, not capable showing the effect of land use change on water quality and is licensed (Lukas and Waterloo, 2017).

The Automated Geospatial Watershed Assessment (AGWA) tool is a continuous-simulation model for use in large watersheds (basin scale). AGWA tool integrates the Soil and Water Assessment Tool and the Kinematic Erosion and Runoff (KINEROS2) hydrologic models, which operate at different temporal and spatial scales to evaluate the impacts of land use and land-cover changes on hydrologic and erosion response. It is a GIS-based hydrologic modeling tool that uses commonly available GIS data layers to fully parameterize, execute, and spatially visualize results for the KINEROS2 and SWAT. The AGWA tool combines these models in an intuitive interface for performing multi-scale change assessment, and provides the user with consistent, reproducible results. Data requirements include elevation, land-cover, soils, and precipitation data. Model input parameters are derived directly from these data using optimized look-up tables that are provided with the tool (Miller et al., 2007).

Better Assessment Science Integrating point and Nonpoint Sources (BASINS) is one of the integrated modeling systems, originally released to link models like HSPF and PLOAD, which allow the user to simulate the loading of pollutants and nutrients from the land surface, and AQUATOX that is used to simulate aquatic ecosystems (Shoemaker et al., 2005). Since this initial release of BASINS, several additional models have been incorporated through a plug-in to BASINS, including SWAT, KINEROS, and WASP. The plug-in for each model uses the BASINS GIS and meteorological data to assemble the required model input (Shoemaker et al., 2005). It is a multi-purpose environmental analysis system, which integrates a geographical information system (GIS), national watershed data, and state-of-the-art environmental assessment and modeling tools into one convenient package designed to help regional, state, and local agencies to perform watershed- and water quality-based studies. It was developed by the U.S. Environmental Protection Agency to assist in watershed management and TMDL development by integrating environmental data, analysis tools, and watershed and water quality models (Mahdi, 2012).

Table 2-1. Summary of models with their simulation capabilities and application considerations

Model	Water Quality							Application Considerations																
								Experience Required				Time Needed				Data Needs			Support Availability			Software Tools		
	Sediment	Nutrient	Toxics	Metals	BOD	DO	Bacteria	Substantial	Moderate	Limited training	Little or no	< 1 month	> 1 month	> 3 months	> 6 months	Low	Medium	High	Low	Medium	High	Low	Medium	High
QUAL2K		X			X	X	X			X		X					X			X			X	
AQUATOX	X	X	X		X	X				X		X					X			X				X
CE-QUAL-W2		X			X	X	X	X							X			X			X		X	
WASP	X	X	X	X	X	X		X							X			X	X			X		
EFDC	X	X	X	X	X	X	X	X							X			X			X			X
HSPF	X	X	X	X	X	X	X	X							X			X			X			X
SWAT	X	X	X	X	X	X			X				X				X			X				X

The watershed and receiving water quality models are also characterized in **Table 2-2** based on their modelling environment, availability, spatial and temporal resolution, nature of the processes and data involved. Other commonly used watershed/water quality models are also characterized based on their type, level of complexity, time step, hydrology and simulation capabilities of quality parameters as shown in **Table 2-3** (Shoemaker *et al*., 2005).

Table 2-2. Water quality models evaluated by their different aspects of simulation

Model	Model Environment					Degree of Analysis			Availability/Cost		Temporal Variability			Spatial Resolution			Process			Support		Process description		Nature of data	
	Hydrodynamic	River WQ	Lake WQ	Estuary WQ	Watershed WQ	Screening	Intermediate	Advanced	Public Domain	Proprietary	Steady State	Quasi dynamic	Dynamic	1-D	2-D	3-D	Flow Model	Transport Model	Both	User Support	User Manual	Empirical	Mechanistic	Deterministic	Stochastic
AQUATOX		x	x			x			x		x		x	x	x				x		x		x	x	x
QUAL2K		x					x		x		x			x					x	x	x	x	x	x	
CE-QUAL-W2	x	x		x		x		x	x		x		x		x				x	x	x		x	x	
WASP	x	x	x	x				x	x				x	x	x	x		x		x	x		x	x	
EFDC	x	x	x	x				x	x				x	x	x	x			x				x	x	
HSPF					x			x	x				x	x					x	x	x		x	x	
SWAT					x			x	x			x			x				x	x	x		x	x	

Applicability considers the defining characteristics of project applications including pollutants, land and water characteristics, management alternatives, data, and user interfaces. The basic capabilities in watershed, receiving water, BMP simulation and some application criteria were used to evaluate the applicability of models to perform TMDL analyses, including training, level of effort, and user interface capabilities.

Model's ability to simulate typical TMDL target pollutants and expressions (e.g., load vs. concentration) and characterizing the models depending on the time-step of the simulation for the target - steady state, storm event, annual, daily or hourly is evaluated by and presented in table 5 (Shoemaker *et al*., 2005).

Table 2-3. Summary of watershed models with their simulation capabilities

Model	**Type**		**Level of Complexity**			**Time-step**				**Hydrology**		**Water Quality**						
	Grid-based	Stream routing included	Export coefficients	Loading functions	Physically based	Sub-daily	Daily	Monthly	Annual	Surface	Surface and groundwater	User-defined	Sediment	Nutrients	Toxics/pesticides	Metals	BOD	Bacteria
AnnAGNPS	—	x	—	—	x	—	x	—	—	x	—	—	x	x	x	—	—	—
BASINS	—	x	x	x	x	x	x	—	—	x	x	x	x	x	x	x	x	x
HSPF	—	x	—	—	x	x	—	—	—	—	x	x	x	x	x	x	x	x
SWAT	—	x	—	—	x	—	x	—	—	—	x	—	x	x	x	x	—	—
Toolbox	—	x	—	—	x	x	—	—	—	—	x	x	x	x	x	x	x	x

Table 2-4. TMDL end point supported

Model	TP load	[TP]	TN load	[TN]	[NO_3]	[NH_3]	TN:TP ratio	Pathogen count	Temp.
AnnAGNPS	⊕	⊕	⊕	⊕	—	—	—	—	—
AQUATOX	—	—	—	—	⊕	⊕	—	—	—
BASINS	●	●	●	●	●	●	●	●	●
HSPF	●	●	●	●	●	●	●	●	●
QUAL2K	+	+	+	+	+	+	+	+	+
SWAT	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
Toolbox	●	●	●	●	●	●	●	●	●
WASP	●	●	●	●	●	●	●	—	—

Key: — Not supported, + Steady state, ⊕ Daily, ● Hourly (or less)

2.9 Water quality model selection

Appropriate model selection for water quality simulation, which meets minimum but acceptable evaluation criteria, depends on the types of water quality problems, potential sources and timing of their occurrence, desired spatial and temporal scales of model results, data availability (sources), accessibility and format, model complexity, uncertainty, and available resources. Models are evaluated mainly on the basis of: application, technicality, operation, data requirements and technical expertise (Rakesh *et al*., 2013; Sharma & Kansal, 2013; Shoemaker *et al*., 2005).

Evaluation with respect to application, as can be seen from **Table 2-1** upto **Table 2-4**, is checking availability of model at reasonable cost; computer hardware limitations; modeling methods for the major process flows, chemical fate and transport processes; type of outputs, output options and level of outputs; and user interface-input helpers, windows based or raw edits of input files, GIS interface for data. Technical evaluation considers modeling environment (such as river, lake, estuary, ocean, watershed); degree of analysis (screening, intermediate, advanced); availability (public, proprietary); type (Steady state, dynamic); level of complexity (1-D, 2-D, 3-D); processes (flow, transport, both); water quality (chemical, biological, radiological, sediment); scale (spatial, temporal) and input data required for model simulation, calibration and validation (Rakesh *et al*., 2013).

Operational evaluation of models takes into account the supporting materials-example input and output data sets, identification of sensitive input parameters, calibration procedures for field measurements, continuing education and training; availability and user friendliness of the interface for ease of input preparation; GIS linkage-for large modeled areas; model availability-model contacts, documentation, source availability, version tracking (Sharma & Kansal, 2013).

Collection and preparation of data even for a simple model requires time and may not even be freely available. On the other hand, since the modeler is the human interface in the whole modeling exercise, he/she not only collects and prepares the data and runs the model but also calibrates the model, validates the results, and interprets the output. Hence, effective modeling is dependent on: level of technical expertise needed and manpower required, training requirements and IT support for the model (Shoemaker *et al*., 2005). Additionally, a critical requirement of several government agencies is to acquire the capability to model “unusual events” in the aquatic environment. These “unusual events” have certain modeling and data unknowns as illustrated below. These unknowns that are the limiting factors for model selection are site characteristics; sources of contamination (point, polygon, instantaneous, continuous); release rate of contaminants and deposition rate of contaminants (Rakesh *et al*., 2013).

Based on the evaluation criteria assessed so far, SWAT is recommended to be applied in this study though it has some limitations as: its difficulty to manage and modify when there are hundreds of input files because the watershed is so large and divided into hundreds of hydrologic response units; inability of simulating sub-daily events such as a single storm event and diurnal changes of DO in a water body; its inability to simulate detailed events based flood and sediment routing; and during the spring and winter months, its difficulties in modeling floodplain erosion and snowmelt erosion (Gao & Li, 2014).

Its preference is because of the fact that SWAT model has the ability to predict changes in nutrient loadings from different management conditions (point and nonpoint sources) and is freely available for public use. The fact that SWAT model is readily applicable through the development of Geographic Information System (GIS) based interfaces and its easy linkage to sensitivity, calibration and uncertainty analysis tools made it popular. The online and free availability of basic GIS data that are required for SWAT made its applicability more straightforward even in data-scarce areas (Griensven *et al*., 2012). The SWAT model is proven to be an effective tool for assessing water resource and nonpoint-source pollution problems for a wide range of scales and environmental conditions globally and it is concluded that it is a very flexible and robust tool that can be used to simulate a variety of watershed problem (Gassman et al. 2007). The study area is large and agricultural dominated and hence according to Shukla (2011) and Borah & Bera, (2004), for such a basin of large spatial extent SWAT is recommended (Arnold et al. 1998).

2.10 The Soil and Water Assessment Tool (SWAT) model

2.10.1 Development of SWAT model

Development of the SWAT model could be traced to the previously developed U.S. Department of Agriculture's Agricultural Research Service (USDA-ARS) models including the Chemicals, Runoff, and Erosion from Agricultural Management Systems (CREAMS) model, the Groundwater Loading Effects on Agricultural Management Systems (GLEAMS) model, and the Environmental Impact Policy Climate (EPIC) model, which was originally called the Erosion Productivity Impact Calculator (Gassman et al. 2007). The current SWAT model is a direct outgrowth of the Simulator for Water Resources in Rural Basins (SWRRB) model, which was designed to simulate management impacts on water and sediment movement for ungauged rural basins (Neitsch, Arnold, Kiniry, & Williams, 2011).

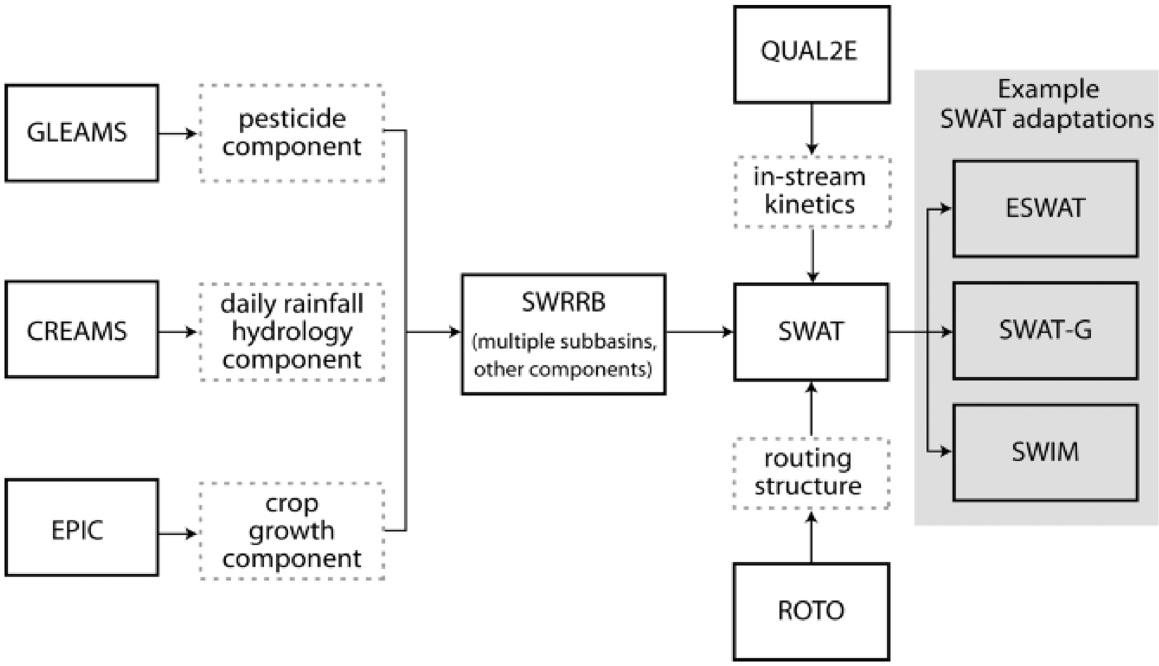


Figure 2-3: Schematic diagram of SWAT developmental history, including selected SWAT adaptations.

Incorporating ground water, reservoir storage, weather, peak runoff predicting method, flood routing, sediment transport, EPIC and other components, the daily rainfall hydrology model, CREAMS, was modified to result in SWRRB. In the late 1980's provision of emphasis to water quality issues led SWRRB to incorporate the pesticide fate and transport component called GLEAMS, the optional Soil Conservation Service (SCS) technology for peak runoff estimation, and sediment yield equation (Neitsch et al. 2011). However, SWRRB model was limited to simulating only a few hundred square kilometer of area by dividing into sub-basins and the materials transported out of the sub-basins are routed directly to the watershed outlet. This drawback led to the development of a model called Routing Outputs To Outlet (ROTO), which overcame the SWRRB limitation by linking multiple SWRRB runs together (Neitsch et al. 2002). But since the input and output of multiple SWRRB files is cumbersome and since all SWRRB runs had to be made independently input to ROTO, which is awkward, ROTO and SWRRB were merged into a single model called SWAT (Neitsch et al. 2011). Since its creation in the early 1990s, SWAT has undergone continued review with key enhancements for previous versions of the model (SWAT94.2, 96.2, 98.1, 99.2, and 2000) (Gassman et al. 2007) (**Figure 2-3**). Detailed theoretical documentation and a user's manual for the latest version of the model (SWAT2009) are given by Neitsch et al. (2011).

2.10.2 Theoretical concepts and general aspects of the SWAT model

SWAT is a long-term, continuous, basin-scale and conceptual hydrologic and water quality simulation model that operates on a daily time step interfaced with GIS. It is designed to predict the impact of land management practices on water, sediment, and agricultural chemical yields with varying soils, land use, and management conditions over long periods of time (Neitsch et al. 2011). The model is a quasi-physically based, computationally efficient, and capable of simulating a high level of spatial detail (Gassman et al. 2007). SWAT is a very flexible, powerful, robust and strong tool that can be used to simulate a variety of land management and conservation problems in different catchments with various climatic and land cover conditions (Kiros et al., 2015).

In SWAT, a watershed is divided into multiple sub-watersheds, which are further subdivided into unique soil, land use and slope characteristics called Hydrologic Response Units (HRUs) (Gassman et al. 2007). The HRUs are used to describe the spatial heterogeneity in terms of land cover, soil type and slope class within a watershed. The water balance of each HRU is represented by four storage volumes: snow, soil profile, shallow aquifer, and deep aquifer. Flow generation, sediment yield and pollutant loadings are added across all HRUs in a sub-watershed, and the resulting flow and loads are then routed through channels, ponds, and/or reservoirs to the watershed outlet (Jha *et al*., 2007).

It simulates eight major components: hydrology (evapo-transpiration, surface runoff, infiltration, percolation, shallow and deep aquifer flow, and channel routing), weather, erosion and sediment transport, soil temperature, crop growth, nutrients, pesticides, and agricultural (land) management for each HRUs (Neitsch *et al*., 2002; Arnold *et al*., 1998; Jha *et al*., 2007). The hydrological components in the SWAT model are simulated in the order of precipitation interception, surface runoff and infiltration, lateral flow and percolation, evaporation and transpiration, groundwater recharge and groundwater flow based on the water balance equation (2-1) (Neitsch et al. 2002):

$$\boldsymbol{SW_t = SW_0 + \sum_{i=1}^{t}\left(R_{day} - Q_{surf} - E_a - w_{seep} - Q_{qw}\right)_i} \quad \ldots\ldots\ (2\text{-}1)$$

where, SW_t is the final soil water content (mm water), SW_o is the initial soil water content in day i (mm water), t is the time (days), R_{day} is the amount of precipitation in day i (mm water), Q_{surf} is the amount of surface runoff in day i (mm water), E_a is the amount of evapo-transpiration in day i (mm water), W_{seep} is the amount of water entering the vadose zone from the soil profile in day i (mm water), and Q_{gw} is the amount of return flow in day i (mm water) (Setegn *et al*., 2010; Kim et al., 2010) taking into account all the processes involved in the hydrologic cycle in **Figure 2-4**.

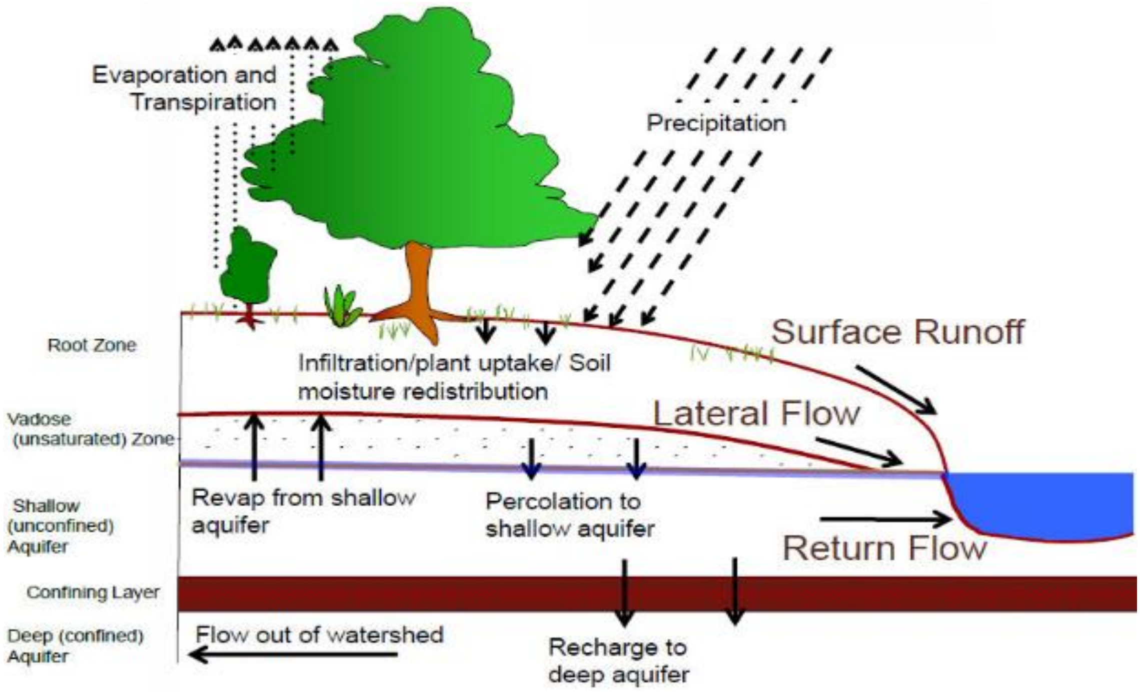


Figure 2-4: Schematic representation of the hydrologic cycle (Neitsch et al., 2009)

The water balance equation **(2-1)** is the driving force behind everything that happens in a watershed no matter what type of problem is simulated with SWAT. To accurately predict the movement of pesticides, sediment, or nutrients the hydrologic cycle, as simulated by the model, must conform to what is happening in the watershed. Simulation of the hydrology of a watershed can be separated into two main divisions: the land phase and the routing phases of the hydrologic cycles. While the first controls the amount of water, sediment, nutrient and pesticide loadings to the main channel in each sub-basin, the second controls the movement of water, sediments, etc. through the channel network of the watershed to the outlet (Neitsch et al., 2011). The hydrological components simulated in the land phase of the hydrological cycle include canopy storage, infiltration, redistribution, evapo-transpiration, lateral subsurface flow, surface runoff, ponds, tributary channels and return flow (Kiros et al., 2015).

2.10.3 Surface runoff and infiltration

Since runoff is the main driving force for pollutant transport, quantifying and characterizing the amount of runoff from catchments based on rainfall pattern is an important issue. Though different modelers have tried to simulate runoff from catchments differently, there are two schools of thoughts for runoff generation: saturation-excess and infiltration-excess.

The infiltration excess mechanism, originally proposed by Horton, (1933) usually occurs in arid and semi-arid regions owing to high rainfall intensities on soils with low infiltration rates. Infiltration-excess overland flow (also known as 'Hortonian overland flow') occurs when the rate at which rain arrives exceeds the rate at which water can infiltrate the soil, assuming that any depression storage has already been filled. This type of runoff is most common in summer in temperate regions, when rainfall intensities are high and the soil infiltration capacity has been reduced because of compaction processes, surface sealing or crusting especially where there is too little vegetation to protect the soil surface from raindrop impact (Bosch and Hewlett, 1982).

Saturation excess overland flow, constituting the main mechanism of runoff generation in humid regions, is generated when the soil is saturated with water and depression storage is filled if rainfall continues. The spatial pattern of saturated areas, including wetlands and lakes, is a key characteristic of boreal landscapes and a factor controlling variables such as stream water quality (Davie, 2008). If a watershed is dominantly producing its runoff through saturation excess overland flow, the proportion of the watershed which produces runoff can be estimated from the ratio of the change of runoff to the corresponding change in precipitation depth (Steenhuis *et al*., 2009).

Generally, the dominant features used to determine the runoff includes topography (digital elevation model) and soil characteristics (depth and hydraulic conductivity of the soil) to distribute and locate saturated areas in the landscape with the soil topographic index (Walter *et al*., 2005; Easton *et al*., 2008). Based on the watershed physical characteristics and the overall goal of the watershed modeling, either SCS CN procedure or Green and Ampt infiltration methods are chosen for SWAT to generate run-off (Zhang & Ficklin, 2013; Kiros et al., 2015).

Green & Ampt infiltration method

It requires sub-daily precipitation data and calculates infiltration as a function of the wetting front matric potential and effective hydraulic conductivity. Water that does not infiltrate becomes surface runoff. SWAT includes a provision for estimating runoff from frozen soil where a soil is defined as frozen if the temperature in the first soil layer is less than 0°C. The model increases runoff for frozen soils but still allows significant infiltration when the frozen soils are dry (Neitsch et al., 2002).

The SCS-CN Method

Though both methods are suggested for SWAT, the SCS curve number method has usually been used to estimate surface runoff because of the unavailability of sub-daily weather data for Green & Ampt method (Kiros et al., 2015). In saturated excess overland flow, the SCS curve number equation is often used to predict storm runoff from a watershed. Indeed, the SCS CN method is estimating the amount of runoff based on local land use, soil type, and antecedent moisture condition (USDA-SCS, 1986; Jha et al., 2007) and is depicted by equation (2-3).

$$Q = \frac{(P-I_a)^2}{(P-I_a)+S} = \frac{P_e^2}{P_e+S} = \frac{(P-0.2S)^2}{(P+0.8S)}, if\ P > 0.2S; Q = 0\ otherwise\ldots \text{(2-2)}$$

Where Q is the accumulated runoff volume or rainfall excess (mm), P is the depth of total precipitation (and snowmelt) for the day (mm); P_e (mm) is the depth of effective precipitation after runoff begins ($P – I_a$), I (mm) is the initial abstraction, S is the retention parameter (mm) (depth of the watershed-wide storage of water in the soil profile) and equals $5I_a$. The retention parameter is defined by equation (2-4).

$$\boldsymbol{S = 254\left(\frac{100}{CN} - 1\right)} \ldots\ldots\ldots\ldots\ldots.. \text{(2-3)}$$

where; CN is the curve number for the day (Chow et al., 1988) which depends on land use, soil type and hydrologic soil condition (Young *et al*., 1989).

Readers can refer for important concepts such as peak runoff rate, transmission losses, channel routing and others that do have significant impacts on hydrological and nutrient balances to Lane, 1983; Lange, 2005; Thornes, 2009; Jha et al., 2007 and from the SWAT user’s manual, Neitsch et al., 2002.

2.10.4 Evapo-transpiration

Evapo-transpiration (consumptive use), which is an essential part of the hydrologic cycle, is a collective term for all processes by which water in the liquid or solid phase at or near the earth's surface becomes atmospheric water vapor. It includes evaporation from rivers and lakes, bare soil, and vegetative surfaces; evaporation from within the leaves of plants (transpiration); and sublimation from ice and snow surfaces (Neitsch et al., 2002; Raghunath, 2006; Chow et al., 1988). The two main factors influencing evaporation from an open water surface are the supply of energy to provide the latent heat of vaporization and the ability to transport the vapor away from the evaporative surface (Han, 2010; Chow et al., 1988). ET is divided into potential and actual.

2.10.4.1 Potential evapo-transpiration (PET)

Potential evapo-transpiration (*ET*) is the measure of the ability of the atmosphere to remove water from the earth's surface through processes of evaporation and transpiration. It is usually expressed as a depth (cm, mm) over the area (Chow et al., 1988). SWAT, being a semi-distributed and physically based model, uses the integrated converting methods, which first estimates potential evapo-transpiration (PET) and then converts it into actual evapo-transpiration (AET) applying the Soil Moisture Extraction Function (Zhao et al., 2013). There are three ways of estimating PET in SWAT: Penman-Monteith, Priestley-Taylor, and Hargreaves' (Neitsch et al., 2002; Jha et al., 2007; Zhao et al., 2013). Hargreaves method is an energy-based method of estimating potential evapo-transpiration selectively in arid and semi-arid as well as for grasslands. It was used during edition of the PET parameter in this study due to its requirement only of temperature as input (Neitsch et al., 2002; Zhao et al., 2013; Wang et al., 2006). The governing equations of all the three are found in Neitsch et al., (2002).

2.10.4.2 Actual Evapo-transpiration (AET)

AET (mm/month) is a measure of the amount of water that is actually removed from earth's surface due to processes of evaporation and transpiration. It is limited to the availability of water by precipitation and soil moisture stored; $AET \leq PET$, and is dependent on vegetation type and availability of soil water content. Other concepts, such as lateral flow; percolation; groundwater flow; and base-flow, which have either positive or negative contributions to the water balance and to the nutrient may be referred from the SWAT theoretical documentation (Neitsch et al., 2011) and user's manual (Neitsch et al., 2002).

2.10.5 Pollutant transport and nutrient dynamics in SWAT

2.10.5.1 Pollutant transport and fate

The fate and transport of pollutants in general and nutrients in particular in a watershed depend on the transformation the compounds undergo in and on the soil. The fate (eventual disposition) of pollutants in water depend on both transport through the water and on sources, sinks, reactions and decay mechanisms. Therefore, the generalized contaminant transport and fate models usually couple source mechanisms with transport, transformation, and removal processes in order to predict the spatial and temporal distribution of pollutants. Their transport is actually governed mainly by processes as advection, dispersion, and diffusion. Advection is the transport of contaminants along with the mean or bulk flow of fluid, diffusion is the mixing of contaminants driven by concentration gradients (molecular diffusion and turbulent diffusion), and dispersion is defined as mixing due to velocity gradients in the fluid (Logan, 1999; Maidment, 1993; Ramaswami et al., 2005; Hemond & Fechner, 2015).

Governing Advection-Diffusion Equation

The governing conservation of mass equation for a constituent can be derived, according to Maidment (1993), by equating the change of mass in a control volume to the sum of the net (advective plus diffusive) flux through the control volume plus sources and sinks. The general three-dimensional form in Cartesian coordinates is given by equation (2-5).

$$\frac{\partial C}{\partial t} + u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} + w\frac{\partial C}{\partial z} = \frac{\partial}{\partial x}\left(E_x\frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(E_y\frac{\partial C}{\partial y}\right) + \frac{\partial}{\partial z}\left(E_z\frac{\partial C}{\partial z}\right) - KC \quad \text{........(2-4),}$$

in which u, v, and w = velocity components in the three coordinate directions, x, y, z; C = concentration in the turbulent flow; E_x, E_y, E_z = nonisotropic (a function of direction), nonhomogeneous (a function of location) turbulent diffusivities in the x, y, z directions; and first-order decay (with coefficient K) is assumed.

For two dimension, the continuity equation becomes equation (2-6);

$$\frac{\partial (hC)}{\partial t} + \frac{\partial (uhC)}{\partial x} + \frac{\partial (vhC)}{\partial y} = \frac{\partial}{\partial x}\left(hE'_x\frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(hE'_y\frac{\partial C}{\partial y}\right) - hKC \quad \text{..................(2-5),}$$

Here the concentration, u and v (velocities in the x and y directions) are vertically averaged over the variable depth h (x, y). Thus, E'_x and E'_y include a diffusive mixing component due to sheer–flow dispersion.

2.10.5.2 Nitrogen and phosphorus dynamics and their simulation in SWAT

Out of the five major life-forming elements: nitrogen (N), carbon (C), phosphorus (P), oxygen (O), and sulfur (S), N has the greatest total abundance (more than the mass of all four of these other elements combined) in Earth's atmosphere, hydrosphere, and biosphere though it is the element least readily available to sustain life. However, more than 99% of this N is not available to more than 99% of living organisms because most of it exists in the form of a non-reactive, molecular nitrogen (N2) (Galloway et al., 2003). Totally five different pools of N (two pools are inorganic forms of N (ammonium [NH_4^+] and nitrate [NO_3]) while the other three are organic forms) and six different pools of P in the soil are monitored by the SWAT model. However, only one of the reactive nitrogen and phosphorus forms (NO_3^-, PO_4^{2-}) were modelled by SWAT completely for the basin, which may be transported with percolation, lateral flow, or surface runoff (Jiang et al., 2014).

Transport and cycling of nutrients from land areas to streams (and water bodies) and atmosphere and vice versa is a result of soil weathering and erosion processes. In the soil, transformations of nitrogen and phosphorus from one form to another are governed by the nitrogen and phosphorus cycles respectively as depicted in and (Neitsch et al., 2001). They may be added to the soil by fertilizer, manure, bacterial fixation, and rain and can also be removed from the soil by plant uptake, leaching, volatilization, denitrification and erosion as can be seen in **Figure 2-5** and **Figure 2-6**.

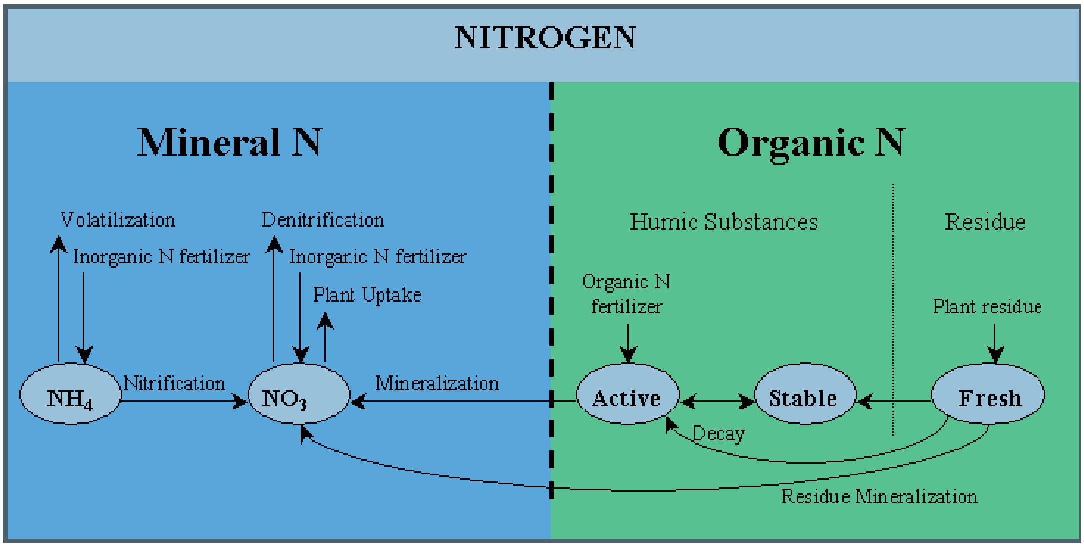


Figure 2-5 SWAT soil nitrogen pools and processes that move nitrogen in and out of pools (Neitsch et al. 2011)

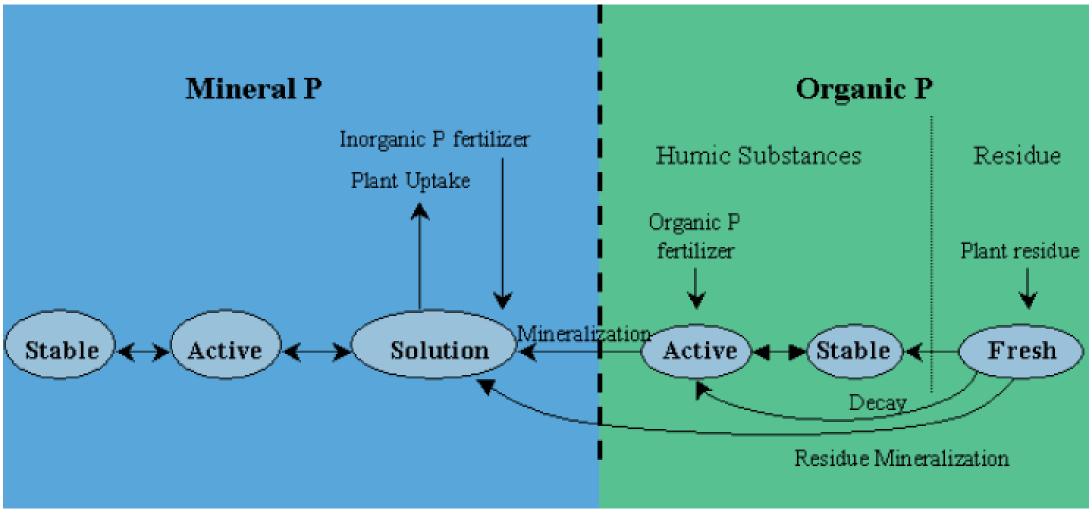


Figure 2-6 SWAT soil phosphorus pools and processes that move phosphorus in and out of pools (Neitsch et al. 2011)

Algorithms governing the movement (with surface runoff, lateral flow or percolation) of mineral forms of nitrogen and phosphorus from land areas to the stream network are found in Neitsch et al., (2001). In SWAT, nutrient routing, transformations and kinetics in streams are controlled by the in-stream water quality component of the model, QUAL2E. The QUAL2E model, operated in a quasi-dynamic mode, simulates temporal variations in water quality conditions under steady flow conditions, and discharges and withdrawals are constant for a given simulation (Neitsch et al., 2001). A detailed theoretical explanation of SWAT and its other major components can be found in Neitsch et al. (2002).

Chapter 3 Materials and Methods

3.1 Description of the study area

3.1.1 Location

The Basin is located between latitudes 7°53′N - 12°0°N and longitudes of 37°57′E - 43°25′E in Ethiopia (**Figure 3-1**). It covers a total land area of about 114,000 km^2 of which 66,000 km^2 is in the western section of the basin. This section of the basin drains to the Awash River or its tributaries. The remaining 48,000 km^2, most of which comprises of the so-called Eastern Catchment and drains into a desert area and does not contribute to the Awash River course. The Awash River has a total length and an annual flow respectively of 1250 km and 4.6 billion m^3 and originates at an elevation of about 3000 m in the central Ethiopian highlands near Ginchi town about 80 km west of Addis Ababa. It flows in north-easterly direction along the Rift Valley through Amhara, Addis Ababa, Oromia (passing through Koka Reservoir), Afar, Dire Dawa, Somali territory and eventually discharging into the low land salty Lake Abbe at the border of Ethiopia and Djibouti, which has an altitude of about 250 m.a.s.l (Getahun & Gebre, 2015; Tessema, 2011; Berhe *et al*., 2013; Degefu *et al*., 2013).

Unlike most of the 12 main rivers in the 12 river basins of Ethiopia, Awash River is characterized by its closed system (no outlet or not trans-boundary) (Fekadu Moreda, 1999) and surrounded by six main national river basins namely: Danakil to the north, Abay (Blue Nile) on its western side, Omo-Gibe and Rift valley lakes to the south west, Wabi shebele and Ogaden river basins to the south east and to the east by the Djibouti territory. Its catchment includes parts of 5 regional states (Oromiya, Afar, Amhara, Somali, and SNNP) and 2 administrative councils (Dire Dawa and Addis Ababa).

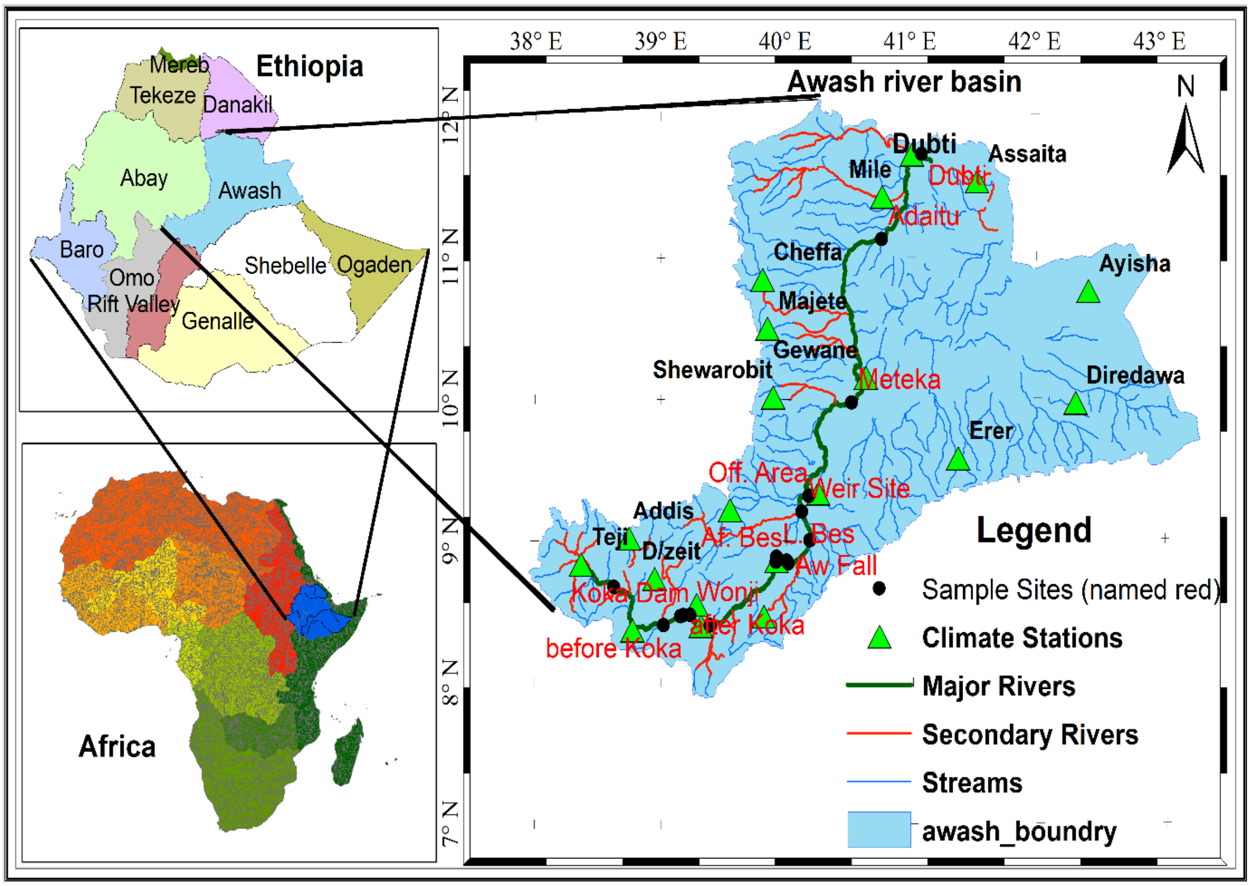


Figure 3-1. Location Map of Awash River basin with the Sampling Sites

3.1.2 Basin physiography

3.1.2.1 Physical characteristics

The physiography of Ethiopia in general and Awash basin in particular is an expression of the underlying geology (Halcrow, 1989). The two main physiographic units of ARB are highlands (Ethiopian plateaus) and the MER widening to the north of Afar triangular depression, in which grassland, shrub-land, woodland and forests are the main units. The basin is endowed with several wetlands of various types as well as artificial and natural lakes (Gedion, 2009; Halcrow, 1989).

Awash upstream of Koka: comprises of the headwaters of Awash River (west of Addis Ababa) down to Koka reservoir/dam. Important rivers like Awash Kunture, Mojo, Little and Great Akaki rivers are found in this sub basin. Awash Awash: includes part of the valley between Koka dam and Metahara. Keleta-Werenso Rivers and Awash Arba 1 and 2 Rivers are located in this sub basin. Awash Halidebi: covers part of the valley between Metahara area (Awash

Falls) and Adaitu. This sub-basin contains Kesem-Kebena Rivers, Ankober River, Negeso-Gera River, Awadi River and Gedebasa Swamp. Awash Adaitu is part of the valley between Adaitu and Tendaho. Awash Adaitu sub-basin includes Ataye River, Borkena River, Cheleka Gewis River and Adaitu River. Awash Terminal: area downstream of Tendaho up to the farthest lake called Abe. In this sub basin Mile River and Logia River are located and drained into the main Awash River. Eastern Catchment: extends from the eastern highlands of Hararghe, stepping down through a series of piedmonts to a vast plain. The surface runoffs (Mulu, Doba, Adu, Harewa, Erer streams) generated in this catchment does not have direct surface access to the mainstream Awash, forming effectively a closed sub-basin.

3.1.2.2 Land use/land cover

As the basin includes the two extreme climatic zones, variety of land uses are observed including agricultural, forest, water bodies, grass, shrub, urban, bare lands, sands, and exposed rocks. There are also a number of natural and artificial lakes in the basin. According to **Figure 3-2** the land use/land cover map of ARB is dominated by bare lands, followed by agricultural lands. Grass, forest, shrub, sandy/exposed rocks, built-up areas and water bodies, in the same order of level of dominance, are other land cover types in the basin on the basis of the 2000 LU/LC data. The current proportion of land use also comprises of cultivation, urbanization and deforestation/land degradation as well as on-going catchment treatment activities.

The main percentage of the shrubs in the middle and lower parts of the basin is taken by the invasive plant species, Prosopis juliflora (also locally called 'Dergihara'). However, this species has a number of socio-economic and ecological impacts. The impacts include: that on food security and livelihoods in the basin as it invades about 15% of the region's productive (cultivable and grazing) land (Admasu, 2008; Mehari, 2015).

The land management is an important factor partly affecting runoff generation in a catchment. The land management system of the highlands, arid and semi-arid agro-ecosystem of Ethiopia is characterized by combination of intensive agriculture (rain-fed and irrigation), pastoralists, and fallow desert areas. Cultivation might reach to valley slopes of 50% gradient or above that exacerbates erosion despite an extension advice to cultivate only lands with slopes below 35%. As land holding of farmers is far less per individual household, the same land is cultivated annually without rest and this aggravated chemical soil degradation. The dominant form of cropped land is occupied by a cereal which is about 90%. Hence, the topsoil is exposed to severe erosion and become of poor soil fertility.

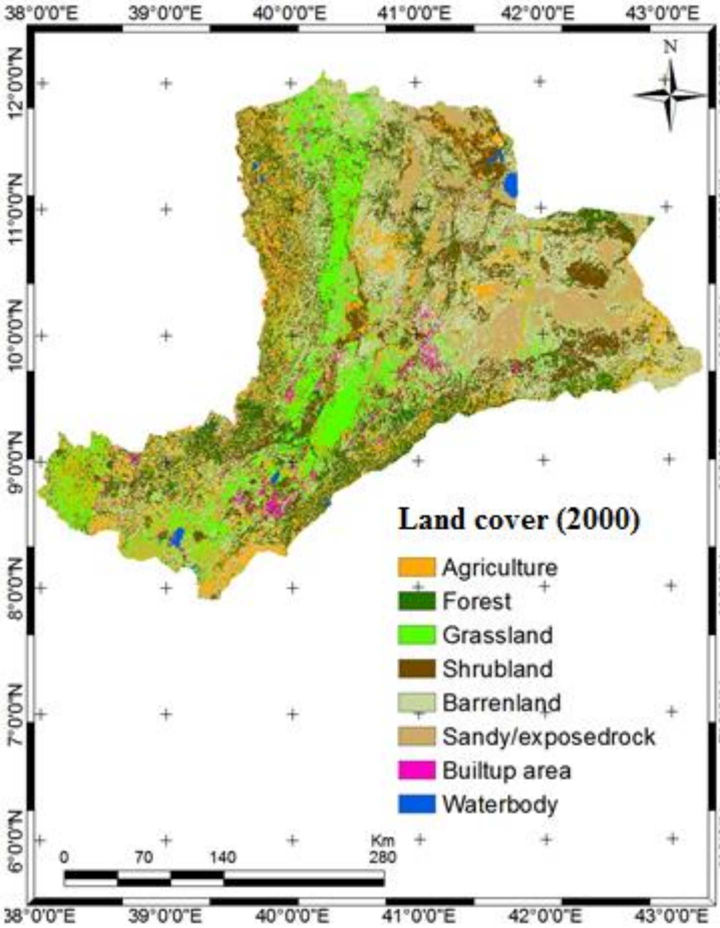


Figure 3-2 Land Use/Land Cover Map of Awash Basin

3.1.2.3 Topography

It consists of various topographical features (flat to mountainous) with elevation ranging from 210 to 4195 meter above sea level (m.a.s.l). The topographical landscape of the basin comprises of highlands, escarpments and rift. Its safe topography and ease of access have made the basin to host the most intensive irrigation developments at substantial scales of all Ethiopian river basins. It is divided generally into sections including upland (above 1500m), middle (1000 – 1500m), lower valley (500–1000m) though the basin's DEM in **Figure 3-3**.Error! Reference source not found. is categorized into 5 topographic classes.

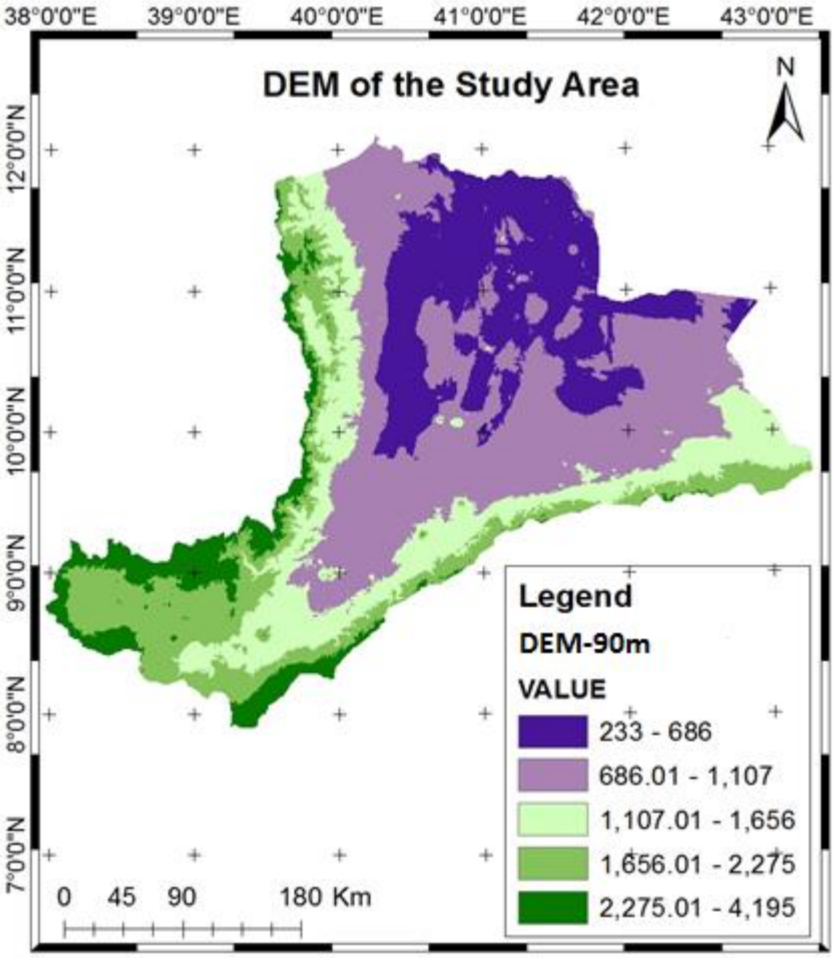


Figure 3-3 DEM of Awash River basin

3.1.3 Hydrology, climate and agro-ecological conditions

3.1.3.1 Hydrology and climate of the Awash River basin

Rainfall of Awash River basin

The seasonal distribution and pattern of rainfall that vary spatially in the Awash Basin is determined by the annual migration of Inter-Tropical Convergence Zone (ITCZ). In March the ITCZ advances across the Basin from the south, bringing the small or spring rains. In June and July, the rainfall reaches its most northerly location beyond the basin which then experiences the heavy summer rains. It then returns southwards during August to October, restoring the drier easterly airstreams which prevails until the cycle repeats itself in March (Halcrow, 1989). The annual rainfall distribution resulting from this cycle is shown most clearly in the two distinct rainy periods which are characteristic of the northern plains of the basin (Belete & Semu, 2013; Gedion, 2009).

Table 3-1 Important features of the main drainage basins of Ethiopia

Basin Name	Temp (ºc)		Catch. Area, %	Annual Discharge, km^3	Mean Rf (mm)	Mean Evaporation (mm)	Surface Water resource potential (Bm^3)
	Min.	Max.					
Abbay	11	25.5	17.56	54.4	1420	1300	54.4
Awash and Ayisha	17	34.5	10.09	4.9	557	1800	4.9
Baro-Akobo	<17	>28	6.51	23.2	1419	1800	23.23
Genale Dawa	<15	>25	15.03	6.1	528	1450	6
Tekeze	<10	>22	7.9	8.2	1300	1400	8.2
Wabishebelle	6	27	17.59	3.16	425	1500	3.4
Omo-Ghibe	17	29	6.87	16.6	1140	1600	16.6
Mereb	18	27	0.52	0.72	na	1500	0.72
Rift Valley Lakes	<10	>27	4.63	5.64	na	1607	5.64
Denakil	5.7	57.3	6.5	0.86	na	na	0.86
Ogaden	25	39	6.77	0	400	na	0

The major source of recharge for the vast surface and groundwater system is the rainfall on the highlands during the rainy season. The main recharge comes from the north-western, south-eastern highlands and upper basin, where annual rainfall is high. Seasonal floods occur in summer and the highland's fractured volcanic cover is favorable for groundwater recharge (Getahun & Gebre, 2015).

Rainfall and evapo-transpiration (especially in the highlands) are also shown to vary linearly with altitude strongly according to Belete & Semu, (2013). The basin mainly experiences two rainy seasons during the periods of spring (February-May) and summer (June to September) depending on the position of the zone (Berhe *et al*., 2013; Gedion, 2009). The Mean annual rainfall varies spatially across the catchment between 160 mm at Asayita and 1978 mm at Ankober per annum according to Berhe *et al*. (2013) and Halcrow, (1989) (**Figure 3-4**).

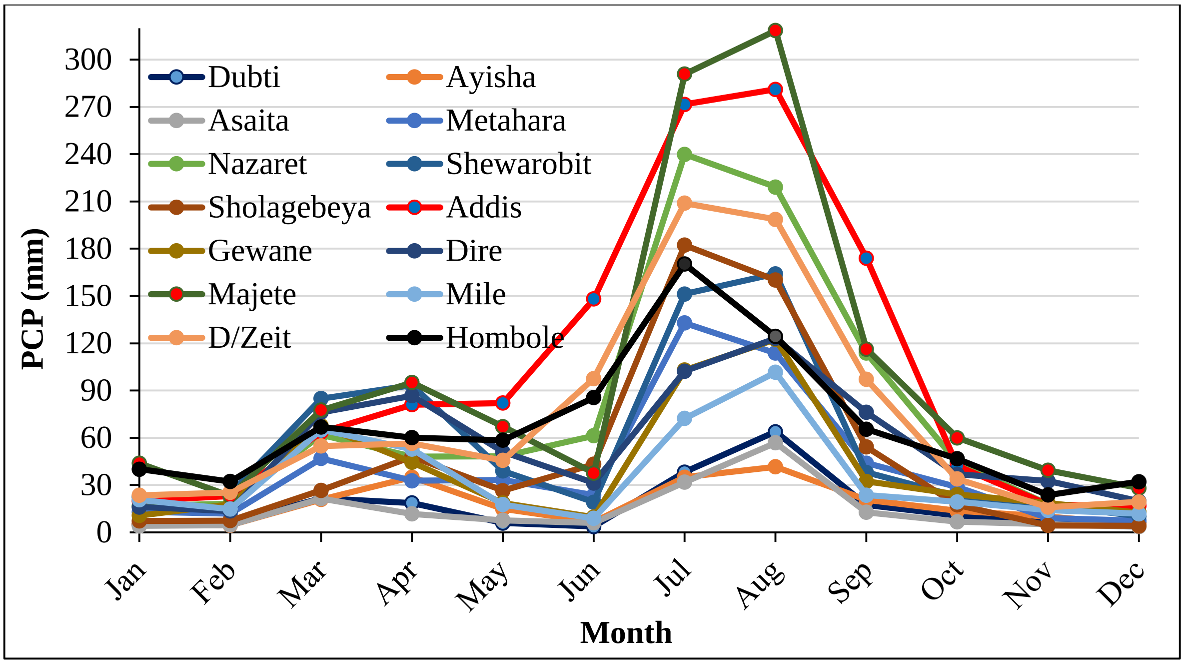


Figure 3-4 Average (1994-2014) monthly rainfall of some stations in the basin (Source: own)

The mean annual rainfall, according to Berhe *et al*. (2013), over the entire western catchment is 850 mm. The total annual water resources of the basin amount to about 4527 MCM (Berhe *et al*., 2013). The area is dominated by a bimodal rainfall pattern. According to the National Meteorological Services Agency, the study area is characterized by a quasi-double maxima rainfall pattern with a small peak in April and maximum peak in August, the intensive rainfall occuings between June and September (Ndomba and Griensven, 2011).

Flow of Awash River

The seasonal flow distributions for few selected stations located in different physiographic units of the basin are portrayed in **Figure 3-5**.

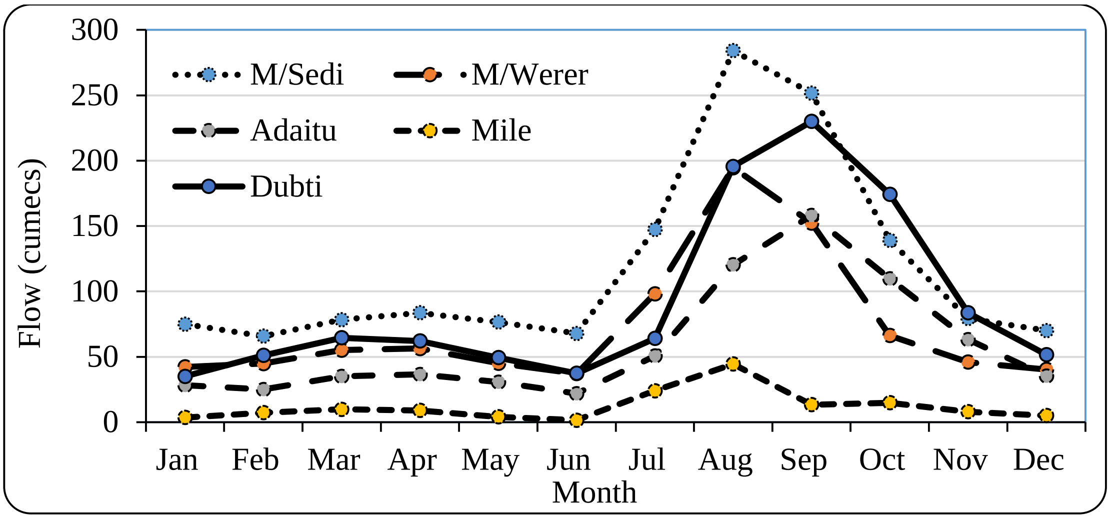


Figure 3-5 Average (1990-2010) Monthly hydrograph (flow) of some stations in the basin

Temperature of Awash Riber basin

There is a considerable variation of mean annual temperature spatially across the basin and ranges from 16.7°C at Addis Ababa to about 34.5°C at Lake Abe area. The mean monthly temperatures, which is highly correlated with altitude, ranges from 9.6°C in the capital Addis to 34 °C around Lake Abe area (**Figure 3-6**). Mean annual relative humidity in the basin varies from 60.2% to 49.7%. The mean annual wind speed is 1.85 m/s. Wind flow patterns are influenced by the seasonal variation of ITCZ. Patterns are bimodal in the Upper Basin Region, with peaks in March and September, and minimum speeds in July and August (Ndomba and Griensven, 2011; Halcrow, 1989; Berhe *et al.*, 2013; Gedion, 2009).

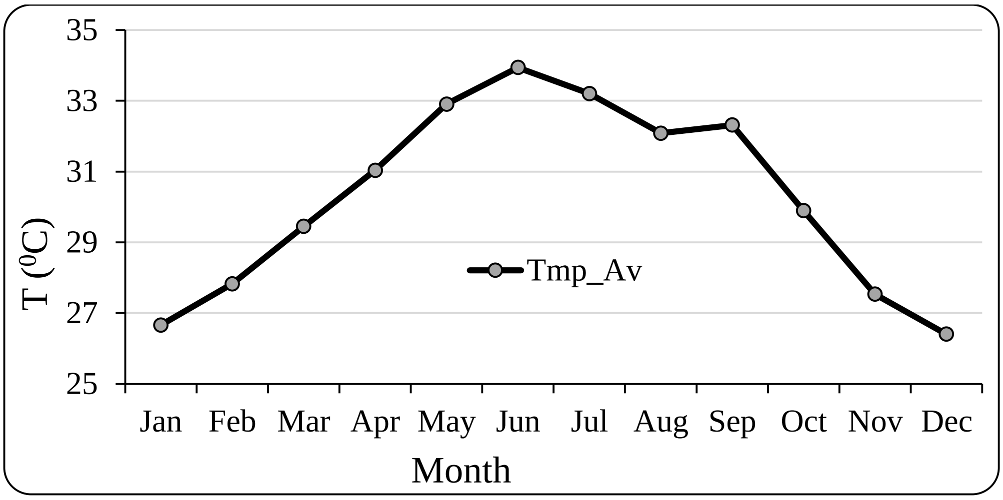


Figure 3-6 Graphical presentation of monthly average temperature (^{0}C) trend of Dubti station on the basis of mean of the 21 years (1994-2014)

3.1.3.2 Agro-ecology

ARB is characterized by wide-ranging agro-climatic zones with various ecological conditions. With extreme ranges of topography, vegetation, rainfall, temperature and soils, the basin extends from both semi-desert (arid) lowlands to cold high mountain (humid subtropical) zones (Gedion, 2009). The upper parts of the basin are characterized by Woina-Dega and partly Dega climatic condition. In this part of the basin rain-fed agriculture is adapted because this area receives a considerable amount of rainfall during belg time (March to April) and the long rainy season Kiremt (June to August). Conversely, the middle and lower parts of the basin is dominantly semi-arid or Lower Kolla to Bereha. These zones are characterized by irrigation practices because the amount of rainfall is minimal to meet the crop water requirement. These parts of the Basin are also the most developed part by irrigation as favorable topography and accessibility of the Awash River water has encouraged irrigation development (ASTU, 2016). Although altitude has been the major determinant for this agro-climatic classification of regions, it can be refined more with temperature and rainfall (Hailemariam, 1999; Gedion, 2009).

3.1.4 Water resources (lakes and tributary rivers) in Awash River basin

Although the basin stands 4th in the catchment area coverage and 7th in the surface water resource potential, annual discharge and total annual runoff (generating about 4.9 BCM) **Table 3-1,** which is smaller as compared to most of the other basins in Ethiopia, Awash is the most utilized and developed basin since 77.4% of the irrigable land in the basin has been cultivated (Adeba et al., 2015; Berhe *et al*., 2013; AwBA, 2014). An estimated 1.05 BCM or 21% of the water resources of the basin are lost by evaporation and seepage due, most likely, to a substantial decrease in annual runoff, which in turn reduce the volume of water bodies over the ARB resulting from the generally warming climate (Hailemariam, 1999). Average specific yield and per-capita availability of surface water are estimated to be 1.4 l/s/km^2 or 44.5 mm/year and 445 m^3/person, respectively (http://www.mowie.gov.et/).

Most of the water resources of the basin exist in or drain from the western plain of the valley. Although the eastern plains account for some 40% of the area of the basin, its drainage channel terminates before reaching Awash River and also receives low rainfall (less than 600 mm per year) (Fekadu, 2006). There are many natural and artificial lakes in the basin. Some of the artificial reservoirs include Tendaho (on almost the terminal of Awash basin in the lower tip), Kesem (the tributary of Awash River and found in Awash Halidebi at the middle basin), Koka, Abasamuel, Legedadi, Dire and Gefersa (found in the upper basin). While Tendaho and Kesem are built for sugarcane production, Koka and Abasamuel were built for hydropower generation though Koka dam is being highly affected by siltation. Legedadi, Dire and Gefersa were constructed purposely for Addis Ababa city water supply. The natural ones are Lake Bishoftu, Lake Kuriftu, Lake Hora, Hora kalu, Lake Babo Gaya, Lake Wedecha, Lake Belbela (which are situated in and around Bishoftu) (located in the upper part), Lake Beseka (found in the middle), Lake Yardi (near Gewane situated in the lower basin), Lake Gamari (just next to Afambo town in the lower basin), lake Afambo, and lake Abe (located at the north-east edge of the basin and terminal point of the Awash River). Tributaries to Awash River include: Abasamuel (joining the river in the upper basin), Keleta, Wererso and Arba (Dengego) (between Koka and Awash station), Kesem and Kebena (between the Awash Station and Gedebessa swamp (Hartale station) and they originate from western highlands), Mile, Borkena, Ataye and Cheleta (joining the river between Hertale station and the Tendaho Station originating from Wollo mountains) and many more ephemeral ones (Fekadu, 2006) all being collected from streams. Additionally, there are a number of hot springs too in the basin namely: Sodere and Addis Ababa springs.

3.1.5 Soil and geology

Two major relief features found in the Awash Basin include: the highlands of the Ethiopian Plateau and the lowlands of the Rift Valley. The bedrock and soil in the area determine the amount and composition of transported sediments in the river. The geology of the basin is dominated by sedimentary rocks such as limestone and sandstone. Through time the river deeply incised and the volcanic masses in the plateau area rose to over 3,000 m. Fault scarps and the effects of Pleistocene and Holocene volcanic activity frequently break the flat floor of the Rift Valley. The alluvium deposits consist of clay, sand, tuff, ignimbrites, and rhyolites.

Texturally, the soil types in the basin are around nine including water: clay, clay loam, loam, sand, sandy clay, sandy clay loam, sandy loam, silty loam, and water (**Figure 3-7**). The basin is comprised of different soil types dominated by Vertisols, Cambisols, Nitosol, and Leptosol. The clay mineral expands when there is a wet condition and shrinks when there is a dry condition, causing cracks at the surface in the dry season (Moreda, 1999; Getahun & Gebre, 2015).

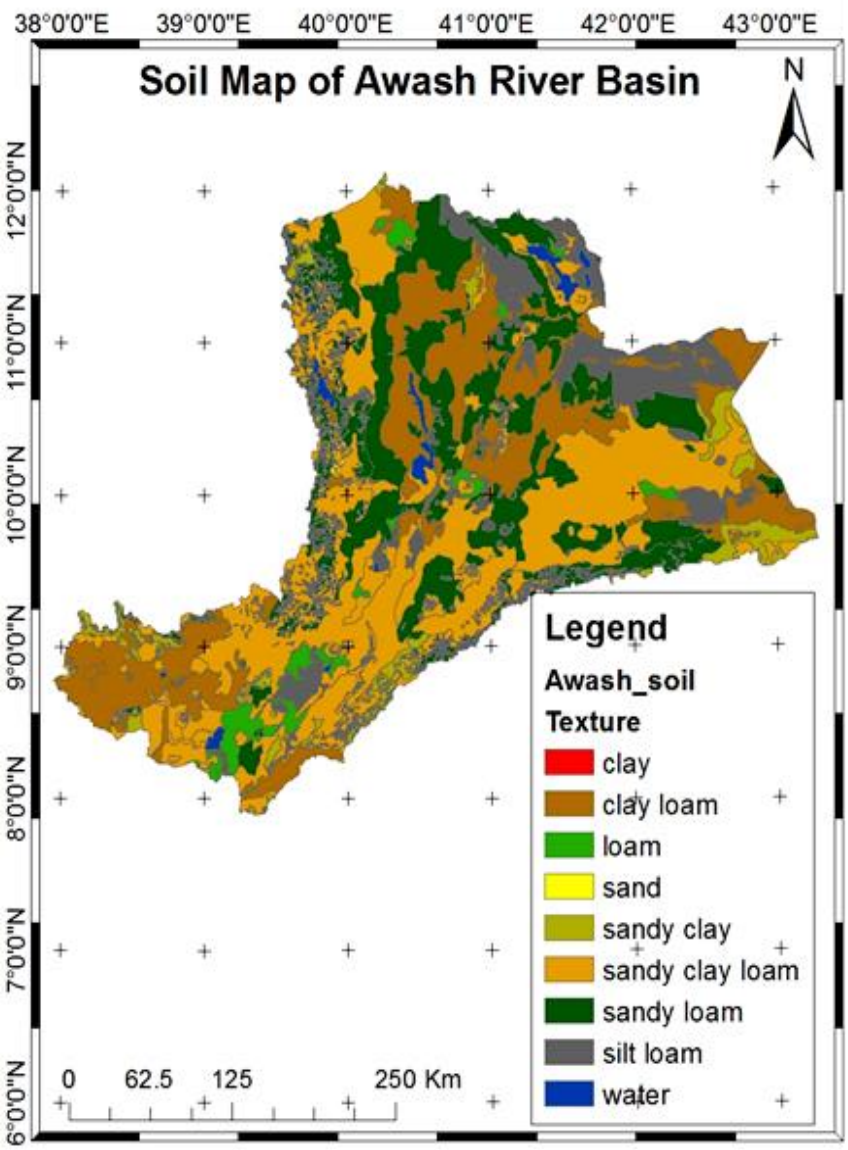


Figure 3-7 Soil Map of the Study Area by Texture

3.1.6 Population, settlement and socio-economy

The ARB, containing main population centers of the country such as Addis Ababa, Dire Dawa, Adama and Bishoftu, has about 14.8 million human populations. These inhabitants are distributed accordingly into Addis Ababa (22.73%), Amhara (18.74%), Afar (9.85%), Dire Dawa (2.71%), Oromia (37.5%), SNNPR (0.9%) and Somali (7.55%) (FAO and MoWIE, 2013). The main population centers lie in the upper part of the basin mainly above an elevation of 1,500m because of its strategy for life supporting (Fufa, 2016). Majority of this population is engaged in agriculture and animal husbandry. From 48 to 70% of the existing large-scale irrigated agriculture (such as Wonji-Shoa, Metehara, Upper Awash Agro-industry, Amibara and Gewane) and more than 65% of the national industries are located in the basin (Tessema, 2011; AwBA, 2014). Wide varieties of crops, ranging from cereals, vegetables, flowers, cotton to perennial fruit orchards and sugarcane, are cultivated in the basin. As there is currently a shift in crop preference following the government's interest, the dominantly cotton cultivating middle and lower valleys have now been transformed to sugarcane production (AwBA, 2014). Settled rain-fed agriculture is practiced with possible double cropping in areas receiving considerable spring rainfall (January-May) in addition to the main summer rainfall. Cultivated lands are mainly croplands under rain-fed or irrigation. Most of the upper basin, north-western and south-eastern highlands including some parts of the upper valley are intensively cultivated. The main crops grown under rain-fed agriculture include 'teff', barely, wheat, beans, maize, lentils, etc.

3.1.7 Water supply and sanitation

Water supply in the rural areas of the basin was inadequate as only about 15% of beneficiaries could get 20 liters of water per day per capita. Moreover, most of the water sources were exposed to waste emanating from human, wild life, livestock and uncontrolled flooding. In other words, sanitary practices in rural areas around Adama town were poor as only about 3.4% had ventilated and improved pit latrine and open pit and/or open field defecation were widely practiced (Tadesse et al., 2013).

Microbiological contamination to the surface and groundwater and pollution by heavy metals concentration of Akai River are indications of absence of adequate sanitation facility in the upper basin. Additionally, in the middle and lower Awash Valley increasing prevalence and severity of water-related diseases such as malaria, schistosomiasis and diarrhoea have been associated with improperly developed irrigated agriculture (Taddese et al., 2003). The higher nitrate and chromium level in the surface and springs of the basin is attributed to the improper waste disposal practice (Alemayehu, 2001).

3.1.8 Industrial and irrigation development

In the ARB, in addition to other socio-economic activities, the main industrial sectors and intensive irrigation agriculture are practiced especially in its upper and middle basins. Though Awulachew et al (2008) has reported that irrigation water used in Wonji/Shoa sugar plantation is of good quality, SAR/adjR_{Na} to EC ratio is shown to indicate that a slight to moderate reduction in the infiltration rate might occur. The observed destruction of the natural structure of the soil in some places of the plantation could possibly be attributed to unfavorable SAR values and SAR/adjR_{Na} to EC ratio in the irrigation water of some of the water samples. The measured pH values of both irrigation water and Factory used water samples varied from 7.4 to 8.1 (Awulachew et al., 2008).

3.2 General frame work of the study

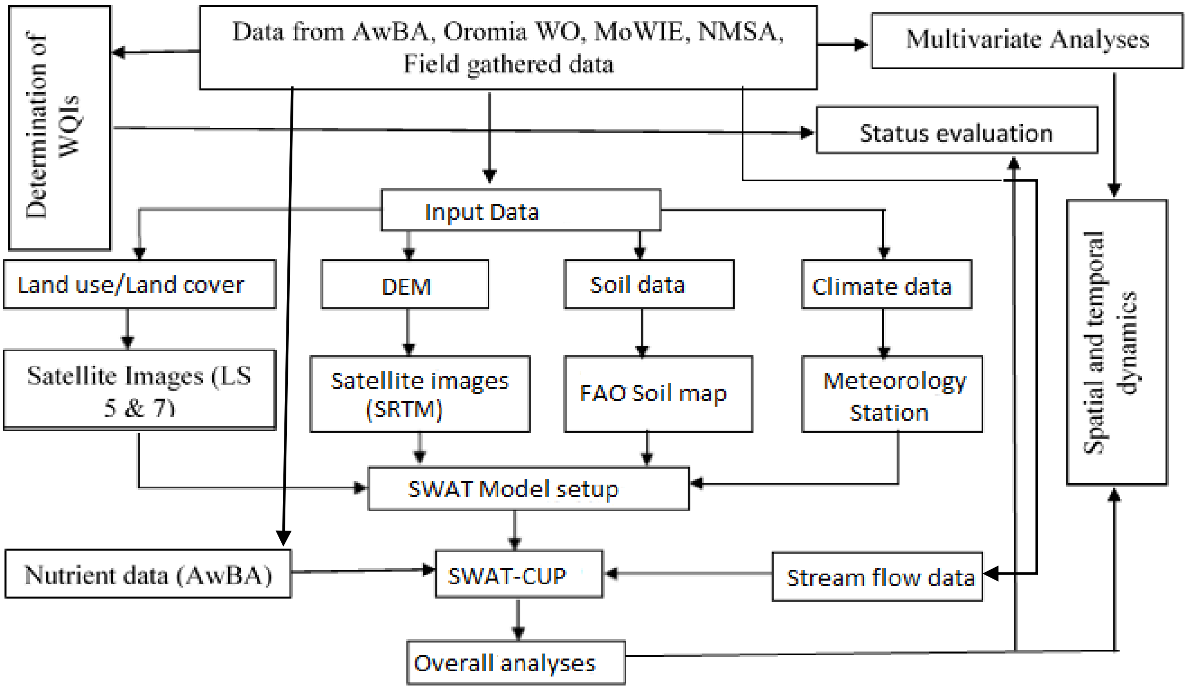


Figure 3-8 General work flow of the study

3.3 Reconnaissance survey, data collection and analytical methods

It is only after certain observations were made that theoretical analysis and modeling can help understand either the hydrodynamics or the water quality processes and produce reliable results for supporting decision-making (Ji, 2008). Hence, preliminary assessment of the study area and gathering information about geography, population, hydrology, socio-economic and demographic data of the catchment area was done using interviews and through observations. To have an overall picture for characterizing, evaluating, spatio-temporal assessment and modeling the water quality of the basin, collection and analysis of both 1^{o} and 2^{o} data were undertaken. The secondary data that have been gathered from different organizations include: long term (11 years') water quality data from the Awash basin authority to see the spatial and temporal trend. Dataset of water quality of different sites in the basin (on the river, tributaries and lakes) has also been collected from MoWIE. A two years' water quality dataset of the upper basin analyzed and compiled in collaboration with Vitens Evides international granting organization of Netherlands and Oromia regional water office was collected from Oromia regional water office. As 1^{o} sources for attaining the objectives, collection of water samples from Awash River and its tributaries in the entire basin was undertaken to analyze the physical and chemical parameters.

3.3.1 Site selection

Sampling points were chosen based on the objectives of looking for spatial and seasonal changes of the parameters. Most of these were judged to be the sites where AwBA has been taking samples for long and additional sites were also selected as of critical importance with respect to sources of pollution. These additional ones were along the river, joining points of the river and tributaries, and tributaries coming from cities and industries just before their mix and just after mixing such as Aba-Samuel tributary. They all took accessibility and inputs of different socio-economic activities into account.

3.3.2 Equipment used, sampling and analyses

3.3.2.1 Equipments used

Since rational sampling and analytical strategy should incorporate carefully selected parameter tests using simple methods and portable water-testing equipments, all the available materials were used to make the collection and analyses of samples as effective as possible. Multi-parameter (HANNA HI 991300) onsite water quality testing meter (used to test pH, EC, TDS and T^o), Global Positioning System (GPS), digital camera, turbidity (NTU) meter, plastic sample containers, plaster, long rope, sample taking vessel, ice box, mobile phone were some of the field materials taken to the field with the researcher. Latitude and longitude of the sampling sites were measured using a hand-held GPS (Garmin).

3.3.2.2 Sampling

To assess the status, spatial and temporal variability of quality of the river water, grab samples were taken continuously at each of the sub-catchments under low flow and high flow conditions. The sampling process has been designed in such a way as to decide the exact number, sites and time the samples were taken. This is done in order that representativeness of the samples is attained. Sampling was done in four phases throughout the study period, twice in each of the dry (February 2016 and January of 2017) and wet seasons (May of 2015 and June 2016). So, in all the phases, grab samples of water have been collected from 17 sites: three of them in the lower, ten in the middle, and four in the upper basins. These were chosen based on accessibility and types of land use (agricultural, urban and industrial) found in the catchment. Since extensive irrigation agriculture and urbanization effects are observable in the upper and middle sub-basins, a lot of sample sites were considered in these sub-basins. From the upper basin it is done from the joining points of the industrial, urban and agricultural sewage with the river. Sampling has begun from the authority branch office in the lower basin, Dubti. It was done in triplicate using the plastic vessel tied with the long rope to bring from representative [midpoint (vertically and laterally)] points of the river as can be seen in **Appendix 7**. The water samples were collected in polyethylene plastic bottles rinsed 3 times with distilled water both for onsite testing and laboratory analysis. All samples for offsite analysis were kept in a refrigerator at 4°C in dark place until further use immediately after each day they were collected.

Quality control procedures while sampling from field

When samples were collected, transported, and preserved from the field, quality control (QC) procedures were followed to produce quality data with respect to precision and accuracy. Therefore, field QC samples such as equipment blank and trip blanks were collected to test the presence or absence of errors occurring in the field according to Zhang, (2007) procedures. The QC samples (totally around 10% of the samples taken for laboratory analysis) that were used for assuring quality during laboratory analysis were duplicates (to know the analytical precision) and blanks (to identify any potential contamination).

3.3.2.3 Analyses

The samples collected in the first and second phases, which were prepared for offsite analyses, were analyzed in WWDSE laboratory using standard methods for examination of water and wastewater (APHA, 1998). AAEPA was also used to test the water quality samples collected from the entire river of the basin in the third and fourth phases by using similar procedures. However, the field analyses for EC, T, pH, and TDS were carried out by the investigator onsite using the HANNA meter (**Appendix 7**) since they would otherwise have changed during storage and transport.

The river water is being consumed mainly for irrigation and domestic uses in the basin. Hence, eco-hydrological parameters affecting these uses such as pH, Turbidity (Turb.), Temperature (Temp.), TDS, Total Solids (TS), Total Hardness (TH), Total Nitrogen (TN), ECo, TC, Alkalinity (Alk.), NH_3, EC, DO, BOD, COD, Na, Ca, Mg, F^-, Cl^-, NO_2^-, NO_3^-, CO_3^{2-}, HCO_3^-, and PO_4^{2-}, SAR, pathogens, nitrogen species and other concentrations with a synoptic sampling scheme were considered for analysis. The parameters analyzed and methods used for their analyses in this study were illustrated in **Table 3-2**.

Quality control procedures while preparing and analysing the samples

The significant errors that can occur during sample preparation are due to cross-contamination from glassware or from chemicals used, contaminant loss owing to sorption or volatilization, matrix effects or interference, and incomplete digestion or extraction of the analyte as a result of an improper procedure. Matrix and surrogate types of spiking QC samples were used for the purpose of QA/QC to assess sample preparation procedures. The three types of QC samples that are used for the QA/QC purpose during laboratory analysis are blanks - used to assess any potential contamination, spikes - used to obtain the percentage recovery and therefore the accuracy, and replicates (duplicates) - used to determine the analytical precision. For each batch (at least one per twenty samples) there were a QC sample including blanks, spikes, and duplicates of various types. Adding all these QC samples together, the total number of required QC samples was around 25% of the samples to be sent out for laboratory analyses**.**

3.3.2.4 Assessment and validation of data errors and anomalies of middle and lower basin

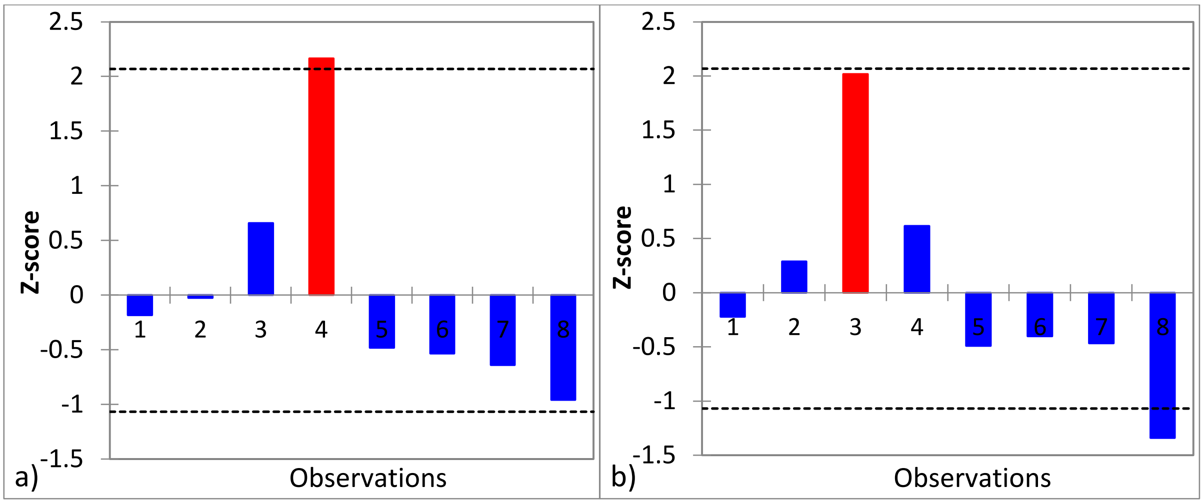
Assessment of integrity and validity of a given data-set based on knowledge, experience and intuition is an important and initial step of any water quality data analysis to draw meaningful conclusions from a study (Rangeti *et. al.*, 2015). It could be realized that the water quality dataset of ARB had lots of errors and anomalies that need to be validated. Data validation is a rigorous process of reviewing the quality of data, which is crucial especially when a secondary data is used for a study. The anomalies observed in the water quality dataset are outliers, missing values and censored data. Errors like pH values of greater than 14 at Adaitu, Meteka and Weir site in 2008, 2009 and 2012, respectively and TDS value of greater than EC at office area in the year 2012 were observed from the visual scan. Some of the errors may be transcription errors like an incorrect positioning of a decimal point at the data entry phase or when converting data from one format to another.

Among the observational (box-plots, time series, histogram, ranked data plots and normal probability plots) and statistical (Grubbs, Dixons, Cochran's C test and Mendel's h and k statistics) techniques available to test outliers, Dixon test is preferred since the number of values to be tested are greater than 6 and less than 25, the test is intended to be undertaken on non-normal raw data (Rangeti *et. al*., 2015). It is based on the ratio of the distance between the potential outlier value to its nearest value (Q_{gap}) to the range of the whole data set (Q_{range}) as shown by equation (3-1).

$$Q_{exp} = \frac{Q_{gap}}{Q_{range}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3\text{-}1)$$

If Q_{gap} is large enough as compared to Q_{range}, then the value is considered as an outlier.

Performing Dixon test on the mean of the 9-years annual average of the non-normalized water quality data set excluding only Beseka shows that most of the parameters such as F^-, Cl^-, Na^+ and alkalinity are outliers at after Beseka. TS, SO_4^- and PO_4^- are outliers respectively at Wonji, Meteka and Awash water supply. The reason of excluding lake Beseka is that it had maximum values of these and other parameters due to property of the lake water (Wubet, 2007; Gedion, 2009; Song *et al*., 2016).



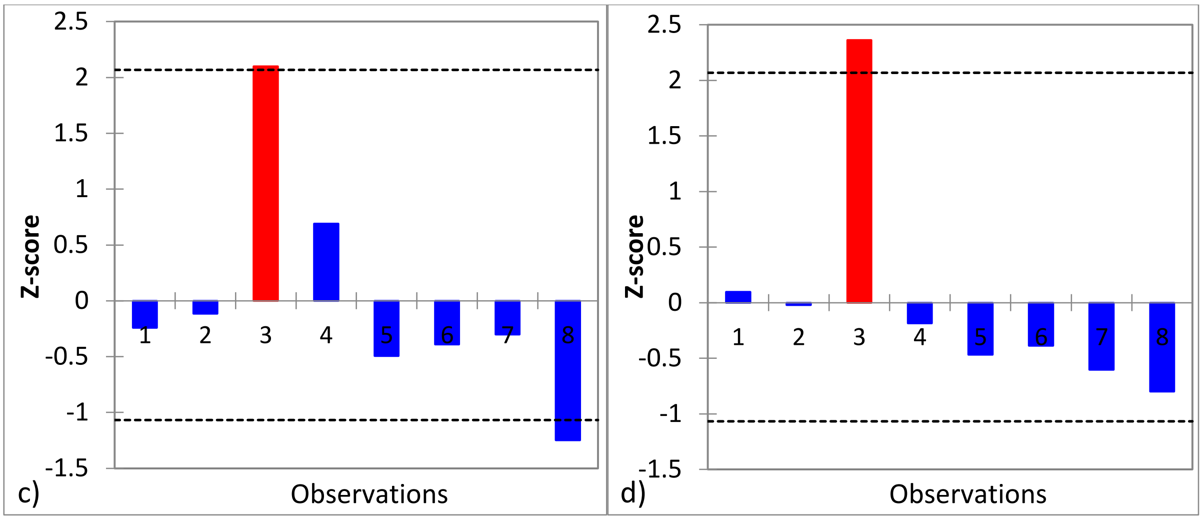


Figure 3-9 Detection of outliers by Dixon test from the mean of the 9-year annual average water quality dataset of the 8 monitoring sites of Awash River with standard score (z-score) values of TDS (a) Alkalinity (b) HCO_3^- (c) and SO_4^- (d).

But since outlying of the mentioned parameters at after Beseka may be the influence of lake beseka, Dixon test is also run excluding both lake beseka and after beseka sites on the same dataset. This resulted in outlying of alkalinity, HCO_3^-, and SO_4^- at Meteka; TDS at office area and PO_4^- at awash water supply as plotted by **Figure 3-9**. Tracing back to the source data, identification of which specific year and month have a significant contribution on the outlier was required. However, running the test for alkalinity, HCO_4^- and SO_4^- of the 9 years' annual average at Meteka show alkalinity and HCO_4- to have no outlier but SO_4- to have an outlier of 1029 in the year 2012 from all years' values of less than 100. Going again back to the contributing months to this annual mean, the specific month having a significant effect on this outlier is identified. Accordingly for the site (Meteka), SO_4^- is found to have an outlier value of 8617 at November since the two-tailed p-value (< 0.0001), computed using 10^6 Monte Carlo simulations, is less than $\alpha=0.05$ while other months' values being in the range from 38.5 to 108.5. This is informed by the lab technicians of the authority to be an error of misplacing the decimal point which had to be 86.17.

Similarly, running the test on the 9 years' concentrations of TDS for the office area, an outlier of 5144.4 in the year 2012 is observed as compared to all years' values of 299.7-592.3. Re-running the test to identify which specific month is the effect resulting from, presence of an outlier is realized since the computed p-value (< 0.0001) is lower than the significance level alpha=0.05 and the outlier is 45960 observed in March, which is too far from the mean of all the remaining months' value 641.4. But TS also had exactly this value in the same month, which needed to be some how greater. Though it had been corrected as 459.60, which might be logically near to other years' mean value, it could have been greater than EC value of the month that is unacceptable. Therefore TS, TDS, EC and Turbidity values of the month are ignored from using in calculating the mean of the 9-years since turbidity is also an unexpected outlier in the month. Running the test on PO_4^- for the Awash water supply, an outlier of 16.29 is observed in the year 2008 from all other years' values ranging from 0.31 to 0.78. Re-running the test to identify the affecting month, an outlier of 174 in April is found, which is too far from the mean of all the remaining months, 0.52. This is corrected, with an informed decision, as 1.74.

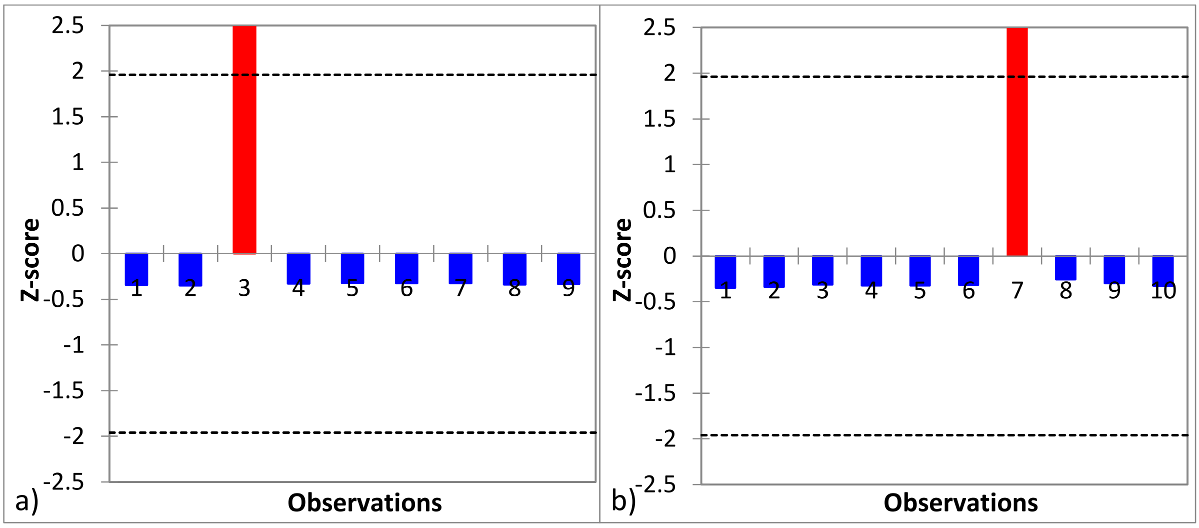


Figure 3-10 Z-score of concentrations of SO_4^- of the 9 months of 2012 at Meteka (a) and TDS of the 10 months of 2012 at Office area (b)

Dixon test on concentration of NO_3^- shows that an outlier of 34.07 is observed at lake Beseka and this is assessed to result from 2005's outlying value of 285 from other years' average value of 2.7. Furthermore, the month from which this outlier is contributed is tested and found to be September of exagerated value 2541, instead of 2.541, as compared to other months' average value of 1.38. Therefore, correcting this resulted in a new mean of the 9-years' annual average 2.57. Dixon test on F^- also shows an outlier of 43.35 to be observed at lake beseka and this is investigated to result from 2013's outlying value of 179.1 from other years' average value of 26.4. Additinally, the month from which this outlier is obtained is tested and found to be December of exagerated value 1954 as compared to other months' average value of 17.74. Communicating the staffs of the authority, together with personal judjement, it is found the value to be 19.54.

In 2010, EC at Adaitu has been wrongly registered as 4045 being the correct mean value of all months' for the year 404.5. Hence correcting this, the mean became 656.16. The outlying year of TS from the 9-year mean value, 490.02, of Wonji is assessed. However, there is no any significant outlying year's value from the contributing ones. The year 2005, recognized by the test here, doesn't mean the real contributing one because all years of value ranging from 334 to 774 are observed to be small as compared to other sites' mean values ranging from 1914.78 to 3613.78. Therefore, the outlying value, 490.02, of TS at Wonji is left as it is as all the years are found to contribute equally to minimize the 9-year mean value. At lake Beseka, SO_4^- was also showing an oulier that came from the 2006 value of 5104. This has come from the wrong placing of average of the months' values of the year, which was 510.14, rather than showing outlier in a month's value. Correcting this resulted in the 9-year SO_4^- mean of 497.84. Mg of value 612 in place of 6.12 and F- of value 27.8 instead of 2.78 at Dubti respectively in August and October of 2008 seem to be outliers, while Mg of value 672 instead of being 6.72 at Adaitu in June of 2011 also seem to be outlier. But they are not the real outliers rather they are born from personal errors.

The statistical test results could also be supported by observing the dataset at some sites. At Adaitu, for instance, exaggerated increments of EC in 2010 and Mg in 2011 is seen while at Weir site a similar increase of TDS (which is unexpectedly greater than its conductivity value) in 2009 and potassium in 2010 are observed. Abnormal exceedences at Dubti of NO_3^-, F^- and Mg in 2008 and TFe in 2007 are also observed. At Beseka, increment of SO_4^- to 5104 in 2006 from the common 300's and 400's in all the eight years and increment of F^- abruptly to 179.1 in 2013 from an average value of 26.4 for all the remaining eight years are also unexpected.

At office area, a sudden increase of TDS and PO_4^- were observed in 2012. This may probably be an error of placing the decimal point (being 514.44 rather than 5144.4) since it contradicts to the fact that TDS needs to be less than EC as in eqn. (3-2) while recording, transferring data or else. At before Beseka, a similar growth of alkalinity, SO_4^-, HCO_3^- and Na in 2012 is seen.

$$EC = k_e * TDS \ldots\ldots\ldots\ldots\ldots\ldots..(3\text{-}2)$$

where TDS is expressed in mg/l and EC is in µs/cm, the factor k_e Є (1.2, 1.8) (Rangeti *et. al.*, 2015).

A rough observation of plots of the after Beseka dataset shows also that except pH, Mg, NO_3^-, TDS, Ca, TH and turbidity, almost all the 13 parameters got larger values in 2009 and 2010 than in other years. These may all be due either to technical, personal, or instrumental errors.

3.3.2.5 Validation of data anomalies of the upper basin

Water quality analysis for the upper basin (UB) has been prepared and compiled by Vitens Evides international granting organization of Netherlands together with Oromia regional water office of Ethiopia in seven rounds at about 2.5 months' interval from 26/06/2014 - 30/11/2015. They considered ten sample sites of which only four sites were of interest and only those parameters having full data in all the sites were selected for the current study. Since a lot of samples were taken from each site, a number of parameters were considered and choice of sampling sites was strategic enough, this dataset was preferred to be used for computation of Water Quality Index (WQI) in the sub-basin.

Validity of the water quality dataset of the upper basin was checked. There were missing and censored values in the dataset marked as x, ?, empty, nil, <R and TNTC and they were refined by ignoring from calculation of the mean (some of them) and appropriate substitution (others). The other anomalies observed in the dataset were outliers. Dixon test (given by eqn. 3-1) was used again to detect the outliers and is shown by **Figure 3-11**.

Accordingly, out of the selected 28 variables, only 3 of them showed outliers. These are turbidity at the 6^{th} (19^{th}) site, chromium at the 4^{th} (17^{th}) site and chlorine at the 5^{th} (18^{th}) site, sites being numbered from the lower tip of the upper (entire basin). But the 19^{th}, 17^{th}, and 18^{th} sites are respectively Awash River at Awash Melka kuntire, Mojo River before Lake Koka, and Akaki River after Lake Aba Samuel, which are respectively exposed usually to high disturbance, tannery effluent and urban sewage effluent. Therefore, high amount of turbidity, chromium and chlorine are expected and hence they are the real and expected outliers and therefore they need no correction.

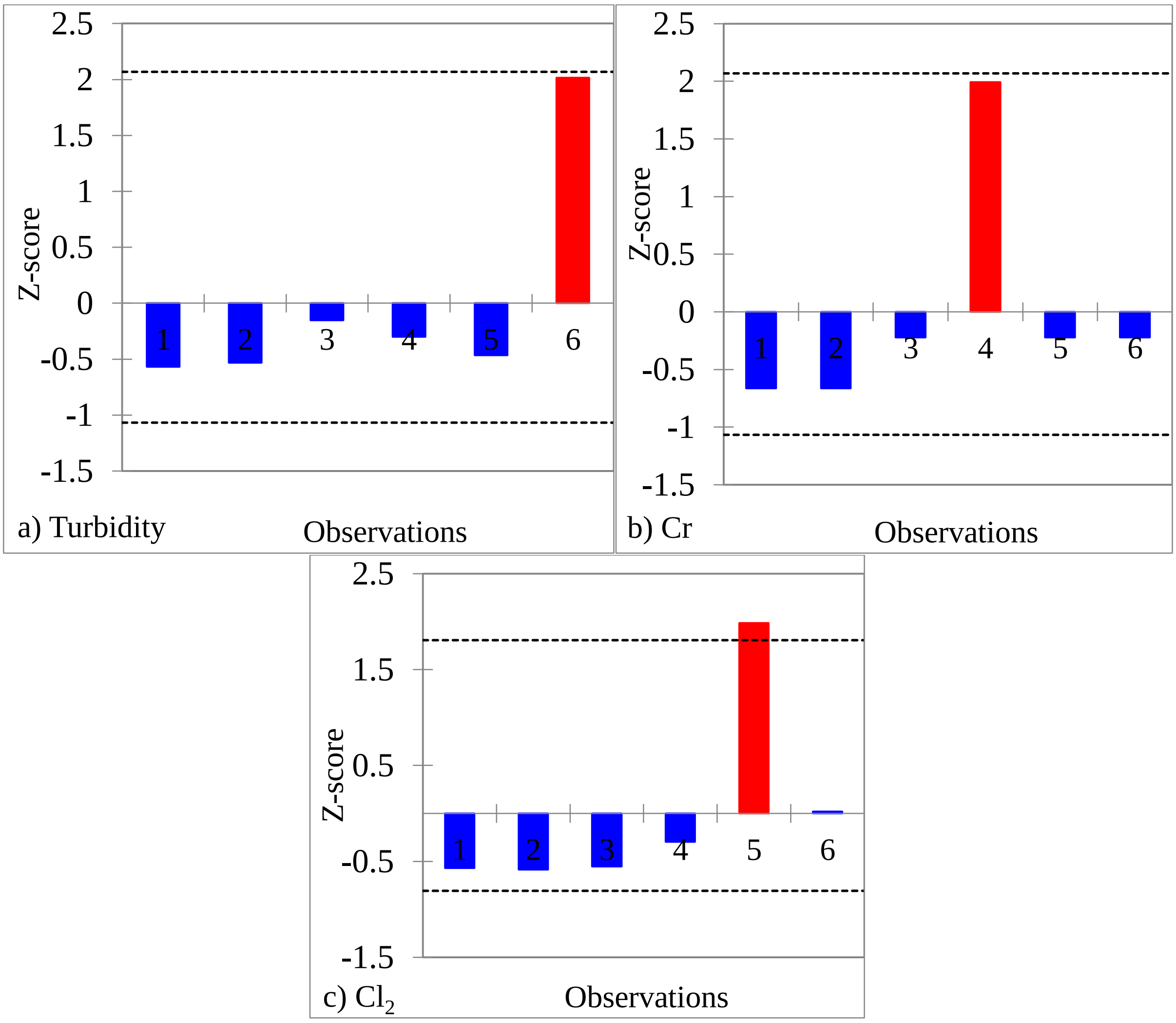


Figure 3-11 Demonstration of standard score of outlying sites for Turbidity (a), Chromium (b) and Chlorine (c)

Since only concentrations of Ca^{2+} and Mg^{2+} ions were given for the upper basin, total hardness (TH) is computed as the concentration of calcium and magnesium ions expressed as equivalent of calcium carbonate ($CaCO_3$) by equation (3-3)[1] (Lenntech, 2014) .

[1] http://www.lenntech.com/ro/water-hardness.htm

$$[CaCO_3] = 2.5 * [Ca^{2+}] + 4.1 * [Mg^{2+}] \ldots\ldots\ldots\ldots..(3\text{-}3)$$

The cations used in the calculation of SAR, which were expressed in mg/L, were all changed into milli-equivalents per liter (meq/L) and the SAR, depicted in **Table 4-2**, is calculated by equation (3-4) (Lesch and Suarez, 2009; Seid and Genanew, 2013; Hussain et al., 2010):

$$SAR\ (meq/\mathrm{L}) = \frac{[\mathrm{Na}^{+}]}{\sqrt{\frac{[Ca^{2+}]+[\mathrm{Mg}^{2+}]}{2}}} \ldots\ldots\ldots\ldots..(3\text{-}4)$$

The other chemical index of irrigation water quality importance such as RSC was also calculated from the measured water quality parameters by using equation (3-5) (Dinka, 2016). The cations and anions, which were expressed in mg/L, were all changed into mili-equivalents per liter (meq/L).

$$RSC = (CO_3^{2-} + HCO_3^{-}) - (Ca^{2+} + Mg^{2+}) \ldots\ldots(3\text{-}5)$$

3.4 Assessment of tools for evaluation and multivariate analysis of water quality

Water quality requirements, expressed as water quality criteria and objectives, are use-specific or are targeted to the protection of the most sensitive water use among a number of existing or planned uses within a catchment. Evaluation of whether a given water body is satisfactorily meeting the criteria for an intended use or not is therefore essential. On the other hand, water quality of water bodies at different localities in a basin may show difference at a time or a given water body may show variation of quality in different time scales. However, determination of the extent and way of these spatial and/or temporal variations is of important concern to decide either for the resource utilization or mitigation of pollution problems. Evaluation of the status of water bodies could be facilitated by WQI by considering selected stations and parameters along Awash River, discussing ranks of indices of sub-basins, determining the water quality status in the basin and assessing extent of suitability for irrigation and drinking purposes. Spatial and temporal variation of the water quality is managed using multivariate statistical analysis as usual.

3.4.1 Evaluation of water quality by WQI

3.4.1.1 Water Quality Indices

Environmental indices provide a broad overview of environmental performance rather than detailed information. WQIs, in particular, are practical methods of describing the problem of pollution in a water body by combining various measurements of different units in a single metric, summarizing bulk of water quality data in a single number that can logically be used for expression, comparison and determination of trends over time. They are, therefore, useful for communication of the results, modification of policies thereby developing a decision making tool as it allows to evaluate the state of a water body easily and make suggestions for a more efficient water resources and river basin management by formulating pollution control strategies (CCME, 2001b; Tyagi *et al*., 2013; Barceló-Quintal *et al*., 2013; Sargaonkar & Deshpande, 2003).

Determination of WQI is a very reliable, useful and efficient way for assessing and communicating the information on the overall quality of water (Gibrilla *et al*., 2011; Barceló-Quintal *et al*., 2013). WQI estimation helps in deciding the suitability of surface water sources for their intended use by humans, aquatic and wildlife (CCME, 2001a). WQI can also be used to assess water quality relative to its desirable state defined by water quality objectives and to provide insight into the degree to which water quality is affected by human activity. Though most indices measure the same attributes of deviation from objectives, there are various ways of determining WQI for evaluating water bodies intended for different uses (Wills & Irvine, 1996). Some of them being used worldwide are: Canadian Council of Ministers of the Environment (CCME) WQI, Weighted Arithmetic WQI (CCME, 2001b), National Sanitation Foundation (NSF) WQI (Kaurish & Youno, 2007), Overall Water Quality Index (OWQI), Oregon WQI and others (Tyagi et al., 2013; CCME, 2001b; Poonam et al., 2015).

Weighted arithmetic WQI method, which classifies the water quality according to the degree of purity by using the most commonly measured water quality variables, according to Tyagi *et al*., (2013), makes use of equation (3-5).

$$WQI = \sum QiWi / \sum Wi \text{..................................}(3\text{-}5)$$

The unit weight (Wi) for each water quality parameter is calculated by using equation (3-6).

$$Wi = K/Si \text{..}(3\text{-}6)$$

Where,

K=proportionality constant and can be calculated using the equation (3-7).

$$K = \frac{1}{\sum(1/Si)} \text{..}(3\text{-}7)$$

The quality rating scale (Qi) for each parameter is calculated by using the expression (3-8).

$$Qi = 100[(Vi - Vo/Si - Vo)] \text{..........................}(3\text{-}8)$$

Where,

Vi is estimated concentration of ith parameter in the analyzed water

Vo (ideal value of this parameter in pure water) = 0 (except pH =7.0 and DO = 14.6 mg/l)

Si is the recommended standard value of i^{th} parameter.

NSF WQI has been developed by selecting parameters, developing a common scale and assigning weights and was based upon nine water quality parameters namely: Dissolved Oxygen (DO), BOD, fecal Coliforms, pH, temperature change, total phosphates, nitrates, turbidity and total dissolved solids (Tyagi *et al*., 2013; Wills & Irvine, 1996; Poonam *et al*., 2015) and is given by equation (3-9).

$$WQI = \sum_{i=1}^{n} QiWi \text{...................................}(3\text{-}9)$$

Where,

Qi = sub-index for i^{th} water quality parameter;

Wi = weight associated with i^{th} water quality parameter;

n = number of water quality parameters.

For this NSFWQI method, the ratings of water quality have been defined as excellent (91-100), good (71-90), medium (51-70), bad (26-50), very bad (0-25)

Overall Water Quality Index (OWQI), on the other hand, was developed following the four steps: parameter selection, development of sub-indices function, assignment of weights and aggregation of sub-indices to construct an overall index (Singh *et al*., 2015) and is given by equation (3-10).

$$OWQI = \sum_{i=1}^{n} Wi.Yi \text{..........................}(3\text{-}10)$$

Where,

Wi=weight of the ith water quality parameter

Yi=sub-index value of the ith parameter

In this index, the quality of a water body is classified into five categories: heavily polluted (0-24), poor (25-49), fair (50-74), good (75-94) and excellent (95-100).

The Oregon WQI, according to Cude (2001), has been developed to provide a simple and concise method of expressing and reporting water quality status and trends of WQ dataset so as to enable decision making. The index has taken into account the parameters: Dissolved oxygen, BOD, pH, total solids, ammonia, nitrate, and fecal coliform and were classified according to impairment category: oxygen depletion, eutrophication or the potential for excess biological growth, physical characteristics, dissolved substances, and health hazards (Cude, 2001). The unweighted harmonic square mean formula, as a method of aggregating sub-index results of OWQI, is given by equation (3-11).

$$WQI = \sqrt{\frac{n}{\sum_{i=1}^{n}(1/SI_i^2)}} \qquad (3\text{-}11)$$

where WQI is water quality index result, n is the number of sub-indices, and SI_i is Sub-index i (Cude, 2001; Tyagi et al., 2013).

3.4.1.2 Comparison of the water quality indices

Though NSF, CCME and OWQI are water quality indices which are frequently used for water quality assessment, CCME is the most efficient for low parameter values. General or Overall WQI (OWQI) is an efficient one but parameters here should be carefully selected depending on the source and time. The main drawback of NSF WQI is the eclipsing effect. Due to this effect one or more parameters which have values above permissible limit are masked if the rest of the parameters are within the limits (Poonam et al., 2015). Oregon WQI aids in the assessment only of water quality for general recreational uses (i.e., fishing and swimming). Additionally, it is designed only for Oregon's streams and its application to other regions or waterbody types need a caution (Cude, 2001). Therefore, it is not recruited to evaluate water quality of the study area as the intention was mainly for the betterment of irrigation and drinking water rather than for recreation.

CCME WQI, on the other hand, is flexible with respect to the type and number of water quality variables to be tested, the period of application, and the type of water body (stream, river reach, lake, etc.) tested. The Council's WQI determining formula is used to simplify complex water quality data from streams, rivers and lakes and communicate the results even to a non-technical audience. The index produces a ranking (good, fair, poor, etc.) based on exceedances of objectives for key water quality variables in the watershed (Andrea *et al.*, 2005). Comparison of different WQI methods, Awash River water quality status is found to be better evaluated using the WQI method proposed by CCME due to its easy computation, accessibility and flexibility.

3.4.1.3 Conceptual Framework of CCME WQI

CCME developed a WQI determining formula to simplify complex water quality data from streams, rivers and lakes and communicate the results to both technical and non-technical audience. The index is based on a combination of three factors: scope (number of variables whose objectives are not met), frequency (frequency with which the objectives aren't met) and amplitude (amount by which the objectives are not met) (Tyagi et al., 2013; CCME, 2001a; CCME, 2001b). CCME WQI is given by eqn. (3-12):

$$\text{CCME WQI} = 100 - \frac{\sqrt{F_1{}^2 + F_2{}^2 + F_3{}^2}}{1.732} \quad \text{..........(3-12)}$$

Where,

F_1 (Scope) = Number of variables whose objectives are not met.

F_1= [No. of failed variables/Total no. of variables] *100

F_2 (Frequency) = Number of times by which the objectives are not met.

F_2= [No. of failed tests/Total no of tests] *100

F_3 (Amplitude) = Amount by which the objectives are not met. This can be determined by three steps as follows:

a) excursion= [Failed test value *i* /Objective]-1

b) normalized sum of excursions (*nse*):

$$(nse) = \sum_{i=1}^{n} \frac{\text{excursions}_i}{No\ of\ tests}$$

c) F_3 = nse/(0.01*nse+0.01) is an asymptotic function that scales the normalized sum of excursions from objectives (nse) to yield a range between 0 and 100.

Based on results of this index calculation, which is based on exceedances of objectives for water quality variables, water quality of a water body is ranked into five classes: excellent (95-100), good (80-94), fair (65-79), marginal (45-64), and poor (0-44) (Tyagi et al., 2013; CCME, 2001a; Andrea et al., 2005; CCME, 2001b). Rules that should be taken into consideration while applying the index, according to CCME (2001b), are: index comparisons should only be made when the same sets of objectives and parameters are being used, care should be taken with older data, the index should be run on parameter sets relevant to the water body being tested, and minimal data sets should not be used (CCME, 2001b).

3.4.2 Analysis of water quality by multivariate statistical techniques

Multivariate statistical analysis approaches have, for long, been used to analyze and characterize water quality data. Such approaches have been useful to deal with complex environmental dataset exposed to varying natural and anthropogenic factors and solve the associated problems without misinterpretation. They provide a means of handling large dataset with large number of variables by summarizing the redundancy, as well as reflecting, detecting and quantifying the multivariate nature of ecological data accurately (Hulya and Hayal, 2008; Wang et al., 2007). Principal Component Analysis (PCA) and Cluster Analysis (CA) are specifically useful for considering several related random environmental variables simultaneously, and thus for identifying a new, small set of uncorrelated variables that accounted for a large proportion of the total variance in the original variables (Wang *et al*. 2007).

3.4.2.1 Principal component analysis

Principal Component Analysis (PCA) was applied to sort the variables of water quality indicators, reducing into smaller but key principal (independent) factors or classify the variations of the water quality indicators. PCA is a very effective tool used to reduce the dimension of a data set consisting of a large number of inter-related variables by reducing the contribution of variables with minor significance, while retaining as much variability of the data set as possible and interprets the total variability of the dataset. This is accomplished by transforming the data set into a small number of new set of variables called Principal Components (PCs). The PCs are orthogonal (non-correlated), linear combinations of the originally observed water quality data and are arranged in decreasing order of importance (Shrestha and Kazama, 2007; Singh *et al.*, 2004). The PCs can be expressed by equation (3-13).

$$Z_{ij} = a_{i1}x_{1j} + a_{i2}x_{2j} + a_{i3}x_{3j} + \cdots + a_{im}x_{mj} \qquad (3\text{-}13)$$

where *Z* is the component score, *a* is the component loading, *x* is the measured value of variable, *i* is the component number, *j* is the sample number and *m* is the total number of variables (Muangthong, 2015; Shrestha and Kazama, 2007).

Dataset of 16 water quality monitoring stations, containing 22 parameters monitored monthly over 11 years (2005-2015) were collected from AwBA for the study. Among the 16 stations and the 11 years' data, only 10 stations and 9 years were selected respectively ignoring others due to incompleteness of data. Taking domestic and irrigation water uses into account, which are dominant in the basin, 19 of the 22 parameters were considered. The water quality parameters considered in this analysis, their abbreviations, their units and methods of analysis (following standard methods for the examination of water and wastewater (APHA, 1998)) are summarized in **Table 3-2**. The means of the monthly measured 9-year data-set on the river water quality are summarized in **Table 4-4**.

Table 3-2 Water quality parameters, their units and methods of analysis (Source: APHA)

Parameters	**Abbreviation**	**Units**	**Methods**
Turbidity	Turb	NTU	Turbid metric method
Total solids 105^{O}C	TS	mg/l	Gravimetric method
Total dissolved Solid	TDS	mg/l	Gravimetric method
Electrical Conductivity	EC	µs/cm	Calorimetric method
pH	pH	-	Calorimetric method
Ammonia	NH_3	mg/l NH_3	Aluminon method
Sodium	Na	mg/l Na^+	Flame photometer
Potassium	K	mg/l K^+	Flame photometer
Total Hardness	TH	mg/l $CaCO_3$	Titrimetric method
Calcium	Ca	mg/l Ca^{+2}	Titrimetric method
Magnesium	Mg	mg/l Mg^{+2}	Periodate oxidation method
Total Iron	TFe	mg/l Fe^{+3}	Phenanthroline Method
Fluoride	F^-	mg/l F^-	SPADNS Method
Chloride	Cl^-	mg/l Cl^-	Argentometric Method
Nitrate	NO_3^-	mg/l NO_3^{-2}	Cadmium reduction method
Alkalinity	Alkal	mg/l $CaCO_3$	Titrimetric method
Bicarbonate	HCO_3^-	mg/l HCO_3^-	Titrimetric method
Sulphate	SO_4^-	mg/l SO_4^{-2}	Turbid metric method
Phosphate	PO_4^-	mg/l PO_4^{-3}	Ascorbic acid, Molybdate blue method

3.4.2.2 Cluster analysis

Cluster analysis (CA) is a multivariate procedure which classifies data based on placing of objects into more or less homogeneous groups, in a manner such that the relationship between groups is revealed. The main idea behind clustering is to combine identical sites as one cluster and group, two clusters of highest similarity as a new cluster, which in turn is combined with another most similar cluster as another new cluster and so on until all clusters become one cluster (Xu *et al.*, 2012). Agglomerative Hierarchical Clustering (AHC) is the most common and iterative classification method in which clusters are formed sequentially by starting with the most similar pair of objects and forming higher clusters step by step (Singh *et al.*, 2004). The Euclidean distance, which is used to quantify the similarities or differences between the two sites (sampling locations) i and j, was calculated by formula (3-14).

$$d_{ij}^2 = \sum_{k=1}^{m} (Z_{i,k} - Z_{j,k})^2 \quad \text{...(3-14)}$$

where d_{ij} is the Euclidean distance, $Z_{i,k}$ and $Z_{j,k}$ - variable k for objects i and j respectively, and m is the number of variables (Gibrilla *et al.*, 2011; Singh *et al.*, 2004). The Euclidean distance, according to Singh *et. al.*, 2004, gives the similarity between two samples and a ‘distance’ can be represented by the ‘difference’ between analytical values from both samples.

3.4.2.3 Mann-Kendall trend test

Mann-Kendall trend test is a rank-based and non-parametric statistical test to detect trends and assess the significance of trends in hydro-meteorological time series data such as water quality, streamflow, temperature, and precipitation. This non-parametric test is also documented to be more suitable and powerful for detecting trends of non-normally distributed and censored data (Yue *et. al*., 2002; H.S. Xu *et. al*, 2012) such as that of ARB. To avoid the influence of streamflow on water quality, only quality data of the same season should be analyzed over some time period. In this regard, seasonal Mann-Kendall trend test has been useful for non-parametric trend analysis of water quality over time. It can be used in place of the parametric linear regression analysis, which requires that the residuals from the fitted regression line be normally distributed. Basically, it separately calculates the test statistics and variance of water quality data in each season and then overall statistics is calculated (H.S. Xu *et. al*, 2012).

Letting x_1, x_2, . . . , x_n, to be a sequence of measurements over time, it is proposed to test the null hypothesis, *Ho*, that the data come from a population where the random variables are independent and identically distributed (Hipel, and McLEOD, 1994). The alternative hypothesis, H_1, is that the data follow a monotonic trend over time. Under H_o, the *Mann-Kendall test statistic* is given by equation (3-15).

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sgn(x_j - x_k) \quad \text{.................................(3-15)}$$

$$\text{where, sgn(x)} = \begin{cases} +1, & x > 0 \\ 0, & x = 0 \\ -1, & x < 0 \end{cases}$$

and S is asymptotically normally distributed and gave the mean and variance of *S*, for the situation where there may be ties in the *x* values, by equation (3-16).

$$E[S]=0$$

$$\text{Var[S]}= \left\{n(n-1)(2n+5) - \sum_{j=1}^{p} t_j(t_j - 1)(2t_j + 5)\right\}/18 \ldots \text{ (3-16)}$$

where *p* is the number of tied groups in the data set and tj is the number of data points in the j^{th} tied group.

When using eqn. 3-15, a positive value of S indicates that there is an upward trend in which the observations increase with time. On the other hand, a negative value of S means that there is a downward trend. Because it is known that S is asymptotically normally distributed and has a mean of zero and variance given by eqn. 3-16, one can check whether or not an upward or downward and is significantly different from zero. If the S is significantly different from zero, based upon the available information *Ho* can be rejected at a chosen significance level and the presence of a monotonic trend, *H1,* can be accepted (Hipel, and McLEOD, 1994). The multivariate statistical techniques were employed here to sort out the variables of water quality parameters and sampling stations.

3.5 Land use/land cover and change detection

3.5.1 Causes of land use/land cover change and image capturing

Land-use/land-cover: Land-cover is the observed biophysical cover of the earth’s land surface and is composed of patterns that occur due to a variety of natural and anthropogenic processes. Land-use, on the other hand, is human utilization of the land, influenced by socio-economic, cultural, political, historical, and land-tenure factors (Rozenstein & Karnieli, 2011).

Causes for land use/land cover change: Land-use and land-cover change means a change in the biophysical cover of the earth’s land surface and are influenced by a variety of biophysical and societal factors operating on several spatial and temporal levels. Biophysical influences include: climate, landform, geology, soils, hydrology, vegetation, and fauna while societal factors are those relating to population structure and dynamics, income and affluence, technology, socio-economic organization, culture, institutions, and political systems, demand for land, land-use patterns and their change (Briassoulis, 2009). Land-cover characterization and definition of land-use through observations of the land-cover is often made possible by remotely-sensed data (aerial imagery or earth observing satellites using their sensors’ capturing information remotely) (Rozenstein & Karnieli, 2011).

Image capturing techniques and sensors: Land Use and Land Cover data of different spatial (5, 15, 30, 90, …, meter), spectral (500-12500 nm), radiometric and temporal resolution needed for change detection and other analyses are captured from sensors remotely. Remote sensing is the science (and to some extent, art) of acquiring information about the earth's surface without actually being in contact with it. Nowadays, Landsat data are widely applied for land-use classification on a regional scale owing to their relatively lower cost, longer history, and higher frequency of archives in comparison to other remote-sensing data sources as MODIS 200m, Quick bird 0.5m, Aster 15m, Spot 5m, and others (Rozenstein & Karnieli, 2011).

Landsat types and characteristics: Landsat (LS) satellites have continuously acquired space-based images of the Earth's land surface since 1972 when Thematic Mapper (TM) on board Landsat-1 was launched but terminated its operations on January 6, 1978. The launches of Landsat 2, Landsat 3, and Landsat 4 followed in 1975, 1978, and 1982, respectively and their respective dates of functional termination were on January 22, 1981, March 31, 1983 and 1993. While Landsat-5 has been launched in 1984, Landsat-7 has been launched in 1999 but Landsat 6 failed to achieve orbit in 1993. Recently in 2013, Landsat 8, has been launched and continued the mission. Landsat 9, is expected to be launched in 2020. They have been providing data that serve as valuable resources for land use/land cover change researches. The data gathered by these satellites are useful to a number of applications including forestry, agriculture, hydrology, geology, regional planning, and education.

Currently, two of the Landsat sensors in orbit are operational: TM on board Landsat-5 and Enhanced Thematic Mapper Plus (ETM+) on board Landsat-7. Both of the sensors acquire measurements in all major portions of the solar electromagnetic spectrum (visible, near-infrared, and shortwave-infrared).

3.5.2 Land use/land cover classification

Automatic classification of remote sensing images is more suitable for mapping land-use in a large area than manual digitization of land-use patches as it is extremely tedious and subjective. However, when automatically classifying a complex landscape from remote-sensing imagery, it is challenging to achieve an accurate classification. This is because automated classification techniques do not possess the superior pattern recognition capabilities of the human brain though land-use and land-cover patterns may be obvious to an image interpreter (Rozenstein & Karnieli, 2011). There are two types of classification: supervised and unsupervised ones, the efficiency of which is dependent on accuracy assessment. There are two types of map accuracy assessment: positional and thematic. Positional accuracy deals with the accuracy of the location of map features, and measures how a spatial feature on a map is far from its true or reference location on the ground. Thematic accuracy deals with the labels or attributes of the features of a map, and measures whether the mapped feature labels are different from the true feature label (Jensen & Lulla, 1987).

3.6 SWAT model

Application of SWAT to assess the impact of land use on water resources in the horn of Africa, in which the study area is located, is well documented by Baker & Miller (2013). Their assessment showed that changes in land use have resulted in an increase in surface runoff, decrease in groundwater recharge and correspondingly hydrologic changes were highly variable both spatially and temporally (Baker & Miller, 2013). Additionally, SWAT is found to be a promising model for continuous and long-term simulations of all major components (hydrology, sediment, and chemical) in predominantly agricultural watersheds (Borah & Bera 2003). The model is applicable to semi-arid and similar environments where there is limited number of gauge stations (Kiros et al., 2015) like that of ARB.

The SWAT model used here is of a release version 2012 and a version number identifying the executable file rev. 632 released on 09 September 2015. The four basic inputs for the model were prepared as follows.

3.6.1 Input data acquisition and preparation

The basic data sets required to simulate the SWAT model as prerequisites included: meteorological data; topography (DEM); soil properties; and vegetation or land use and land cover data. Others usually considered as inputs are hydrological and hydraulic data (including river discharge gage data and water quality data) as well as land management practices undertaken in a basin (Neitsch et al. 2011). The SWAT model has limitations of not explicitly allowing for inclusion of spatial data as model inputs. Dataset need to be processed into a form that the model can use. Processing these data, even with the help of GIS, is tedious and time consuming due to the large number of model parameters required to run the model. The spatial variation of the outputs of the model was visualized making use of SWAT output viewer software of version 0.1.

3.6.1.1 Hydro-meteorological Data

Climate in a basin gives the moisture and energy that controls the water balance and determines the relative importance of different components in the hydrologic cycle (Neitsch et al., 2002). The climate data needed by the model include daily values of: precipitation, maximum and minimum temperature, relative humidity (required only if either Penman-Monteith or Priestley-Taylor methods are used to calculate evapo-transpiration (Gassman et al., 2007)), sun shine hour (solar radiation) and wind speed (only necessary if the Penman-Monteith method is used for ET determination) of the 20 stations (Neitsch et al., 2011).

These daily meteorological datasets for the required weather stations (for 1/1/1994-12/31/2014) in the study area were gathered from the National Meteorological Service Agency (NMSA). Some data were also captured from the global weather database (http://globalweather.tamu.edu/) of Texas A&M University Climate Forecast System Reanalysis (CFSR) to fill the missing parts as recommended by Dile & Srinivasan, (2014) and Fuka et al., (2013). Then the data is formatted in such a way that it can be fed to the SWAT model.

The observed data (though not complete) on flow for the period 1972 – 2009 (though the time period for all the gaging stations were not uniform) were collected from the hydrology and water quality department of Federal Ministry of Water, Irrigation and Energy (MoWIE) of Ethiopia. Shape files and all the GIS data were gathered from the GIS department of the MoWIE.

For all the 20 stations **Figure 3-15**, a summary of the monthly average values of all the 14 parameters [TMPMX (average maximum air temperature for month (°C)), TMPMN (average minimum air temperature for month (°C)), TMPSTDMX (standard deviation for maximum air temperature in month (°C)), TMPSTDMN (standard deviation for minimum air temperature in month (°C)), PCPMM (average amount of precipitation falling in month (mm H_2O)), PCPSTD (standard deviation for daily precipitation in month (mm H_2O), PCPSKW (skew coefficient for daily precipitation in month (mm H_2O)), PR_W1 (probability of a wet day following a dry day in month), PR_W2 (probability of a wet day following a wet day in month), PCPD (average number of days of precipitation in month), RAINHHMX (extreme half-hour rainfall for month (mm H_2O)), SOLARAV (average daily solar radiation for month ($MJ/m^2/day$)), DEWPT (average daily dew point temperature in month (ºC)), and WNDAV (average daily wind speed in month (m/s))] over the 21 years together with their TITLE (the first line of the .wgn file of 80 spaces reserved for user comments), locations [WLATITUDE (latitude of weather station) & WLONGITUDE (longitude of weather station)], WELEV (elevation of weather station (m)), RAIN_YRS (the number of years of maximum monthly 0.5 h rainfall data) were prepared supported by pcpstat program, filled into the weather generator input file (.WGN) and formatted for input to SWAT. Totally, (14*12+4) *20=3440 entries of an excel sheet have been filled and imported into the database. Likewise, daily dataset of precipitation, maximum and minimum temperature, sun shine hour (solar radiation), relative humidity, and wind speed are prepared according to the format recommended by Neitsch et al., (2002) and Arnold et al., (2012).

3.6.1.2 Topography

Along with soil, meteorology, and land use/land cover data, topography data is one of the main inputs for SWAT. It is used to delineate the watershed and to further divide the watershed into multiple sub-basins and Hydrologic Response Units (HRUs). It calculates the basin's and sub-basins' parameters such as slope and slope length. Resolution of the DEM is too critical to affect the watershed delineation, stream network, and sub-basin classification in the model. It affects the number of sub-basins and HRUs, which in turn affects the predicted sediment yield for a watershed (Gassman et al., 2007; Bingner et al., 1997). A decrease in DEM resolution leads to a decrease in stream flow and watershed area. Since the runoff volume and total sediment load depends on the watershed area, the decrease in the DEM resolution resulted in large error in the predicted output. Input DEM data resolution affected SWAT model predictions by affecting total area of the delineated watershed, predicted stream network and sub basin classification (Chaubey et al., 2005).

Topography data was made available from the Global Land Cover Facility (GLCF) website to prepare Digital Elevation Model (DEM) of the basin. It was of 90-m spatial resolution (because of the vast spatial extent of the study area) and obtained from the Shuttle Radar Topography Mission (SRTM) of paths 44 and 45 and rows 10 and 11 (http://www.landcover.org/data/srtm/). This DEM was used as input for the model from which the flow direction, flow accumulation, stream length, outlet selection, watershed discretization and delineation were determined.

3.6.1.3 Soil Data

Two files, the soil input file (.sol) (the required physical properties) and the soil chemical input file (.chm) (information on the optional chemical properties) contain the soil properties used by SWAT. The soil input file, defining the physical properties and initializing chemical quantities for all layers in the soil, governs the movement of water and air through the profile and have a major impact on the cycling of water within the HRUs. The soil chemical input file, initializing additional chemical quantities for the first soil layer, sets initial levels of the different chemicals in the soil (Neitsch et al., 2002).

Variables in the soil input file of the model include: soil name (SNAM), soil hydrologic group (A, B, C, or D) (HYDGRP), maximum rooting depth of soil profile (mm) (SOL_ZMX), fraction of porosity (void space) from which anions are excluded (ANION_EXCL), crack volume potential of soil (SOL_CRK), texture of soil layer (TEXTURE), depth from soil surface to bottom of layer (mm) (SOL_Z), moist bulk density (Mg/m^3 or g/cm^3) (SOL_BD), available water capacity of the soil layer (mm H_2O/mm soil) (SOL_AWC), saturated hydraulic conductivity (mm/hr) (SOL_K), % organic carbon content (SOL_CBN), % clay content (CLAY), % silt content (SILT), % sand content (SAND), % rock fragment content (ROCK), moist soil albedo (SOL_ALB), USLE equation soil erodibility (K) factor (units: 0.013 (metric ton m^2 hr)/(m^3-metric ton cm)) (USLE_K), and electrical conductivity (dS/m) (SOL_EC) (Neitsch et al., 2002).

ARB is covered by fourteen (as shown by **Figure 3-12**) of the 28 major soil groups in the legend of soil map of the world (FAO/UNESCO): Luvisols, Leptosols, Vertisols, Fluvisols, Nitosols, Regosols, Cambisols, Acrisols, Andosols, Arenosols, Gleysols, Phaeozems, Solonchaks, and Gypsisols (Xerosols and Yermosols). The general characteristics of only major soil groups in the basin is presented briefly as follows (Driessen et al., 2001; FAO et al., 2012; Engida, 2010).

Leptosols: Very shallow soils over hard rock or in unconsolidated very gravelly material mostly located at medium-high altitude and strongly dissected topography. They are found in all climatic zones, in particular in strongly eroding areas. By and large, they are free draining and have low water holding capacity.

Vertisols: are dark-coloured cracking and swelling deep clay soils that expand upon wetting and shrink upon drying. They are found in level to undulating terrain with distinct wet and dry periods. They are poorly drained and largely have good water holding capacity.

Fluvisols: These are young soils developed in fluvial, alluvial, lacustrine or marine deposits and are common along rivers and lakes, in floodplains and deltaic areas. Fluvisols in upstream parts of river systems are normally confined to narrow strips of land adjacent to the actual riverbed. In the middle and lower stretches, the flood plain is wider and has the classical arrangement of levees and basins, with coarsely textured fluvisols on the levees and more finely textured soils in basin areas further away from the river. Fluvisols on river levees are porous and better drained than those in low landscape positions.

Regosols: are soils in unconsolidated material without significant evidence of soil formation. They are particularly common in mountainous regions associated with Leptosols. They are well-drained and medium-textured soils with lower water holding capacity.

Cambisols: are soils at an early stage of soil formation. They exhibit different characteristics depending on the environmental setting in which they are developed. However, most cambisols are medium-textured soils with high porosity, good water holding capacity and internal drainage.

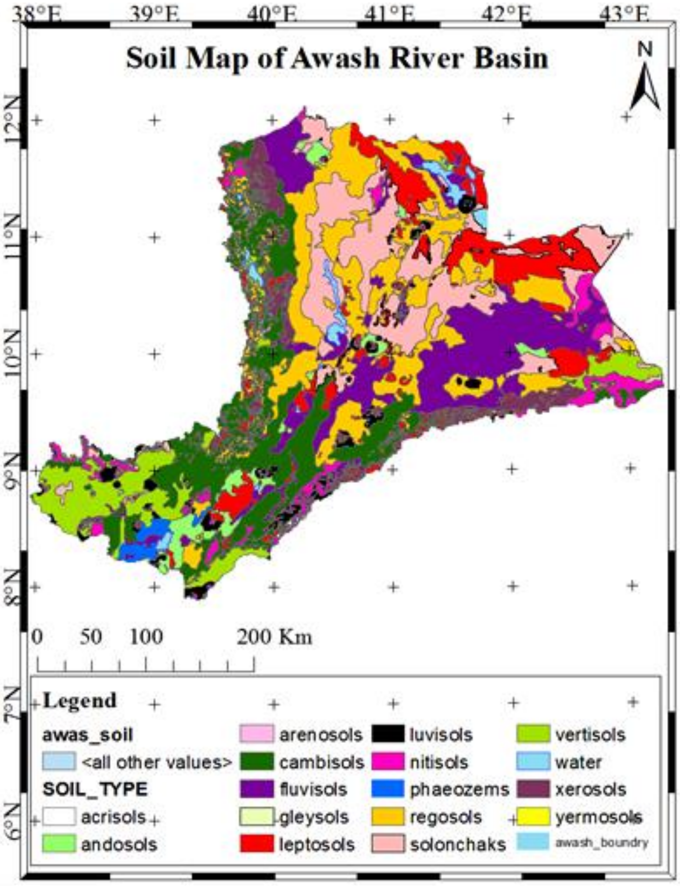


Figure 3-12 Soil Map of the Study Area by Soil Type

Arenosols: consists of sandy soils developed either in residual sands or in recently deposited sands as occur in deserts and beach lands. They exist in all climatic regions extending from extremely cold to extremely hot. Arenosols are permeable to water and depending on the grain size distribution and organic matter content, the Available Water Storage Capacity (AWC) may be as low as 3 to 4 percent or as high as 15 to 17 percent. They have relatively high bulk density and their saturated hydraulic conductivity and infiltration vary. Arenosols in *humid temperate* or *tropical* regions are deeply leached and contain little or poorly decomposed organic matter. *Solonchaks*: includes soils that have a high concentration soluble salts. are largely confined to the arid and semiarid climatic zones and to coastal regions in all climates notably in seasonally or permanently waterlogged areas with grasses and/or halophytic herbs, and in poorly managed irrigation areas where evapo-transpiration is considerably greater than precipitation. *Solonchaks* with extreme salinity and thick surface crusts occur in depressions that collect water from surrounding (higher) land in the winter but dry out in the warm season. The *salic* soil horizon of *solonchaks* has an electrical conductivity value in excess of 15 dS/m at 25ºC at some time of the year.

Xerosols and *Yermosols* (are merged as Gypsisols in the revised legend of soil map of the world): are mostly of unconsolidated alluvial, colluvial or aeolian deposits of base-rich weathering parent materials. They are soils with substantial secondary accumulation of gypsum ($CaSO_4.2H_2O$). They are found in the driest parts of the arid climate zone where the natural vegetation is sparse and dominated by xerophytic shrubs and trees and/or ephemeral grasses like that of the study area. The typical Gypsisol has 20 to 40 cm of yellowish brown, loamy or clayey surface soil over a pale brown subsurface soil with distinct white gypsum pockets and/or pseudo-mycelium. Saturated hydraulic conductivity values vary from 5 to >500 cm/d. Infiltration of surface water is almost zero in severely encrusted soils. Higher gypsum contents (>25 %) upset the nutrient balance and lower the availability of essential plant nutrients, which in turn harm plants.

Therefore, the soil data requirement for the SWAT model was prepared from the FAO/UNESCO Digital Soil Map of the World, which is too large in resolution to fetch the detail information regarding soil of the study area and is given by **Figure 3-13**. It was first cut by the study area's shape file and conversion of vector into raster and vise-versa is undertaken. It is of 1:5,000,000 scale FAO/UNESCO digital soil map of the world.

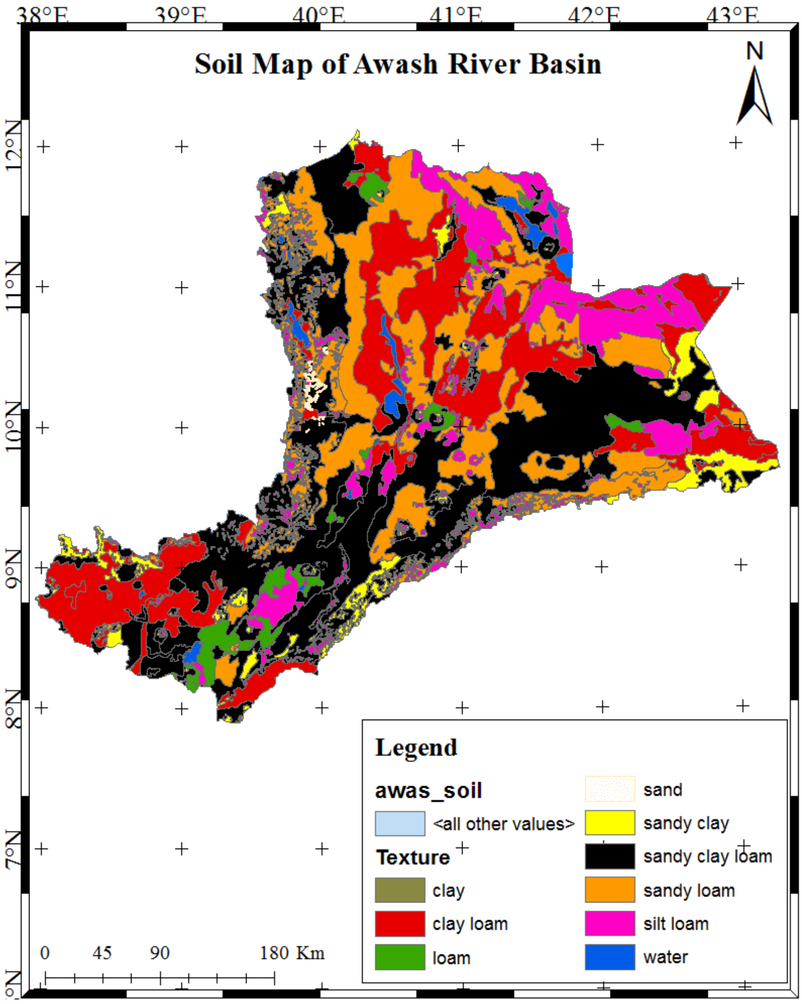


Figure 3-13 Soil Map of ARB by Texture

In addition to soils' properties fetched from FAO soil, additional characteristics of soil required to set up the SWAT model such as soil saturated hydraulic conductivity, bulk density, soil available water content and texture class of each soil type class at different soil depths were determined using the Soil Plant Air Water (SPAW) Hydrology model as depicted in **Figure 3-14**. SPAW hydrology is a daily hydrologic budget model for agricultural fields and ponds (wetlands, lagoons, ponds and reservoirs). It also Includes irrigation scheduling and soil nitrogen while its data input and results are graphical screens. This SPAW hydrology program characterizes the soil and water in the terrain. Soil water characteristics, soil texture (percentages of clay and sand) and percentage of organic carbon content were fed as an inputs by the SPAW model and the soil characteristics such as texture class, wilting point, field capacity and saturation in percent by volume, available soil water, saturated hydraulic conductivity and bulk density were computed.

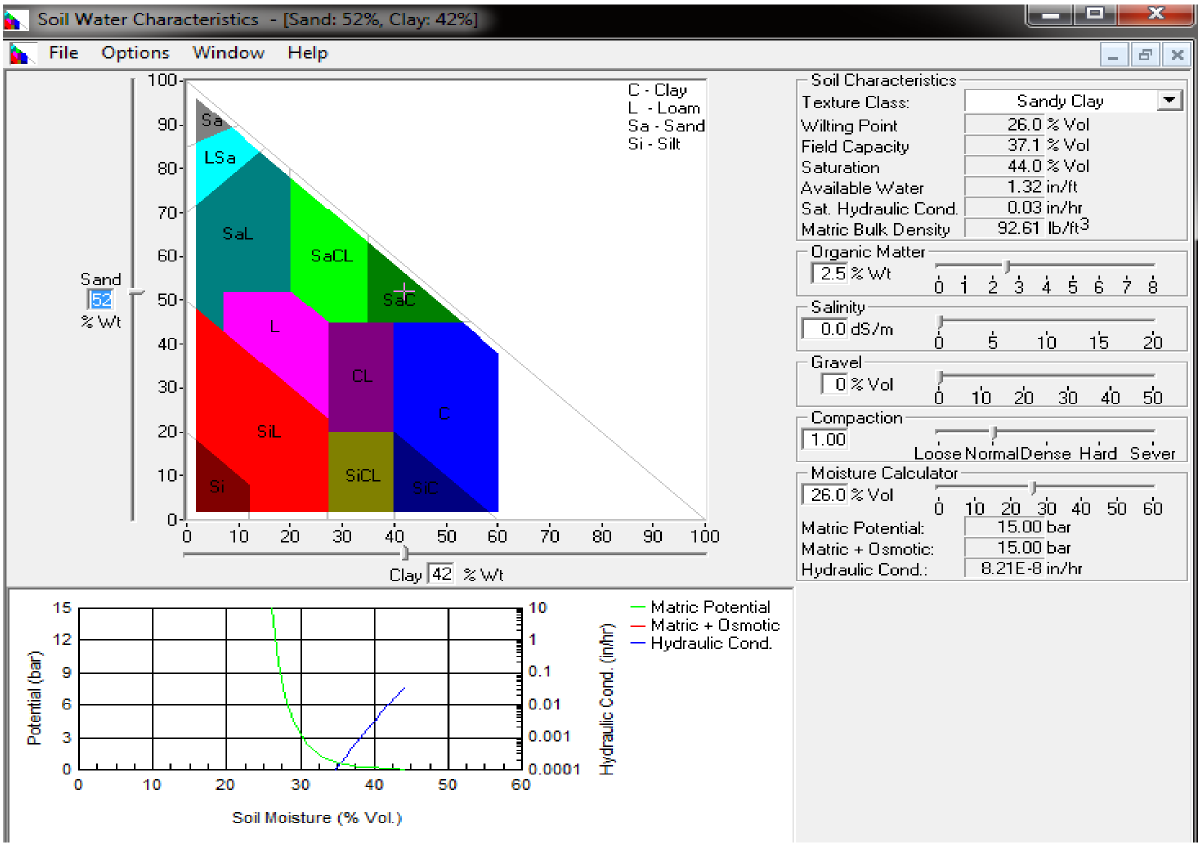


Figure 3-14 Print screen of the SPAW hydrology model

3.6.1.4 Land use/land cover

The source for LULC data was Earth Resources Observation and Science (EROS) Center of U.S. Geological Survey (USGS) Global Visualization (GloVis) Viewer (http://glovis.usgs.gov/). From the site, three years' (1994, 2000 and 2014) Landsat Thematic Mapper cloud-free Imagery of eight scenes to cover the study area were downloaded. The scenes were of respective paths and rows: 166-53, 167-52, 167-53, 167-54, 168-52, 168-53, 168-54, and 169-54. After layer stacking these images, mosaicking and cutting by the study area shape file, they were made ready for classification.

The 1994 and 2000 images were Landsat 5 but the 2014 images were Landsat 7. The reason why the 1994 images were chosen is to represent the 1990's LU/LC when the governmental transition was observed in the nation (1991), which was associated with a change in economic policy. Likewise, the 2000 images were taken to get the 2000's representation (draught, flood) and the 2014 images were taken to get the recent overview of the basin's LU (2010's). These images were then layer stacked, mosaicked and cut by the study area shape file. Next, their preliminary classifications were performed by supervised classification technique coupled with maximum likelihood classification algorithm.

Verification of the land use

GPS readings of sub-classes of each land use class were collected from different locations of the catchment to be used as training sites for the classification. That is, four different coordinates for five of the land use classes, and five coordinates for the remaining three land use classes were collected to verify the land uses. It is verified using these ground truth data of land use and land cover and being supported by Google Earth. The three years' land use images were then finally classified using maximum likelihood of supervised image classification technique. Lookup table (containing two columns for SWAT_CODE and LANDUSE_ID) for land use of the study area has been prepared and loaded to the SWAT database.

3.6.2 The SWAT project

The fundamental processes embraced in the modeling are: SWAT project setup, watershed delineation, HRU analysis, writing input tables, editing SWAT inputs, and SWAT simulation.

3.6.2.1 SWAT project setup, watershed delineation and HRU analysis

In setting up the SWAT model, pre-processing tasks, such as making map units similar, were carried out before applying the maps in the model. These helped to facilitate overlaying of DEM, Land use, soil and slope maps. Then lookup tables (table for soil containing two columns of SNAM and SOIL_ID and that for land use containing two columns of land use ID and SWATCODE) of the study area have been prepared. Furthermore, soil and land use maps along with their respective prepared look up tables were loaded to the the SWAT database for reclassification according to SWAT coding convention.

The model configuration divided the basin into a number of sub-basin spatial units (about 53). The sub-basin delineation of the study area was made based on the 90m X 90m resolution DEM at a scale of 1:50,000 and matches the available flow and water quality monitoring stations. The DEM was used to determine the slope and flow direction, which is used to determine sub-basin outlets and areas contributing discharge to the outlets.

The sub-basins were further discretized using areas with the same land use, soil types and slope to create the SWAT model computational units that are assumed to be homogeneous in hydrologic response, also called Hydrologic Response Units (HRUs). Each HRU has its own unique parameters that are utilized in the simulation process. The rest necessary spatial datasets and database input files for the ARB SWAT model were all prepared and organized following the guidelines of Neitsch et al. (2001) and Arnold et al., (2012).

3.6.2.2 Writing input tables, editing SWAT inputs, and SWAT simulation

All stations' daily max temp, min temp, precipitation, relative humidity, wind and solar radiation data for all the 21 years are arranged vertically in MS excel containing two columns of date and respective weather data. The userwgn database file is prepared by using the WGNMaker4.xlsm excel macro. This is designed to create user's weather station files, which are used by SWAT's weather generator to fill in the missing information and/or simulate weather data.

Temperature and relative humidity

Then to prepare the SWAT database, the input file storing the maximum and minimum daily temperature [^oC] and the average daily humidity [%] data are made ASCII text files with three columns. The first column stores the maximum temperature data, the second column the minimum temperature data and the third column the average daily humidity data. Since the period of temperature and humidity measurement must start on January 1st and end on December 31st, they are made so. Finally, putting both the text file and the dew02.exe software in a folder, the software is run being fed the file name of the text file as an input (Liersch, 2003a). The program calculates the dew-point temperature of each day by first deriving the saturation vapor pressure from the daily minimum and maximum temperature data.

Precipitation (PCP)

The input file storing the daily precipitation [mm] data is made ASCII text files with a column of rainfall. Since the period of rainfall measurement must start on January 1st and end on December 31st, they are made so. Finally, putting both the text file and the pcpstat.exe software in a folder, the software is run being fed the file name of the text file as an input (Liersch, 2003b). The program generates the *pcp.out* (which gave PCP_MM, PCPSTD, PCPSKW, PR_W1, PR_W2, and PCPD needed by the SWAT database), *totalpcp.sta* and *mean_pcp.sta* files from the daily rainfall data.

Solar Radiation

Since the sunshine hour collected from the meteorological agency is not ready-made for the solar radiation consumption for the model's database, Hargreaves calculation sheet was used to determine solar radiation of each station (Hanief & Laursen, 2017). This program uses elevation, latitude, longitude, minimum and maximum temperatures of the station as inputs corresponding to the respective dates.

Maximum Half Hour Rainfall (RAINHHMX)

The maximum half hour rainfall in the database is calculated following the method described by Arnold and Williams (1989) and stated by equation (3-17). This method uses the assumption that precipitation amounts are exponentially distributed. Either historically recorded daily measured amounts or that estimated by weather generators such as WGEN are input to the model (Arnold and Williams 1989).

$$R_{0.5p} = \alpha_{0.5}R \ldots\text{(3-17)}$$

Where, $R_{0.5p}$ is maximum 0.5 h rainfall amount in mm, $\alpha_{0.5}$ is the parameter that expresses the maximum portion of total rainfall occurring during 0.5 h (dimensionless), and R is total daily rainfall in mm (Arnold and Williams 1989). Supplying 1/3 to the value of $\alpha_{0.5}$, maximum half-hour rainfall (RAINHHMX) of the day could be estimated and RAINHHMX in the entire period of record for the months is taken as being the average of the daily RAINHHMX estimated (Neitsch et al., 2011; Essenfelder, 2016).

Filling the missing data

i. Inverse Distance Weighting (IDW)

One of the main challenges faced in modeling most hydrological processes has been the limited availability of hydro-meteorological data (Dile & Srinivasan, 2014) and ARBa is no exception since the weather data gathered from the national meteorological agency is full of gaps (missing). However, this need to be filled for the model to simulate, for instance in this case, the water quality with the required reliability. To fill missed data of the stations, interpolation technique is used. Spatial interpolation methods offer tools to fulfil the values of an environmental variable at unmeasured sites using data from point observations within the same region (Li and Heap, 2008). Different interpolation methods such as Deterministic methods (Nearest Neighborhood (NN) and triangulation, Inverse Distance Weighting (IDW), Polynomial functions (splines), Linear regression, Artificial Neural Networks (ANN)) and probabilistic methods (Optimum interpolation, and different Kriging types) were reviewed (Sluiter, 2009) to determine the missing relative humidity, solar radiation and wind data of stations such as Hombole, Awash Sheleko, and Cheffa, which were neither principal nor synoptic meteorological stations.

IDW interpolation was used to fill the data gap of the stations since it is found to be fast, easy to implement and easily “tailored” for specific needs and widely used in meteorology (Li and Heap, 2008; Sluiter, 2009). This method explicitly makes the assumption that things that are close to one another are more alike than those that are farther apart. To predict a value for any unmeasured location, IDW uses the measured values surrounding the prediction location. The measured values closest to the prediction location have more influence on the predicted value than those farther away. IDW assumes that each measured point has a local influence that diminishes with distance. That is, it gives greater weights to points closest to the prediction location, and the weights diminish as distance increases hence the name inverse distance weighted. The principle of IDW methods is to assign more weight to nearby points than to distant points (Deraman et al., 2014; Ly et al., 2013). The expression for IDW is:

$$Z(s_0) = \sum_{k=1}^{n} \lambda_k Z(s_k) \text{.........(3-18)},$$

where, $Z(s_0)$ = the value to be predicted for location s_0, n = the number of measured sample points surrounding the prediction location that will be used in the prediction, λ_k = the weight assigned to each measured point to be used, $Z(s_k)$ = the observed value at location s_k.

The classical form of the weight function, λ_k , is:

$$\lambda_k = \frac{h_i^{-p}}{\sum_{j=1}^{n} h_j^{-p}} \ldots\ldots\ldots\ldots(3\text{-}19),$$

where p is an arbitrary positive real number called the power parameter (typically, $p=2$) and h_i=the distance between the station for which data is calculated and the scatter station from which data is used to calculate the unknown, which is determined from the measure toolbar of ArcGIS using the distance formula given by equation (3-20):

$$h_i = \sqrt{(x - x_i)^2 + (y - y_i)^2} \ldots\ldots\ldots\ldots(3\text{-}20),$$

where (x, y) are the coordinates of the interpolation point and (x_i, y_i) are the coordinates of each scatter point. The weight function varies from a value of unity at the scatter point to a value approaching zero as the distance from the scatter point increases. The weight functions are normalized so that the weights' sum is unity (1). Accordingly, interpolation is done taking into account combination of highland and lowland stations relative to the station of interest and the weighting factor, w*i*, is determined as depicted by **Table 3-3**.

Table 3-3 Four stations and their calculated weighting factors by IDW from the neighboring stations

Inter. Stn.	**Hombole**			**Awash Sheleko**		
Sca. Stn	Melkasa	Nazareth	D/Zeit	Gewane	Metahara	Sholla Gebeya
hi (m)	92744	78485	38632	153194	251996	210503
wi	0.12	0.17	0.71	0.2	0.48	0.32
Inter. Stn.	**Teji**			**Cheffa**		
Sca. Stn	Hombole	Addis	D/Zeit	Majete	Gewane	
hi (m)	68280	46625	65101	38282	118173	
wi	0.24	0.51	0.26	0.91	0.09	

ii. **Global weather database (TAMU) Climate Forecast System Reanalysis (CFSR)**

Though different studies have used satellite and different statistical methods to improve the quality of conventional meteorological data, the global weather data generator called Climate Forecast System Reanalysis (CFSR) of the National Centers for Environmental Prediction (NCEP) of TAMU is found to handle such an incomplete data soundly. It can reliably be used as inputs in place of the traditional land-based weather station data (Fuka *et al*., 2013; Dile & Srinivasan, 2014; Tolera et al., 2018). They concluded that CFSR-derived data could well predict stream flow and other hydrological processes deficient with data because of the fact that these data are averaged over areas comparable to watershed areas they tested. Though

CFSR data solely is proved not to be recommendable especially for small watersheds, it is advantageous for comprehensive watersheds and for filling longer gaps in conventionally recorded weather data (Roth and Lemann, 2016).

After capturing the weather data from global weather database site, it is corrected using the fixweather application. This program is used to look for weatherdata-*.csv files in the folder in which it is run and within each of these files it searches for missing dates and then assigns records of -99's for these missing days. Then the usual interpolation technique using the IDW method is applied to estimate the data gaps of some stations. Weather data of global stations from both uplands and lowlands (in the vicinity) of the stations of interest (Erer, Ayisha, Asaita, Mile, Shewarobit, and Sholagebeya) were used to calculate the missing data. Only these out of the 20 stations are chosen as their data gaps (missing) were more than 25% of the total. Since one grid of latitude 10.15^0 and longitude 40.63^0 lies exactly on Gewane, some of its weather values were used to fill the missing parameters of the station at Gewane.

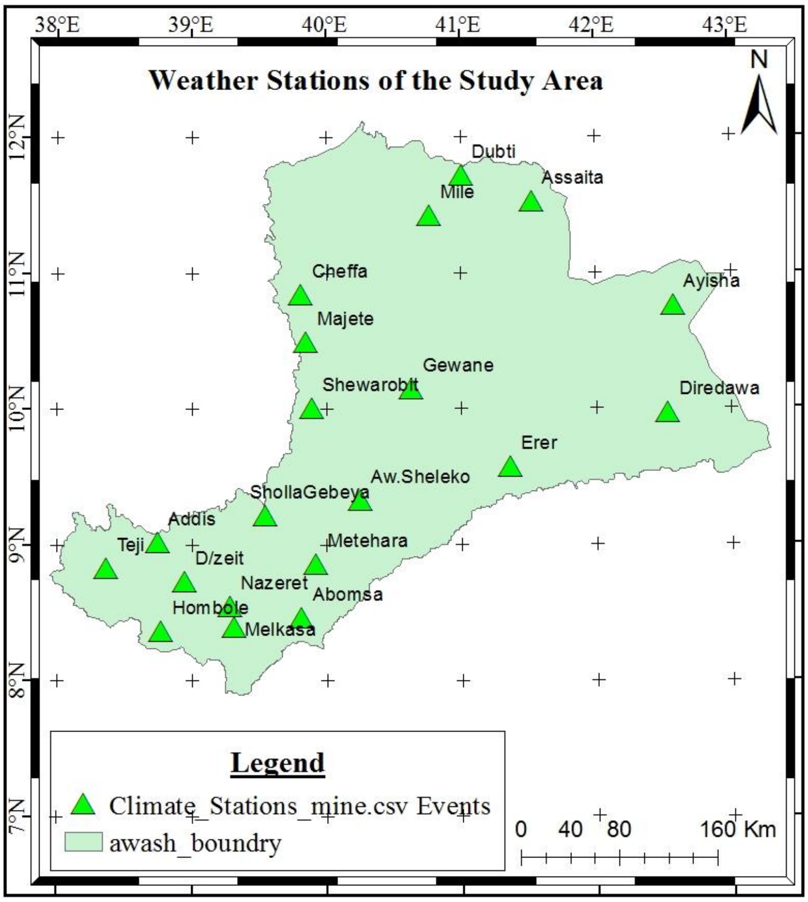


Figure 3-15 Weather stations considered in simulating the model (Source: own)

3.7 SWAT model performance evaluation

Performance of hydrological models need to be evaluated: a) to examine improvements to the modeling approach through adjustment of model parameter values, model structural modifications, the inclusion of additional observational information, and representation of important spatial and temporal characteristics of the watershed; b) to get a quantitative estimate of the model's ability to reproduce historic and future watershed behavior; and c) to compare current modeling efforts with previous study results (Krause et al., 2005).

The software that was used for evaluating performance of the SWAT model was a public domain computer program called SWAT Calibration and Uncertainty Programs (SWAT-CUP), version 5.1.6. It has been developed in the Swiss Federal Institute of Aquatic Science and Technology (Eawag) (Abbaspour, 2009). The program is capable of linking each of the Sequential Uncertainty FItting Version 2 (SUFI2), Particle Swarm Optimization (PSO), Generalized Likelihood Uncertainty Estimation (GLUE), Parameter Solution (ParaSol), and Markov Chain Monte Carlo (MCMC) procedures (algorithms) to SWAT outputs. They enable sensitivity analysis, calibration, validation, and uncertainty analysis of SWAT model results (Abbaspour, 2015). Here in SWAT-CUP, users can manually adjust parameters and ranges iteratively between auto-calibration runs (Arnold et al., 2012).

The logical procedure suggested by literature is followed for calibrating SWAT outputs. Hence first and foremost hydrology is calibrated then water quality parameters. In this study, it is to the SUFI2 procedures of SWAT-CUP program that SWAT 2012 outputs were linked for calibration to see the overall performance in the program. This is because SUFI2 procedures enable sensitivity analysis, calibration, validation, and uncertainty analysis of the SWAT model results. It is practically impossible to include all pollutant sources as it is difficult to represent all components of the system in the modeling effort (Engel et al., 2007). Therefore, only nitrate and phosphate were considered here as pollutants of interest because they are causes for freshwater eutrophication which in turn have effects of increased growth of algae and aquatic weeds that interfere with the use of water for fisheries, recreation, industry, agriculture, and drinking and consequently loss of aquatic bio-diversity (Carpenter et al., 1998).

Pruning (validation) of flow data

Mostly, performance evaluation of watershed modeling projects involves comparison of model output to the corresponding measured data with the assumption that all errors are contained within the predicted values and that observed values are error free. However, measured data are practically not error free (Moriasi et al., 2007). Therefore, before calibrating the simulated result, value of the Relative Error (RE) was calculated to see the extent to which the observed data is close to the seasonal expectations and simulated one. The RE, which is used to check the monthly observed data, is given by equation (3-21).

$$RE = \frac{O_i - P}{O_i} * 100 \quad ...(3\text{-}21)$$

The calculation has shown the error for some of the months to be above tolerable limit, i.e., greater than 20%. This was indicating the fact that the simulated one were somehow far from the observed ones for the respective months. Hence, before the observed data is used for calibration, it is prunned with repect to the rainfall data.

3.7.1 Sensitivity analysis

Hydrologic and water quality models usually involve a large number of adjustable parameters the impact of which on selected model outputs is thus investigated with the help of Sensitivity Analysis (SA) so as to measure the performance. SA is used mainly to quantify the strength of the relationships between model inputs and outputs or it determines the extent to which model outputs are changed with respect to changes in model inputs (parameters) and decreases the number of parameters for the calibration procedure by eliminating the parameters identified as not sensitive (Arnold et al., 2012; Yuan et al., 2015; Abbaspour et al., 2017). The sensitivity of various outputs of the SWAT model are determined specifically by different specialized parameters. For instance, important parameters for surface runoff are curve number (CN2), available water capacity of the soil layer (AWC), soil evaporation compensation factor (ESCO), plant uptake compensation factor (EPCO).

On top of that, while the organic P settling rate in the reach at 20°C, rate constant for mineralization of P to dissolved P, fraction of algal biomass that is phosphorus, phosphorus percolation coefficient, and phosphorus soil partitioning coefficient are influential for phosphorus loss, the rate constant for hydrolysis of organic N to NH_4^+ in the reach at 20°C, nitrate percolation coefficient, and denitrification threshold water content are influential parameters for nitrogen loss (Yuan et al., 2015).

SA, in general, is the process of determining the rate of change in model output with respect to changes in model inputs (parameters). There are two types of sensitivity analyses. These are global and local sensitivity analyses.

a) Global sensitivity analysis: In global or all-at-a-time (AAT) sensitivity analysis, sensitivities of parameters are determined by calculating the multiple regression system, which regresses the Latin hypercube generated parameters against the objective function values in the file goal.txt as:

$$g = \alpha + \sum_{i=1}^{m} \beta_i b_i \dots \dots \dots (3\text{-}22)$$

A *t*-test is used to identify the relative significance of each parameter, *bi*. The sensitivities given above are estimates of the average changes in the objective function resulting from changes in each parameter, while all other parameters are changing. Here, the larger, in absolute value, the value of t-stat, and the smaller the p-value, the more sensitive the parameter. This global sensitivity analysis has a limitation that it needs a large (500–1000 or more, depending on the number of parameters and procedure) number of simulations to see the impact of each parameter on the objective function (Abbaspour, 2007; Abbaspour et al., 2017; Arnold et al., 2012).

b) Local sensitivity analysis: Local or one-at-a-time (OAT) sensitivity analysis shows the sensitivity of a variable to changes in a parameter if all other parameters are kept constant. The drawback of this approach is that it is not capable of showing what the value of those other constant parameters should be, which need to be considered as sensitivity of one parameter is dependent on the value of the other (Abbaspour et al., 2017). On the other hand, *OAT* design is an example of an integration of a local to a global sensitivity method. It is a technique that falls under the category of screening methods. In the OAT sensitivity analysis, each model run involves perturbation of only one parameter in turn. This way, the variation of model output can be unambiguously attributed to the perturbation of the corresponding factor. The output analysis is based on the study of the random sample of observed elementary effects, which are generated from each considered input (Mengistu, 2009).

3.7.2 Calibration and validation

Calibration and validation are basic processes used to show that hydrologic and water quality models can produce suitable results in a particular application and need to be undertaken before using the result in research and real-world applications (Guzman et al., 2015; Moriasi et al., 2012). SWAT, being semi-physically based model, need calibration and validation tools for its outputs (Arnold et al., 2012). In hydrologic and water quality models like SWAT, calibration (parameter optimization) is a process in which the model is adjusted so that the model predictions better represent site-specific processes and conditions or it refers to a procedure where the difference between model simulation and observation are minimized (Abbaspour et al., 2017). It is done by selecting model parameter values carefully, adjusting them within their recommended ranges, and comparing predicted output variables with observed data for a given set of conditions (Daggupati et al., 2015). In calibration, model parameters are optimized to increase accuracy or reduce model prediction uncertainty (Arnold et al., 2012).

On the other hand, validation (V) is the process of demonstrating that a given site-specific model is capable of making sufficiently accurate simulations, though this sufficient accuracy may vary based on project goals (Moriasi et al., 2007). It is used to build confidence in the calibrated parameters. Hence, the calibrated parameter ranges are applied to an independent measured dataset of different time period, without changing the parameter values. Doing one iteration with the same number of simulations as in the last calibration iteration is required to see applicability of the model (Abbaspour et al., 2017).

These model calibration and validation are measured by p-factor, r-factor and objective functions such as: Coefficient of determination (R^2), Nash-Sutcliffe Efficiency (NSE), and RMSE-observations standard deviation ratio (RSR), which are described as follows.

Coefficient of determination (R^2): indicates the strength of the relationship between observed and simulated values as in eqn. (3-23). It describes the proportion of the variance in measured data explained by the model. R^2 ranges from 0 to 1, with higher values indicating less error variance, and typically values greater than 0.5 are considered acceptable (Moriasi et al., 2007).

$$R^2 = \frac{\left[\sum_{i=1}^{n}\left(O_i - \bar{O}\right)\left(P_i - \bar{P}\right)\right]^2}{\sum_{i=1}^{n}\left(O_i - \bar{O}\right)^2 \sum_{i=1}^{n}\left(P_i - \bar{P}\right)^2} \dots\dots\dots\dots\dots\dots\dots \text{(3-23)}$$

where, O_i, $\bar{O}$, P_i and $\bar{P}$ are respectively the i^{th} observation, the mean of observed data, the i^{th} simulated (predicted) value, and the mean of predicted data for the constituent being evaluated.

Nash-Sutcliffe Efficiency (NSE): The Nash-Sutcliffe efficiency (NSE) is a normalized statistic that determines the relative magnitude of the residual variance ("noise") compared to the measured data variance ("information"). NSE indicates how well the plot of observed versus simulated data fits the 1:1 line (Moriasi et al., 2007). NSE is computed by equation (3-24).

$$NSE = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i-1}^{n}\left(O_i - \bar{O}\right)^2} \dots\dots\dots\dots\dots\dots\dots \text{(3-24)}$$

Where, O_i is the i^{th} observation for the constituent being evaluated, P_i is the i^{th} simulated (predicted) value for the constituent being evaluated, $\bar{O}$ is the mean of observed data for the constituent being evaluated, and n is the total number of observations.

RMSE-observations standard deviation ratio (RSR): To explicitly qualify the low value of RMSE recommended by Singh et al. (2004) for good model performance, Moriasi et al. (2007) developed RSR that standardizes RMSE using the observations standard deviation, and it combines both an error index and additional information as scaling/normalization factor for the resulting statistic and reported values can apply to various constituents. RSR varies from the optimal value of 0 to a large positive value. The lower RSR, the lower the RMSE, and the better will be the model simulation performance. RSR is calculated as the ratio of the RMSE and standard deviation of observed data, as shown by equation (3-25) (Moriasi et al., 2007).

$$\mathbf{RSR} = \frac{\mathbf{RMSE}}{\mathbf{STDEV_{obs}}} = \frac{\sqrt{\sum_{i=1}^{n}(O_i - P_i)^2}}{\sqrt{\sum_{i=1}^{n}\left(O_i - \overline{P}\right)^2}} \text{..........(3-25)}$$

Where, Where, O_i is the i^{th} observation for the constituent being evaluated, P_i is the i^{th} simulated (predicted) value for the constituent being evaluated, $\overline{P}$ is the mean of predicted data for the constituent being evaluated, and n is the total number of observations.

Performance evaluation criteria for the recommended statistical performance measures for watershed-scale models as formulated by Moriasi et al., 2007 and Moriasi et al., 2015 were indicated by **Table 3-4**.

Table 3-4 General performance ratings for the recommended statistics for a monthly time step

Objective function	Output Response	Performance Ratings			
		Very good	Good	Satisfactory	Unsatisfactory
R^2	Streamflow	$0.85 < R^2 \leq 1.0$	$0.75 < R^2 \leq 0.85$	$0.60 < R^2 \leq 0.75$	$R^2 \leq 0.60$
	N, P	$R^2 > 0.70$	$0.60 < R^2 \leq 0.70$	$0.30 < R^2 \leq 0.60$	$R^2 \leq 0.30$
RSR	Streamflow N, P	$0 \leq RSR \leq 0.50$	$0.50 < RSR \leq 0.60$	$0.60 < RSR \leq 0.70$	$RSR > 0.70$
NSE	Streamflow	$0.80 < NSE \leq 1.0$	$0.70 < NSE \leq 0.80$	$0.50 < NSE \leq 0.70$	$NSE \leq 0.50$
	N, P	$NSE > 0.65$	$0.50 < NSE \leq 0.65$	$0.35 < NSE \leq 0.50$	$NSE \leq 0.35$

adopted from both Moriasi et al., (2015) & Moriasi et al., (2007)

Calibration and validation of flow and water quality are typically performed with data collected at the assumed outlet of the basin. The basin outlet for this study is assumed to be a sampling site located at Dubti to which approximately about 80% of the entire basin drains (**Figure 4-15**).

The dataset used as observed for calibration and validation of the simulated nutrients is generated from the monthly analyzed water quality result of eight years (2006-2013). The first 5 years' data was utilized for calibration while that of the remaining 3 years' was set for validation. The concentrations of NO_3^- and PO_4^{2-} in mg/l were converted into mg/m^3; the flow in m^3/s is changed into m^3/month; and then the mass (mg/m^3) is multiplied with the flow

(m^3/month) and finally the resulting mass (in mg/month) is converted into kg/month since it was the monthly run model (of loads in kg) which was required to be calibrated. The snapshot below illustrates print screen of the sample of the excel calculation of mineral phosphorus mass for month 1, 2006 and the mass of nitrate was similarly computed.

	G	H	I	J	K	L	M	N
1	Month	Cal/Val format	mg/l	mg/m3 (=I2*1000)	flow (m3/s)	flow (m3/m) (=K2*2592000)	Mass (mg) (=J2*L2)	Mass (kg) (=M2*10^-6)
2	1	PO4_OUT_1_2006	0.84	840	53.94	139812480	1.17442E+11	117442.4832

Alternatively, the dataset for calibration and validation of the two nutrient loads could identically be generated, according to Smarzyńska & Miatkowski (2016), from the monthly discharge and water quality data related by equation (3-26).

$$L = \sum_{t=1}^{t=T} \left(86.4\overline{Q_t}C_t^I\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3\text{-}26)$$

where: L = NO_3^- and PO_4^{2-} loads, kg; C_t^I = mean monthly NO_3^-/ PO_4^{2-} concentrations, mg/l; $\overline{Q_t}$ = mean monthly discharge, m^3/s; t = time, months.

3.7.3 Uncertainty analysis

Uncertainty originates from the fact that almost all measurements are subject to some error, models are simplifications of reality, and the inferences are usually statistical (Abbaspour et al., 2017). The conceptual model uncertainty (structural uncertainty) could be due to: a) simplifications in the conceptual model, b) processes occurring in the watershed but not included in the model, c) processes that are included in the model, but their occurrences in the model are unknown to the modeler, and d) processes unknown to the modeler and not included in the model either. Specifically, in SUFI-2, parameter uncertainty accounts for all sources of uncertainties such as uncertainty in driving (input) variables, conceptual model, parameters, and measured data. Input uncertainty is due to errors in input data such as rainfall, and more importantly, extension of point data to large areas in distributed models like SWAT (Abbaspour, 2015). Parameter uncertainty is usually caused as a result of inherent non-uniqueness of parameters in inverse modelling. Parameters represent processes. The fact that processes can compensate for each other gives rise to many sets of parameters that produce the same output signal (Abbaspour, 2015).

The degree to which all uncertainties are accounted for (model output uncertainty) is quantified by a measure referred to as the *P-factor*, which is the percentage of measured data bracketed by the 95% prediction uncertainty (95PPU) band. The percentage of data captured (bracketed) by the prediction uncertainty is a good measure to assess the strength of our uncertainty analysis (Abbaspour et al., 2007). The other measure quantifying the strength of a calibration/uncertainty analysis is the *R-factor*, which is the average thickness of the 95PPU band divided by the standard deviation of the corresponding measured data (Abbaspour, 2009).

The goodness of fit and the degree to which the calibrated model accounts for the uncertainties are assessed by the above two measures. Theoretically, the value for *P-factor* ranges between 0 and 100%, while that of *R-factor* ranges between 0 and infinity. A *P-factor* of 1 and *R-factor* of zero is an ideal simulation that exactly corresponds to measured data, which can be attained with no uncertainty at all but in practice lots of uncertainties are faced in modeling. The degree to which we are away from these numbers can be used to judge the strength of our calibration. A larger *P-factor* can be achieved at the expense of a larger *R-factor*. Hence, often a balance must be reached between the two. In the final iteration, when acceptable values of *R-factor* and *P-factor* are reached, then the parameter uncertainties are taken as the desired (calibrated) parameter ranges (Abbaspour, 2013).

Chapter 4 Results and Discussion

4.1 Evaluation of water quality in Awash River basin

4.1.1 Comparison of upper basin water quality parameters with drinking and irrigation water quality standards

Before the index was calculated the water body, variables, and appropriate objectives have been defined. Though the time period chosen depends on the amount of data available, here dataset of two years has been used since data from different years can be combined when monitoring in certain years is incomplete (CCME, 2001a; CCME, 2001b). Looking at the averages (Av) overall sites of each parameter, those which failed to meet the WHO DWQG (S), according to WHO (2011, 2017), were turbidity, DO, BOD, COD, Pb, Fe, Mn, NH_3, Cu, TH, ECo and TC in the UB as depicted by **Figure 4-1 (a) and (b)**. Those that are not in harmony with the FAO irrigation water quality guideline, according to Ayers & Westcot (1985), were TN, K^+, SO_4, Mn, NH_3, Cu, Mg, TH, ECo and TC in the UB.

4.1.2 Determination of WQI and status of Awash River in the upper basin

Temperature, DO, NO_2^- and TH were excluded while calculating WQI and evaluating the status for irrigation as their guideline values were not available. The calculation of WQI in the UB was done assuming values of TNTC of fecal and total coliforms to be 270 each while nil in the MLB was assumed to be zero. In the calculation of amplitude (F3), the objectives of ECo and TC were assumed to be 1 to prevent an infinity excursion though the actual standard was 0. The only parameters in **Table 4-1** considered in the index calculation were those for which the WHO, FAO or US EPA guidelines were specified. The three factors F1, F2, and F3 determining the CCME WQI and the resulting indices were computed for drinking and agricultural uses. The factors in this sub-basin got the respective values of 39.29, 42.31 and 97.08 for drinking and 36, 27.72 and 80.97 for irrigation uses. The drinking and irrigation WQIs for the basin, which were computed using equation (**3-12**), were found respectively to be 34.79 and 46.39 (**Table 4-3**).

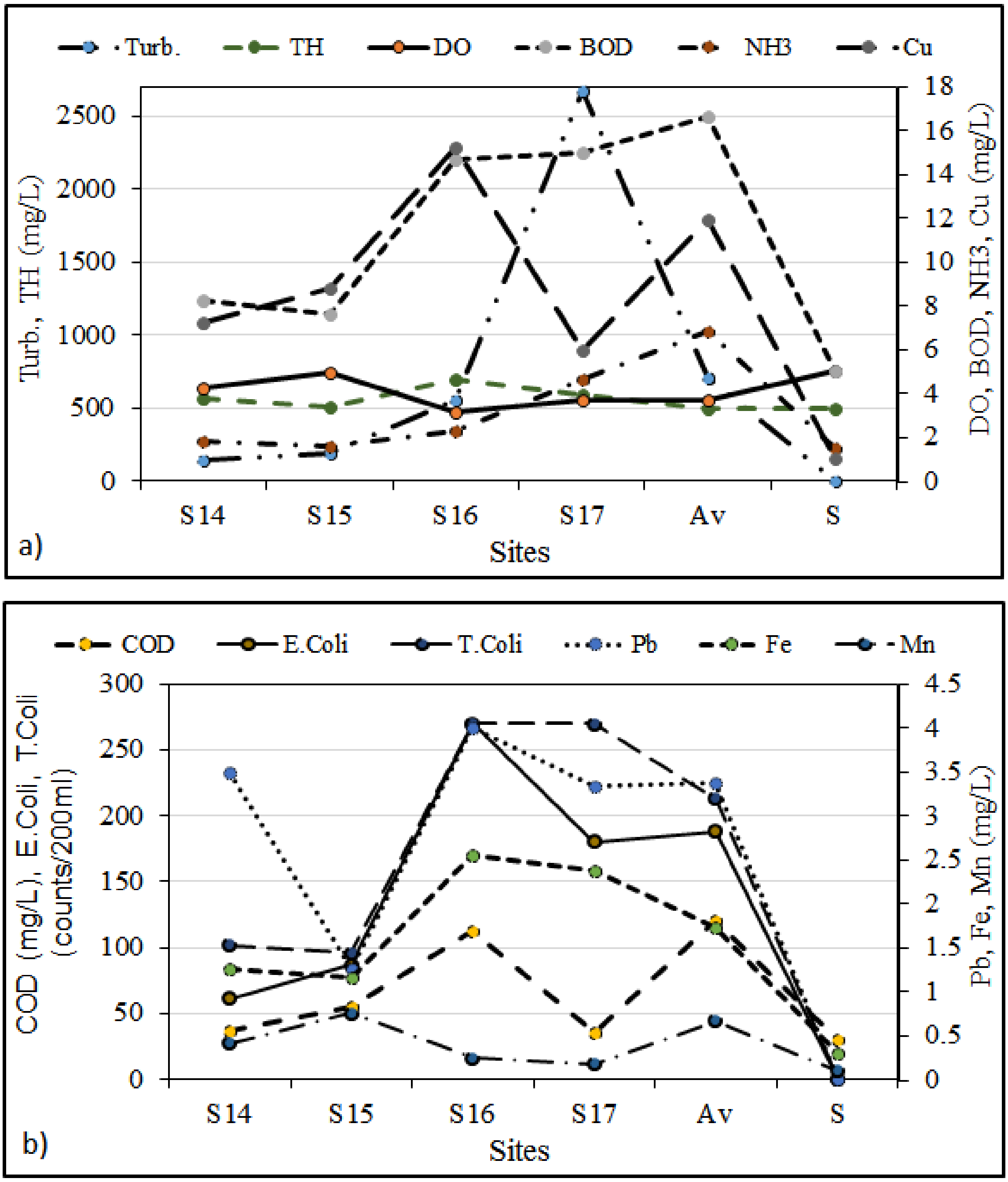


Figure 4-1 Parameters in the four sites of the UB exceeding the DWQG (S)

4.1.3 WQI and status of Awash River in the middle and lower basins

Since guideline values for TS and SAR were not available, these parameters were excluded from the calculation of drinking WQI. For the same reason, TS, TH and NO_2^- were ignored in the calculation of irrigation WQI (**Table 4-2**). The total number of tests was reduced by two as there were two no data values of CO_3^{2-} for the tenth and eleventh sites. Taking average values of water quality parameters for the two seasons (dry and wet) in the sub-basins, the three factors

Table 4-1 Mean values of water quality parameters in the six sites of UB[2]

Par.	S14	S15	S16	S17	G1	G2	Par.	S14	S15	S16	S17	G1	G2
Turb.	**149**	**185**	**556**	**2675**	4	2	SO_4^{2-}	25.1	23.7	24.86	21.3	250	20
pH	7.25	7.46	7.12	7.41	6.5-8.5	8.5	Fe	**1.25**	**1.15**	**2.55**	**2.37**	0.3	5
Temp.	22.8	23.3	22.9	20.4	15-30	**NS**	Mn	**0.41**	**0.75**	**0.24**	**0.17**	0.1	0.2
TDS	169	163	219	167.9	1000	2000	F^-	0.71	0.8	0.59	0.41	1.5	1
EC	338	323	437	335.6	1500	3000	NH_3	**1.8**	**1.56**	**2.26**	**4.62**	1.5	5
DO	**4.21**	**4.92**	**3.13**	**3.67**	>5	**NS**	Cu	**7.2**	**8.8**	**15.2**	**6**	1	0.2
BOD	**8.23**	**7.59**	**14.7**	**14.98**	<5	<10	Cl_2	0.11	0.1	0.12	0.5	5	10
COD	**36.4**	**54.8**	**112**	**35.2**	<30	<60	Cl^-	20.3	18.6	14.3	25	250	355
Pb	**3.5**	**1.25**	**4**	**3.33**	0.01	5	Ca	98.9	104	163	153	200	400
Zn	0.05	0.05	0.03	0.07	4	2	Mg	78.6	59.1	69.4	50.9	150	61
Cr	0.02	0.02	0.03	0.03	0.05	0.1	TH	**569**	**502**	**691.8**	**590**	500	**NS**
TN	2.36	3.44	11.64	6.2	55	5	Alk.	143	138	180	184	400	750
K^+	6.68	5.57	8.17	4.02	20	2	ECo	**61.6**	**86.6**	**TNTC**	**180**	0	<10
NO_3^-	11.5	7.5	19.48	3.39	50	30	TC	**102**	**96**	**TNTC**	**TNTC**	0	<50
NO_2^-	0.07	0.04	1.07	0.06	3	**NS**							

The sites: S14= Awash River after Lake Koka, S15= Awash River at Koka Dam, S16= Awash River before Lake Koka, S17= Awash River at Awash Melka Kuntire, G1= WHO & US EPA Drinking Water Quality Guidelines (DWQG), G2= FAO Irrigation Water Quality Guidelines (IWQG), TNTC= Too Numerous To Count, and NS= No Standard, Bold numbers=parameters violating DWQG, and Red numbers=those parameters violating the IWQG

F1, F2, and F3 determining the CCME WQI were computed for the respective water uses, drinking and irrigation. Accordingly, their respective values were found to be 60, 33.16 and 95.25 for drinking and 57.14, 24.44 and 17.14 for irrigation uses. As a result, the drinking and irrigation WQIs for the basin were computed using equation (3-12) and were found respectively to be 32.25 and 62.78 (**Table 4-3**).

Looking at the averages (Av) overall sites of each parameter, those which failed to meet the WHO DWQG (S), according to WHO (2011, 2017), were TH, Na, F^-, alkalinity, and PO_4^- in the MLB as depicted by **Figure 4-1 (a) and (b)**. Those that are not in harmony with the FAO irrigation water quality guideline, according to Ayers & Westcot (1985), were Na, F^-,

[2]All parameters, except Turbidity, EC, Temperature, pH, ECo and TC, were expressed in mg/L. Turbidity, EC and Temperature were measured respectively by NTU, µS/cm, and °C; ECo and TC both in counts/100ml; while pH is unit less

alkalinity, HCO_3^-, PO_4^-, and SAR in the MLB. The drinking and irrigation WQIs in both UB and MLB were respectively in the poor and marginal categories of the Canadian water quality classification except that in the MLB the irrigation quality index (62.78) approaches to fair as compared to the UB.

Comparison among sites within the UB showed that S16 (Awash River just before Koka dam) had higher values of almost all parameters than S17 (Melka kuntire) (**Figure 4-1, Figure 4-2** and (**Table 4-1**), i.e, as one goes from uplands to downstream, except turbidity, BOD, TC and NH_3, all have shown increasing trends. This may be attributed to effluents discharged from tanneries, oil mill factories, slaughterhouses and poultry farms around Mojo town (discharging their raw effluent directly into the Mojo river-a tributary of Awash), similar wastes of Addis Ababa city (through Great and Little Akaki Rivers, which in turn converge to Abasamuel-another tributary of Awash) and that of the nearby rural areas concentrated by floriculture and other industrial establishments (Degefu *et al*., 2013).

However, some others such as COD, Fe, ECo, and TC were observed to decrease in the way from the 16^{th} to the 14^{th} site. Comparison among sites within the MLB also indicates some variation with exceptional peaks especially of EC, TDS, and alkalinity at S9 and S12 (Lake Beseka and Sodere hot spring respectively) (**Figure 4-2** & **Figure 4-3 (a)**).

The graphical representations of the spatial variation of the determining parameters indicate clearly why domestic water quality decreases as one goes from upper to downstream sub-basins and why the opposite is true for irrigation water quality.

Abundance of nutrients in the UB is expected from the ground truth that agricultural activities using intensive nutrients are pronounced more in the UB than that in the downstream basins. Hardness, as expected, is higher in the UB since ground water is being utilized and released into the River and the discharge of greywater, full of Ca and Mg, from urban centers can potentially raise hardness.

Table 4-2 Mean values of water quality parameters in the two dry and two wet months of the middle and lower basins (MLB) of the Awash River

Par	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**	**S11**	**S12**	**S13**	**G1**	**G2**
TDS	327.7	505.4	569.4	580.7	559.2	610.6	804.7	933.9	2275	240.7	520.0	1445	229.0	1000	2000
TS	722.9	1855	1793	2577	6233	1689	859.8	1457	3621	812.4	704.0	1514	456.0	**NS**	**NS**
NH_3	0.9	1.7	1.4	1.3	2.5	1.7	3.7	1.4	1.3	1.0	0.9	0.7	1.0	1.5	5.0
TH	**663.0**	**959.0**	**737.0**	**713.0**	**610.5**	435.0	100.0	**520.5**	437.0	**1071**	**664.0**	**635.0**	**686.5**	500.0	**NS**
Na	104.4	153.9	**210.6**	182.3	180.4	**251.2**	**290.3**	**423.2**	**1279**	55.6	188.0	**557.5**	44.6	200.0	220.8
Ca	31.6	32.3	31.4	29.4	27.6	28.0	27.1	27.2	8.6	34.1	30.4	20.7	30.5	200.0	400.0
Mg	7.3	9.3	10.5	8.6	7.3	6.3	6.8	8.7	3.2	6.7	3.4	9.2	7.0	150.0	61.0
F^-	0.7	1.3	**2.2**	**2.3**	**2.7**	**2.3**	**2.7**	**2.6**	**2.2**	1.3	**2.4**	**5.3**	**1.6**	1.5	1.0
Cl^-	57.9	107.8	92.4	102.8	108.1	153.6	211.1	171.3	211.0	55.0	80.3	181.1	47.3	250.0	355.0
NO_2^-	0.0	0.0	0.1	0.1	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.0	0.1	3.0	**NS**
NO_3^-	0.2	0.8	0.7	1.0	1.1	2.0	3.2	1.3	2.8	0.5	2.9	1.3	4.3	50.0	30.0
Alk.	**655.0**	**692.5**	**916.5**	**903.0**	**1217**	**827.0**	**506.0**	**827.5**	**1292**	**647.0**	**805.0**	**1188**	**572.0**	500.0	750
EC	593.7	944.4	1040	1097	980.8	1115	1370	1437	3823	435.8	915.0	2201	405.5	1500	3000
CO_3^{2-}	10.6	10.0	30.9	37.0	102.7	106.3	101.9	85.9	493.0	**ND**	**ND**	288.0	6.8	250.0	180
HCO_3^-	252.2	370.1	434.6	401.2	375.4	457.5	436.8	470.3	982.0	310.2	896.7	1111	334.6	580.0	518.5
PO_4^{2-}	**2.3**	**22.5**	**9.7**	**8.3**	**0.8**	**4.5**	**0.4**	**6.7**	**3.4**	**7.6**	**4.5**	**0.8**	**5.6**	0.0	2.0
SAR	4.4	6.3	8.3	7.5	7.9	11.7	12.9	17.6	98.3	2.3	8.6	25.7	1.9	**NS**	15.0
RSC	2.3	4.02	5.73	5.64	7.6	9.12	8.65	8.5	31.8	**ND**	**ND**	26	3.6	**NS**	7.5

Where the sites, S1= Dubti, S2= Adaitu, S3= Meteka, S4= Office area, S5= Weir site, S6= Awash water supply, S7= Awash fall, S8= After Beseka, S9= Lake Beseka intake, S10= Before Beseka, S11= Mix of Sodere & Awash, S12= Sodere spring, and S13= Wonji, G1= WHO & US EPA DWQG, G2= FAO IWQG, ND= No Data, NS= No Standard, Bold numbers=those violating DWQG, and Red numbers=those parameters violating the IWQG.

Table 4-3 WQIs for domestic and irrigation water uses and status of Awash River

Water Use	Zone	Calculated WQI	Status (With Reference to CCME WQI)
Domestic Water Use	UB	34.79	Poor
	MLB	32.25	Poor
Irrigation Water Use	UB	46.39	Marginal
	MLB	62.78	Marginal

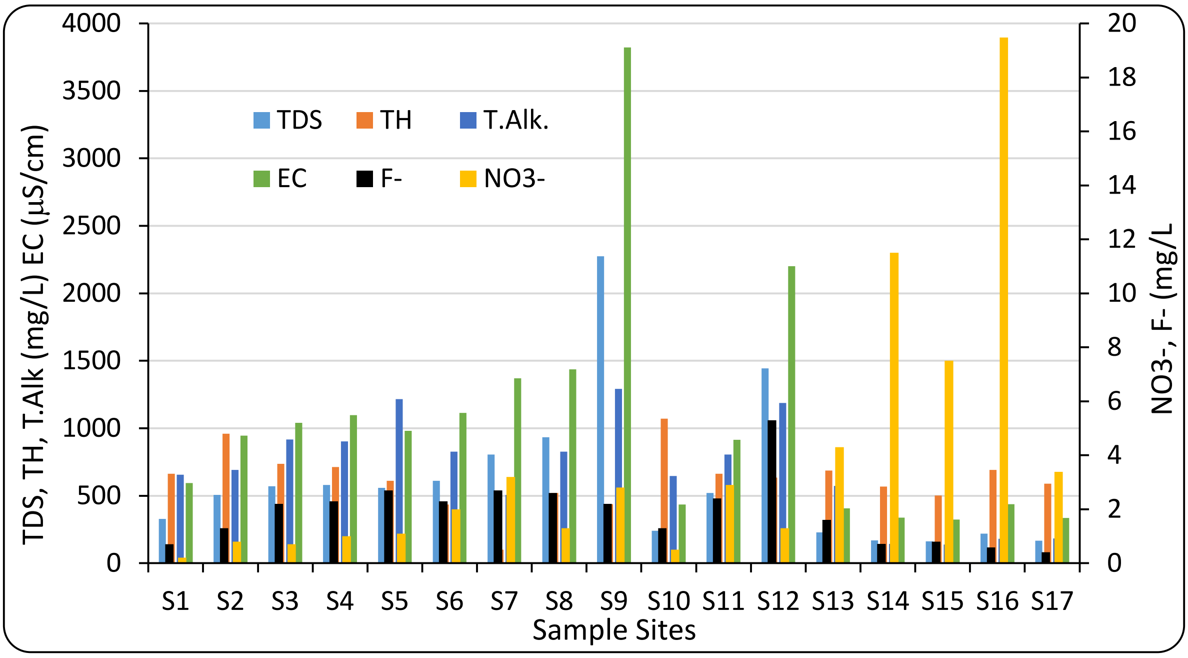
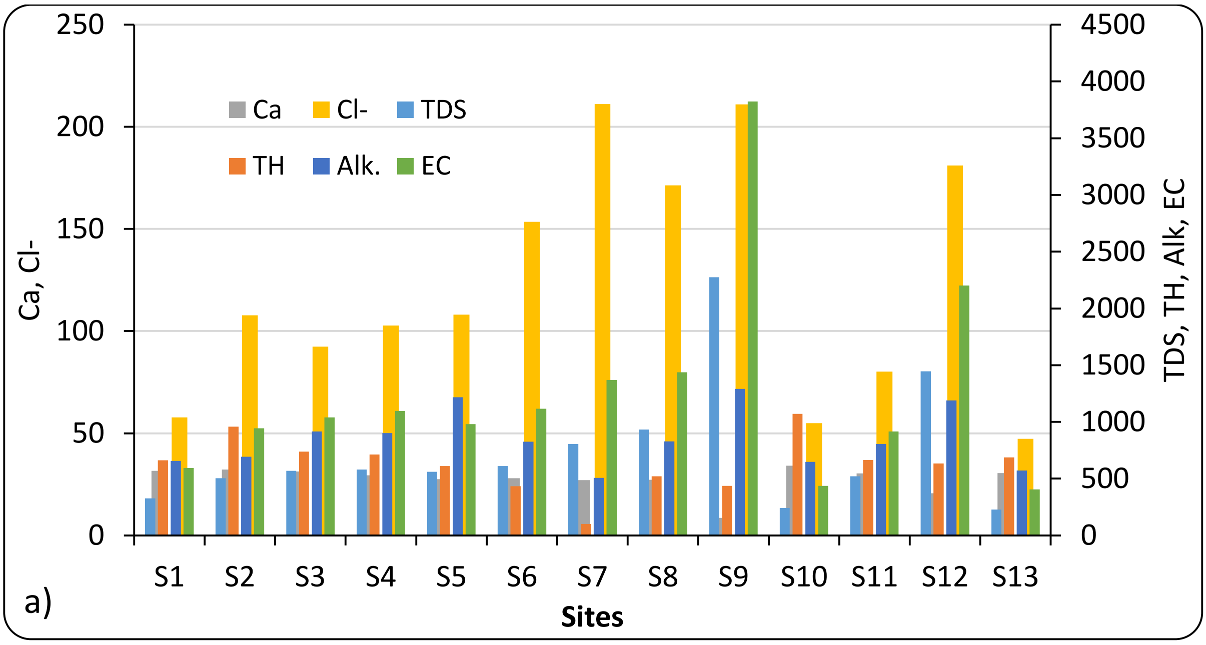


Figure 4-2 Spatial variation of some parameters in the basin



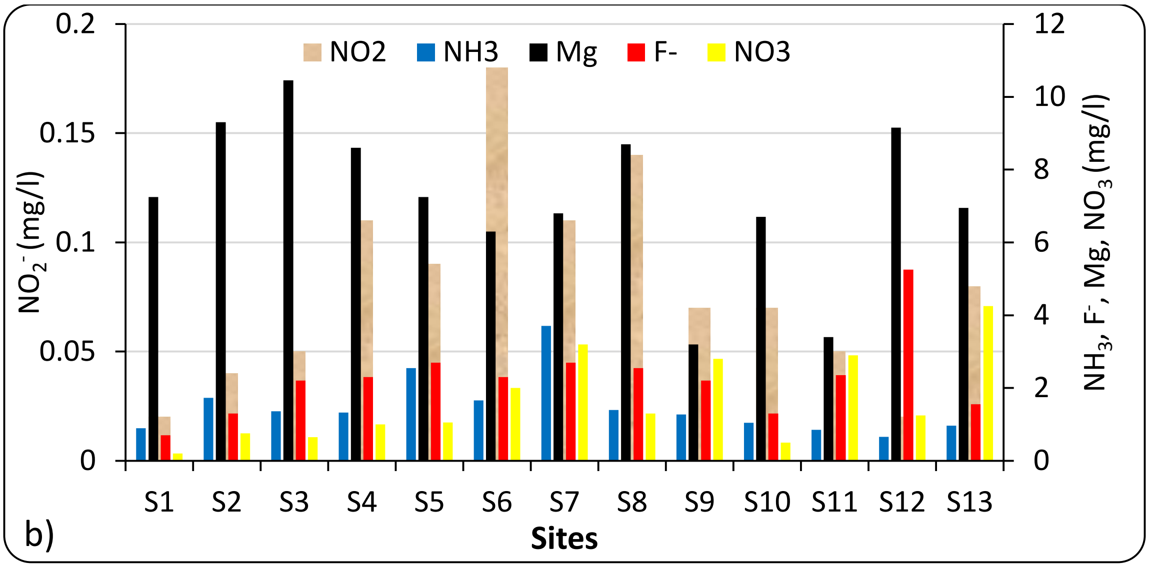


Figure 4-3 Spatial variation of water quality variables (both a & b) in the MLB

The water quality status for irrigation use in the MLB seems to have significantly been improved from that of the post-Addis UB. This might be attributed to the natural purification process in the course of the River and the release of relatively smaller amount and less polluted effluent in the MLB. Though it may be difficult to compare due to the fact, for instance, that the bacteriological parameters like ECo and TC having significant impact weren't considered in the MLB, it can clearly be seen from **Figure 4-2** that the upper basin's waste is being stabilized at Lake Koka (S15) after attaining peak values at the 16th site (just before Lake Koka). Alemayehu *et al*., (2006) also found out that the domestic water quality status seems to have been deteriorated more in the MLB than that in the UB. This might be the impact of the hydro-geochemical nature of the downstream sub-basin, which includes part of the Ethiopian rift valley (Dinka, 2017).

On the other hand, the value of SAR for sites S8, S9 and S12, which were respectively After Beseka, Lake Beseka and Sodere spring, exceeded the FAO guideline and hence these water bodies were found not to fit for irrigation unless some intervention is exercised at these hotspots. Similarly, RSC for sites S5, S6, S7, S8, S9, and S12 was greater than 7.5 and hence these sites were found to be unfit for irrigation while only S1 and S2 were shown to lie respectively in the fit and marginal ranges (**Table 4-2**). This finding is supported by the conclusions of Dinka, (2017) and Alemayehu *et al*., (2006), who reported that Lake Beseka's and other rift valley lakes' salinity, sodicity and alkalinity were too high to affect the River.

Means of the commonly analyzed 11 variables (TDS, EC, NO_3^-, NO_2^-, NH_3, F^-, Cl^-, Ca, Mg, TH and alkalinity) were compared between the UB and MLB and between sites in each sub-basin as shown by **Figure 4-2** and **Figure 4-3 (a)** & **(b)**. The comparison showed that TDS, EC, F^-, Cl^-, and alkalinity were greater in the MLB than that in the UB. However; NO_3^-, NO_2^-, NH_3, Ca, Mg, and TH showed higher values in the UB than that in the downstream. This is in agreement with that studied by Dinka *et al*., (2015), which may be due to the fact that the upper basin is relatively more dominated by agro-chemicals and hardness. The former is consistent with the fact that the water from Sodere hot spring and Lake Beseka is of exceptionally high TDS and EC values and to previous studies such as that conducted by Reimann *et al*., (2003) and Halcrow (1989) indicating high fluoride concentration in Awash valley.

4.2 Investigation of the spatial and temporal surface water quality dynamics in Awash River basin

Testing normality of the data using MS XLSTAT and SPSS, except turbidity, TS, NH_3, TFe, pH and Mg, all the parameters were not normally distributed. This is justified by the significant values of both Kolmogorov- Smirnov and Shapiro-Wilk tests which are relatively large (> 0.05) for the normal ones but close to zero for the rest. However, transformation into normality, according to Singh *et. al*., 2004, increases the influence of variables whose variance is small, reduces the influence of those whose variance is large and also eliminates the influence of different units of measurement thereby making the data dimensionless. Therefore, eight of these non-normal ones; EC, Na, K, F^-, Cl^-, NO_3^-, SO_4^-, and PO_4^- are transformed to normal by Box-cox (Osborne, 2010) variable transformation of the software (XLSTAT). While TDS is standardized using a combination of logarithmic and inverse transformation, Ca and TH are transformed respectively by cubing (x^3) and squaring (x^2) their values (Cook & Wheater, 2005) using IBM SPSS Statistics 20. Alkalinity is transformed by Rv.T functions and special variables under random numbers function group of SPSS but HCO_3^- is normalized by inverse transformation. After transforming, their normality is checked by XLSTAT and all are then found to conform to normality.

In the raw water quality dataset, there were a number of variables containing missing values, which may either be due to imperfect data entry, equipment error, loss of sample before analysis or incorrect measurements. But they are ignored while calculating the mean. Some censored data such as 'nil' and 'trace' were also identified in the dataset, which are also treated as non-contributing for the mean and then the desired multivariate statistical analyses are done on all the remaining dataset.

The original whole dataset is computed by spearman rank-order correlation to study the correlation structure between variables to account for non-normal distribution of water quality parameters (Shrestha and Kazama, 2007). From the resulting correlation matrix of **Table 4-5**; TS, TDS and EC are highly correlated with each other while Ca, Mg and TH are observed to show a similar correlation to each other as expected. The table also clearly shows that Na, Cl, Alkal and PO_4^{2-} are strongly correlated with K, TS, TDS and EC. On the other hand, variables which highly correlate to HCO_3^- like TDS, EC, Na, Cl, and alkalinity do also the same to SO_4^- while HCO_3^- and alkalinity are similarly correlated to TDS, EC, Na, K, F and Cl. Additionally, alkalinity, HCO_3^-, SO_4^{2-}, and PO_4^{2-} are highly correlated to each other and to TDS, EC, Na, and Cl, while turbidity is correlated only to NH_3. These correlations are attributed to their chemical nature and activity in the water media. However, pH, TFe, and NO_3^- are observed not to be positively correlated with the rest of the variables significantly.

4.2.1 Principal Component Analysis (PCA)

Before undertaking the analysis, suitability of the data for PCA was checked in terms of sampling adequacy and internal consistency of the data using Kaiser–Meyer-Olkin (KMO) and Cronbach's alpha respectively. They are measures of testing consistency of variable values by offering information on whether or not data can be modelled with PCA. If the KMO value is greater than 0.50, it can be said that a data set can be factorized (Sen, *et. al.*, 2016; Ghosh and Jintanapakanont, 2004). Accordingly, for this study KMO is found to be 0.563 (>0.5). Additionally, it resulted in an overall Cronbach's alpha test score of 0.78 verifying internal

Table 4-4 Mean values of water quality parameters for the ten sampling sites of ARB during 2005-2013. (Source: AwBA)

par\site	Stat.	Dubti	Adaitu	Meteka	Off. Area	Weir Site	AwWSupp	Af. Bes	L. Bes	Bef. Bes	Wonji
Turb	mean	1003.89	1435.71	674.36	1537.61	871.43	1650.4	1199.75	40.8	795.05	233.09
	SD	1283.52	538.44	477.99	951.35	561.38	1257.08	715.72	20.44	464.34	69.02
TS	mean	1914.78	3551.92	2369.96	3116.61	2255.12	3438.4	2453.73	4273.5	2040.39	490.02
	SD	1641.66	1449.15	1338.07	1806.37	1122.53	1328.32	1420.73	613.61	1462.16	121.72
EC	mean	603.48	656.16	880.93	647.8	436.28	473.26	1164.12	5825.31	432.66	322.1
	SD	57.32	130.39	231.62	214.52	103.69	192.25	1062.65	606.16	202.72	35.42
pH	mean	7.98	8.32	8.23	7.88	7.9	7.9	8.03	9.42	7.72	8.25
	SD	0.17	0.61	0.61	0.19	0.23	0.27	0.46	0.17	0.38	0.87
NH_3	mean	0.51	0.88	0.48	0.76	0.67	0.75	0.94	0.66	0.73	0.65
	SD	0.23	0.82	0.17	0.41	0.24	0.26	0.59	0.29	0.24	0.33
Na^+	mean	90.72	101.66	154.75	108.34	65.14	75.24	279.27	1474.85	63.73	36.09
	SD	13.36	25.51	51.76	53.49	28.98	52.9	311.44	190.3	58.71	8.53
K^+	mean	6.06	7.35	11.11	9.7	9.56	9.04	11.77	55.55	10.31	6.93
	SD	0.67	1.37	2.96	3.74	4.2	2.78	4.07	8.39	4.27	0.7
Ca^{2+}	mean	35.83	32.65	31.87	33.42	31.19	29.06	26.71	6.25	31.22	28.55
	SD	6.69	4.07	1.89	4.74	1.82	4.02	6.37	1.82	1.6	1.12
Mg^{2+}	mean	8.35	7.08	9.68	7.67	6.51	6.56	6.77	2.25	6.25	5.37
	SD	2.64	1.03	2.32	4.24	2.07	3.61	4.57	1.62	2.86	1.33
TFe	mean	0.34	0.2	0.14	0.37	0.23	0.25	0.27	0.15	0.27	0.25
	SD	0.76	0.16	0.06	0.34	0.16	0.2	0.16	0.08	0.21	0.17
F^-	mean	1.39	1.45	2.12	2.07	2.01	1.43	5.65	25.43	1.67	1.49
	SD	0.39	0.49	0.31	0.27	1.08	0.49	6.27	9.64	0.6	0.38
Cl^-	mean	42.37	47.73	61.51	44.25	25.91	27.64	91.11	492.06	24.16	15.57
	SD	8.64	12.16	19.24	20.19	10.5	16.65	93.8	68.65	17.45	2.79
NO_3^-	mean	4.96	3.01	2.09	2.88	3.56	4.27	3.51	2.57	2.9	3.52
	SD	7.33	1.47	0.86	1.08	1.16	2.76	0.77	2.35	1.02	1.61
Alkal	mean	196.88	224.93	320.05	242.95	182.22	187.08	439.54	2253.48	183.53	135.47
	SD	25.7	35.84	79.76	72.33	46.9	75.58	372.52	396.43	86.7	18.14
SO_4^{2-}	mean	55.21	49.65	57.04	41.79	28.5	32.27	94.78	497.84	21.99	12.72
	SD	13.61	13.1	24.05	22.73	16.15	21.17	101.47	116.34	16.97	6.34
PO_4^{2-}	mean	0.45	0.8	0.62	0.79	0.48	0.54	0.86	2.68	0.46	0.5
	SD	0.18	0.5	0.22	1.11	0.13	0.16	0.51	0.37	0.17	0.28

Table 4-5 Correlation matrix (Spearman)

Var.	Turb	TS	TDS	EC	PH	NH_3	Na^+	K^+	TH	Ca^{2+}	Mg^{2+}	TFe	F^-	Cl^-	NO_3^-	Alkal	HCO_3^-	SO_4^{2-}	PO_4^{2-}
Turb	**1**																		
TS	0.31	**1**																	
TDS	-0.07	**0.65**	**1**																
EC	-0.01	**0.70**	**0.99**	**1**															
PH	-0.42	0.35	0.50	0.52	**1**														
NH_3	**0.67**	0.49	0.15	0.18	-0.19	**1**													
Na^+	0.01	**0.67**	**0.98**	**0.99**	0.43	0.16	**1**												
K^+	-0.30	0.45	0.64	0.62	0.07	0.16	**0.66**	**1**											
TH	0.33	-0.24	-0.08	-0.09	-0.19	-0.33	-0.08	-0.54	**1**										
Ca^{2+}	0.41	-0.21	-0.14	-0.15	-0.37	-0.12	-0.14	-0.50	**0.89**	**1**									
Mg^{2+}	0.47	-0.03	0.27	0.28	-0.14	-0.05	0.30	-0.19	**0.84**	**0.76**	**1**								
TFe	0.44	-0.38	-0.31	-0.30	-0.59	0.32	-0.21	-0.28	0.12	0.32	0.16	**1**							
F^-	-0.42	0.35	**0.66**	0.61	0.20	0.08	**0.66**	**0.92**	-0.47	-0.50	-0.19	-0.26	**1**						
Cl^-	-0.01	**0.70**	**0.99**	**1.00**	0.52	0.18	**0.99**	0.62	-0.09	-0.15	0.28	-0.30	**0.61**	**1**					
NO_3^-	0.38	-0.39	-0.53	-0.52	-0.22	0.04	-0.54	**-0.72**	0.15	0.08	-0.03	0.39	**-0.73**	**-0.52**	**1**				
Alkal	-0.01	**0.66**	**0.95**	**0.98**	0.41	0.18	**0.99**	**0.68**	-0.12	-0.13	0.28	-0.18	**0.65**	**0.98**	-0.59	**1**			
HCO_3^-	-0.08	0.60	**0.94**	**0.95**	0.37	0.16	**0.96**	**0.72**	-0.14	-0.10	0.26	-0.15	**0.68**	**0.95**	**-0.65**	**0.99**	**1**		
SO_4^{2-}	-0.07	0.55	**0.95**	**0.96**	0.50	0.02	**0.95**	0.54	-0.03	-0.12	0.32	-0.24	0.52	**0.96**	-0.37	**0.94**	**0.92**	**1**	
PO_4^{2-}	0.03	**0.81**	**0.78**	**0.81**	0.58	0.45	**0.79**	0.61	-0.41	-0.44	-0.08	-0.32	**0.66**	**0.81**	-0.56	**0.78**	**0.75**	**0.65**	**1**

consistency of the data. Both values imply that the sample is adequate and PCA can suitably be applied on the dataset. Removing the three redundant variables TDS, TH and HCO_3^- from the list of 19 parameters that are highly correlated to others, PCA on the normalized 16 variables was then computed to produce significant PCs and to further reduce the contribution of variables with minor significance. It is done using Pearson type of correlation automatically without fixing the number of components/factors to be generated because of the width of the study area.

Table 4-6 Eigenvalues

	F1	F2	F3	F4	F5	F6	F7	F8	F9
Eigenvalue	9.02	2.61	1.62	1.05	0.78	0.42	0.34	0.12	0.04
Variability(%)	56.39	16.32	10.1	6.57	4.87	2.62	2.13	0.75	0.26
Cumulative(%)	56.39	72.71	82.81	89.38	94.24	96.86	98.99	99.74	100

The 16 variables were reduced by PCA to 9 factors. PCA based on the water quality dataset indicated that 4 factors were significant (i.e., PCs with an eigenvalue >1). These were retained as the principal (significant) components because they could explain about 89.38% of the total variation as shown by **Table 4-6**. This table shows the sorted Eigen values (variances of the PCs) from large to small and percentage of variability versus principal components.

Table 4-7 Factor loadings and correlations between variables and the principal factors

	Turb	TS	EC	PH	NH_3	Na^+	K^+	Ca^{2+}	Mg^{2+}	TFe	F^-	Cl^-	NO_3^-	Alkal	SO_4^{2-}	PO_4^{2-}
F1	-0.29	0.73	0.92	0.79	0.15	0.93	0.84	-0.72	-0.48	-0.52	0.85	0.91	-0.54	0.97	0.89	0.88
F2	0.88	0.41	0.29	-0.42	0.40	0.31	-0.18	0.50	0.54	0.48	-0.09	0.32	0.25	0.19	0.34	0.16
F3	0.21	0.15	-0.19	-0.01	0.79	-0.14	0.11	-0.42	-0.61	0.25	0.08	-0.19	0.36	-0.12	-0.16	0.19
F4	-0.21	-0.05	0.13	0.26	-0.31	0.11	-0.29	-0.01	-0.25	0.34	-0.06	0.16	0.66	0.05	0.26	-0.14

As can be seen in the factor loadings and correlations between variables and factors of **Table 4-7** and **Table 4-8**, the analysis also revealed that the first component, explaining about 56.39% of the total variance, was highly and positively correlated with TS, EC, pH, Na, K, F^-, Cl^-, Alkal, SO_4^- and PO_4^- and negatively to Ca and TFe. The second component, of 16.32% variability explanatory, was relatively more correlated with turbidity, Ca and magnesium. The third and the fourth ones were related respectively to NH_3 and NO_3^-.

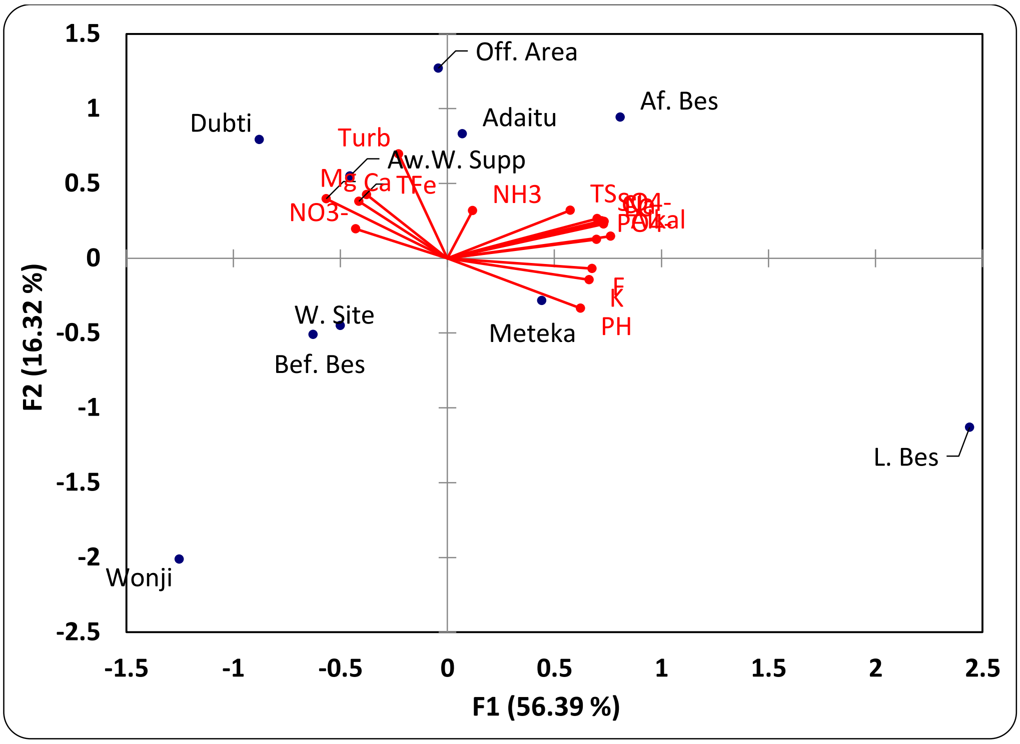


Figure 4-4 Biplot of sample sites and water quality variables (axes F1 and F2: 72.71 %) obtained from principal component analysis

A biplot of the variables and the sampling sites is shown by factors F1 against F2 in **Figure 4-4**. Both the plot and **Table 4-8** indicate that F1 had a high and positive loading in TS, EC, pH, Na, K, F^-, Cl^-, Alkalinity, SO_4^- and PO_4^- which were 0.73, 0.92, 0.79, 0.93, 0.84, 0.85, 0.91, 0.97, 0.89 and 0.88 respectively. These large and positive loadings show strong linear correlation between the factor and parameters. From the table of correlation (percentage contributions) of variables to the four principal components, it can also be observed that F1 is affected most by TS, EC, pH, Na, K, F^-, Cl^-, alkalinity, SO_4^{2-} and PO_4^{3-}; F2 by turbidity, Ca and Mg; F3 by NH_3 and F4 by NO_3^-.

When contribution of each of the sites to the factors is examined with reference to **Table 4-8**, the largest percentage of about 59.5 for F1 is taken by lake Beseka. This is consistent with the respective factor loading values (0.73, 0.92, 0.79, 0.93, 0.84, 0.85, 0.91, 0.97, 0.89 and 0.88) of TS, EC, pH, Na, K, F^-, Cl^-, Alkalinity, SO_4^- and PO_4^- of the water being taken from the sites. Similarly, it can also be seen from the table that among the remaining sampling sites F2 was affected most by Wonji, F3 by Meteka, and F4 by Dubti and hence these sites are considered as the most important pollution generating ones. However, the pH values of the 10 stations in **Table 4-4** showed generally less variation as it ranges only from 7.72 to 9.42 though it deviates a bit from the common pH range of surface water system, which is 6.5-8.5.

Table 4-8 % contribution of the variables to the PCs (a) and % contribution of observations to the PCs (b)

a) % Contribution of the Variables to PCs						**b) % Contribution of the Observations to PCs**					
Variables		**F1**	**F2**	**F3**	**F4**	**Sites**		**F1**	**F2**	**F3**	**F4**
Turbidity	**% Contribution of variables**	0.92	**29.7**	2.69	4.16	**Dupti**	**% Contribution of Observations**	7.73	6.31	13.7	**59.2**
TS		**5.84**	6.33	1.35	0.2	**Adaitu**		0.05	6.91	1.12	5.24
EC		**9.45**	3.21	2.32	1.63	**Meteka**		1.95	0.81	**62.2**	15.6
pH		**6.85**	6.83	0	6.3	**Off.Area**		0.02	16.2	0.48	2.68
NH_3		0.24	6.2	**38.2**	9.41	**W.Site**		2.5	2.03	0.15	0.37
Na^+		**9.53**	3.7	1.27	1.08	**Aw.W.Supp.**		2.08	3.01	8.7	0.01
K^+		**7.78**	1.28	0.76	7.95	**Af.Bes.**		6.51	8.88	8.61	0.12
Ca^{2+}		5.69	**9.67**	10.9	0.01	**L.Bes.**		**59.5**	12.8	0.83	9.78
Mg^{2+}		2.52	**11.1**	22.9	6.14	**Bef.Bes.**		3.93	2.61	0.54	6.72
TFe		3.03	8.86	3.98	11	**Wonji**		15.7	**40.5**	3.68	0.27
F^-		**8.08**	0.29	0.41	0.35						
Cl^-		**9.21**	3.84	2.24	2.36						
NO_3^-		3.25	2.37	8.07	**41**						
Alkalinity		**10.3**	1.33	0.95	0.22						
SO_4^{2-}		**8.69**	4.32	1.66	6.4						
PO_4^{3-}		**8.61**	0.95	2.25	1.83						

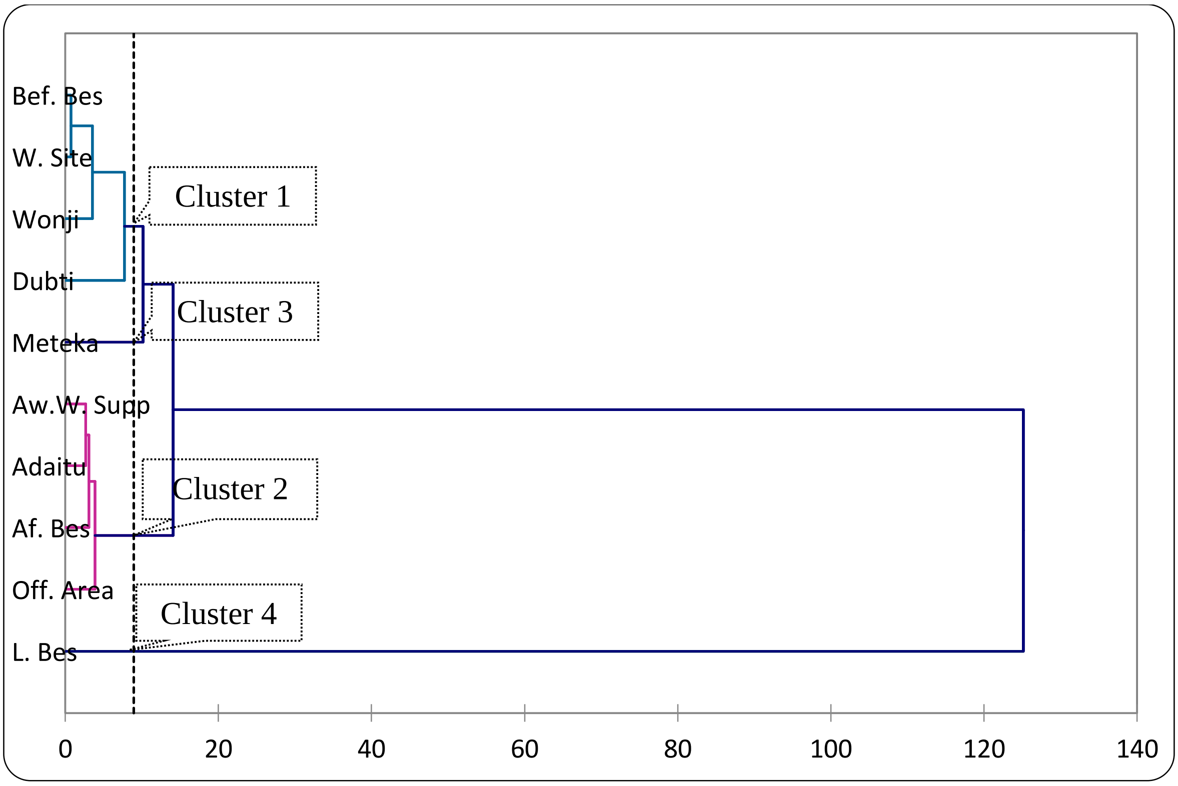
4.2.2 Cluster Analysis (CA)

Agglomerative hierarchical clustering (AHC) using Euclidean distance with Ward's method was applied on the original dataset to assess the similarity among sampling sites. All the 10 sites of the basin are grouped into four statistically significant clusters at $(D_{link}/D_{max})*100<20$. Results of application of the cluster analysis are best visualized by a dendrogram or binary tree given by **Figure 4-5**. The clustering has also offered the proximity matrix shown by **Table 4-9**.

Table 4-9 Proximity matrix (Euclidean distance)

Sites	Dubti	Adaitu	Meteka	Off. Area	W. Site	Aw.W. Sup	Af. Bes	L. Bes	Bef. Bes	Wonji
Dubti	0									
Adaitu	4.53	0								
Meteka	4.67	3.90	0							
Off.Area	3.52	2.71	4.44	0						
W.Site	2.90	**2.56**	3.26	2.77	0					
Aw.W.Sup	3.30	2.30	4.61	2.57	**2.14**	0				
Af.Bes	4.28	**2.35**	4.69	2.71	2.61	2.54	0			
L.Bes	13.04	11.75	11.74	12.33	11.98	12.15	**10.85**	0		
Bef.Bes	3.56	2.84	3.58	2.55	**1.20**	2.71	2.53	12.02	0	
Wonji	3.75	4.33	4.18	4.37	2.36	4.13	3.80	12.09	**2.40**	0

This table shows Euclidean distance between paired samples. The smaller the number of point of intersection of two sites is, the more similar the sites are. e.g. before Beseka is more similar to Weir site (1.20) than to L.Bes (12.02).



$(D_{link}/D_{max})*100$

Figure 4-5 Dendrogram showing clustering of sampling sites based on the water quality characteristics of Awash River.

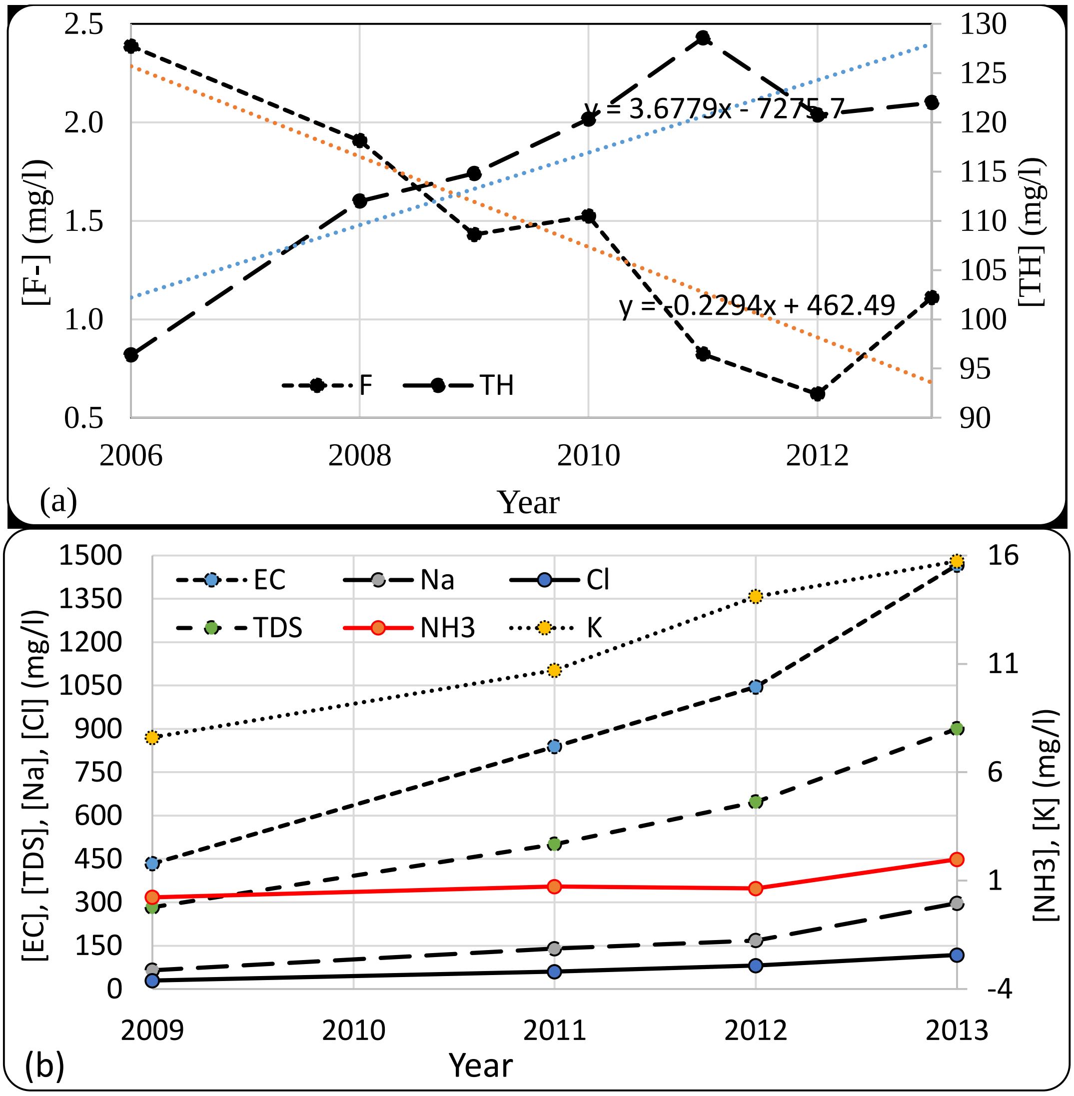
The dendrogram in **Figure 4-5** clearly depicts grouping of the sites based on similarity of water quality characteristics. Accordingly, it classified before Beseka, Weir site, Wonji and Dubti as cluster 1. This grouping seems to be reasonable as these sites resemble in that they all are in the vicinity of specialized sugarcane state farms. Adaitu, Office area, Awash water supply and after Beseka are grouped as cluster 2. This is also consistent to the ground truth that the sites receive waste contributing to turbidity, TS and NH_3 from dominantly urban and bare-lands. However, Meteka and Lake Beseka are categorized respectively as clusters 3 and 4. Meteka seems to be unique in that it receives waste from small subsistence-oriented and diversified agricultural and rural areas. Similarly, Lake Beseka is unique in that the lake water quality is by far different from others as it shows the highest values of almost all parameters except for turbidity, TH, Ca, Mg, TFe and NO_3^-. This is confirmed by the study of Dinka (2016) who has urged in his conclusion to avoid even the contact of Lake Basaka water to crops and productive soil in the region because of its pollution. The observations in the second cluster of brown color are relatively more homogeneous than cluster 1 as they are more flat by the truncation. This is confirmed by the within class variance shown by **Table 4-10**, where its value is less than that of cluster 1.

Table 4-10 Results by class

Class	1	2	3	4
Objects	4	4	1	1
Within-class variance	780685.8	442212.0	0	0
Average distance to centroid	669.3	502.3	0	0

4.2.3 Temporal trend analysis

Trend analysis of TDS, EC, pH, NH_3, Na, K, TH, F, Cl, and NO_3 is performed in the 9 years' period (2005 – 2013) by Mann-Kendall's (MK) two tailed trend test for the 4 sites in the basin including Dubti, office area, after Beseka and Wonji. The analysis at 5% significant level in the dry season (Dec-Feb) of Dubti showed that except TH and F none of the parameters are found to show any trend since their p values computed by exact method are greater than the significance level α=0.05. The test done for Dubti revealed that TH had a significant increasing and F- a decreasing trend since their respective computed p-values 0.011 and 0.03 are less than the significance level α=0.05 as can be explained by **Figure 4-6** (a). Similarly, the analysis for the office area indicated that only TDS has shown a trend, which is monotonic upward throughout the years of consideration, and EC, NH_3, Cl, Na and K also show increasing trends only after 2009 (**Figure 4-6** (b)) but the rest are all found to show no trend at all. At Wonji in the dry season, except TH none of the parameters indicated a trend in the years from 2006 – 2013; TH has shown a significant increasing trend in the period as can be seen by **Figure 4-6** (d). The test is undertaken in the wet season (June-August) of the parameters and most of them are found to show no trend. However, TH and K respectively at Dubti and Wonji showed a significant decreasing and increasing trends as depicted in **Figure 4-6** (c).



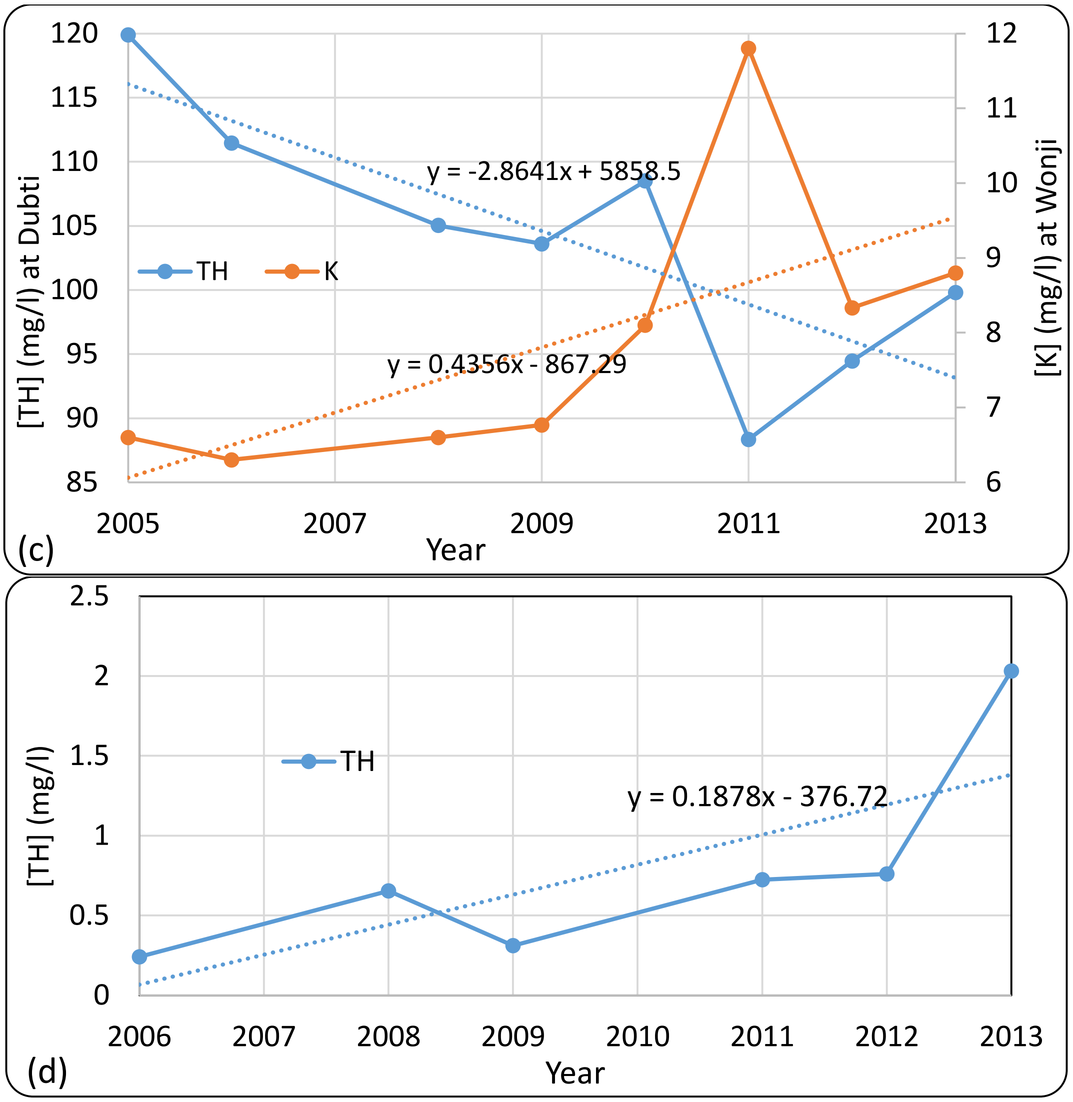
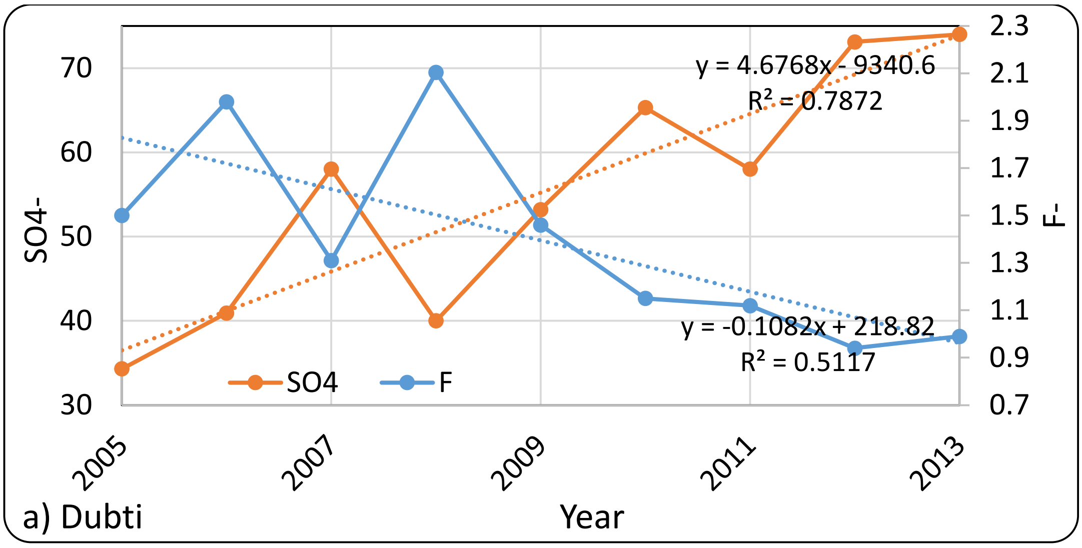
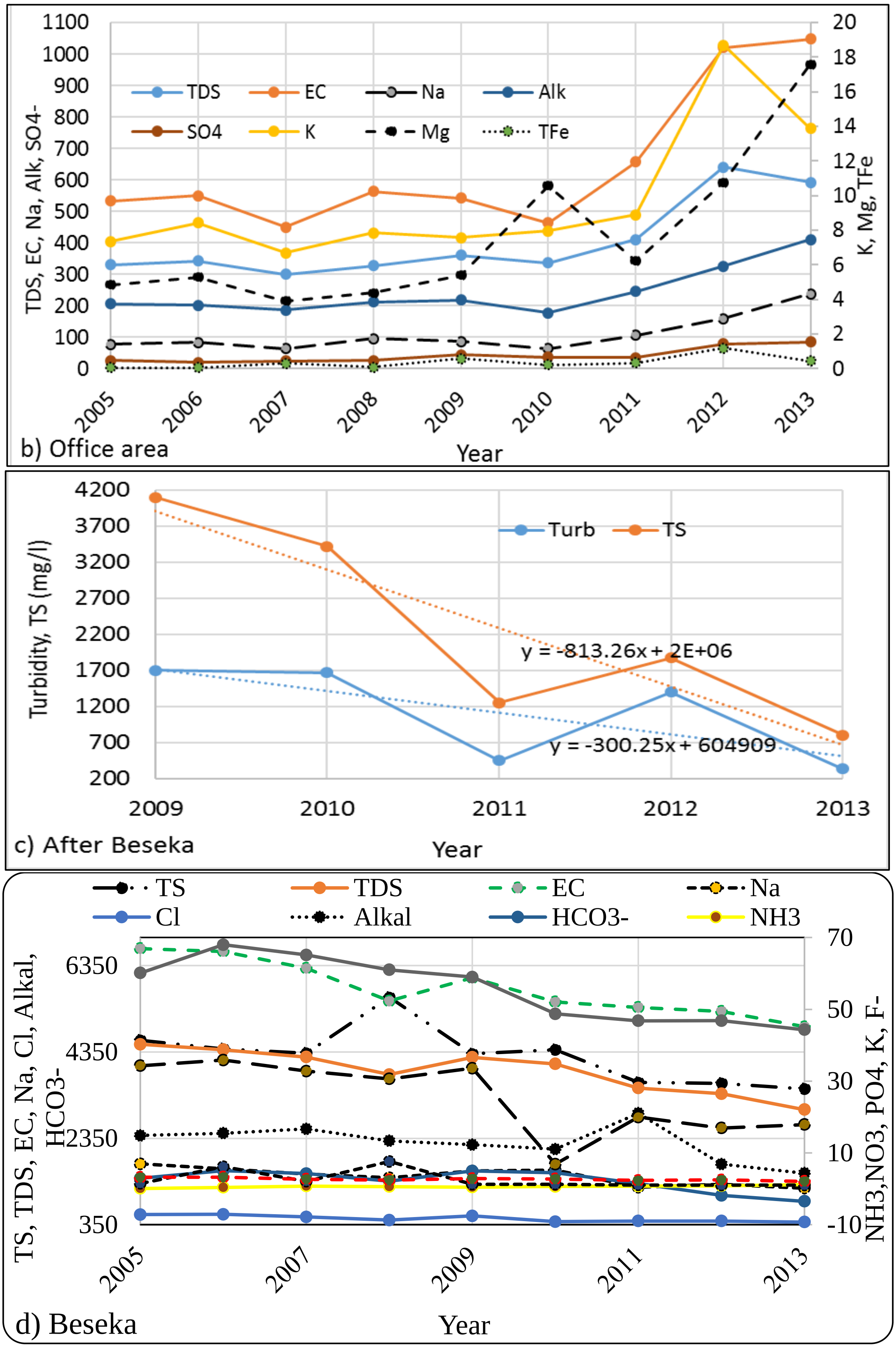


Figure 4-6 Temporal Variation of TH and F^- at Dubti (a); EC, TDS, NH_3, Na, K, and Cl at the Office area (b); TH at Wonji (d) in the Dry Seasons and that of TH at Dubti and K at Wonji in the Wet Seasons (c).

Temporal trend analysis of the annual average values of turbidity, TS, TDS, EC, pH, NH_3, Na, K, TH, Ca, Mg, TFe, F, Cl, NO_3^-, alkalinity, HCO_3^-, SO_4^- and PO_4^- is undertaken throughout the nine years' period by MK two tailed trend test for Dubti, Adaitu, office area, Weir site, after Beseka, Beseka, Before Beseka, and Wonji. The analysis at 5% significant level for Dubti tell us that only SO_4^- and F^- show a trend while others all don't as their p-value, computed by the exact and approximation methods, is greater than the significance level alpha=0.05. While the former showed an increasing trend, the later a decreasing one (**Figure 4-7**a). A similar analysis at office area indicates that TDS, EC, Na, K, Mg, TFe, alkalinity and SO_4^- show an increasing trend since their computed p-value is lower than the significance level alpha=0.05. The test at Beseka resulted in the fact that TS, TDS, EC, NH_3, Na, K, F, Cl, NO_3^-, alkalinity, HCO_3^- and PO_4^- to have shown trends since their p-values is smaller than alpha=0.05. Among these, except NH_3, all of them are decreasing. While both turbidity and TS show a decreasing trend at after Beseka, the rest all are found to show no trend at all.

On the other hand, performing MK test on NH_3, K, Mg, TH and SO_4^- show increasing while F- a decreasing trend at Wonji as show by **Figure 4-7** (e) as their p-values computed by exact method is lower than the significance level alpha=0.05 while others all don't. At before Beseka TDS, EC, NH_3, Na, K, TH, TFe, Cl^-, alkalinity, and HCO_3^- show a trend in the years 2005-2013 while at Weir site TDS, EC, NH_3, Na, K, Mg, TFe, Cl^-, alkalinity, HCO_3^-, SO_4^-, and PO_4^- show a trend. With a similar argument MK test indicated at Adaitu that only EC, NH_3, HCO_3^-, and SO_4^- have shown trends.





1100
1000
900
800
700
600
500
400
300
200
100
0
20
18
16
14
12
10
8
6
4
2
0
TDS
EC
Na
Alk
SO4
K
Mg
TFe
TDS, EC, Na, Alk, SO4-
K, Mg, TFe
2005
2006
2007
2008
2009
2010
2011
2012
2013
b) Office area
Year
4200
3700
3200
2700
2200
1700
1200
700
200
Turb
TS
y = -813.26x + 2E+06
y = -300.25x + 604909
Turbidity, TS (mg/l)
2009
2010
2011
2012
2013
c) After Beseka
Year
TS
TDS
EC
Na
Cl
Alkal
HCO3-
NH3
6350
4350
2350
350
70
50
30
10
-10
TS, TDS, EC, Na, Cl, Alkal, HCO3-
NH3,NO3, PO4, K, F-
2005
2007
2009
2011
2013
d) Beseka
Year

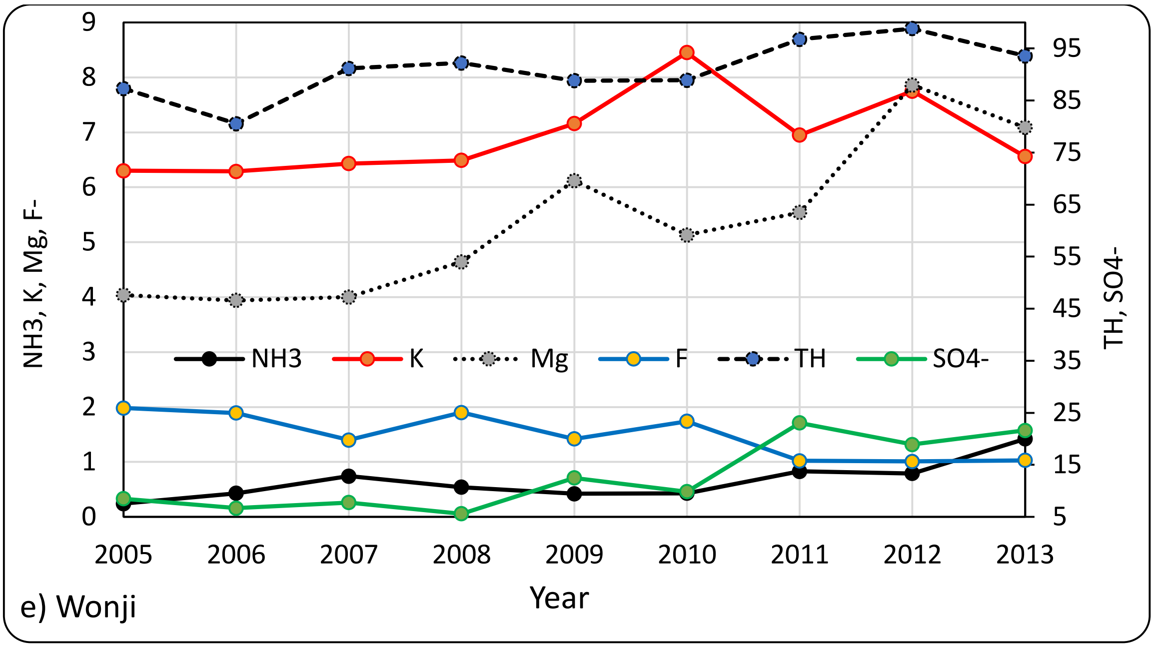
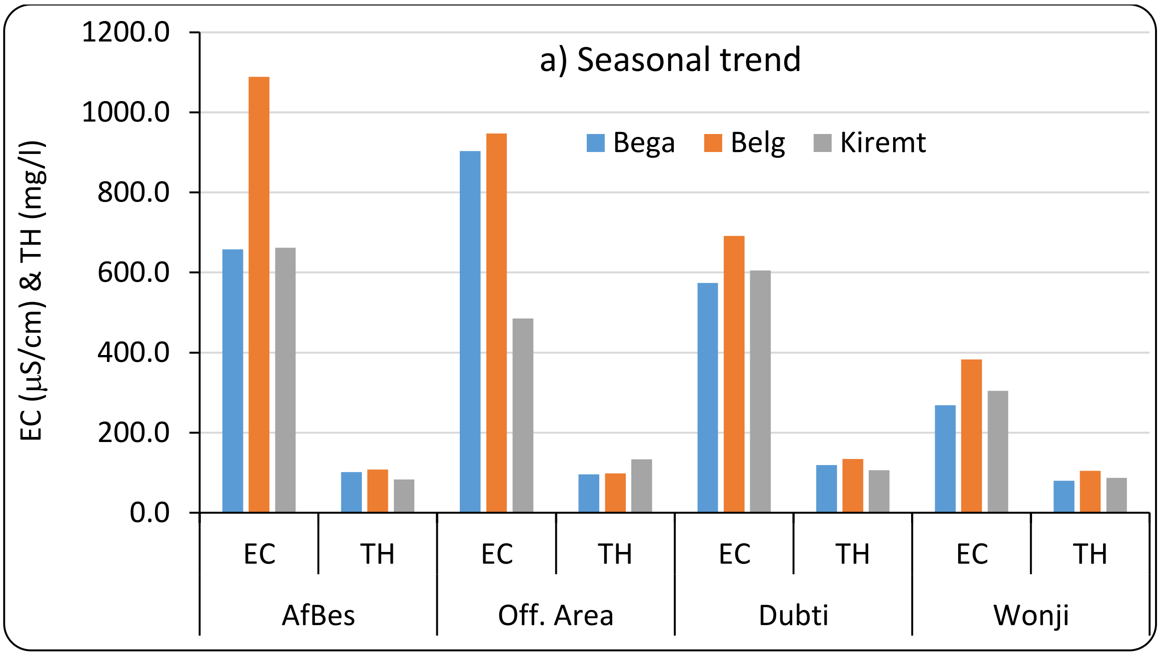


Figure 4-7 Trend analysis of the water Quality data in the nine years' period at Dubti, Office area, After Beseka, Beseka and Wonji



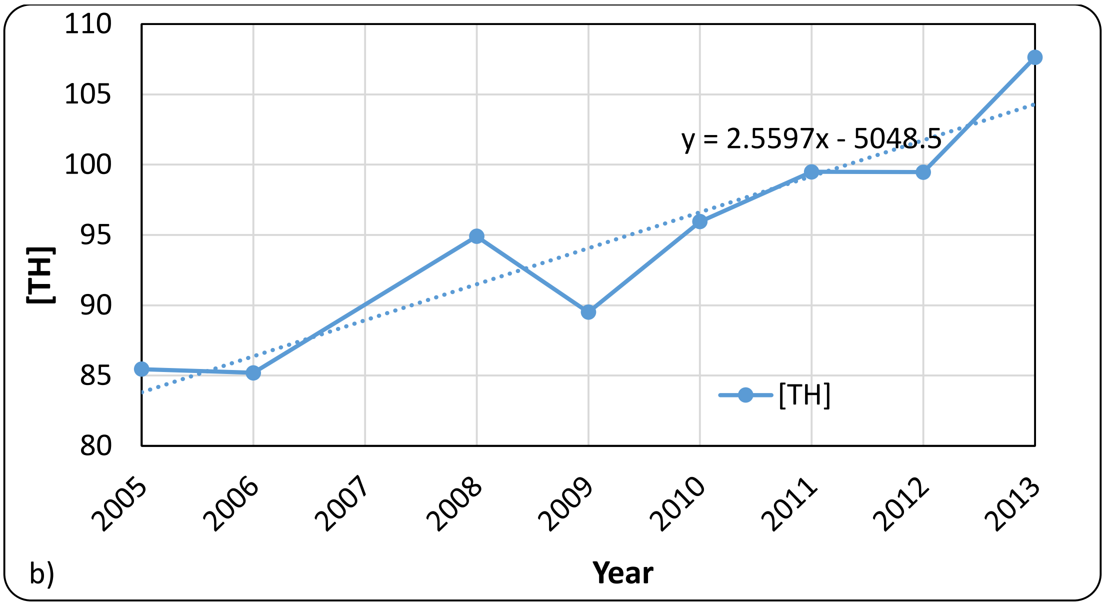


Figure 4-8 Seasonal Variation of EC and TH in the three main seasons of the year (a) and of average [TH] of all sites in february over the years 2005-2013 (b)

Investigation of water quality parameters such as EC and TH is undertaken to see the temporal trends along Ethiopian seasons of Bega (October-January), Belg (February-May) and Kiremt (June-September) at the four sites namely Dubti, Office area, after Beseka and Wonji. MK trend test for an average over all sites of [TH] in a month of February on the eight years (2005-2013) is also examined. The graphs in **Figure 4-8** (a) exhibit that both variables get absolute maximum values in the Belg season at all sites except that TH got largest value in Kiremt at the Office area. In the MK trend test for [TH], the null hypothesis declaring absence of a trend in the series of [TH] along the years is rejected and the alternative hypothesis saying that there is a trend in the series is accepted since the computed p-value = 0.001, is lower than the significance level α=0.05. The type of trend is positive though not monotonic as can be seen by **Figure 4-8** (b).

Analysis of EC, pH, NH_3, TH, TDS and alkalinity is done to see their general change in the dry (October-January) and wet (June-September) seasons of the 14 monitoring sites namely: Dubti, Adaitu, Meteka, Office area, Weir site, Awash W. Supp, Awash fall, Af. Bes., Beseka, Bef. Beseka, Sodere, Wonji, Koka dam and Mojo. The general truth, as can be seen in **Figure 4-9**, is that average values of all of them is higher in the dry than in the wet season.

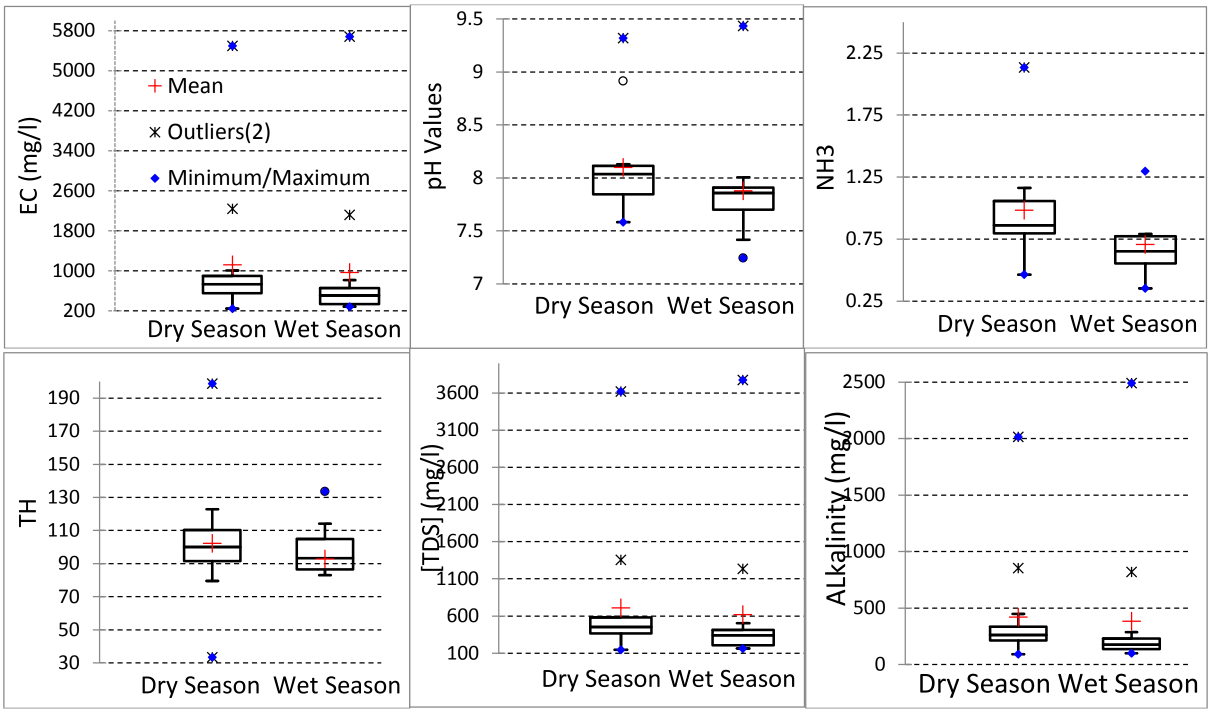


Figure 4-9 Seasonal trend analysis of the water quality parameters in the dry and wet seasons

4.2.4 Spatial trend analysis

Spatial analysis of water quality parameters was assessed at the 14 sampling sites of ARB. From slopes of trendlines of graphs of the water quality indicators, it can be seen generally that as one moves from upper to lower parts of basin in the dry season (October-January), EC, TH and Cl were observed to be decreasing (**Figure 4-10**). From the trendlines of the graphs, one can also observe that the parameters change abruptly and significantly in and around the hot springs and lake Beseka.

TH was slightly increasing while TDS, Cl, and SO_4^{2-} were decreasing in the same direction in the rainy season (June-September). It can also be seen from the graph that among the sites in both the dry and wet seasons, Cl and EC/TDS/SO_4^{2-} were maximized respectively at bef Beseka and Beseka. At Beseka in both seasons, TH showed a trend opposite to that of EC/TDS/ SO_4^{2-}, i.e it revealed an absolute minimum. The most important sites responsible for the spatial variation were Beseka, before Beseka and Sodere spring as they are where, for instace, EC, TDS, TH, Cl, and SO_4^{2-} showed significant variation. The reason of decreasing concentraion of most pollutants (immersed into the river mostly from the upper basin) might be the natural purification process taking place in the course of the river.

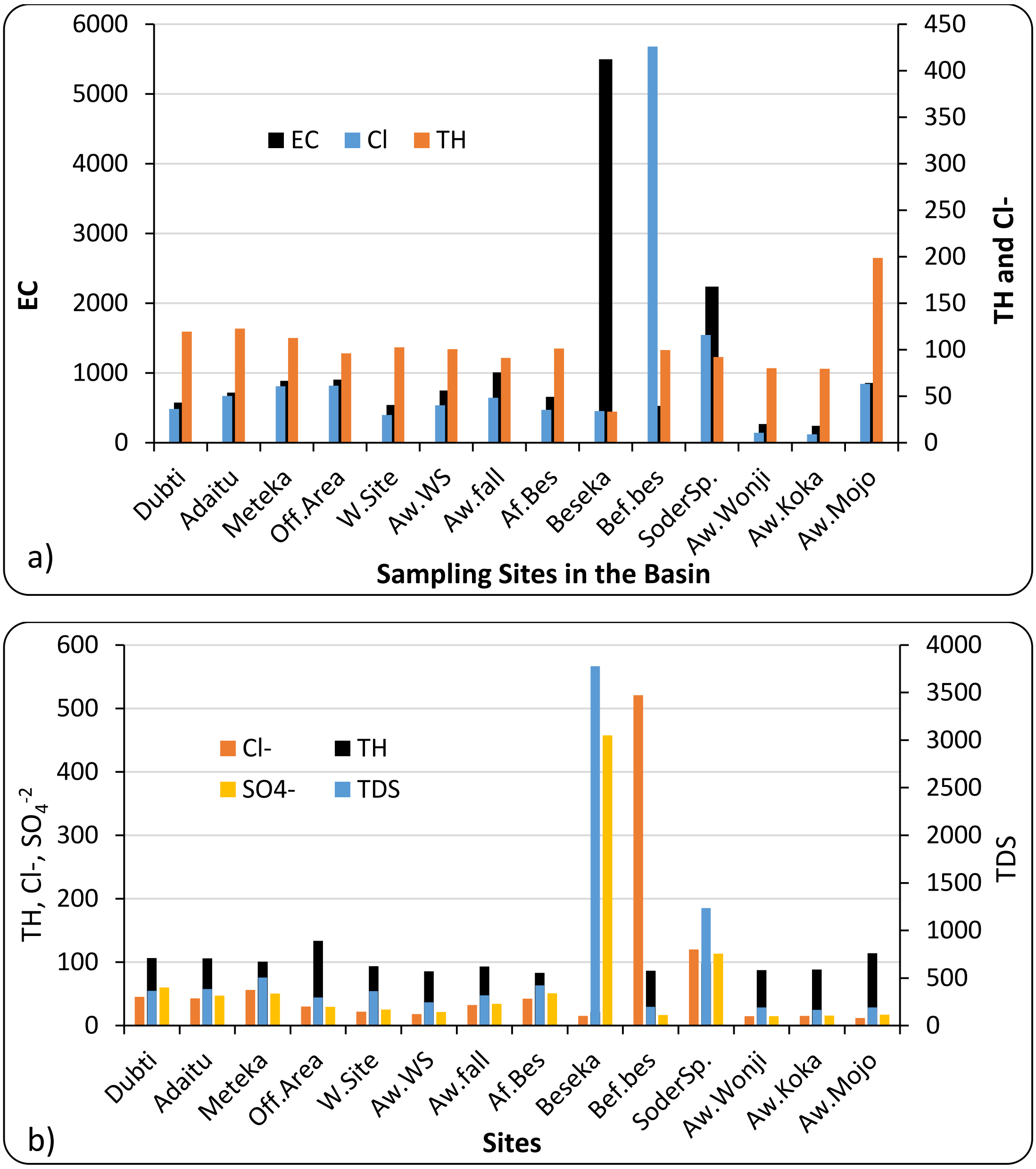


Figure 4-10 Spatial Variation of EC, TH, and Cl in the Dry (a) and TH, Cl, SO_4^{2-} and TDS in the Wet (b) Seasons of ARB.

The MK test at Beseka resulted in the fact that TS, TDS, EC, Na, K, F^-, Cl^-, NO_3^- TDS, EC, Na, K, F^-, Cl^-, NO_3^-, showed decreasing trends. This finding is in agreement with that of Dinka (2017) who found that in the previous two decades (1960-1980) water quality parameters especially ionic concentrations had shown decreasing trends in response to the fast increasing volume of the lake, which has a dilution effect although his finding has unexpectedly shown stability of most and even increasing trend of other parameters post 2000. Throughout the years from 2005 to 2013, almost all parameters except NH_3 in **Figure 4-7** (**d**) were showing a temporal decreasing trend. This is suggested to be due to ever increasing volume of the lake from time to time which could dilute the water more (Alemayehu et al., 2006; Dinka, 2017).

On the other hand, EC (salinity-determinant) has shown a spatially increasing trend from upper to middle and then decreasing afterwards (**Figure 4-10**), though it was concluded by Taddese et al. (2003) that salinity is generally increasing from the upper to lower basin. The state of EC being maximum in the middle seems, however, to be reasonable since there are Lake Beseka and Sodere spring here having high EC values. Cl has also shown a similar trend as EC throughout the basin while TH showed decreasing trend in the upper and increasing trend in the middle and lower sub-basins. Most other pollutants (discharged into the River from the upper basin) are also seen to decrease their concentration in the downstream (except for EC, TDS, SO_4^-, and Cl^- at lake Beseka and Sodere hot spring). This might be due to the natural purification process taking place in the course of the river and the lesser amount of waste discharged into the river in the middle and lower basins though the climate is worsening in the downstream tending to concentrate the pollutants while concurrently diminishing the volume of the river due to diversion for different purposes in the lower part.

4.3 Land use/land cover and water quality

Since rivers are vulnerable to land use changes, understanding the relationship between water quality and land use is useful for identifying primary threats to water quality. These understandings are meaningful for effective water quality management because they can be used to target critical land use areas and to institute relevant measures to minimize pollutant loadings (Ding et al., 2015).

4.3.1 Land use/land cover dynamics

The changes in land use and land cover in the three years considered were attributed to factors such as draught year, transition of government, economic and land use policy change observed in the nation at large and in the basin in particular.

Land use-land cover analysis of Awash basin was carried out aiming to address its effect on water quality of the basin. After appropriate classification of the three years' images, accuracy of the classification and statistics for the classified images such as percentages of each land use classes in the three years were computed. The land use-land cover change detection analysis in Awash basin for the years 1994, 2000 and 2014 is illustrated in **Table 4-11**, **Table 4-12**, and **Table 4-13** and also demonstrated in **Figure 4-11**. There were about eight land use types identified in the basin, namely agriculture, forest, grassland, shrub land, barren land, sandy/exposed rock, built-up area, and waterbodies. The accuracies of supervised classifications were found satisfactory according to Congalton & Green, (2008); Jensen & Lulla, (1987), since for the 1994, 2000 and 2014 land use/ land cover classification overall accuracies of 79.9, 85.5 and 81.6% were attained respectively.

The LULC classification output for the period 1994-2014 showed that the dominant LULC of Awash basins were agriculture, barren land, and shrub-lands though shrub-lands are dramatically declining in 2000 and 2014. On the other hand, few LULC types such as sandy/exposed rock, built-up areas, and water bodies were only covering small area of the basin. Agriculture and barren land, covering larger areas, took percentages of about 23.62 and 25.84 in 1994; 21.05 and 26.55 in 2000 and 28.08 and 22.85 in 2014.

Agriculture

During the period of comparison, it was compared to the base year 1994 of 27175.73km^2 (23.6%) agriculture. Agricultural land was only slightly declining by 2977km^2 (2.57%) in 2000. This is also evident from the map (**Figure 4-11**) shown on the upper part of Awash. Latter in 2014, it was increased by 5160km^2 (4.46%) as could be depicted in **Figure 4-11**. It can be seen from the figures that, the increase in agriculture land was also detected on the lower Awash basin.

Table 4-11 Area contribution of the land use classes in hectare and percentage

LU classses	1994		2000		2000-1994	2014		2014-1994
	Area_km^2	%	Area_km^2	%		Area_km^2	%	
Agriculture	27175.73	23.62	24198.74	21.05	-2.57	32335.80	28.08	4.46
Forest	9466.82	8.23	15671.71	13.63	5.41	12905.76	11.21	2.98
Grassland	12087.29	10.51	15990.50	13.91	3.41	13900.25	12.07	1.56
Shrubland	27109.39	23.56	15464.67	13.45	-10.11	15904.15	13.81	-9.75
Barrenland	29730.16	25.84	30521.42	26.55	0.71	26315.10	22.85	-2.99
Sandy/Exposed rock	5223.07	4.54	9449.03	8.22	3.68	7543.49	6.55	2.01
Builtup area	2134.59	1.86	2614.78	2.27	0.42	5416.63	4.70	2.85
Waterbodies	2128.53	1.85	1027.24	0.89	-0.96	851.90	0.74	-1.11

Nowadays, improper management of wastes from urban and rural areas such as that of farm residues, fertilizer and agro-chemical, as in the case of catchments in many developing nations, the burden on the quality of water increases.

Built up areas

The built up areas include both urban and rural areas builtups. This was only covering 2134.59km^2 (1.9%) in 1994. The built-up area cover was consistently increasing to 2.3% and 4.7% of the basin in 2000 and 2014 respectively. Compared to its base year 1994, the cover of built-up areas was increased by 2.9% in 2014. Built-up areas were the major source of non-point sources of pollution. There are several towns and cities found in ARB, which have continuously increased their cover since 1994. The growth in number and size of these towns and cities were accompanied by industries, large service providing centers, manufacturers, which are inevitably release their effluent to the nearby surface water. Built-ups, including impervious areas such as roads and rooftops, accelerate movement of wastes with storm water that ultimately release directly into running water especially during rainy seasons.

Sandy /Exposed rock

Sandy and exposed rocks are often found in the lower parts of south-eastern Awash basin. This is an area inhibiting vegetation growth. Sand and exposed rock was only covering 5223.07km^2 (4.5%) in 1994, this was remarkably increased by 3.7% and 2% in 2000 and 2014 respectively.

This is susceptible to erosion especially during erratic rainfall conditions, which releases waste into the river to affect quality of water.

Shrub-land

The lower region of Awash basin is a low-lying semi-arid area dominated by shrub-lands covering large area in 1994 (about 27109.39km^2 or 23.6%). This was depleted in 2000 and 2014. Shrub-land is one of the three dominant land covers with agriculture and barren-land by 1994 in Awash basin. This has dramatically fallen to 15464.67km^2 (13.5%) and 15904.15km^2 (13.8%) in 2000 and 2014 respectively.

Barren land

Barren lands show slight change in the period, 1994-2014. From the three years, the largest coverage was detected in 2000 for an estimated cover of 30521.42km2 (26.5%). It was latter declined by 390188ha (3%) in 2014 from the base year. All forms of land use land cover change affects water quality of the basin, however agriculture and barren lands were important in the basin due to their large and persistent coverage. Both land uses assume exceptionally major source of accelerated soil erosion due to its loosen soil particles and agrochemicals added on the farmlands. These and others forms of residues consequently enter into the river and affect water quality.

Grass lands

Grassland was another LULC noticed in the basin. According to **Figure 4-11**, it is largely found between the buffer of forest areas and shrub-land. It was also significantly found on the gorges of Awash basin (**Figure 4-11**). About 12087.29 km^2 (10.5%) was covered by grass lands in 1994, and this was increased by 3.4% and 1.6% in 2000 and 2014 respectively.

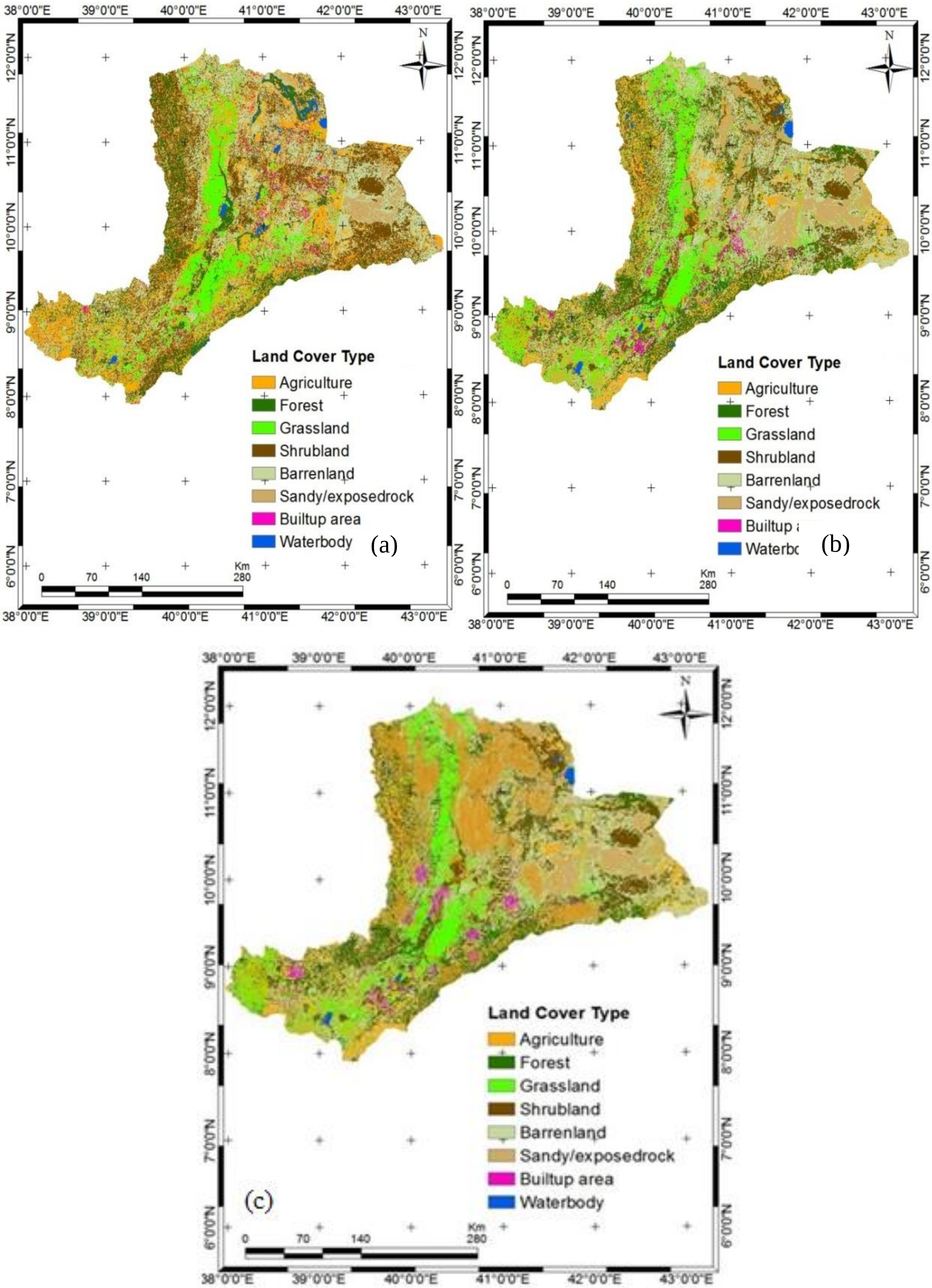


Figure 4-11 LU/LC maps of the study area in 1994 (a), 2000 (b), and 2014 (c)

Forest

Relative to the large area coverage of Awash basin, it was only a small portion that is covered by forest. Most of the forest cover was located on the upper region of Awash basin (**Figure 4-11**). The forest cover was estimated to be 9466.82 km^2 (8.2%) in 1994, while this was increased by 5.4% and 3% in 2000 and 2014 respectively. In other words, forest cover of 2014 reduced by 2.4% from 2000. According to **Figure 4-11**, the upper escarpment of Awash basin was persistently covered with forest for the period 1994-2014.

Water bodies

Water bodies were other important land cover types identified in Awash basin. The change in area coverage of water appeared to reduce by 0.96% in 2000 relative to the base year 1994, which was 2128.53km^2 (1.8%). This was only slightly reduced by 1.1% in 2014.

Transition matrices

A matrix is produced by multiplying columns in the transition probability matrix by the number of cells of corresponding land uses in the later image. The transition matrix produced for land use maps of years 1994 and 2014 is shown by **Table 4-12**. The transition matrices between 1994 and 2014 indicated that about 18.3% of agriculture is converted to built-up area from 1994 to 2014 largest proportion of 43.8% of forest was cleared for cultivation (farm land). Significant proportion of grass land was converted to agriculture (29.5%), to barren land (30%) and built-up area (25.5%). Similarly, shrub land was largely converted to agriculture (35.7%). There was about 38.8% water bodies shrunk due to cultivation. Similarly, large proportion of built up areas (37.7%) and (27.6%) were also converted to barren-land and agriculture respectively.

Table 4-12 Transition probability table (Confusion matrix) showing transformation of one land use type to another from 1994 to 2014

		2014							
	LULC	Agriculture	Forest	Grass	Shrub	Barren	Sand	Built-up	Water
1994	Agriculture	27.1%	15.1%	12.6%	3.3%	17.9%	5.0%	18.3%	0.8%
	Forest	43.8%	32.5%	8.0%	1.2%	6.2%	1.5%	5.9%	1.0%
	Grass	29.5%	1.6%	6.3%	2.6%	33.0%	1.2%	25.5%	0.2%
	Shrub	35.7%	11.7%	16.7%	5.7%	19.9%	1.3%	8.7%	0.2%
	Barren	19.3%	5.7%	13.4%	4.7%	31.6%	10.3%	14.8%	0.1%
	Sand	8.3%	3.8%	2.2%	1.8%	18.6%	46.5%	18.6%	0.2%
	Builtup	27.6%	4.2%	9.9%	1.6%	37.7%	0.0%	18.7%	0.2%
	Water	38.8%	20.1%	2.9%	0.6%	5.9%	0.0%	6.6%	25.2%

Unit of area of change is in percent (%).

Such LU/LC changes are not healthy either from environmental or socio-economic points of view and therefore, are matters of concern. The land cover dominance in the basin has shifted from bare lands (in 1994) to agricultural (in 2014). This result is in line with the suggestion of ASTU (2016) that in middle Awash shrub and pasture lands were cleared for irrigation recently and hence increase in percentage of the agricultural land. The LULC changes and associated human activities have deteriorated the water quality in the study areas as evident from low DO, higher electrical conductivity, total hardness, total dissolved solids, turbidity, nitrate, chloride, sulphate, BOD and total coliform, presence of pollution tolerant macro-invertebrates etc.

4.3.2 Land use-water quality relationship in Awash River basin

The land use land cover change in the basin was compared to values of some water quality parameters for the period 2000-2014 (**Figure 4-12**).

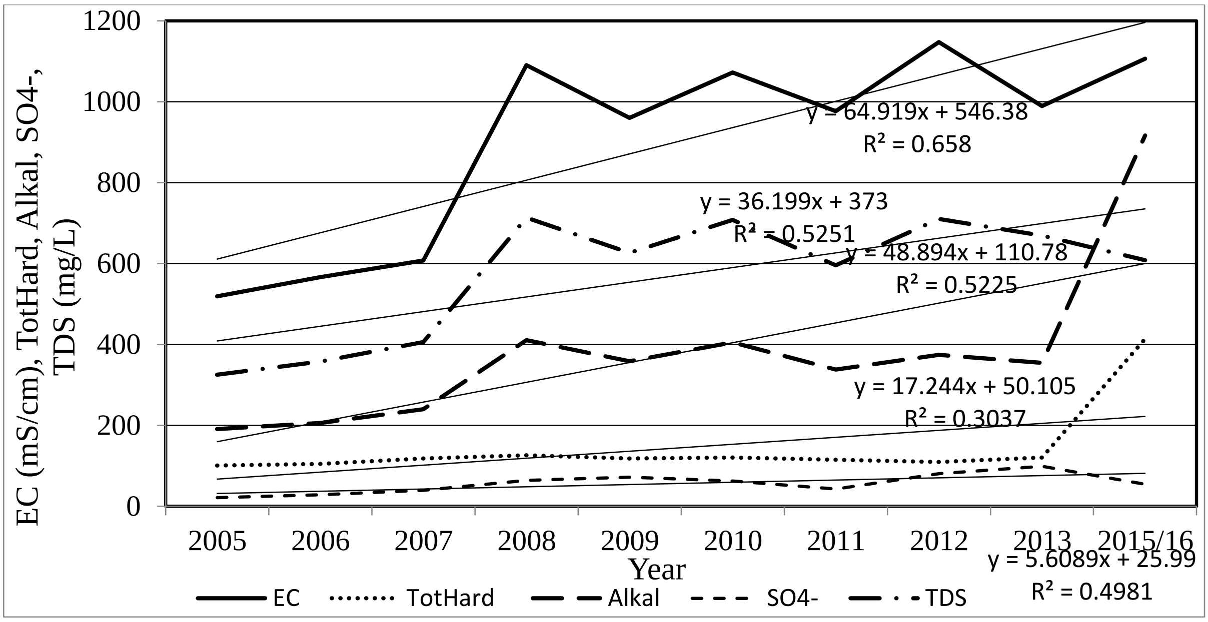


Figure 4-12 Trends of EC, Total hardness, Alkalinity, SO_4, and TDS in 2000's and 2010's

Most water quality parameters did not show a trend for the period 2000-2014, while few of which including EC, TDS, Alkal, TotHard and SO_4 were significantly showing trends. There was an increase in agriculture and built-up areas by 6.8% and 2.5% respectively from 2000 to 2014; on the other hand, there was a decrease in forest and grassland by 2.4 and 1.8% respectively in the period. In association with these land use changes, the water quality parameters EC, TDS, Alkal, TotHard and SO_4^{2-} were rising 64.92, 36.2, 48.89, 17.24 and 5.61 times a year for the period 2005-2014. Exceptionally, barren land was reduced by 3.4% which was expected to affect the water quality positively. This might be attributed to the location of the change in barren land, which was eastern region of Awash basin.

After classification of images of 2000 and 2014, the area in hectare (ha) and percentage statistics for the classified images of each land use class in the two years, around which the water quality data were collected, have been computed. **Table 4-13** clearly shows why some parameters like SO_4^{2-}, TH, EC, Na^+, Cl^-, K^+, and NH_3 increase monotonically at some sites and why the rest vary in the other sites of the basin temporally, which is corresponding to the land use changes in the respective sites. For instance, agriculture and built-up areas have significantly increased in the basin from 2000 to 2014. The associated pollution by agro-chemicals, nutrients, and hardness resulting from urbanization and agricultural intensification was observed. From the 2014 land use map, the land is more degradable as one moves from upper to lower basin.

Table 4-13 Percentages of land uses of the basin in 2000 and 2014

LU classses	2000		2014	
	Area_km^2	%	Area_km^2	%
Agriculture	24198.74	21.05	32335.80	28.08
Forest	15671.71	13.63	12905.76	11.21
Grassland	15990.50	13.91	13900.25	12.07
Shrubland	15464.67	13.45	15904.15	13.81
Barrenland	30521.42	26.55	26315.10	22.85
Sandy/Exposed rock	9449.03	8.22	7543.49	6.55
Builtup area	2614.78	2.27	5416.63	4.70
Waterbodies	1027.24	0.89	851.90	0.74

The land in the lower part of the basin is mostly bare, sandy, rocky and the rest is covered by shrubs, which is an indication of an arid zone. In the middle part of the basin, there are Lake Beseka and Sodere hot spring, both of which are located in a tectonically active Main Ethiopian Rift region and discharge to Awash River. Lake Beseka is not only the fastest growing unlike other lakes in the region but also unique in its water quality characteristics (Dinka, 2017; Alemayehu et al., 2006). The exceptional pollution of this lake and at the site just before it, found in this study by parameters as EC, TDS, SO_4^- and Cl^-, is in line with these findings. This is found to be due to the underlying anthropogenic (increased discharge of the hot springs and discharge of huge amount of irrigation wastewater upstream of the lake, discharges from factory and domestic sewage), natural (weathering of rocks, soil erosion, sediment loading, deposition of animal and plant debris, and solution of minerals in the basin), climatic and geologic factors (Goerner et al., 2009; Dinka, 2017).

The relationship between important land use types with respect to pollution and mean values of water quality in wet season is also visualized by **Figure 4-13** and **Figure 4-14.** Two of the land use types are tributaries to the river and one of them is the river itself, which are differentiated as Agriculture-dominated (AD), Industry-Dominated (ID) and Urban-dominated (UD). AD land use (Wonji) is the one that is a mixture of rural housing and dominantly agricultural areas. Agricultural activities typically cover the cultivation of vegetables and arable crops for subsistence consumption and large-scale irrigation schemes of sugarcane. UD land use (Abasamuel just before mixing Awash) is the one that is dominated by built-up areas of residential and commercial (encompassing a variety of industries).

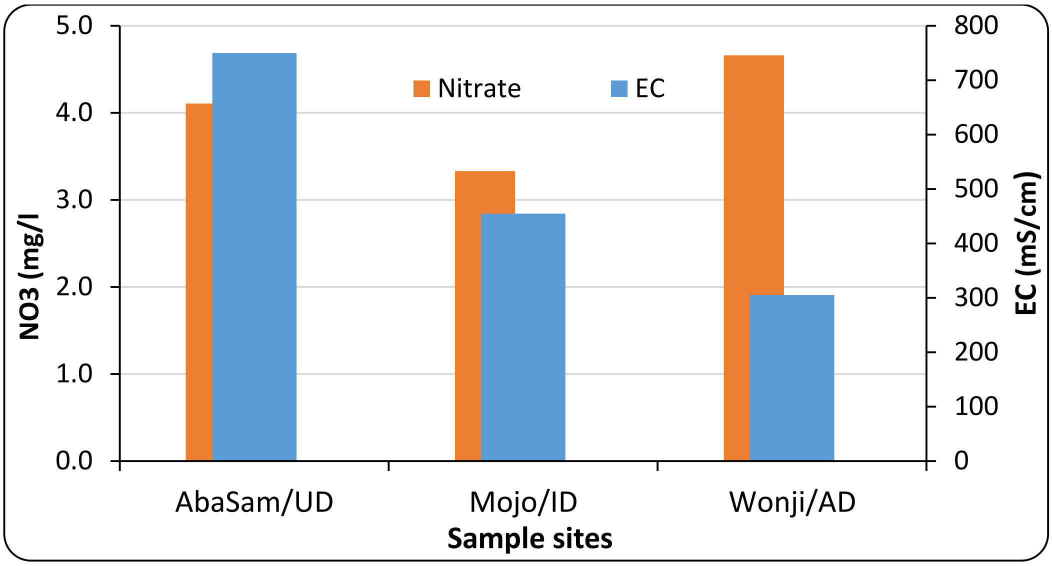


Figure 4-13 Variation of Nitrate and Electrical conductivity with landuses

ID land use (Mojo river) is also part of the built-up in the classified land use but it is a combination of partially urbanized (mostly industrial firms of various specialty) and rural settlements.

The values of Electrical Conductivity (EC) (**Figure 4-13**) for all the land-use types that is, AD (305.0 µS cm^{-1}), ID (454.3 µS cm^{-1}), and UD (750.0 µS cm^{-1}), were all within the WHO DWQG acceptable limit of 1500 µScm^{-1}. Higher magnitude of EC within the urban and industrial land uses is closely associated to the generation of acidic substances such as nitrate among other anions contained in solid wastes entering into the water bodies as well as effluent discharged from industries into water ways.

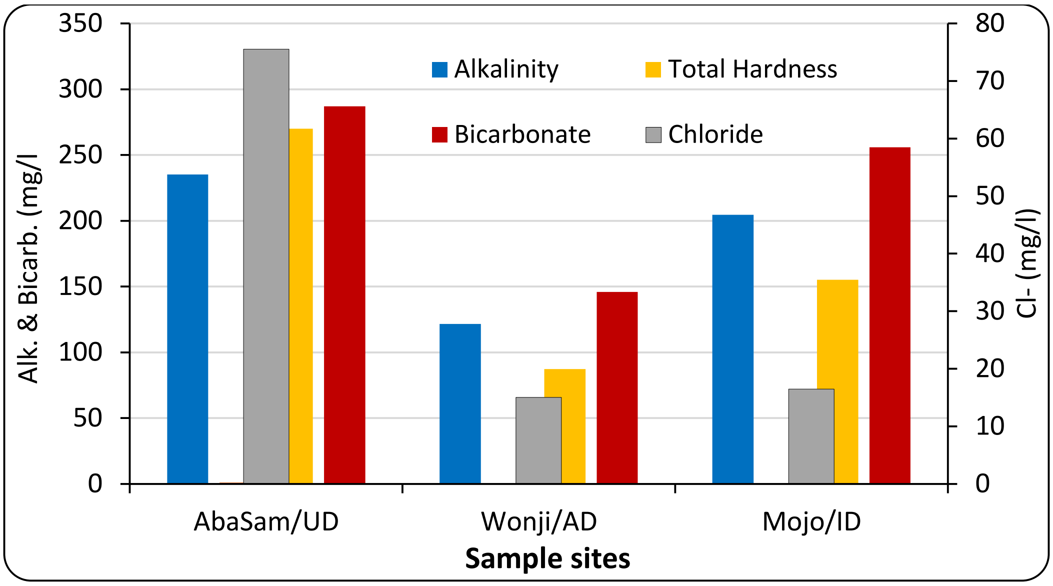


Figure 4-14 Variation of Alkalinity, Bicarbonate, Total hardness and Chloride with landuses

Increasing levels of conductivity may also be due to the existence of inorganic suspended solids in runoff as well as the presence of chloride and nitrate from sewage systems as well as the product of decomposition and mineralization of organic materials (Alemayehu, 2006, 2001, 2000). On the other hand, nitrate is observed to be higher in agriculture-dominated areas of Wonji than that in the urbanized and industrial areas although each of these generate to some extent. **Figure 4-14** generally depicts higher concentration of anions (bicarbonates and chlorides) and hardness to have been generated from urbanized areas than that from the agricultural areas. For instance, the mean chloride concentration of 75.54 mg/l was the highest in the UD land use. This could be as a result of wastewater from industries such as that of metal (Paul, 2000).

4.4 Water quality modeling

In addition to simulating flow, sediments, nutrients and other water quality determinants, the GIS-interfaced SWAT model here is also found to be a good tool to visualize the temporal and spatial changes of water quality parameters due to change in land uses. This is assisted by the model keeping all other input parameters of the model fixed since performance of the SWAT model is found to be satisfactory to very good in analyzing land use land cover changes in semi-arid environment (Kiros et al., 2015) like the study area. So, considering the three years' (1994, 2000, and 2014) land uses of the basin, the change in the water quality is examined resulting from changes in LU/LC from 1994 to 2000, from 2000 to 2014 and from 1994 to 2014.

4.4.1 Watershed delineation and characterization

ARB covers an area of about 115,055.58km^2 (11,505,558ha). Various GIS data preprocessing tasks were done beforehand. Generally, the watershed delineation task was accomplished by overlaying the Digital Elevation Model (DEM), soil, stream network, slope and land use and land cover maps. Awash basin consisted of 8 land uses, 8 soil texture classes and 5 major slope classes. There were also 20 metrological stations considered in the basin.

The DEM was used to delineate the topography, characterize the watershed and determine the hydrological parameters of the watershed such as slope, flow accumulation and direction, and stream network. The watershed delineation step discretizes the watershed in to 53 sub-basins. The sub-basins were overlaid with land uses and soil data to produce 561, 665 and 507 HRUs in running the model with the 1994, 2000 and 2014 land uses respectively but the basin having in each case constantly 53 sub-basins (**Figure 4-15**). The reason why the number of HRUs vary is that there is a slight difference in the total area of the catchment that may be obtained by buffering the watershed by different distances in the three cases (as the DEM was required to be a bit greater than the basin). The HRUs were determined by unique intersections (overlaying) of the land use and land cover, slope and soils within the watershed. This process allows capturing the heterogeneity of the physical properties. The HRUs are the spatial level at which the model computes the effect of management practices on water quality. In each sub-basin, each land use representing over 10% of the sub basin area was included in the model; also included were each soil representing 2% or more of that land use area and each land slope representing 5% or more of that land use area.

Finally, the 20 weather stations were submitted and all the necessary data were fitted to run SWAT model successfully. The model was then setup and run for the three land use land cover years 1994, 2000 and 2014.

4.4.2 The SWAT model simulation

The preliminary model was set up using drainage areas of 115055.582, 114938.084, and 115173.08km^2 respectively in the 1994 (base year), 2000 and 2014 lad uses as the threshold for delineation of the watershed. This resulted in 53 sub-basins in all cases which were characterized by dominant soil, land use, and slope (**Figure 4-15**). The initial simulation period was 1997–2014, considering the first 3 years' time (1994-1996) as a setup (warm-up) period.

Modeling of nutrients (nitrogen and phosphorus) was made after calibration and validation of SWAT's hydrology component.

4.4.2.1 Sensitivity Analysis of Flow

The first step in the process of calibration and validation of simulation results of the SWAT model is determination of the most sensitive parameters for a given basin (Arnold et al., 2012). The parameter sensitivity analysis was conducted using the global sensitivity analyses that is integrated to SWAT2012.

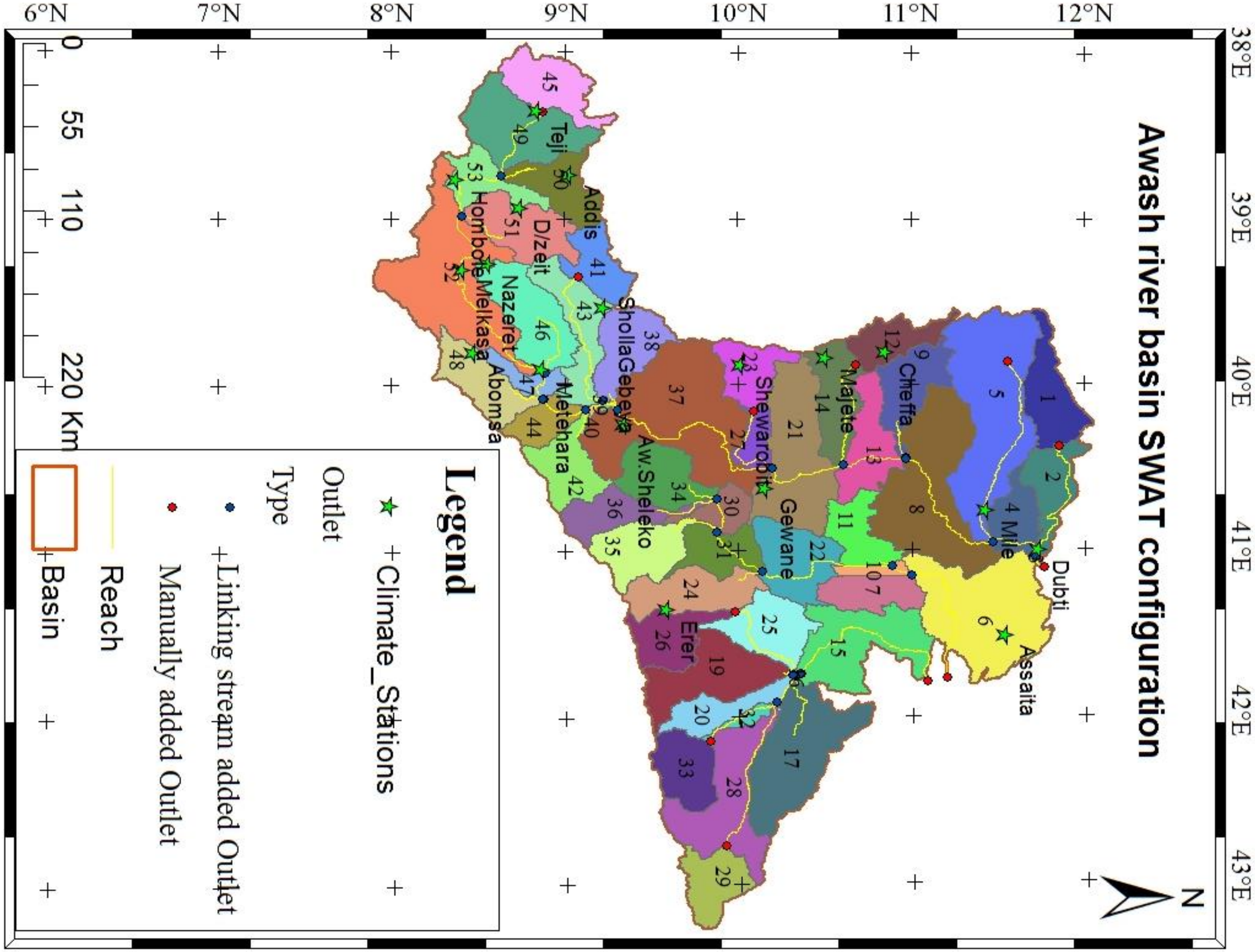


Figure 4-15 ARB SWAT Configuration with the Sub-basins and Weather Stations

Table 4-14 Selected input parameters to SWAT-CUP in the sensitivity analysis to stream flow

No.	Input Parameter Name	Description of Parameter	Min	Max	t-Stat	P-Value	Rank
1	17:V_CH_K2.rte	Effective hydraulic conductivity of channel (mm/hr)	0	0.3	-0.151	0.880	19
2	2:R_OV_N.hru	Manning's "n" value for overland flow	-0.1	1	0.213	0.831	18
3	10:V_GW_REVAP.gw	Groundwater "revap" coefficient	0.02	0.2	-0.286	0.775	17
4	18:V_ALPHA_BF.gw	Base flow alpha factor (days)	0	1	0.581	0.561	16
5	14:V_ALPHA_BNK.rte	Base flow alpha factor for bank storage (days)	0	1	0.621	0.535	15
6	6:V_SURLAG.bsn	Saturated hydraulic conductivity (mm/hr)	-10	24	0.708	0.479	14
7	9:V_REVAPMN.gw	Threshold water level in shallow aquifer for revap or percolation to deep aquifer (mm H_2O)	0	500	0.990	0.323	13
8	16:V_CH_N2.rte	Manning's "n" value for the main channel	0	15	-1.103	0.270	12
9	12:R_SOL_AWC(..).sol	Available water capacity of the soil layer (mm H_2O/mm soil)	-0.2	0.4	1.917	0.056	11
10	3:V_GW_DELAY.gw	Groundwater delay (days)	0	500	2.017	0.044	10
11	8:V_EPCO.bsn	Plant water uptake compensation factor	0.01	1	-2.091	0.037	9
12	15:V_RCHRG_DP.gw	Aquifer percolation coefficient	0	1	-2.362	0.019	8
13	13:V_ESCO.hru	Soil evaporation compensation factor	0.01	1	-2.953	0.003	7
14	19:V_GWQMN.gw	Threshold water level in shallow aquifer for base flow (mm H_2O)	0	5000	-3.122	0.002	6
15	5:R_SOL_K(..).sol	Saturated hydraulic conductivity (mm/hr)	0	2	-3.184	0.002	5
16	11:R_SOL_BD(..).sol	Bulk density of soil's first layer (Mg m^{-3})	-0.5	0.6	-5.276	0.000	4
17	4:V_SLSUBBSN.hru	Average slope length (m)	10	150	5.436	0.000	3
18	7:V_HRU_SLP.hru	Average slope steepness (fraction)	-0.5	1	-7.341	0.000	2
19	1:R_CN2.mgt	SCS runoff curve number	-15	15	-33.018	0.000	1

Explanations: V— existing parameter value is to be replaced by given value or absolute change; R— existing parameter value is multiplied by (1 + a given value) or relative change (Abbaspour, 2009). (..) first layer of soil profile.

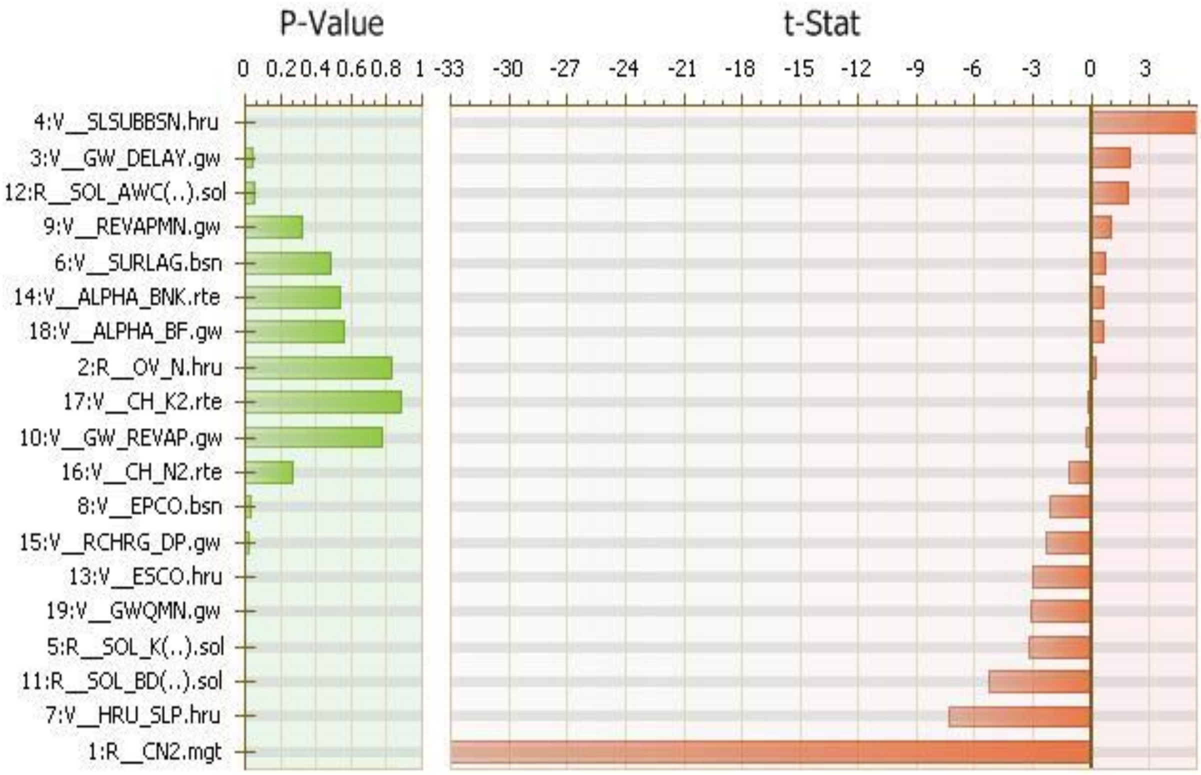


Figure 4-16 Plot of Global Sensitivity Analysis of parameters of stream flow sorted by t-Stat

Accordingly, nineteen hydrologic parameters that may have an influence on streamflow of Awash River were used in the sensitivity analysis. **Table 4-14** shows the model parameters and the sensitivity analysis result, ranked with most sensitive parameter in its last row. The parameters used were: REVAPMN.gw, SOL_AWC(..).sol, RCHRG_DP.gw, GWQMN.gw, ALPHA_BF.gw, EPCO.bsn, OV_N.hru, ALPHA_BNK.rte, SOL_K(..).sol, CH_N2.rte, GW_DELAY.gw, SURLAG.bsn, GW_REVAP.gw, CH_K2.rte, HRU_SLP.hru, CN2.mgt, SLSUBBSN.hru, ESCO.hru, and SOL_BD(..).sol,

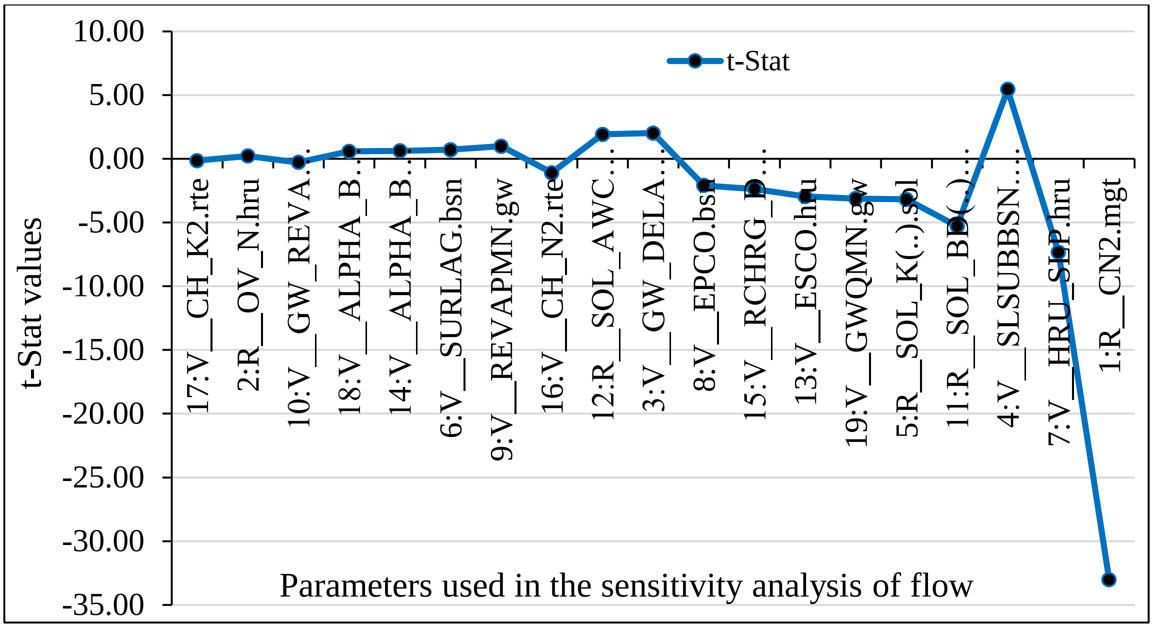


Figure 4-17 Global Sensitivity Analysis Setting of the 19 Parameters

With respect to absolute values of t-Stat values in the grid from the global SA, plotted in **Figure 4-17**, sensitivities of the parameter were ranked and put in **Table 4-14** according to (Khalid et al., 2016). Parameters of larger t-Stat in absolute values or those of p-values less than or equal to 0.05 have been taken as those to which the streamflow was most sensitive. On the basis of the p-values, ten parameters were therefore pointed out to be more sensitive, namely (in the increasing order of sensitivity); V_GW_DELAY.gw, V_EPCO.bsn, V_RCHRG_DP.gw, V_ESCO.hru, V_GWQMN.gw, R_SOL_K(..).sol, R_SOL_BD(..).sol, V_SLSUBBSN.hru, V_HRU_SLP.hru, and R_CN2.mgt. Hence, these parameters were found to be the most crucial parameters for the studied basin as they generally govern the surface hydrological processes and stream routing. The hydrology is observed to be exceptionally sensitive to curve number (CN2).

4.4.3 Quantification of the SWAT model performance

Calibration of such a large-scale model was not straight forward. Important issues to address were how to deal with the availabile input data, watershed parameterization, and uncertainties associated with input data accuracy and scarcity (flow, rainfall), model uncertainty and parameter non-uniqueness.

4.4.3.1 Monthly calibration and validation of the river flow

a) Calibration and uncertainty analysis

Three groundwater parameters (GW_REVAP.gw, RCHRG_DP.gw, GWQMN.gw), two soil parameters, (SOL_BD(..).sol and SOL_K(..).sol), one evaporation parameter (ESCO.hru), one plant water uptake parameter (EPCO.hru), one runoff parameter (CN2.mgt), and two HRU general input files (HRU_SLP.hru and SLSUBBSN.hru) were considered in the model calibration (**Table 4-15**) of the flow. Simulated monthly streamflow versus the observed streamflow is also plotted in **Figure 4-19**.

Automatic calibration of the model is handled making use of the long term monthly flow data on these ten flow determining parameters. Dataset of 1997-2005 with a 3 escape years (1994-1996) were used for calibration of the streamflow at Dubti. The resulting calibration at Dubti gaging station depicted that the 95PPU were satisfactory for monthly time series simulations of discharge (**Figure 4-18**). This is because of the fact that out of the Dubti station data, about 46% of observed stream flow is bracketed by the 95PPU band and thickness of the 95ppu measured by r-factor was found to be 0.52 a bit close to zero.

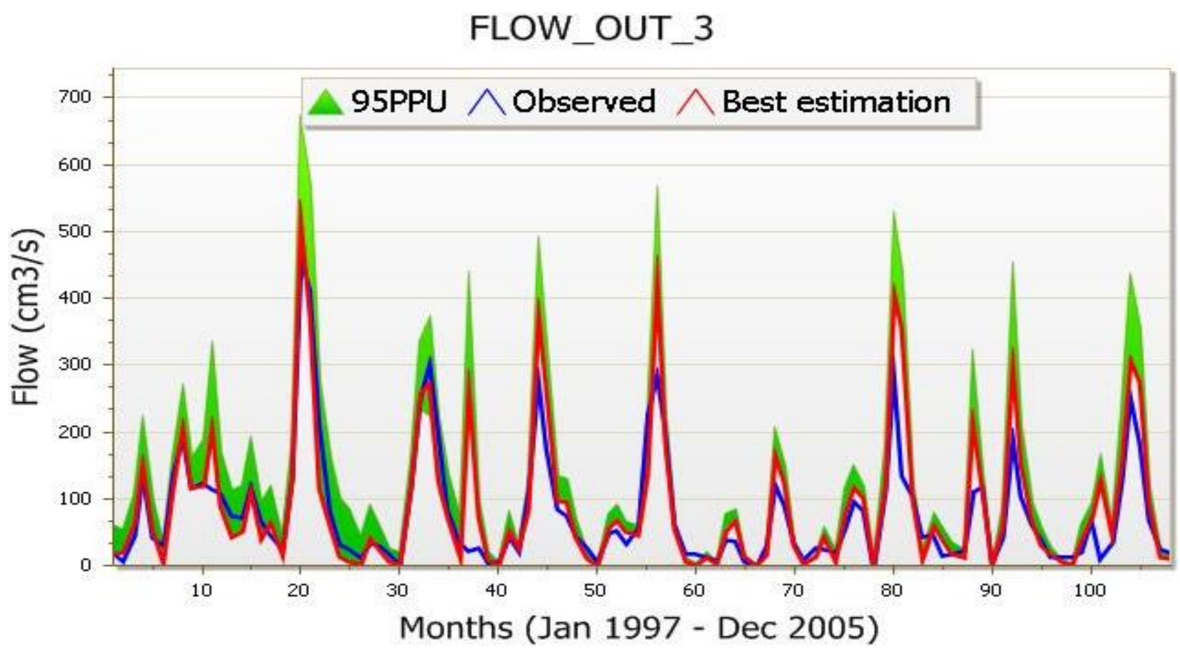


Figure 4-18 The 95ppu plot of uncertainty analysis for the monthly calibration of the flow at the basin outlet

Similarly, the discrepancy between observed and predicted streamflow was less at (R^2=0.79) and (NS=0.64) for monthly flow data (**Table 4-16**) with best parameters of fitted values shown in **Table 4-15**.

Table 4-15 Best Parameters got while calibration of streamflow

```
Goal_type=Nash_Sutcliff, No_sims=500, Best_sim_no=34,
Best_goal =6.439793e-001
```

Parameter_Name	**Fitted_Value**	**Min_value**	**Max_value**
1:R__CN2.mgt	-3.993096	-13.570066	-0.610702
2:V__GW_DELAY.gw	-397.004883	-489.422699	4.790226
3:V__SLSUBBSN.hru	133.293579	68.106537	135.798172
4:R__SOL_K(..).sol	0.788159	0.503117	1.353989
5:V__HRU_SLP.hru	-1.436584	-1.744218	-0.376954
6:V__EPCO.bsn	0.813819	0.527633	1.039593
7:R__SOL_BD(..).sol	0.148233	-0.057827	0.399069
8:V__ESCO.hru	0.048375	-0.318278	0.326104
9:V__RCHRG_DP.gw	0.041405	-0.038465	0.384129
10:V__GWQMN.gw	993.384277	618.995544	3932.170166

Table 4-16 Values of objective functions while calibrating the streamflow at the Dubti station (Outlet point)

Station	Variable	p-factor	r-factor	R^2	NSE	RSR
Dubti	FLOW_OUT_3	0.46	0.52	0.79	0.64	0.60

For the monthly calibration result of the model simulation by the 2000 LU, the values of R^2, NSE and RSR measuring goodness-of-fit were 0.79, 0.64 and 0.60 respectively shown in **Table 4-16**.

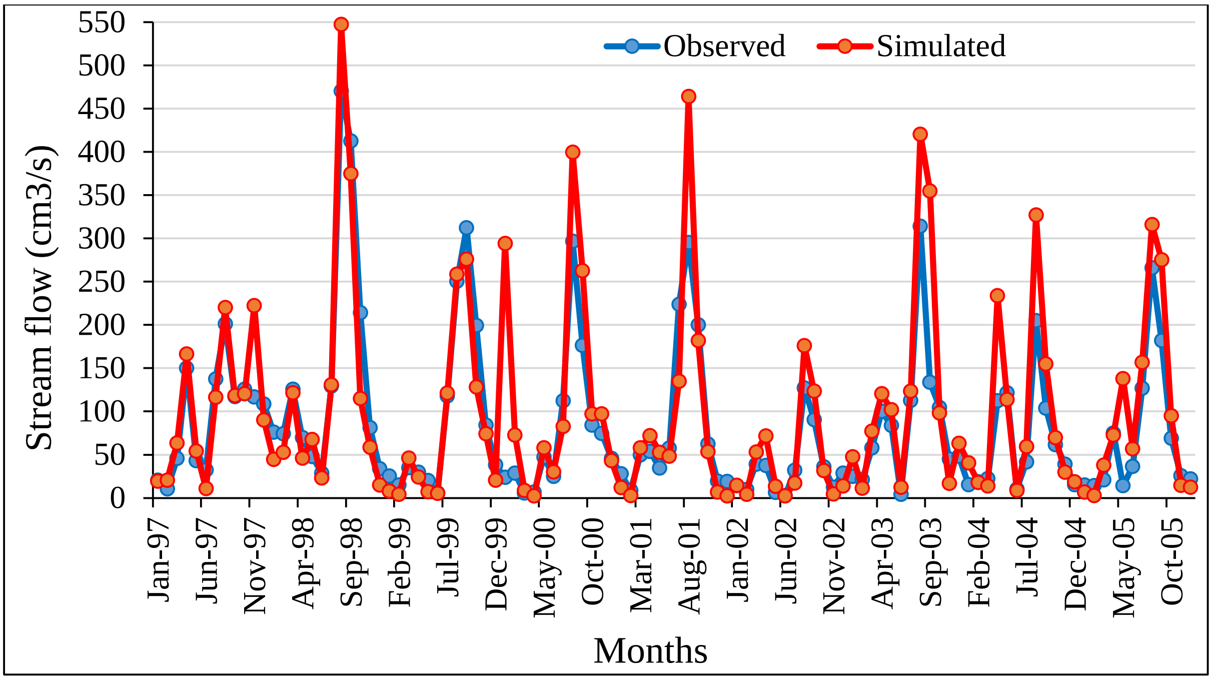


Figure 4-19. Observed and predicted hydrograph after monthly calibration of the model simulation by the 2000 LU/LC

The same model parameters of Awash basin that were used for calibrating the model run by the 2000 land use (**Table 4-14**) were also used for calibrations of the model outputs of 1994 and 2014 land uses. In order to distinguish the resulting difference in water quality from different land use/land covers, the same meteorological data from same stations was given to the SWAT model and run.

b) Validation of Flow

The validation process was performed by running the model for time periods different from that of calibration, (dataset of 2006-2014), using the previously calibrated input parameters. **Figure 4-20** show the monthly graphical performance evaluation of SWAT model during validation period. The monthly graph implied that the model simulation is best fitted with the observed flow measurement. The three goodness-of-fit measures were also calculated for the validation period.

Table 4-17 Values of objective function for validating the streamflow at the Dubti station

Station	Variable	p-factor	r-factor	R^2	NSE	RSR
Dubti	FLOW_OUT_3	0.59	0.82	0.81	0.52	0.70

For the monthly validation result of the model simulation by the 2000 LU, shown in **Table 4-17**, the values of the objective functions measuring goodness-of-fit such as R^2 and NSE were 0.81 and 0.52 respectively. Moriasi et al., (2015) in their performance evaluation criteria for recommended statistical performance measures for watershed-scale models, suggested that NSE in the range of (0.5, 0.7] to be satisfactory and R^2 in the range of (0.75, 0.85] to be good. According to these arguments, the values indicated that the model performance was good and is in the acceptable limit. Then the model is re-run with these calibrated parameters taken into account.

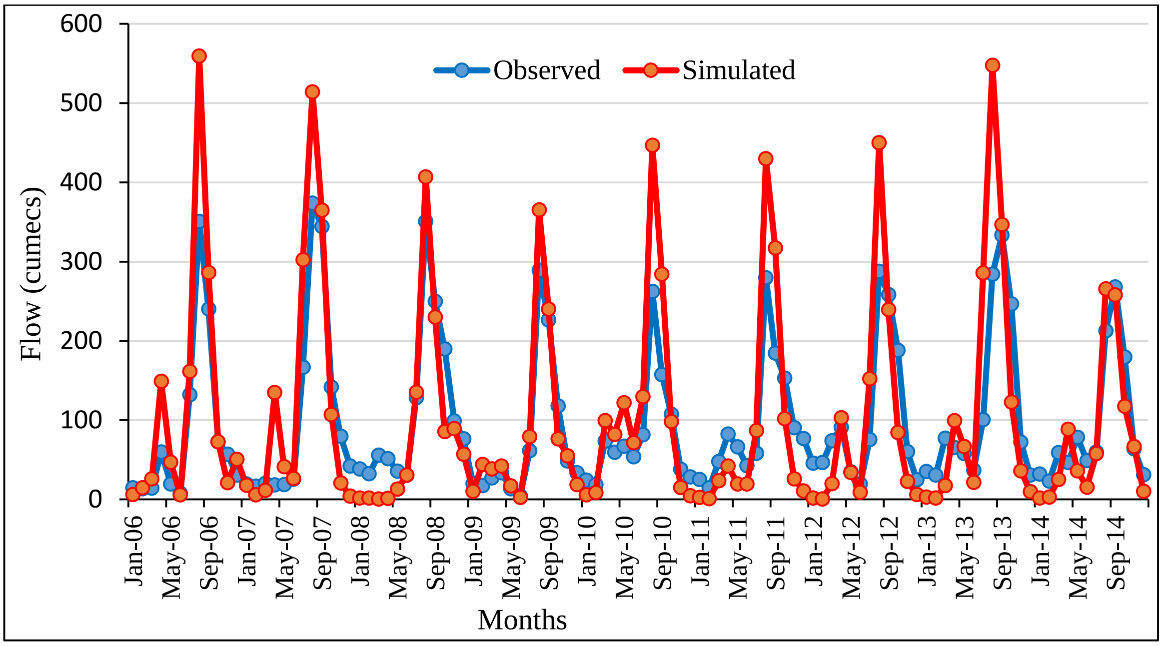


Figure 4-20. Observed and predicted hydrograph after monthly validation of the model simulation by the 2000 LU/LC

Uncertainty analysis

Different studies carried out previously to test the applicability of the SWAT model in tropical regions reported reasonable accuracy. For instance, in the Anjeni watershed of northwestern Ethiopia, Setegn et al. (2010) assessed soil loss rate using ArcSWAT model and an R^2 value of 0·9 and NSE value of 0·9 were provided as model performances for monthly time step sediment simulation. On the other hand, an NSE of 0·7 and R^2 values of 0·7 for monthly time steps, were achieved when simulating sediment yield for the Hombole watershed in central

Ethiopia (Alamirew, 2006). Results of this study also revealed that ArcSWAT model is capable of simulating various hydrological and water quality components.

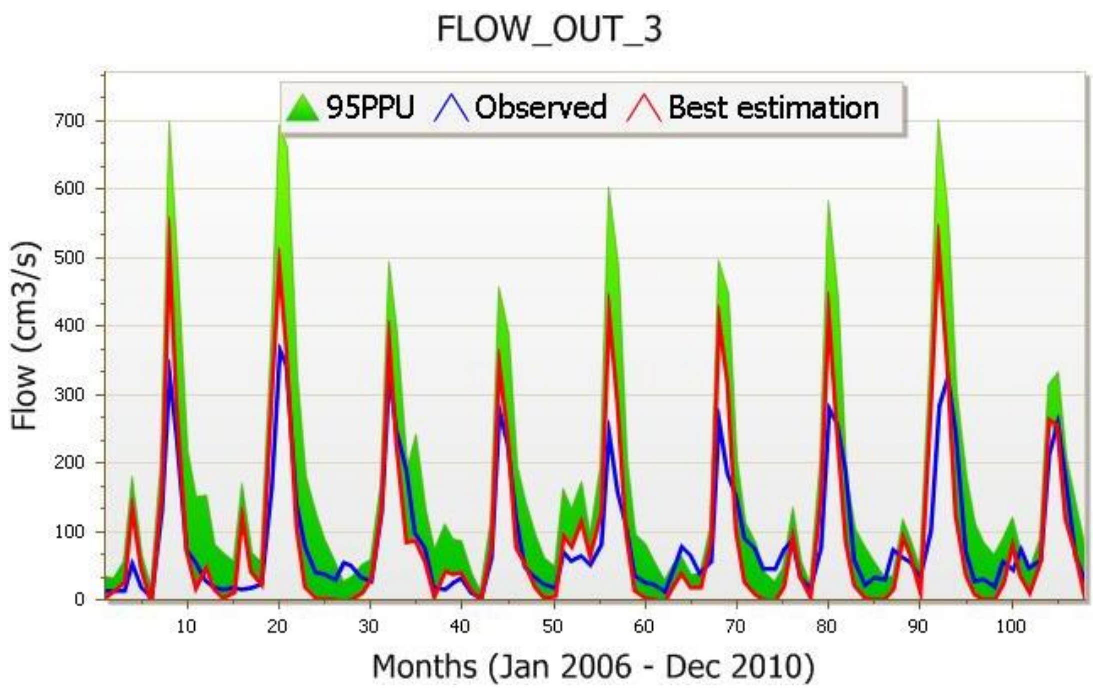


Figure 4-21 Illustration of the 95ppu plot of uncertainty analysis for the monthly validation of the flow at the basin outlet

Model efficiency during monthly calibration of the model flow simulation by the 2000 LU evaluated by R^2, NSE and RSR measuring goodness-of-fit of stream flow were respectively 0.79, 0.64 and 0.60 as shown in **Table 4-16**. Likewise, during validation 0.81, 0.52, and 0.70 were obtained as their respective values (**Table 4-17**). For monthly and watershed-scale hydrological models, Moriasi et al., (2015) and Moriasi et al., 2007 in their evaluation criteria for recommended statistical performance measures put in **Table 3-4** suggested both for calibration and validation that NSE in the range of (0.5, 0.7], in which flow NSE of the study lie, is satisfactory. Their suggestion of R^2 in the range (0.75, 0.85], where value of this study lie, indicate that the model performance is good. Similarly, RSR values of 0.60 and 0.70 generated by the SWAT-CUP program respectively during calibration and validation of flow were also in permissible ranges as its ratings as recommended by Moriasi et al., 2007 are good and satisfactory. According to the arguments by Moriasi et al., 2007 and 2015, the values of the objective functions of this study both in the calibration and validation periods indicated that the model's overall performance for flow was good and is in the acceptable limit since they conform to the standard.

There were deviations and abnormal patterns of the observed data from the corresponding months' simulated ones as could be exemplified by the 16th, 24-29th, 85th, 87th, 88th, 100th and 101st months. This may actually be due to inaccuracies in the rainfall data used in running the model. It can also probably be due to inaccurate measurement of discharge at the gaging station instead of the input rainfall data of the model. The reason why the unexpected mismatch between the observed and simulated values, which were seen especially in some months may also be due to Tendaho reservoir just upstream of the station. This stores water during the rainy season and releases afterwards (as required for development). There were some values of flow encountered both in the observed and simulated results like in Jan 2000, Aug 2000, Aug 2001, Aug 2002, Sep 2003, Apr 2004, Aug 2004, and Aug 2005 that were too far from expectations in the respective seasons. Some values of flow, e.g., increasing in Nov 1997, Sept 1999, Jan 2000, April 2004, being dry seasons and decreasing in all years of June being wet seasons. The reason for such a result in the observed flow may be due to the sudden releasing of the dam's discharge while in cause for the predicted case may be attributed to inaccuracies in the inputs to the model. Generally, the model simulation is realized to give higher values of flow than the observed ones.

Gessesse et al. (2015) had assessed the response of stream flow to changes in land use/land cover from 1973 to 2007 for the mojo watershed of the upper basin by using the same model. The flow modeling seemed to have shown better performance than that of this study as the NSE values in monthly calibration of both 1973 and 2007 LUs was 0.9 and validation of both years was 0.8 while those of this study were 0.64 and 0.52. The reason of deviating efficiency of this study from the sub-basin's counterparts may be large size of the study area, difference of the parameters tuned in the process of calibration, estimation of the flow data used for calibration. Anyway, the set standard statistical value for the model by Moriasi et al. (2007) states that the monthly time step calibration and validation for flow of NSE > 0·5 can be accepted as ‘satisfactory’. According to the standard, this study’s performance is also satisfactory and hence was proved to be acceptable.

Though bracketing of the observed data by the 95ppu (46%) seems to be somehow far from the ideal expectation of unity, thickness of the band confirmed by the r-factor value of 0.52 (close to 0) is relatively good. This implies that the model is within the acceptable range of uncertainty since it is compromised by good NSE and R^2 values. P-factor could be made as close to 1 as possible at the expense of r-factor by repeating the iteration but such actions have risks of reducing values of R^2 and NSE sometimes.

4.4.3.2 Sensitivity analysis, calibration and validation of the monthly nitrate

a. Sensitivity analysis of parameters determining NO_3^-

Out of the five major life-forming elements: nitrogen (N), carbon (C), phosphorus (P), oxygen (O), and sulfur (S), N has the greatest total abundance (more than the mass of all four of these other elements combined) in the Earth’s atmosphere, hydrosphere, and biosphere though it is the element least readily available to sustain life. However, more than 99% of this N is not available to more than 99% of living organisms because most of it exists in the form of a non-reactive, molecular nitrogen (N_2) (Galloway et al., 2003). Here one of the reactive nitrogen forms, NO_3^- is modelled by SWAT for the basin.

The relative sensitivity of different parameters to nitrate-nitrogen was analyzed. For this analysis, eighteen water quality parameters, ANION_EXCL.sol, BC1_BSN.bsn, BC2_BSN.bsn, BC3_BSN.bsn, CDN.bsn, CH_ONCO.rte, CMN.bsn, ERORGN.hru, FIXCO.bsn, N_UPDIS.bsn, NFIXMX.bsn, NPERCO.bsn, RCN.bsn, RSDCO.bsn, SDNCO.bsn, SHALLST_N.gw, SOL_NO3().bsn, SOL_ORGN().bsn (**Table 4-18**) that might have a potential influence on mineral nitrogen load of Awash River, were used in the sensitivity analysis. Setting the number of simulations to be 600, SWAT-CUP was run with these parameters.

Table 4-18 Selected input parameters to SWAT-CUP in the sensitivity analysis of NO_3

No.	Input Parameter	Description of Parameter	Min and Max Range	t-Stat	P-Value	Rank
1	V_BC1_BSN.bsn	Rate constant for biological oxidation of NH_3	0.1 - 1	-0.73	0.46	13
2	V_BC2_BSN.bsn	Rate constant for biological oxidation NO_2 to NO_3	0.2 - 2	-1.04	0.30	8
3	V_BC3_BSN.bsn	Rate constant for hydrolysis of organic nitrogen to ammonia	0.02 - 0.4	0.60	0.55	15
4	V_NFIXMX.bsn	Maximum daily-n fixation	1 - 20	-0.31	0.76	17
5	V_CMN.bsn	Rate factor for humus mineralization of active organic nitrogen	0 - 0.7	-0.47	0.64	16
6	V_NPERCO.bsn	Nitrogen percolation coefficient	0 - 1.0	-22.40	0.00	1
7	V_N_UPDIS.bsn	Nitrogen uptake distribution parameter	10 - 60.0	1.26	0.21	6
8	V_SOL_NO3.bsn	Initial NO_3 concentration in the soil layer	0 - 100	0.91	0.36	9
9	V_SOL_ORGN.bsn	Initial organic N concentration in the soil layer	0 - 100	0.74	0.46	12
10	V_RSDCO.bsn	Residue decomposition coefficient	0 - 0.5	-0.90	0.37	10
11	V_SDNCO.bsn	Denitrification threshold water content	0 - 1.0	-11.37	0.00	3
12	R_ANION_EXCL.sol	Fraction of porosity from which anions are excluded	0 - 1.0	1.31	0.19	5
13	V_CDN.bsn	Denitrification exponential rate coefficient	0 - 3	13.41	0.00	2
14	V_CH_ONCO.rte	Channel organic nitrogen concentration in basin	0 - 100	0.86	0.39	11
15	V_ERORGN.hru	Organic N enrichment ratio	0 - 1	1.15	0.25	7
16	V_FIXCO.bsn	Nitrogen fixation coefficient	0 - 1	0.70	0.48	14
17	V_SHALLST_N.gw	Concentration of nitrate in groundwater Contribution to streamflow from sub-basin	0 - 0.05	1.91	0.06	4
18	R_RCN.bsn	Concentration of nitrogen in rainfall	0 - 15	0.00	1.00	18

V-parameter value is replaced by given value or absolute change; R-parameter value is multiplied by (1 + a given value) or relative change.

Sensitivities of the parameter are ranked and put in **Table 4-18** according to Khalid et al., (2016). The table shows the model parameters, minimum values, maximum values, t-Stat, p-value and their sensitivities (ranked in its last row) with respect to absolute values of t-Stat values in the grid from the global SA plotted in **Figure 4-22**. Therefore, out of the eighteen, eight parameters are pointed out to be more sensitive to NO_3, namely (in the increasing order of sensitivity); BC2_BSN.bsn, ERORGN.hru, UPDIS.bsn, ANION_EXCL.sol, SHALLST_N.gw, SDNCO.bsn, CDN.bsn and NPERCO.bsn, as their p-values are less than or equal to 0.05 and those of little bit greater than 0.05 (t-stat value in absolute value greater than 1.0). Hence, these parameters were found to be the most crucial parameters for the studied basin as they generally govern the surface nitrate loading.

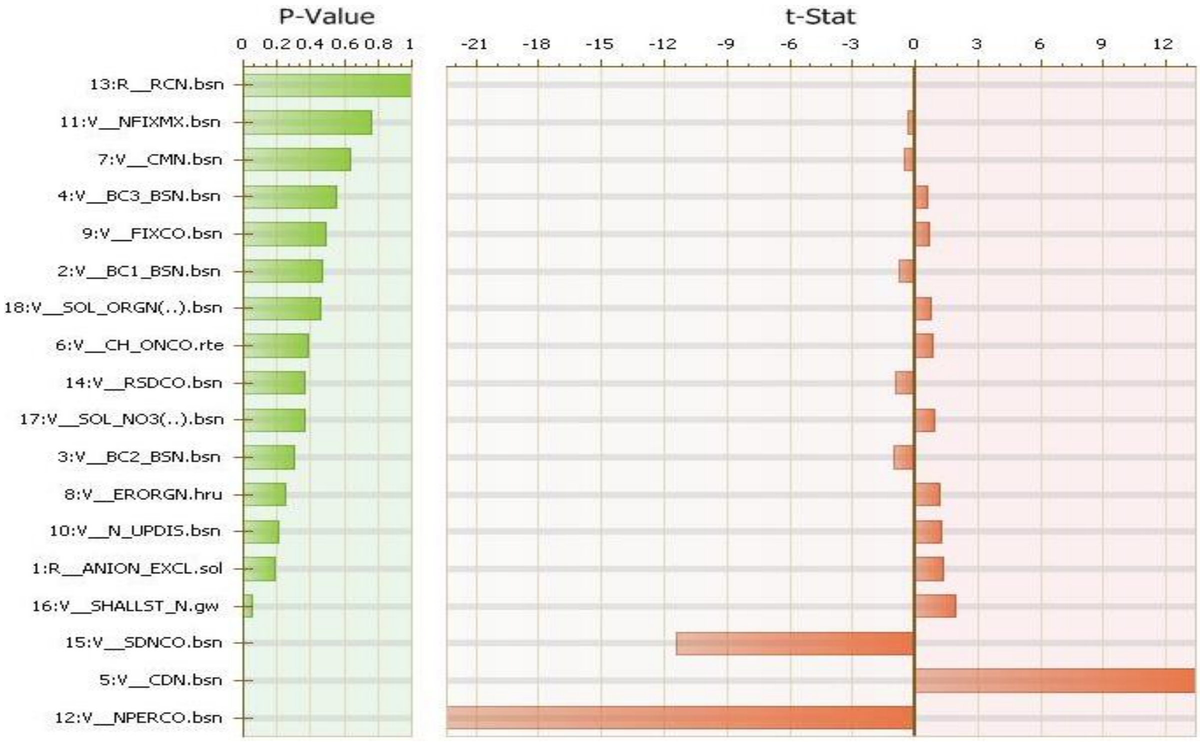


Figure 4-22 Plot of Global Sensitivity Analysis of parameters of nitrate sorted by P-values

Among the eight sensitive parameters filtered above, sensitivity analysis is again done and ranked as depicted in **Figure 4-23.** The figure shows that NO_3 was most sensitive to NPERCO followed by CDN, and then by SDNCO.

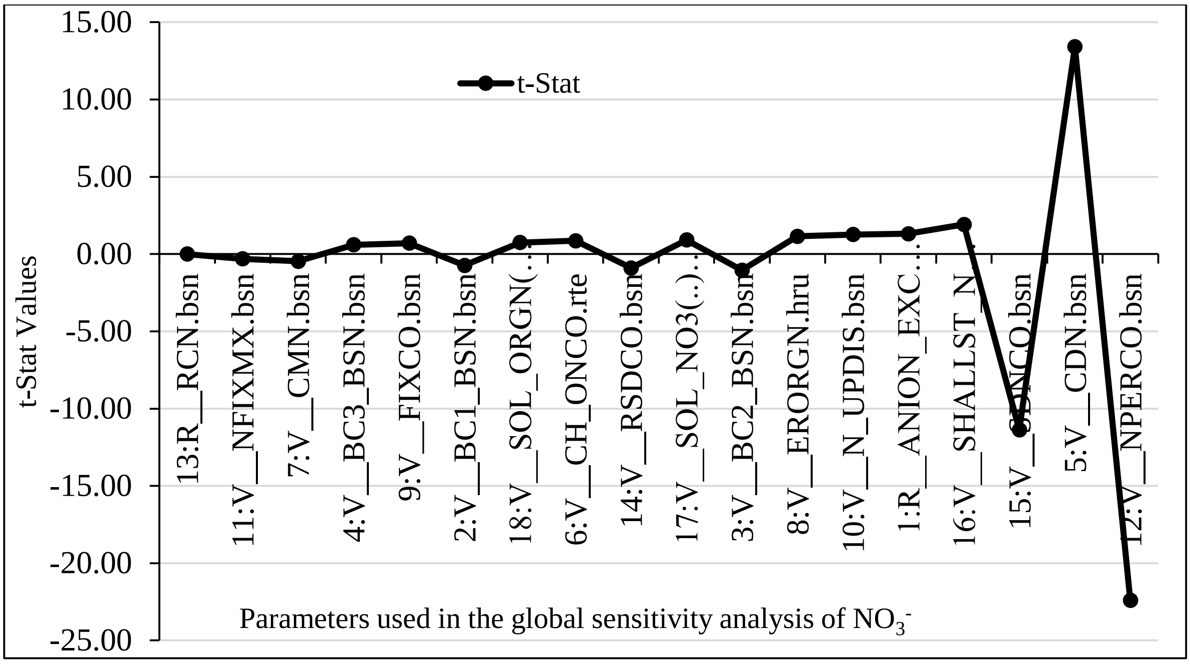


Figure 4-23 Global sensitivity analysis of parameters determining NO_3^-

b. Monthly calibration and uncertainty analysis of nitrate (NO_3^-)

After calibration and assessment of hydrologic simulations, NO_3-N-related variables reported in **Table 4-18** were adjusted during calibration to observed monthly NO_3-N concentrations. Calibration and validation of the SWAT model for NO_3-N are very important since the nitrogen components in the model are very complex and its input data requirements are intensive. Observed long-term dataset of 2006-2010 were used for calibration. The ARB SWAT model calibration and validation was made on a monthly basis using r-factor, p-factor, coefficient of determination (R^2), Nash–Sutcliffe simulation efficiency (NSE) and RSR values as measuring objective functions. With the identified sensitive parameters of minimum and maximum ranges remaining as that of the sensitivity analysis, SWAT-CUP was run for 500 simulations first. Then re-running the program now and then replacing the parameters of initial min and max ranges by the new pars generated in the previous iteration, optimum values of objective functions were obtained in the summary stat of the last iteration of the SUFI-2 algorithm.

As a first output of calibration of this iteration, the 95 percent prediction uncertainty plot is produced and is presented in **Figure 4-24**.

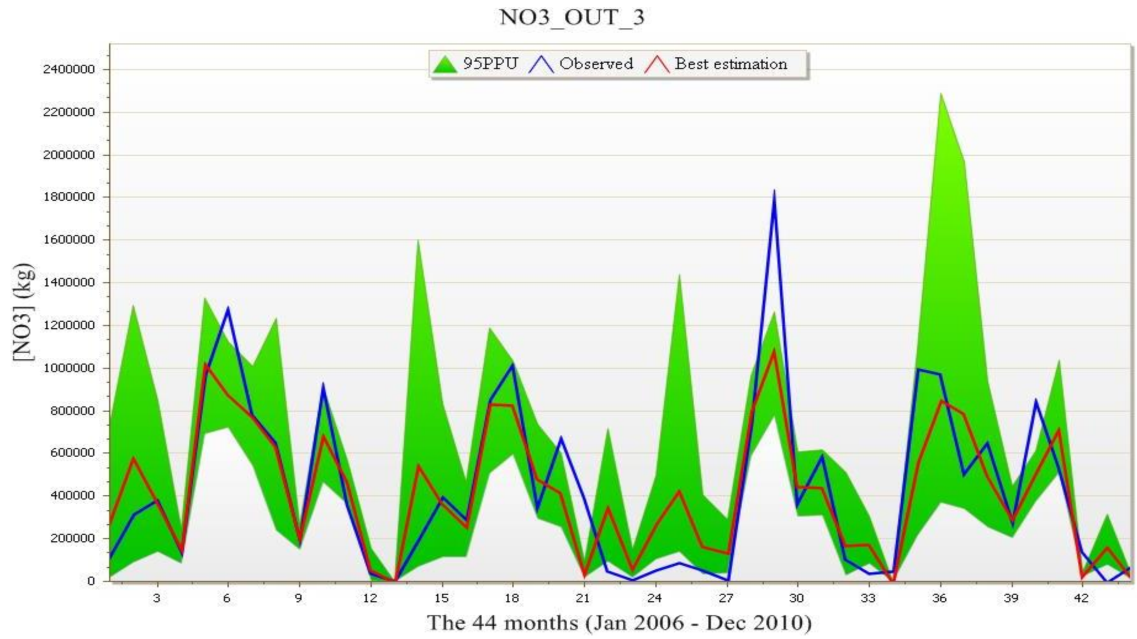


Figure 4-24 Illustration of the 95ppu of the simulated and observed monthly nitrate load carried at the basin outlet

The best parameters that produced the optimum objective functional values, their minimum and maximum values and the fitted values are put in **Table 4-19**. The model is exceptionally sensitive to nitrogen percolation coefficient (NPERCO) as can be seen by **Figure 4-23**. It is secondly most sensitive to CDN.bsn, followed by SDNCO.bsn and so on.

Table 4-19 Best parameters got while calibration of nitrate

`Goal_type= Nash_Sutcliff; No_sims= 500; Best_sim_no= 298; Best_goal = 7.120754e-001`

Parameter_Name	**Fitted_Value**	**Min_value**	**Max_value**
1:R__ANION_EXCL.sol	-0.219045	-0.226832	0.481048
2:V__BC2_BSN.bsn	1.749598	1.334103	2.110730
3:V__CDN.bsn	-0.771819	-1.233156	0.023892
4:V__ERORGN.hru	1.290814	0.811160	1.298118
5:V__N_UPDIS.bsn	82.777107	58.501129	85.148743
6:V__NPERCO.bsn	0.062949	-0.065246	0.200168
7:V__SDNCO.bsn	1.198989	1.080159	1.677293
8:V__SHALLST_N.gw	-0.001281	-0.014063	0.003471

Table 4-20 Values of objective functions while calibrating Nitrate at the Dubti station

Station	Variable	p-factor	r-factor	R^2	NSE	RSR
Dubti	NO3_OUT_3	0.64	1.24	0.73	0.71	0.54

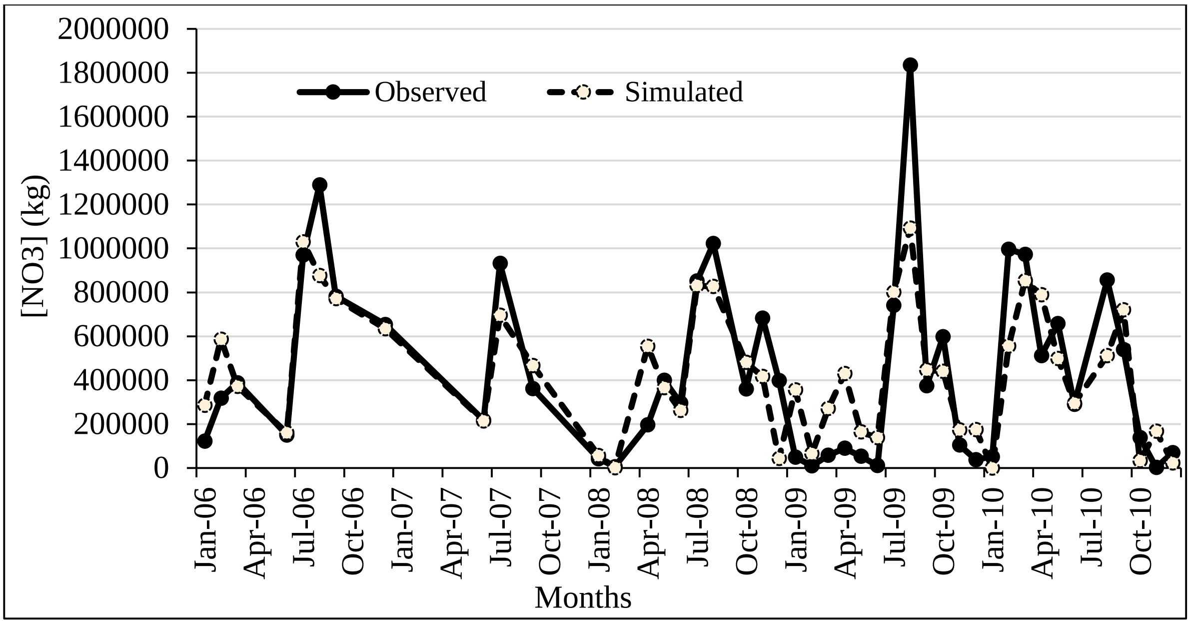


Figure 4-25 Observed and predicted Nitrate after monthly calibration by the 2000 LU

After performing 500 simulations for calibration and uncertainty analysis in the iteration that gave good measure, dotty plots were produced as an output. These plots show the distribution of the number of simulations in parameter sensitivity analysis after comparing the parameter values with the objective function (NSE) for the monthly calibrations via SUFI-2. The vertical numbered axes in the left show performance measured by NSE and the horizontal ones in each of the plots give values of the parameters **Figure 4-26**.

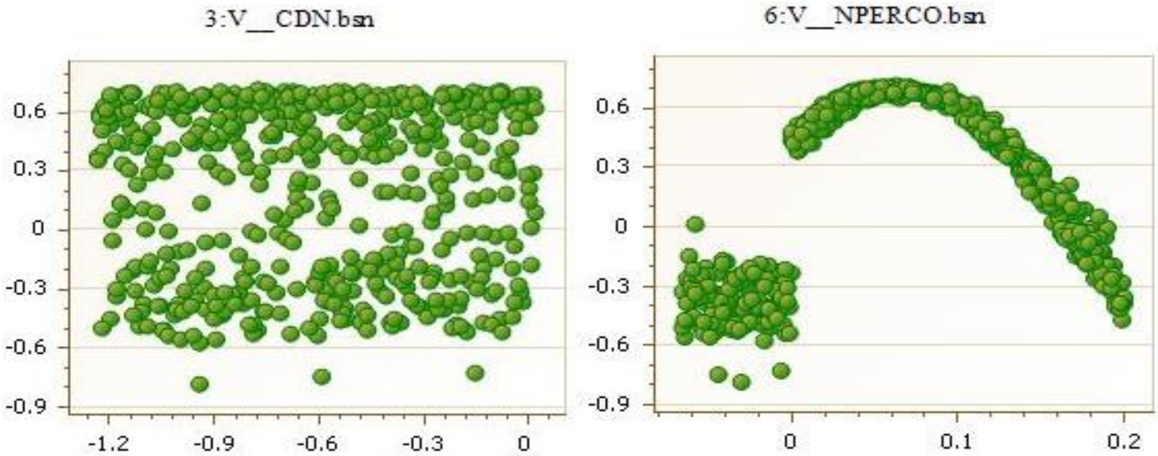


Figure 4-26 Dotty plots illustrating performance measured by NSE (vertical-y) versus values of the parameters (horizontal-x) for less sensitive (CDN) and the most sensitive (NPERCO) parameters while calibrating NO_3^-

c. **Monthly Validation of Nitrate (NO_3^-)**

The validation process was performed by running the model for time periods 2011 – 2013 using the previously calibrated input parameters. **Figure 4-27** show the monthly graphical performance evaluation of SWAT model in validating NO_3. The monthly graph implied that the model simulation is best fitted with the observed flow measurement. The three goodness-of-fit measures were also calculated for the validation period.

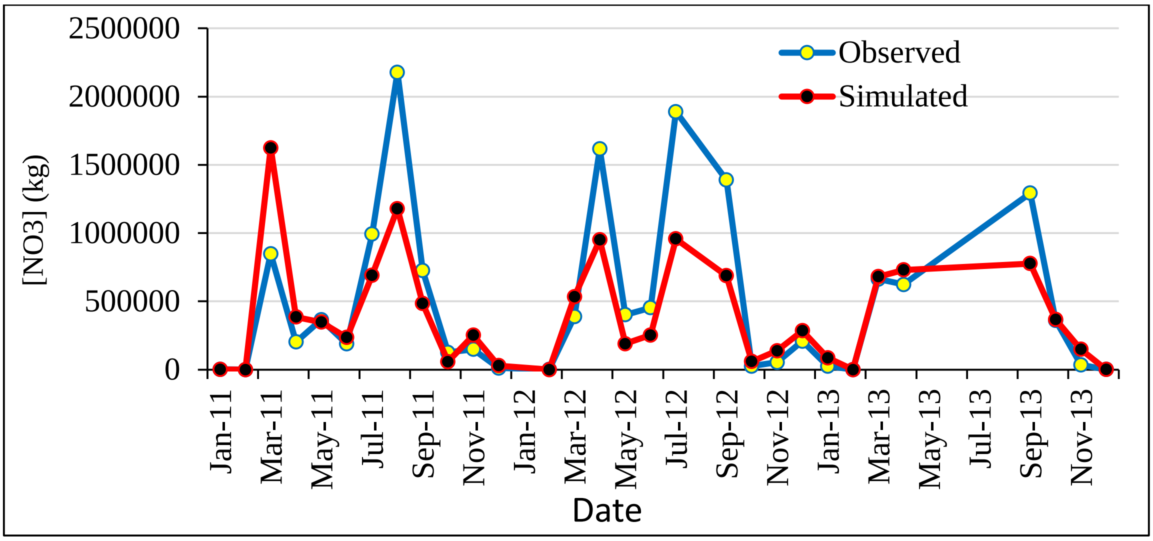


Figure 4-27 Observed and predicted Nitrate after monthly validation of the model simulation for the 2000 LU/LC scenario

Assessment of performance of the calibration process of nitrate at the presumed outlet station was undertaken in a monthly basis to see goodness-of-fit of the simulated dataset with the observed one. This monthly calibration result of the model simulation by the 2000 LU,

Table 4-21 Values of objective functions while validating the Nitrate at the Dubti station (Outlet point)

Station	Variable	p-factor	r-factor	R^2	NSE	RSR
Dubti	NO3_OUT_3	0.53	0.72	0.68	0.63	0.61

shown in **Table 4-20**, produced R^2, NSE and RSR values of 0.73, 0.71 and 0.54 respectively. While the first two measuring functions, R^2 and NSE, lie in their respective 'very good' rating ranges recommended for nutrients, the last one, RSR lies in the 'good' range of Moriasi et al., (2015) and Moriasi et al., (2007). The functional values of R^2, NSE and RSR obtained during monthly validation of NO_3, shown in **Table 4-21**, were respectively 0.68, 0.63 and 0.61. The first two numbers, however, lie in the good rating range while the third one, value of RSR, lies in the satisfactory range of **Table 3-4**. Generally speaking, all the values were found to be in an acceptable limit, indicating that the observed data fits well with the predicted ones.

There were under prediction of NO_3 in months, for instance, of August 2006, July 2007, August 2008, August 2009, and August 2010, which may be associated to the lower values of weather data (fed to the model) at the station surrounding Dubti while the actually observed one is from the water collected from sub basins upstream of the station. However, this is consistent with the under prediction of the flow by the model as could be seen in **Figure 4-20**. The p-factor in the case of nitrate has grown to 64% as opposed to that of flow at the expense of going further away of r-factor (value 1.24) from zero. Similar to the case of flow, because efficiencies, measured by NSE and R^2, of calibration of nitrate were in the acceptable ranges and the p-factor is good enough to approach to 1, the uncertainty can also be taken as in the tolerable limit.

4.4.3.3 Sensitivity analysis, calibration and validation of the monthly phosphate

a. <u>Sensitivity analysis of parameters determining mineral phosphorus (PO_4^{2-}- P)</u>

The relative sensitivity of different parameters to phosphate was analyzed. For this analysis also, seventeen phosphorus-related parameters listed in the second column of **Table 4-22** that might have a potential influence on phosphate load of Awash River were used in the sensitivity analysis.

After running 500 simulations, level of sensitivity of phosphate to the parameters was identified and the global SA for phosphate was plotted in **Figure 4-29**. With respect to absolute values of t-Stat in the grid from the global SA, sensitivities of the parameter are ranked and put in **Table 4-22** according to Khalid et al., (2016).

The table shows the model parameters and the sensitivity analysis result, with level of sensitivities ranked in its last row. Therefore, nine parameters are identified to be more sensitive, namely (in the increasing order of sensitivity (t-Stat value)); V__SOLP_CON.hru, V__PSETLP1.pnd, V__ORGP_CON.hru, R__SOL_LABP(..).chm, V__PHOSKD.bsn, V__P_UPDIS.bsn, V__SOL_ORGP(..).chm, V__BC4.swq, and V__ERORGP.hru, as their t-stat value in absolute value is greater than 1.0. Hence, these parameters were found to be the most crucial parameters for PO_4^{2-} of the studied basin as they generally govern the surface phosphate loading.

a. <u>Monthly Calibration and uncertainty analysis of Mineral Phosphorus</u>

Calibration and validation of the SWAT model for PO_4-P are equally important as that of nitrate since the phosphorus components in the model are also very complex and its input data requirements are also intensive. After calibration and assessment of the hydrology, PO_4-related variables reported in **Table 4-22** were optimized during calibration. Observed long-term dataset of 2006-2010 were used for calibration.

The ARB SWAT model calibration and validation was made on a monthly basis using r-factor, p-factor, coefficient of determination (R^2), and Nash–Sutcliffe simulation efficiency (NSE) values as measuring objective functions. With the identified sensitive parameters of minimum and maximum ranges remaining as that of the sensitivity analysis, SWAT-CUP was run for 500 simulations first.

Table 4-22 Selected input parameters to SWAT-CUP in the sensitivity analysis of PO_4^{2-}

Input Parameter	Description of Parameter	Min and Max Range	t-Stat	P-Value	Rank
PSP.bsn	Phosphorus sorption coefficient	0.01 - 0.7	-0.66	0.51	13
PHOSKD.bsn	Phosphorus soil partitioning coefficient	100 - 200	3.06	0	5

P_UPDIS.bsn	Phosphorus uptake distribution parameter	0 - 100	6.8	0	4
SOL_ORGP(..).chm	Initial organic P concentration in surface soil layer	0 - 100	-12.9	0	3
BC4.swq	Rate constant for decay of organic phosphorus to dissolved phosphorus	0.01 - 0.7	-17.7	0	2
ERORGP.hru	Organic P enrichment ratio	0 - 5	-21.4	0	1
CH_OPCO.rte	Channel organic phosphorus concentration in basin	0 - 100	-0.5	0.62	15
RSDCO.bsn	Residue decomposition coefficient	0.02 - 0.1	-0.88	0.38	10
PSETLP1.pnd	Phosphorus settling rate in pond for months IPND1 through IPND2	0 - 20	-1.15	0.25	8
PSETLW2.pnd	Phosphorus settling rate in wetlands for months other than IPND1-IPND2	0 - 20	-0.01	0.99	17
PSETLP2.pnd	Phosphorus settling rate in pond for months other than IPND1-IPND2	0 - 20	-0.62	0.54	14
PSETLW1.pnd	Phosphorus settling rate in wetland for months IPND1 through IPND2	0 - 20	0.67	0.5	12
SOL_LABP(..).chm	Initial labile (soluble) P concentration in surface soil layer	0 - 100	-1.84	0.07	6
SOLP_CON.hru	Soluble phosphorus concentration in runoff, after urban BMP is applied	0 - 3	1.14	0.26	9
GWSOLP.gw	Concentration of soluble phosphorus in groundwater contribution to streamflow from sub-basin	0 - 0.5	0.22	0.83	16
ORGP_CON.hru	Organic phosphorus concentration in runoff, after urban BMP is applied	0 - 50	1.69	0.09	7
PPERCO.bsn	Phosphorus percolation coefficient	9.04 - 16.45	0.72	0.47	11

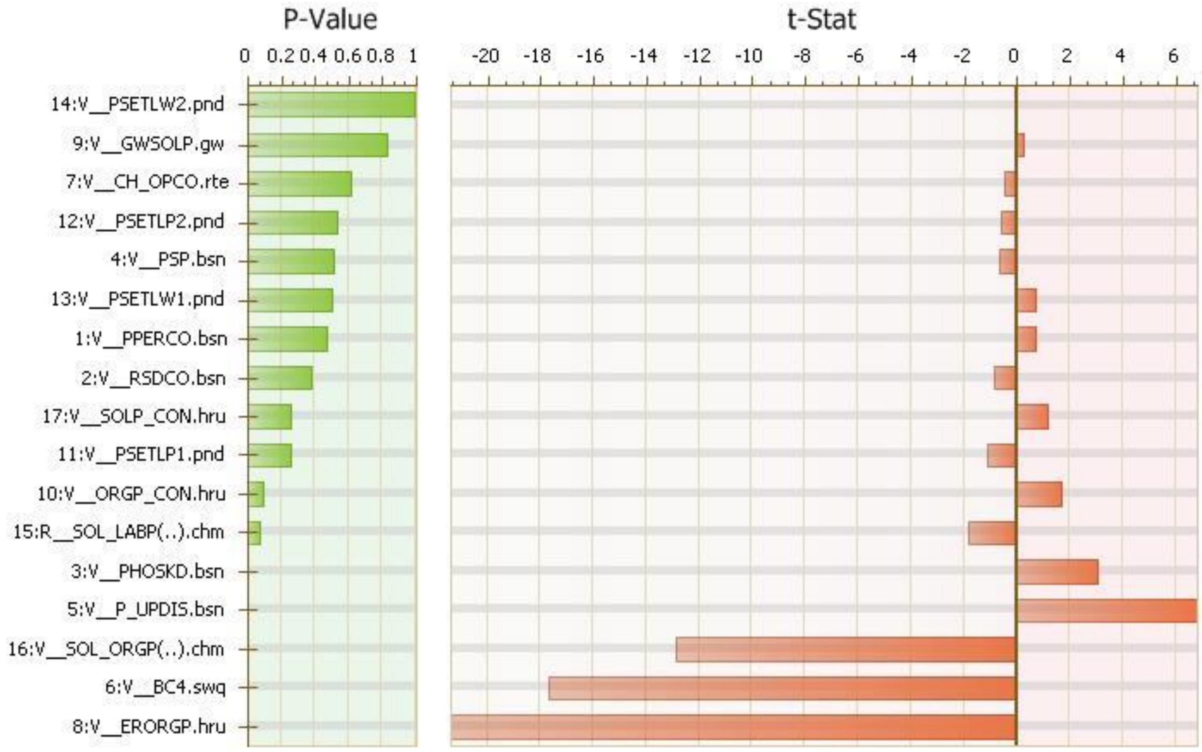


Figure 4-28 Plot of Global Sensitivity Analysis of parameters of phosphate sorted by P-values

Then re-running the program now and then replacing the parameters of initial min and max ranges by the new pars generated in the preceding iteration, optimum values of objective functions were obtained in the summary stat of the last iteration of the SUFI-2 algorithm. Accordingly, the resulting best parameters offering the required objective functional values together with their respective fitted values, and min and max values of the parameters are given in **Table 4-23**.

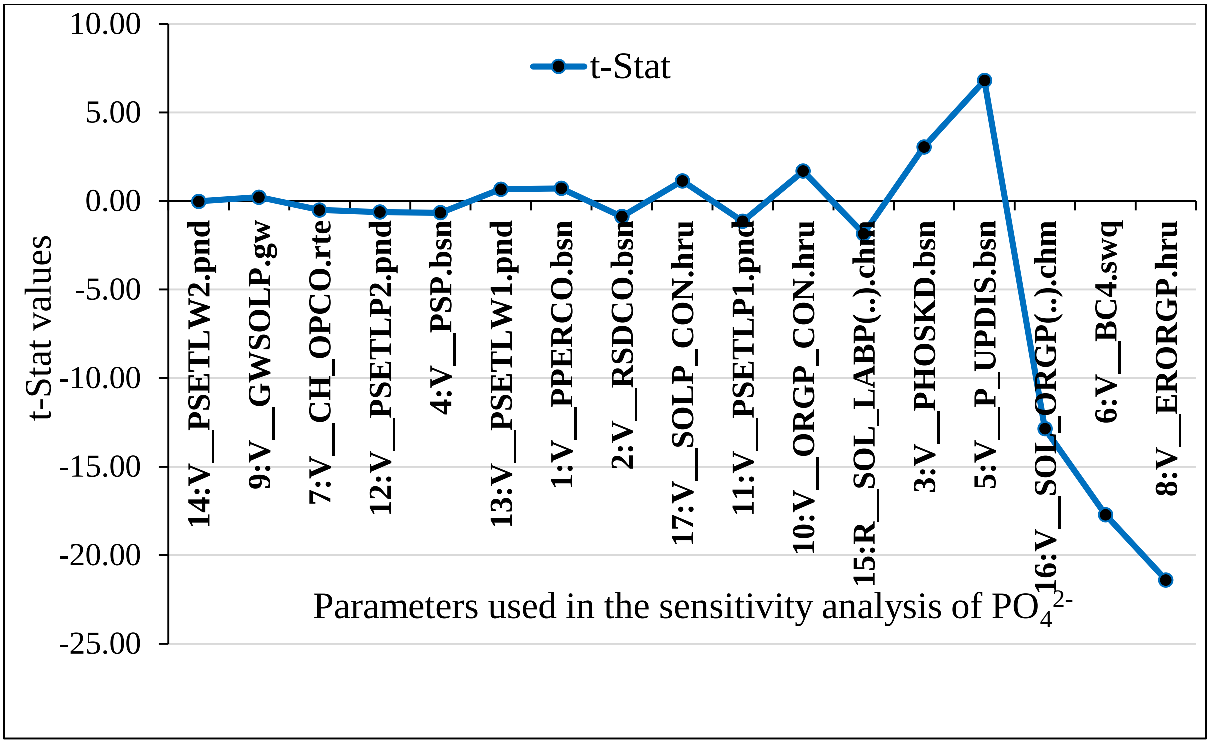


Figure 4-29 Global sensitivity analysis of parameters determining PO_4^{2-}

Table 4-23 Best parameters got while calibration of phosphate

Goal_type= Nash_Sutcliff, No_sims= 500, Best_sim_no= 9, Best_goal = 7.612467e-001

Parameter_Name	**Fitted_Value**	**Min_value**	**Max_value**
1:V__PHOSKD.bsn	168.441025	117.639984	172.560028
2:V__P_UPDIS.bsn	42.802216	25.139648	75.460350
3:V__BC4.swq	0.594467	0.309038	0.907422
4:V__ERORGP.hru	0.150025	-2.043099	2.653099
5:V__ORGP_CON.hru	43.735344	24.320002	72.980003
6:V__PSETLP1.pnd	5.808162	2.928020	14.311979
7:R__SOL_LABP(..).chm	50.610909	-7.859918	64.059921
8:V__SOL_ORGP(..).chm	-20.041847	-37.560593	54.160591
9:V__SOLP_CON.hru	1.933549	1.180195	3.541805

The resulting performance of the model after calibrating gives respective values of the objective functions given in **Table 4-24**.

Table 4-24 Values of objective functions while calibrating phosphate at the Dubti station

Station	Variable	p-factor	r-factor	R^2	NSE	RSR
Dubti	PO4_OUT_3	0.32	1.34	0.77	0.76	0.49

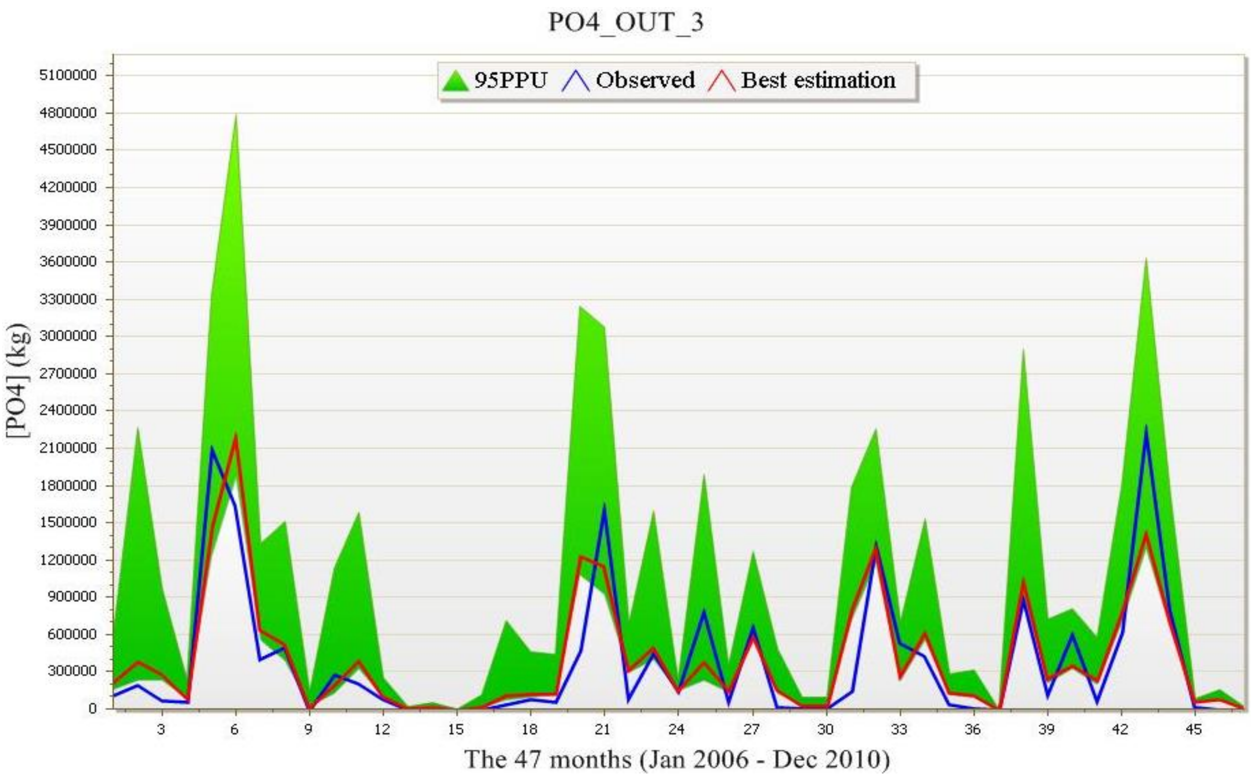


Figure 4-30 Illustration of the simulated and observed monthly mineral phosphorus loads at the basin outlet

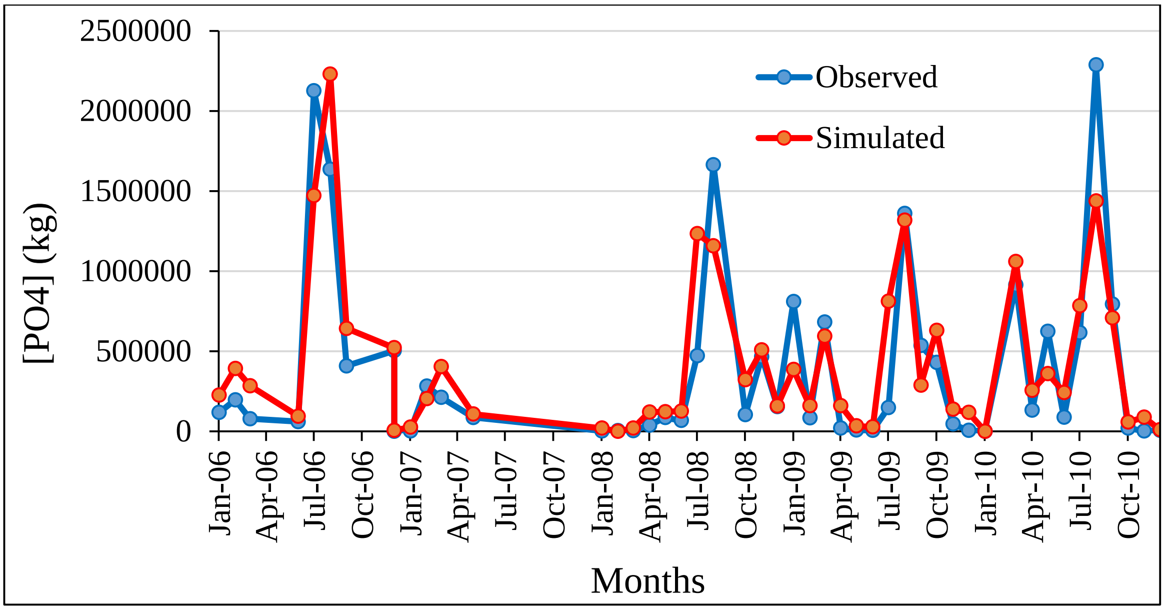


Figure 4-31 Observed and predicted phosphate after monthly calibration of the model simulation by the 2000 LU

The table tells us that the functions measure the model to perform very good since the Nash Sutcliffe Efficiency and R^2 values respectively of 0.76 and 0.77 are above 0.65 and 0.70. These results show the fact that there is a very good fit between the simulated and the observed concentrations as the calibration output is depicted by **Figure 4-31**.

After performing 500 simulations in the iteration that gave good performance, dotty plots were produced as an output. These plots show the distribution of the number of simulations in parameter sensitivity analysis after comparing the parameter values with the objective function (NSE) for the monthly calibrations via SUFI-2. The vertical axes show performance (measured by NSE) and the horizontal line gives values of the parameters as can be seen in **Figure 4-32**.

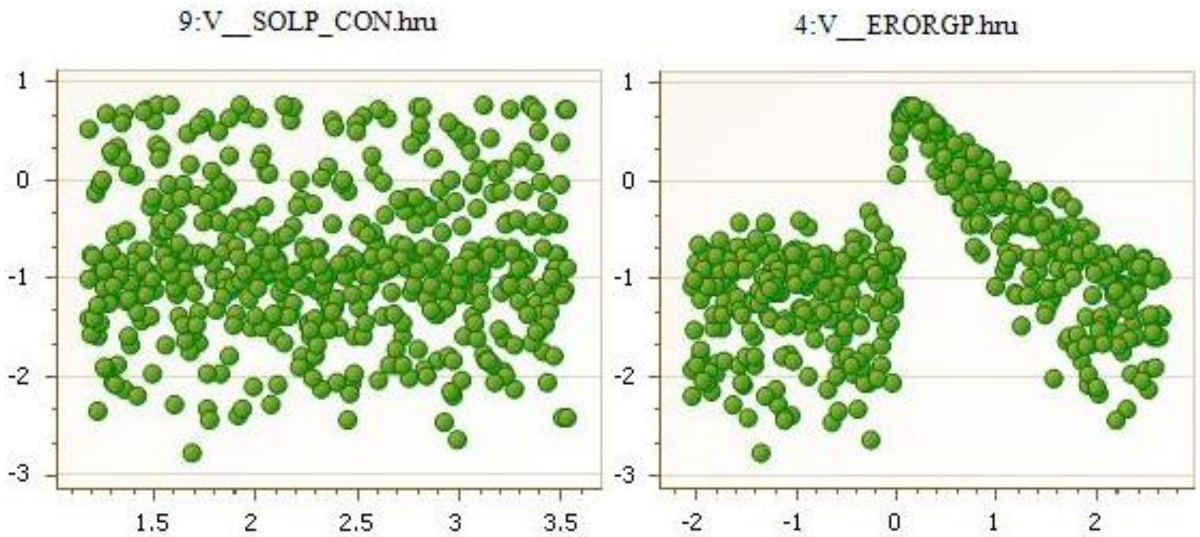


Figure 4-32 Dotty plots illustrating performance measured by NSE (vertical-y) versus values of the parameters (horizontal-x) for less sensitive (SOL_CON) and the most sensitive (ERORGP) parameters while calibrating PO_4^{2-}

b. Monthly Validation of Mineral Phosphorus (PO_4^{-2})

The validation process was performed by running the SWAT-CUP for time periods 2011 – 2013 using the previously calibrated input parameters. **Figure 4-33** show the monthly graphical performance evaluation of SWAT model in validating PO_4^{2-}. The monthly graph implied that the model simulation is best fitted with the observed phosphate measurement. The three goodness-of-fit measures were also calculated for the validation period.

Table 4-25 Values of objective functions while validating the phosphate at the Dubti station

Station	Variable	p-factor	r-factor	R^2	NSE	RSR
Dubti	PO_4_OUT_3	0.33	1.09	0.82	0.81	0.44

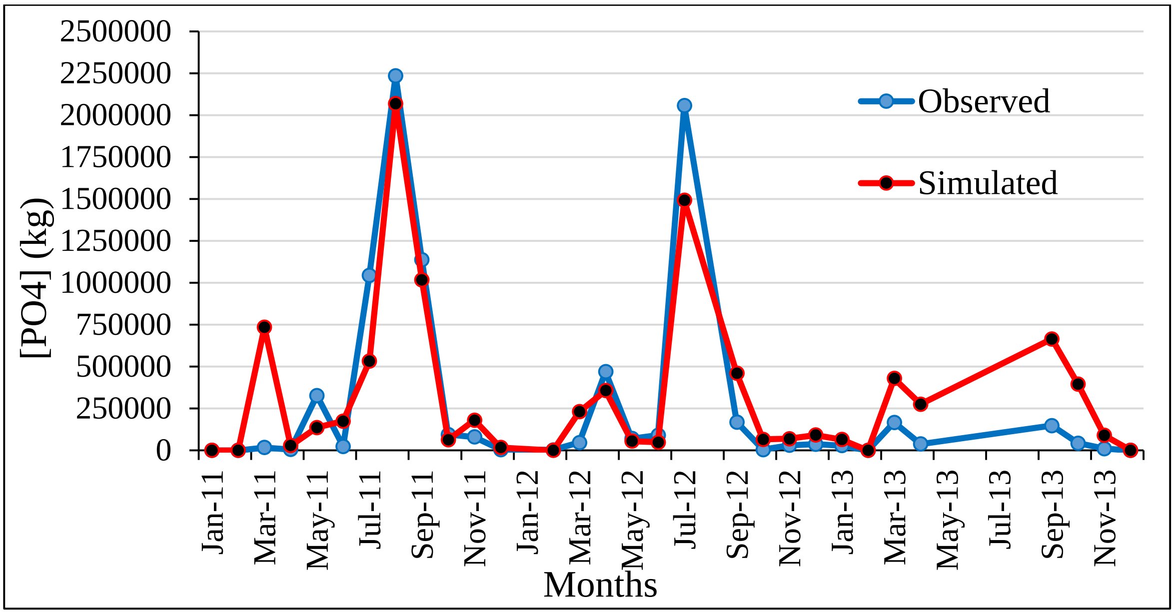


Figure 4-33 Observed and predicted phosphate after monthly validation of the model simulation by the 2000 LU/LC scenario

Monthly calibration of the model simulation of phosphate by the 2000 LU was also evaluated for goodness-of-fit and shown in **Table 4-24**. Values of the performance measuring statistics: R^2, NSE and RSR were 0.77, 0.76 and 0.49 respectively. According to **Table 3-4**, their performance ratings were all 'very good'. On the other hand, the values for the respective objective functions during validation, shown in **Table 4-25**, were 0.82, 0.81 and 0.44, which all are also in the 'very good' rating ranges for nutrients. This implies that the predicted mineral phosphorus agrees nicely to the observed one. Similarly, phosphate prediction is also seen to be less than the observed ones in wet seasons as in the case of August 2008 and August 2010 during calibration and as in July 2012 and August 2011 during validation. The under-prediction of phosphorus loading could be due to the fact that P from atmospheric deposition and stream banks were not taken into consideration in the SWAT model.

Here in the validation the evaluating statistics of the model, R^2 and NSE, were slightly better than those got in the calibration. This shows that the model has an ability to mimic discharge and phosphate load in a wide range of hydrologic conditions.

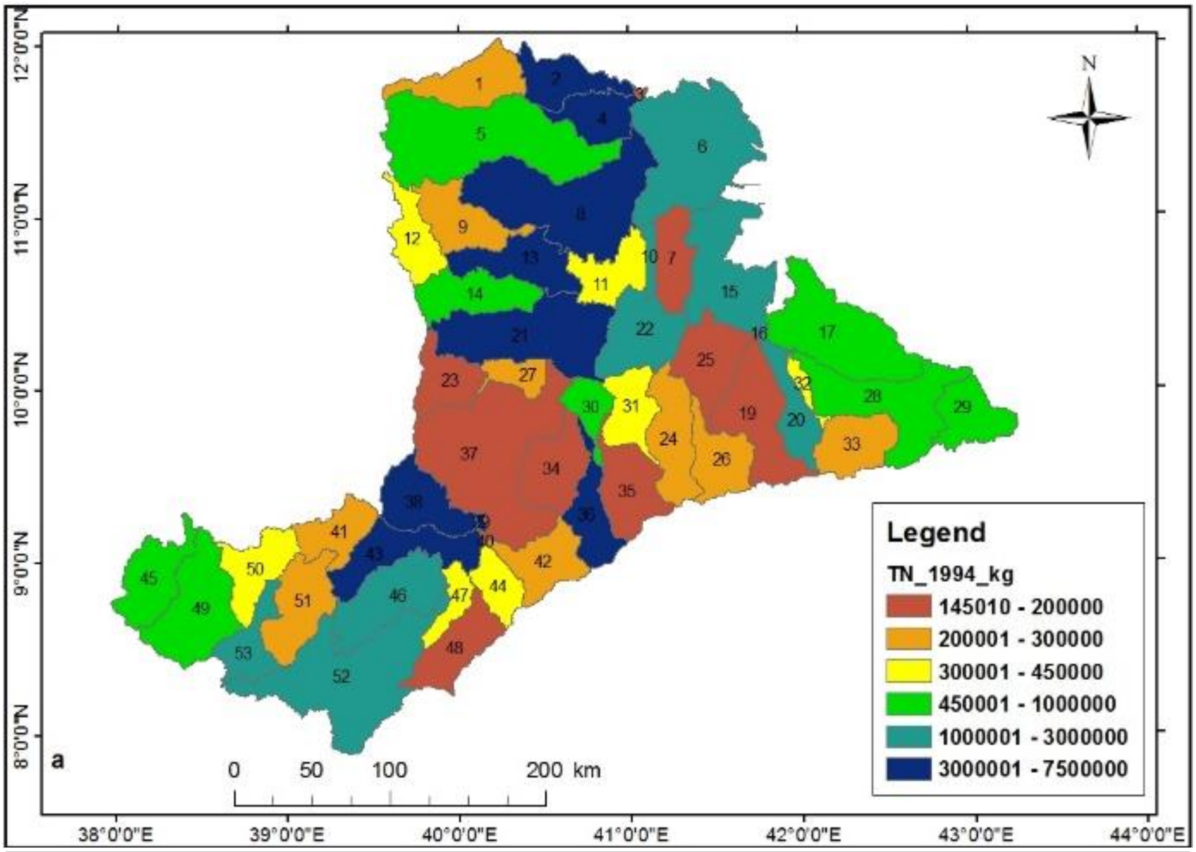
4.4.4 Distribution of nutrients temporally and spatially

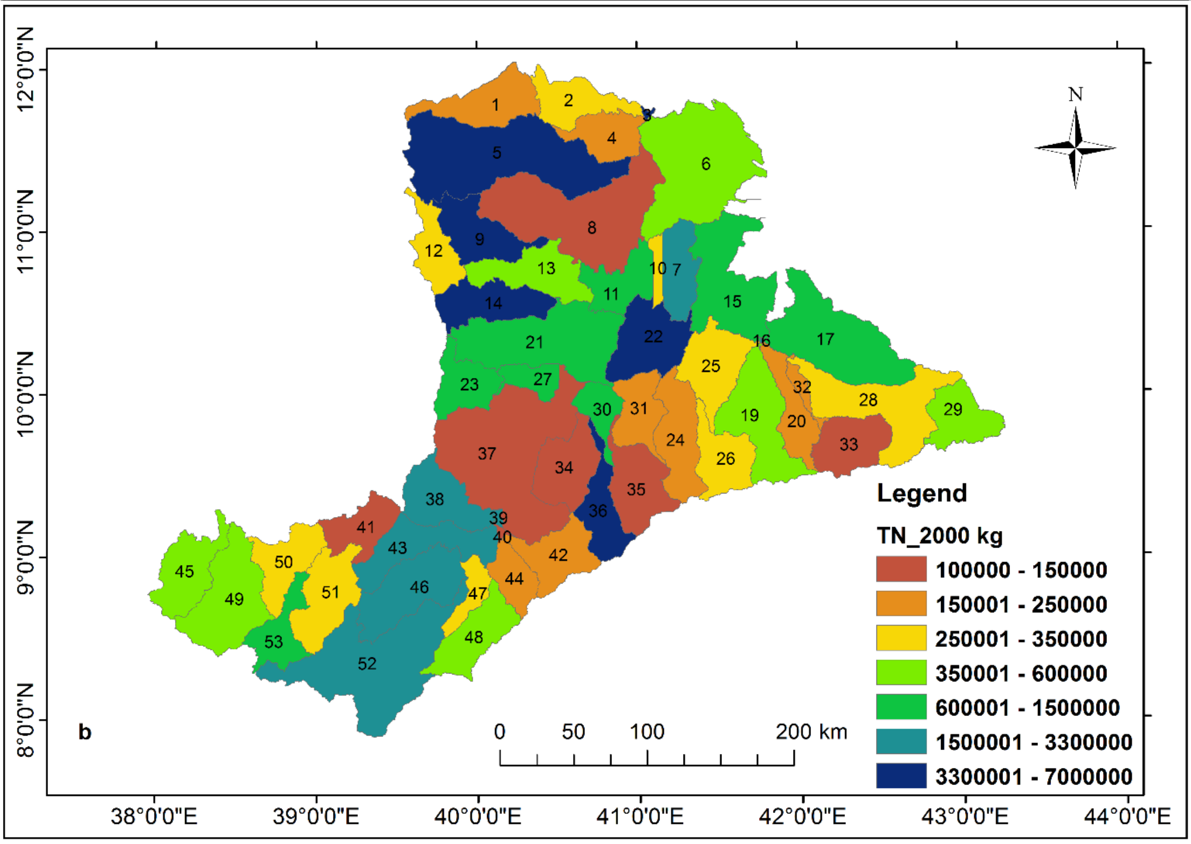
After setting up and running SWAT model, the most sensitive parameters were identified, and then calibration and validation were performed. Modeling the water quality (nutrients) of Awash River was carried out following calibration of stream flow of the basin. Following the calibration and validation of the model simulations (including those resulted from 1994 and 2014 land uses), re-running of the model for all the three scenarios is undertaken. Pivot table of the MS excel has made the huge output of the model too summarized and manageable. The 'rch' file of the database that resulted from re-running the model after calibration offered information enabling us to judge if there were either increasing or decreasing changes of nutrients with time and space.

4.4.4.1 Subbasin-based (spatial) distribution and comparative analysis of nutrients and hotspot areas of pollution

With the help of SWAT output viewer, the spatial variations of nutrients produced by all the three years' land uses have been investigated.

The 53 subbasins have been scrutinized for their exportation of nutrient loads. Comparison of the nutrient loadings among the sub-basins suggest generally that the western highlands take the major share of export (**Figure 4-34** and **Figure 4-35**). About 5.92 kg/ha of NO_3, 5.89 kg/ha of PO_4^{2-}, 39.16 kg/ha of TN and 12.5 kg/ha of TP are found to be exported annually from the basin as computed by the 2000 LU. Subbasins in the western side adjacent to the river in the middle and lower subbasins are shown to produce largest TN and TP in kg per subbasin. Specifically, subbasins 4, 8, 13, 21 and 39 are hotspots both in 1994 and 2014 with respect to TN and TP.


a
N
Legend
TN_1994_kg
145010 - 200000
200001 - 300000
300001 - 450000
450001 - 1000000
1000001 - 3000000
3000001 - 7500000
0 50 100 200 km
38°0'0"E
39°0'0"E
40°0'0"E
41°0'0"E
42°0'0"E
43°0'0"E
44°0'0"E
8°0'0"N
9°0'0"N
10°0'0"N
11°0'0"N
12°0'0"N


b
N
Legend
TN_2000 kg
100000 - 150000
150001 - 250000
250001 - 350000
350001 - 600000
600001 - 1500000
1500001 - 3300000
3300001 - 7000000
0 50 100 200 km
38°0'0"E
39°0'0"E
40°0'0"E
41°0'0"E
42°0'0"E
43°0'0"E
44°0'0"E
8°0'0"N
9°0'0"N
10°0'0"N
11°0'0"N
12°0'0"N

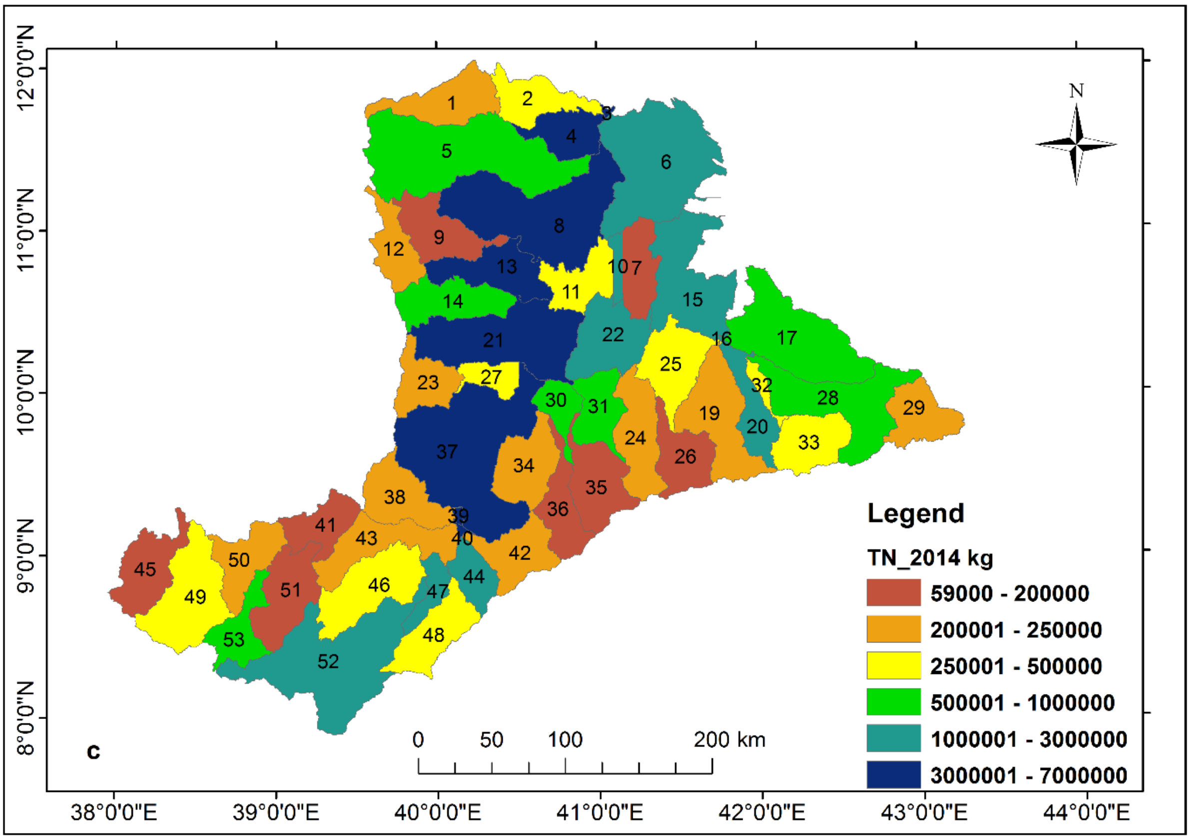
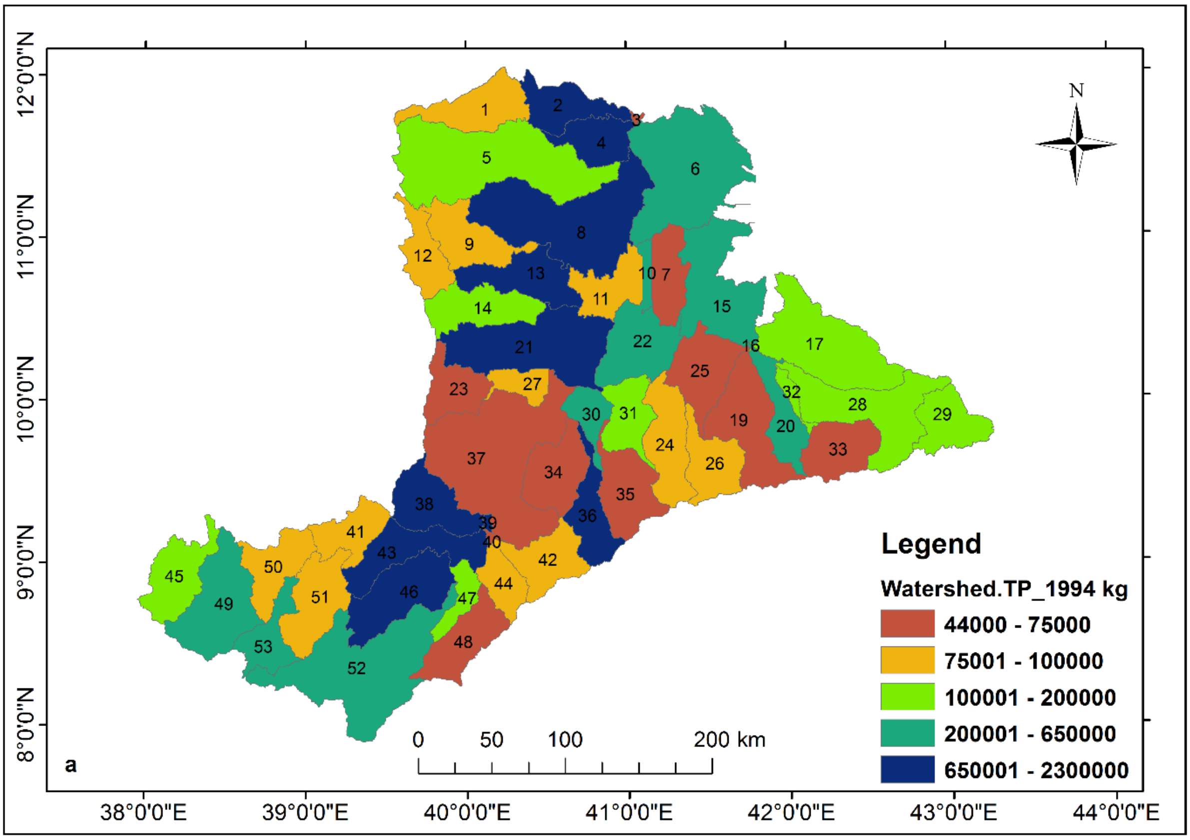


Figure 4-34 Spatial distribution of total nitrogen in kg per sub-basin simulated from the 1994 (a), 2000 (b) and 2014 (c) LU's



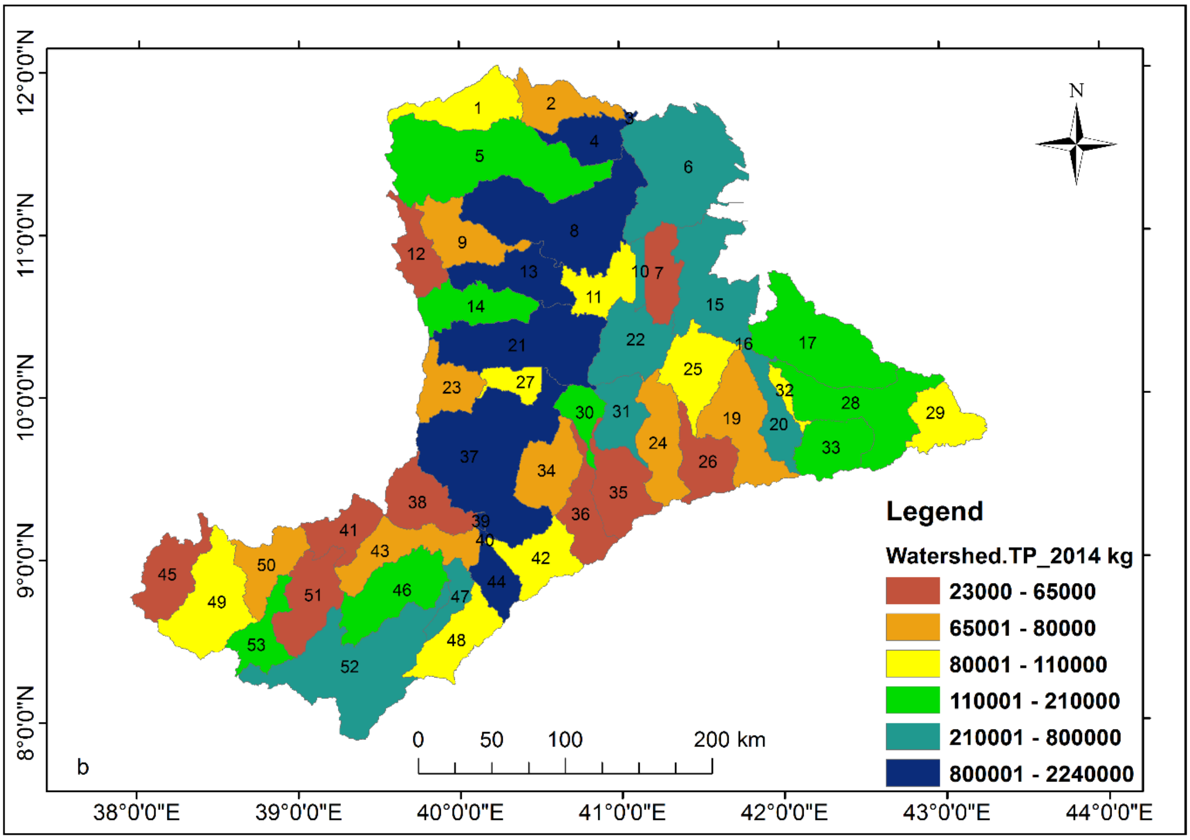


Figure 4-35 Spatial distribution of total phosphorus in kg per sub-basin simulated from the 1994 (a), and 2014 (b) LUs

4.4.4.2 Temporal variation of nutrients as LU changes from 1994 to 2014

Dynamics of nutrients was explored by considering the monthly averages overall the years from 1997 to 2014 of sub-basin 3. From this examination, it is found that the rainy months are exporting higher amounts of nutrients. One can observe from **Figure 4-36** that the three months, March, July and August, account for about 58% and 54% of TN and NO_3^- respectively from the total annual while only the two, July and August, account for about 45% and 41% of the respective parameters. On the other hand, only these two months account for 47% and 47.8% of the TP and PO_4^{2-} losses respectively while the three, including March, account both for 60% of the TP and PO_4^{2-}.

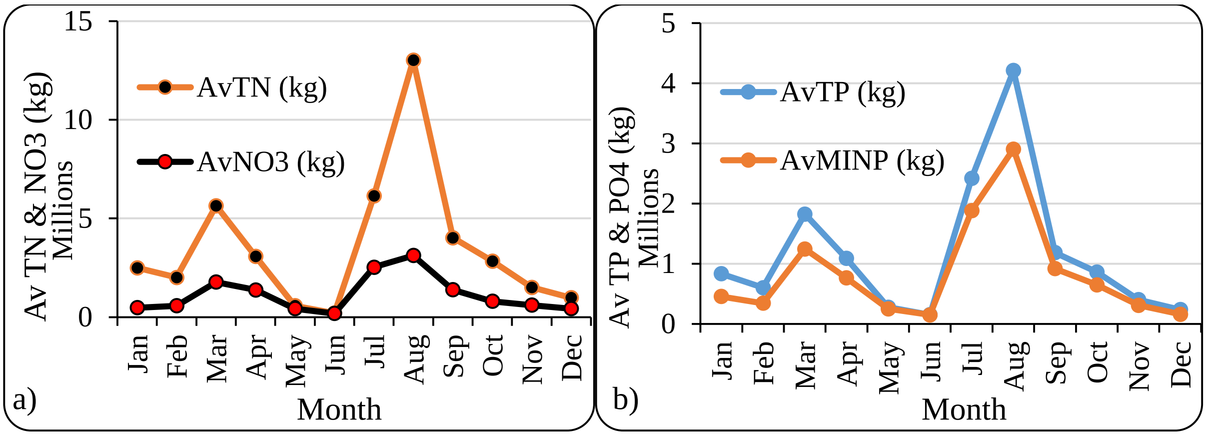


Figure 4-36 Average monthly distribution of nitrogen loss by 2014 LU (a) and phosphorus loss by 2000 LU (b) in the ARB (1997-2014)

Nutrients have also been compared for the two years' simulation (2000 and 2014) **(Figure 4-37)**. Here the 18 years' monthly averages of the two LU simulations were computed and compared.

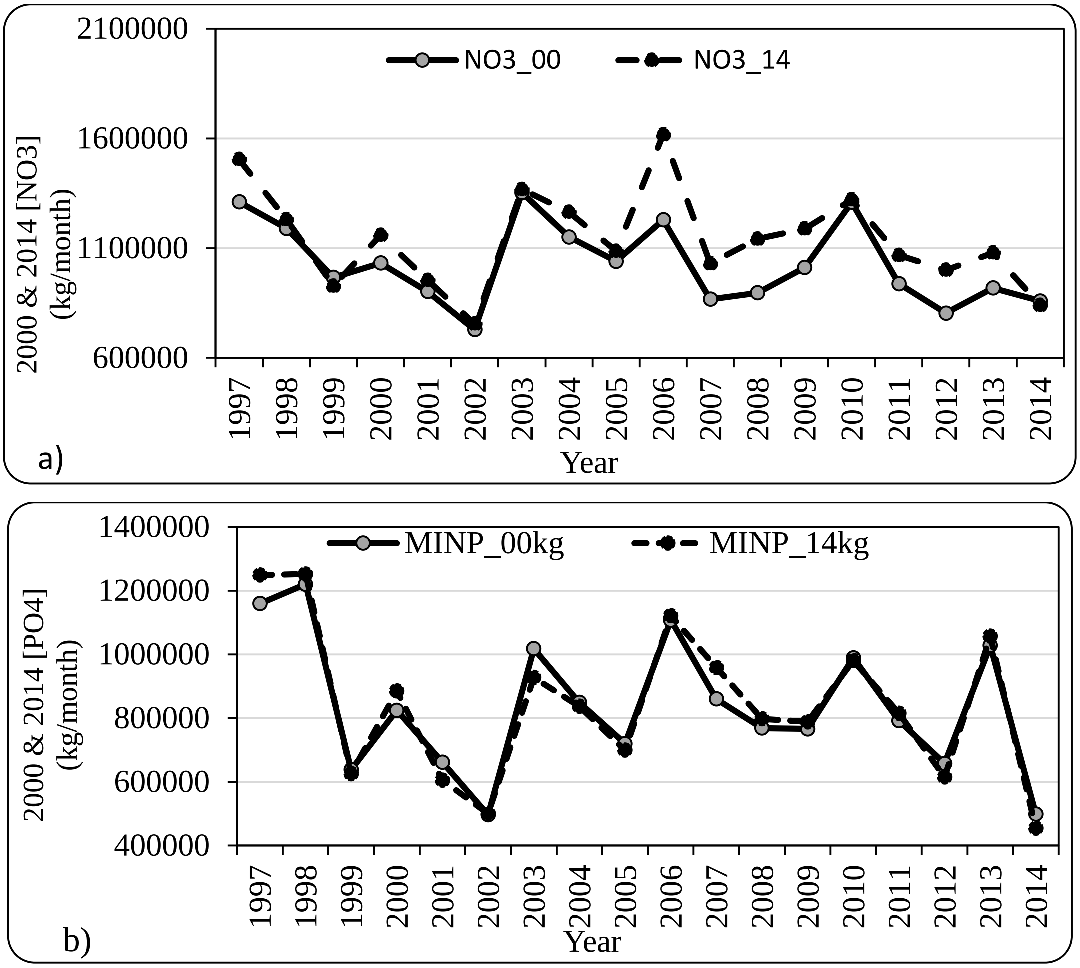


Figure 4-37 Monthly average NO_3^- (a) and PO_4^{2-} (b) loads in the basin based on 2000 and 2014 LULC data

From **Figure 4-37**, one can see that the nitrate (a) and phosphate (b) losses from the basin are generally greater in the 2014 than that in the 2000 LU-based simulation. To see the effects of land use change on the TN and TP, the two years' simulation results (that of 2000 and 2014) were also considered. Similarly, net increments of TN and TP are observed generally as one goes from 2000 to 2014 as can be evident from **Figure 4-38 (a and b)**.

Even though there is a general increase in nutrients due to the landuse change from 2000 to 2014, the trend lines of each of the graphs in **Figure 4-37** and **Figure 4-38** show decreasing temporally though it is increasing after 1999. The decrease may be attributed to other factors than land use/cover such as climate.

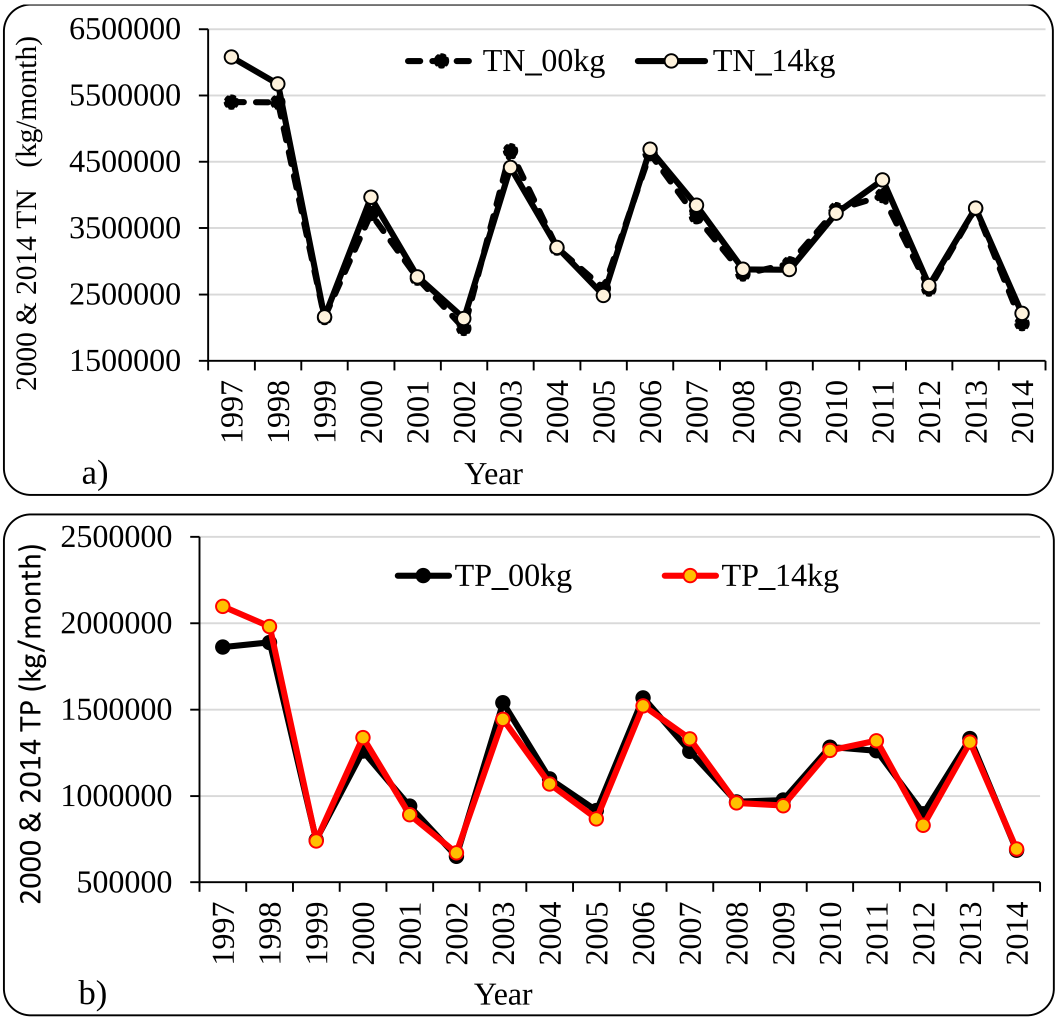


Figure 4-38 Monthly average total N (a) and total P (b) loads in the basin based on the 2000 and 2014 LULC data

Spatial and Temporal variation of nutrients as LU changes from 1994 to 2014

a. Total Nitrogen (TN)

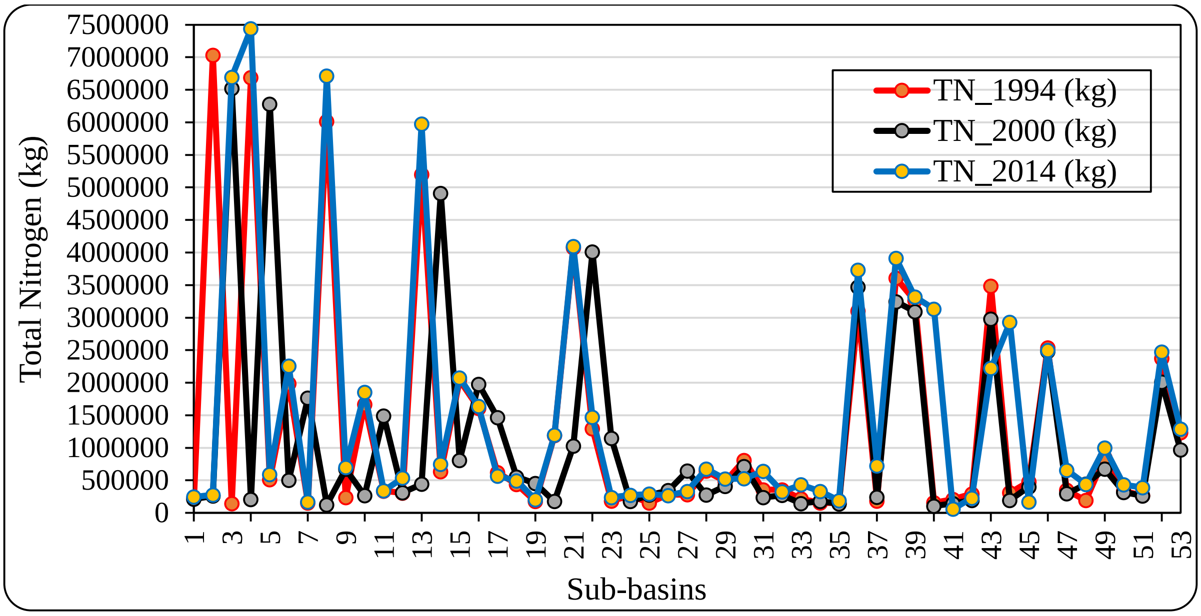


Figure 4-39 Total nitrogen in ARB in the three years: 1994, 2000 and 2014

To investigate the changes in TN as LU changes from one year to the other, subtraction of total nitrogen of 1994 from that of 2000, total nitrogen of 2000 from that of 2014 and finally that of 1994 from that of 2014 for each of the 53 sub-basins is undertaken. Therefore, details of the calculations being given in **Appendix 5**, the indicative result so generated is given by **Table 4-26**, which can show clearly whether there is a positive or a negative change in the nutrients of 2014 from the base year's (1994) counterparts.

Table 4-26 Percentage change of TN due to LU changes between the three years

	2000-1994	**2014-2000**	**2014-1994**
Sum of all -ve differences	-34926776	-16581759	-4456252
Sum of all +ve differences	25697819.9	36589361	15234899
Net	**-9228956.5**	**20007603**	**10778646**

TN from **Table 4-26** and graph of **Figure 4-39** is shown to be decreasing as one goes from 1994 to 2000 but increasing afterwards. However, the net (cumulative) of both 2014-2000 and 2000-1994 differences (i.e 2014-1994) is positive. That is, as one goes from 1994 to 2014, it can be generalized that TN is showing an increasing trend.

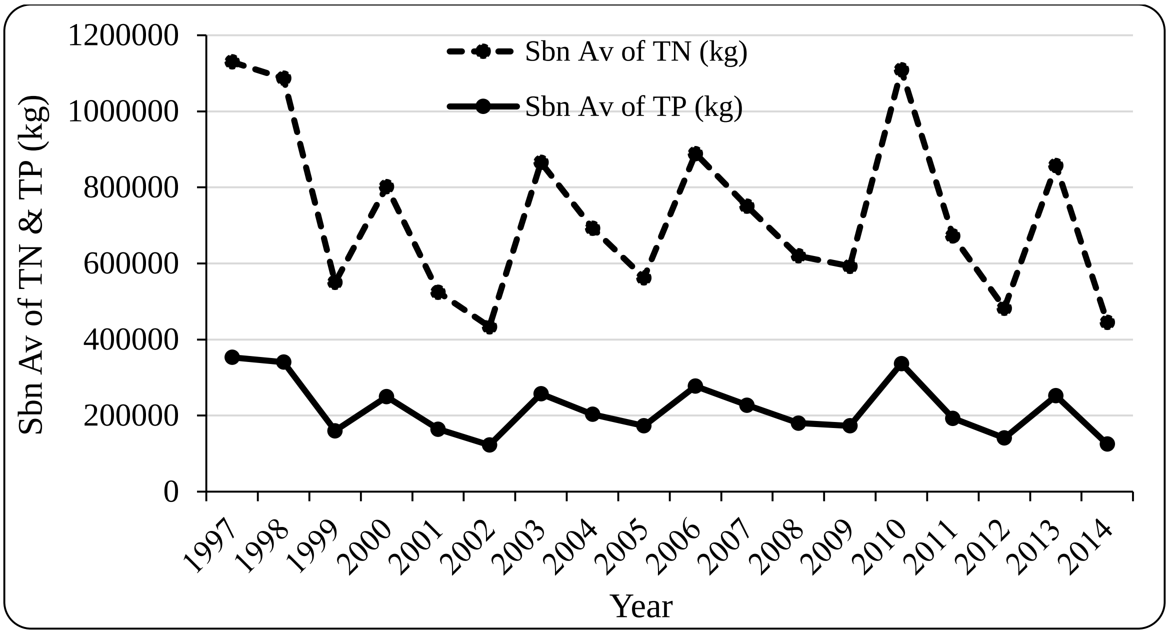


Figure 4-40 Temporal variation of subbasin averages of total N and total P loads in the basin based on 1994 LULC data

b. Total Phosphorus (TP)

Similarly, to assess the changes in TP as LU changes from one year to the other, subtraction of total phosphorus of 1994 from that of 2000, total phosphorus of 2000 from that of 2014 and finally TP of 1994 from that of 2014 for each of the 53 sub-basins is undertaken. Therefore, the details of the calculations being given in **Appendix 6**, the summarized and indicative result so generated is given by **Table 4-27**, which can show clearly whether there is a positive or a negative change.

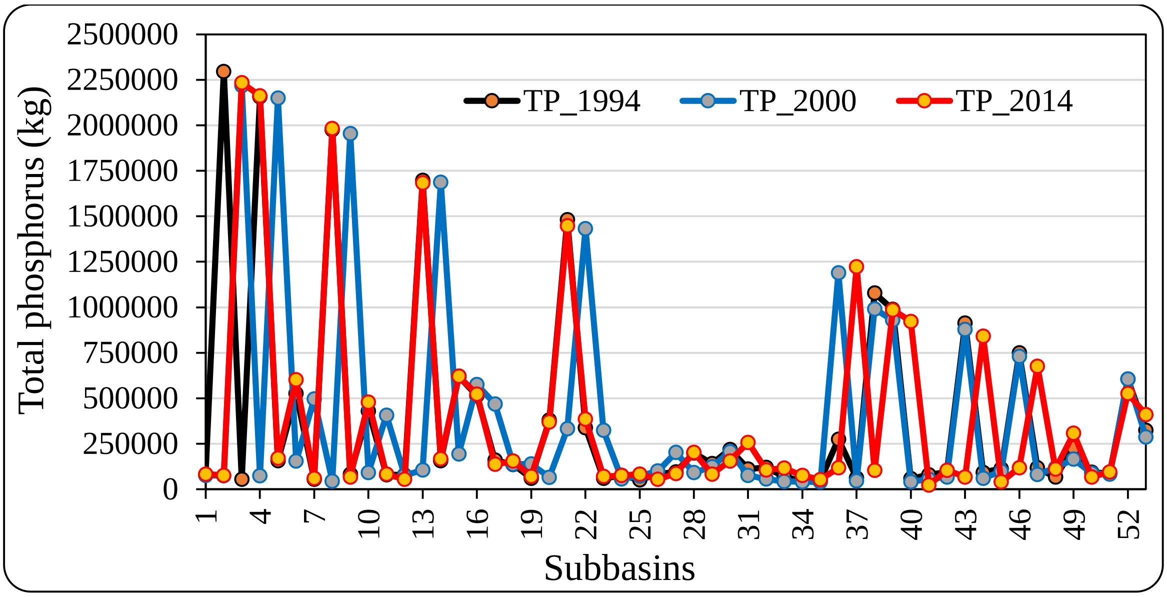


Figure 4-41 Total phosphorus in ARB in the three years: 1994, 2000 and 2014

Accordingly, from the net sum of the differences depicted by **Table 4-27** and the trend plotted in **Figure 4-41**, one can see that total phosphorus in the basin is generally increasing in the time span from 1994 to 2014.

Table 4-27 Percentage change of TP due to LU changes between the three years

TP	2000-1994	2014-2000	2014-1994
Sum of all -ve differences	-10290339	-11469367	-5158623
Sum of all +ve differences	10330041	12341673	6070631
Net	**39702.07**	**872306.12**	**912008.2**

Chapter 5 Conclusion, implications and recommendations

5.1 Conclusion

The study evaluated the physico-chemical (throughout the Awash River) and bacteriological (only in its UB) water quality for drinking and irrigation water uses. The water quality analysis results examined from different sites of the River showed that most of the parameters of concern do not comply with the drinking water quality guidelines and hence unsuitable for drinking. It also showed that most parameters need great care to be used even for irrigation. Domestic WQIs of both UB and MLB lie in the poor while the irrigation WQI throughout the basin is in the marginal range of the CCME ranking. Although the difference in the used water quality dataset of the two cases might contribute for the difference in the indices to some extent, it was generally conceivable that the water quality of the River was below even the fair rank of the council.

Spatial-temporal water quality analyses usually involve huge multi-dimensional data that need multivariate statistical methods. Since the dataset used for multivariate analysis is secondary, it was validated for errors and anomalies and normalized before applying the multivariate statistical methods. The PCA resulted in four principal components representing the whole dataset and most parameters are shown by the analysis to vary spatially. It could also identify the most contributing sites and parameters for the principal components. The most sensitive site for the variation is found to be Lake Beseka for which appropriate management need to be sought. Here, agglomerative hierarchical cluster analysis is used to group the ten sampling sites into four clusters pertaining to water quality characteristics. The seasonal Mann-Kendall trend test detected that most of the parameters show temporal as well as spatial trends. If special attention is not payed to the water quality parameters that show a monotonic increasing trends such as EC, TDS, Na, alkalinity, SO_4^{2-}, NH_3, K, and Cl at the Office area; K, Mg, SO_4^{2-} at Wonji; and TH in all the sites, the water quality of the river and the basin in general will be deteriorated to the extent that it will not be fit for the intended uses. Thus, the multivariate statistical techniques were proved to be excellent exploratory tools in the analysis and interpretation of the complex dataset on water quality and in understanding their temporal and spatial variations.

In the present study, the ArcSWAT hydrological model was used to see how the changes in LU/LC results in nutrient dynamics in the ARB. Performance of SWAT was evaluated in this study when simulating flow and nutrients in the basin although it has not yet been applied to model these variables in the entire basin. Setting up and running the model with the 1994, 2000 and 2014 land uses, respectively 561, 665 and 507 number of HRUs were produced and the basin is commonly divided into 53 sub-basins in each case. Then the simulated flow was calibrated and validated using the long-term record of observed data on a monthly basis and the performances measured by R^2, NSE and RSR were found to be good. Next, the simulated nitrate and phosphate were also calibrated and validated with their historical records of observed data. The objective functional values during calibration and validation of the nutrients were found to be within the acceptable ranges of the standards put in literature. Though nutrient transport in (and/or export to) a running water is conditional on landscape features like hydrology, climate, topography and soil types, the impact of land use on nutrient dynamics is seen here by comparing the simulation results of the model (in which climate, topography and soil types have been considered) corresponding to the three years' land uses. Based on the result obtained from the modeling and its performance, the hydrological and water quality model, SWAT, was proved to be a promising model to predict flow and nutrients in the basin successfully since its performance evaluated by the functions was good.

From results of the modeling, it can be concluded that concentration of nutrients is both season and place dependent. Spatially, the sub basins identified as exporting higher amounts are those that are intensively cultivated and residential areas. Temporally, nutrient export is observed to be higher in rainy than in the dry seasons. Likewise, nutrient load is also seen to be land cover dependent. This is because the load from the 1994 LU has evidently been greater than that of 2000 while the overall load resulting from 2014 LU is greater than that from both 1994 and 2000.

5.2 Implications of the study and contribution to knowledge

Previous literature results, though did not address detail spatial and temporal dynamics in relation specifically to land use, reported only water quality characterization of some parts of Awash basin. The outcomes of this research in one of the most polluted basins of the nation, Awash river basin, improve our understanding of the water quality status and quality dynamics resulting mostly from various anthropogenic activities in the basin. Results of the status, spatial and temporal dynamics, and relationship of the quality with land use of Awash River basin have a number of applications. To mention some:

1. It has a scientific and practical significance in that it fills the existing knowledge gap and establishes a water quality database.
2. It facilitates informed decision making and implementation of sound management options since it provides ample information on the status so as to suggest if the water is suitable for intended use.
3. It can be customized as a framework (roadmap) for studies dealing with similar issues in other river basins of the nation.

5.3 Recommendations

One ultimate goal of water resources management in a basin is to implement programs that conserve water quality. Therefore, from the study conducted, the following recommendations are forwarded.

- The higher concentrations of nitrogen and phosphorus suggest that nutrient abatement from domestic wastewater are strongly needed to recover the water quality of this river. Therefore, wastewater infrastructure should be constructed and revitalized regularly in line with the fast industrialization and urbanization in the basin and wastewater treatment facilities should be upgraded to improve their nitrogen and phosphorus removal efficiencies. Inter-sectoral consultation and adaptation of integrated planning approach for the wastewater infrastructure's effectiveness need to be developed.
- It would be imperative to have a continuous and long-term monitoring program at selected sites. This program, together with establishment of municipal wastewater and storm-water treatment plants for identified dischargers (for point sources) (at hotspot areas, for instance, effluent from Mojo town and Addis Ababa city) in the basin, would be among the potential solution to increase the indices, which show improvement of the River water quality.
- Identifying all pollutant sources exhaustively in the basin and allocating loads for the non-point sources and waste loads for each of the point sources discharging to the river or its tributaries is essential. This can be realized by developing waste load allocation models for TMDL assignment (facilitated by applying BMP's at the hotspot sub-basins of the basin) that helps as a roadmap to meet standards. Results of the present study are therefore expected to be used as tools in this regard.
- Application of distributed hydrological models and forecasting necessitate availability of long period of quality data. The application of SWAT model was very challenging and a lack of appropriate data was one of the biggest concern throughout the modeling activities. Without proper data, modeling is very difficult if not impossible. The use of new data gathering techniques should be envisaged for the basin especially.

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Appendix 1: Long term (9 years') water quality data (AwBA)

Dubti

Year	Turb	TS	TDS	EC	P^H	NH_3	Na	K	TH	Ca	Mg	TotFe	F	Cl	NO_3-	Alkal	HCO_3-	SO_4-	PO_4-
2005	1203	1932	336	551	7.87	0.02	71	5.5	125.0	38	7.2	0.04	1.5	36	2.6	196	239	34	0.24
2006	529	3420	430	650	8.08	0.5	103	6.7	109.0	32	7.25	0.06	1.98	49	2.03	222	264	41	0.67
2007	3788	5081	329	495	7.9	0.43	73	4.72	112.0	53.4	13.8	2.5	1.31	29	1.62	168	204	58	0.26
2008	2768	3749	445	680	8.01	0.55	116	7.07	111.0	34.9	5.91	0.07	2.1	51	25.6	251	292	40	0.66
2009	76	489	377	574	7.8	0.45	90	6.36	115.0	32.02	7.81	0.02	1.46	44	3.1	202	237	53	0.28
2010	334	848	372	568	8.11	0.99	91	5.7	98.5	30.43	5.42	0.08	1.15	34	3.71	163	190	65	0.4
2011	93	543	391	661	8.28	0.6	100	5.83	103.0	30.6	8.63	0.11	1.12	54	1.95	195	218	58	0.66
2012	163	668	407	643	8.04	0.58	86	6.45	108.1	36.62	7	0.1	0.94	49	2.72	197	221	73	0.56
2013	81	503	334	609	7.69	0.5	87	6.21	208.0	34.51	12.09	0.11	0.99	35	1.35	179	219	74	0.3
Mean	1004	1915	380	603	7.98	0.51	91	6.06	121.1	35.83	8.35	0.34	1.39	42	4.96	197	231	55	0.45
StDev	1284	1642	40	57	0.17	0.23	13	0.67	31.5	6.69	2.64	0.76	0.39	9	7.33	26	29	14	0.18

Adaitu

	Turb	TS	TDS	EC	P^H	NH_3	Na	K	TH	Ca	Mg	TotFe	F	Cl	NO_3-	Alkal	HCO_3-	SO_4-	PO_4-
2005	1691	4034	400	637	8.07	0.45	102	6.7	110.0	33.98	6.13	0.09	1.74	48	1.64	219	241	42	0.38
2006	814	3504	429	663	8.16	0.39	107	6.97	100.1	28.32	7.24	0.07	2.07	49	2.03	225	262	37	0.5
2007	1220	2298	333	501	8.17	0.3	65	6.05	143.0	42.7	8.77	0.07	1.49	33	0.96	201	4	41	0.36
2008	1272	2678	445	678	8.48	0.53	114	7.52	106.9	33.3	5.57	0.05	1.9	54	3.38	245	284	46	0.89
2009	1570	2910	413	633	9.95	0.47	104	7.79	103.7	30.43	6.74	0.06	1.57	45	2.84	235	273	38	0.48
2010	2457	6562	284	405	8.01	3.1	55	4.8	104.5	28.12	8.19	0.47	0.41	22	4.37	143	175	47	2.09
2011	1361	3986	461	753	8.28	0.85	109	7.77	84.0	31.37	6.41	0.22	1.73	60	3.4	241	279	53	0.95
2012	1962	4738	479	782	8.04	0.71	113	9.72	108.1	32.48	6.44	0.33	1.05	60	6.15	231	301	65	0.65
2013	576	1258	492	854	7.73	1.14	146	8.79	105.9	33.19	8.2	0.42	1.08	59	2.35	284	336	79	0.89
Mean	1436	3552	415	656	8.32	0.88	102	7.35	107.4	32.65	7.08	0.2	1.45	48	3.01	225	239	50	0.8
StDev	538	1449	64	130	0.61	0.82	26	1.37	14.5	4.07	1.03	0.16	0.49	12	1.47	36	93	13	0.5

Meteka

	Turb	TS	TDS	EC	P^H	NH_3	Na	K	TH	Ca	Mg	TotFe	F	Cl	NO_3-	Alkal	HCO_3-	SO_4-	PO_4-
2005	1182	3578	326	519	7.86	0.32	73	7.08	101.1	31.44	5.6	0.07	1.95	30	2.61	192	232	21	0.23
2006	1453	3882	358	567	8.04	0.38	84	8.27	105.4	32.2	6.21	0.06	2.08	37	1.82	206	248	29	0.39
2007	684	1252	406	608	8.17	0.35	99	8.6	118.3	32.44	9.03	0.13	1.61	40	0.97	240	288	40	0.9
2008	155	900	714	1090	8.08	0.39	201	12.4	126.6	30.64	11.83	0.17	2.62	79	2.77	410	491	65	0.78
2009	577	4706	627	960	7.88	0.32	182	10.7	118.2	28.41	11.48	0.04	2.33	65	1.8	358	435	72	0.41
2010	291	1228	708	1072	8.19	0.44	208	12	120.8	31.45	10.23	0.2	2.42	72	3.85	405	471	63	0.55
2011	302	2557	596	977	8.35	0.58	154	11	115.0	36.11	9.38	0.21	2.33	70	1.6	338	391	43	0.64
2012	1272	2327	710	1147	9.84	0.65	199	17.8	109.5	31.96	10.4	0.14	1.81	88	2.32	375	438	81	0.79
2013	154	899	669	989	7.63	0.85	195	12.2	120.8	32.14	12.95	0.2	1.89	73	1.06	355	390	99	0.88
Mean	674	2370	568	881	8.23	0.48	155	11.1	115.1	31.87	9.68	0.14	2.12	62	2.09	320	376	57	0.62
StDev	478	1338	151	232	0.61	0.17	52	2.96	7.7	1.89	2.32	0.06	0.31	19	0.86	80	91	24	0.22

Office area

	Turb	TS	TDS	EC	P^H	NH_3	Na	K	TH	Ca	Mg	TotFe	F	Cl	NO_3-	Alkal	HCO_3-	SO_4-	PO_4-
2005	576	1229	330	533	7.86	0.46	78	7.35	99.4	31.78	4.87	0.07	2.34	33	2.55	207	252	26	0.26
2006	1670	6612	342	551	7.83	0.55	83	8.42	101.6	32.22	5.28	0.05	2.33	35	1.54	202	246	19	0.27
2007	3570	5597	300	450	8.07	0.35	64	6.7	105.0	35.57	3.92	0.32	1.6	29	1.1	187	224	24	0.45
2008	1912	3158	328	563	8	0.44	96	7.84	92.4	29.9	4.39	0.1	2.02	40	4.09	213	269	27	0.67
2009	2493	3139	360	542	7.74	0.38	86	7.59	111.2	35.69	5.4	0.58	2.08	31	3.99	219	267	44	0.34
2010	1327	3360	337	463	7.91	1.31	64	7.95	122.8	30.7	10.57	0.23	2.15	28	4.16	178	153	36	0.7
2011	922	2418	410	658	8.14	0.7	106	8.9	100.4	29.79	6.22	0.33	1.84	46	3.46	245	287	36	0.53
2012	950	1415	641	1021	7.9	1.29	159	18.7	94.7	45.34	10.76	1.19	1.79	64	3.05	327	424	79	3.86
2013	419	1121	592	1049	7.46	1.4	239	13.9	164.7	29.78	17.6	0.46	2.49	93	1.98	411	478	85	0
Mean	1538	3117	405	648	7.88	0.76	108	9.7	110.2	33.42	7.67	0.37	2.07	44	2.88	243	289	42	0.79
StDev	951	1806	117	215	0.19	0.41	53	3.74	21.1	4.74	4.24	0.34	0.27	20	1.08	72	95	23	1.11

Weir site

	Turb	TS	TDS	EC	P^H	NH_3	Na	K	TH	Ca	Mg	TotFe	F	Cl	NO_3-	Alkal	HCO_3-	SO_4-	PO_4-
2005	1874	4377	249	384	7.88	0.5	50	7	100.0	30.7	5.4	0.09	1.95	19	3.66	153	182	19	0.36
2006	647	1469	146	346	7.82	0.44	50	7.71	98.0	31	5	0.11	2.19	19	2	156	190	17	0.32
2007	1731	2155	194	288	8.22	0.55	32	5.3	98.0	27.5	7.1	0.09	1.08	14	2.3	124	146	20	0.35
2008	944	1680	249	378	7.98	0.57	50	6.72	93.4	29.4	4.85	0.1	1.3	22	3.69	158	190	13	0.5
2009	288	1542	554	414	7.62	0.51	53	7.4	106.8	33.9	5.3	0.12	2.14	23	4.21	169	206	26	0.38
2010	389	3344	259	392	7.97	0.78	51	20.1	96.2	33.17	5.41	0.42	1.47	20	5.74	159	188	24	0.51
2011	423	3506	349	562	8.23	0.7	84	8.91	104.9	31.83	6.07	0.34	1.77	35	3.45	213	246	31	0.6
2012	425	1164	356	571	7.88	0.76	82	11.4	109.0	31	7.75	0.26	1.3	31	4.72	218	248	37	0.66
2013	1122	1059	461	592	7.48	1.26	134	11.6	108.8	32.17	11.75	0.54	4.88	50	2.31	289	347	70	0.66
Mean	871	2255	313	436	7.9	0.67	65	9.56	101.7	31.19	6.51	0.23	2.01	26	3.56	182	216	29	0.48
StDev	561	1123	123	104	0.23	0.24	29	4.2	5.5	1.82	2.07	0.16	1.08	11	1.16	47	55	16	0.13

Awash W. Supply

	Turb	TS	TDS	EC	P^H	NH_3	Na	K	TH	Ca	Mg	TotFe	F	Cl	NO_3-	Alkal	HCO_3-	SO_4-	PO_4-
2005	1435	3873	235	372	8.02	0.45	46	6.94	93.1	30.91	3.87	0.08	1.83	18	2.21	151	172	17	0.31
2006	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
2007	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
2008	1968	2692	250	380	8.13	0.53	52	6.91	92.6	30.1	4.22	0.07	1.5	21	2.66	159	187	15	0.63
2009	4538	4987	204	315	7.83	0.55	37	6.1	83.0	25.62	4.59	0.03	1.23	14	10.7	125	152	20	0.37
2010	1125	2931	193	276	7.8	1.12	33	8.25	75.1	20.88	5.49	0.63	0.49	15	4.57	110	134	20	0.78
2011	749	5225	316	504	8.3	0.88	73	8.54	100.7	31.21	5.44	0.38	1.27	28	4.27	192	211	27	0.53
2012	1234	3318	382	593	7.82	0.59	88	13.5	114.0	33.66	7.26	0.26	1.57	32	3.12	223	266	52	0.46
2013	504	1042	531	874	7.39	1.11	197	13	104.4	31.04	15.03	0.31	2.15	65	2.36	351	434	76	0.73
Mean	1650	3438	302	473	7.9	0.75	75	9.04	94.7	29.06	6.56	0.25	1.43	28	4.27	187	222	32	0.54
StDev	1257	1328	112	192	0.27	0.26	53	2.78	12.1	4.02	3.61	0.2	0.49	17	2.76	76	95	21	0.16

After Beseka

	Turb	TS	TDS	EC	P^H	NH_3	Na	K	TH	Ca	Mg	TotFe	F	Cl	NO_3-	Alkal	HCO_3-	SO_4-	PO_4-
2005	508	1175	236	373	8.16	0.41	48	7.41	89.1	28.87	4.16	0.12	2.23	19	2.54	149	170	16	0.27
2006	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
2007	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
2008	2331	4544	260	395	8.17	0.56	55	12.4	89.5	26.8	5.4	0.13	1.9	23	4.5	163	181	18	0.48
2009	1702	4099	1838	2692	8.28	0.39	709	18.9	63.4	19.5	3.6	0.04	14.4	224	3.7	1028	756	222	1.41
2010	1670	3422	2062	2969	8.74	2.22	820	7.65	54.3	15.2	3.87	0.43	16.6	251	3.43	1015	799	281	1.84
2011	449	1256	337	544	8.1	0.9	79	9.7	99.5	30.6	5.5	0.45	1.54	38	3.31	202	230	31	0.69
2012	1404	1873	285	437	7.44	0.93	56	9.98	114.1	33.59	7.24	0.27	1.14	22	4.6	181	218	31	0.69
2013	334	807	446	738	7.29	1.2	189	16.4	105.0	32.44	17.61	0.46	1.74	61	2.52	338	408	64	0.66
Mean	1200	2454	781	1164	8.03	0.94	279	11.8	87.8	26.71	6.77	0.27	5.65	91	3.51	440	395	95	0.86
StDev	716	1421	745	1063	0.46	0.59	311	4.07	20.2	6.37	4.57	0.16	6.27	94	0.77	373	253	101	0.51

Lake Beseka

	Turb	TS	TDS	EC	P^H	NH_3	Na	K	TH	Ca	Mg	TotFe	F	Cl	NO_3-	Alkal	HCO_3-	SO_4-	PO_4-
2005	8	4621	4529	6745	9.12	0.12	1758	60.1	15.5	4.5	1.1	0.03	34.3	585	1.5	2418	1426	480	3.23
2006	6	4420	4403	6678	9.52	0.42	1645	68	19.8	6.21	1.09	0.12	35.9	592	6.15	2469	1604	510	3.27
2007	57	4325	4233	6288	9.63	0.76	1525	65.1	46.3	8.85	5.9	0.22	32.8	531	2.1	2568	1533	397	2.69
2008	39	5617	3829	5531	9.62	0.61	1437	61	33.0	9.77	2.08	0.12	30.6	458	7.61	2292	1360	475	2.44
2009	44	4308	4226	6068	9.39	0.49	1595	59	15.2	4.48	1.33	0.06	33.6	554	1.29	2205	1595	554	2.84
2010	49	4404	4075	5510	9.47	0.67	1613	48.8	17.7	5.6	0.9	0.3	6.9	422	1.3	2100	1557	792	2.73
2011	42	3645	3513	5382	9.51	0.77	1218	46.8	18.0	4.55	1.56	0.23	20	438	1.08	2932	1306	427	2.33
2012	74	3624	3383	5292	9.32	0.85	1286	46.9	21.7	5.34	1.99	0.15	17	437	1.04	1754	1028	374	2.48
2013	47	3498	3017	4934	9.21	1.22	1196	44.3	21.6	6.92	4.31	0.15	17.9	412	1.03	1543	892	473	2.08
Mean	41	4274	3912	5825	9.42	0.66	1475	55.6	23.2	6.25	2.25	0.15	25.4	492	2.57	2253	1367	498	2.68
StDev	20	614	483	606	0.17	0.29	190	8.39	9.6	1.82	1.62	0.08	9.64	69	2.35	396	240	116	0.37

Before Beseka

	Turb	TS	TDS	EC	P^H	NH_3	Na	K	TH	Ca	Mg	TotFe	F	Cl	NO_3-	Alkal	HCO_3-	SO_4-	PO_4-
2005	1698	5255	207	315	7.77	0.55	36	6.86	9.8	30.12	3.88	0.08	1.78	14	2.1	132	154	17	0.35
2006	357	1007	207	323	7.79	0.53	33	7.9	100.9	31.62	5.41	0.12	1.86	16	1.71	138	169	10	0.25
2007	1102	605	230	345	8.29	0.67	44	8.05	88.5	28.12	4.33	0.19	1.55	18	3.74	154	170	19	0.49
2008	1202	2183	218	331	7.92	0.6	38	7.05	91.3	34.4	3.85	0.2	1.45	17	5	140	170	8	0.41
2009	384	2159	249	381	7.65	0.41	49	7.84	101.3	31.54	ND	0.09	1.47	20	3.59	167	204	16	0.33
2010	658	3188	275	419	7.65	0.81	53	10.4	114.0	30.67	9.03	0.28	1.46	22	1.82	179	218	21	0.39
2011	278	755	239	380	7.89	0.86	44	8.66	102.0	32.12	5.12	0.51	3.21	20	2.91	150	253	15	0.76
2012	1063	2700	645	998	7.77	0.84	229	16.7	100.5	30.6	5.81	0.18	1.23	73	3	425	512	68	0.73
2013	413	511	232	401	6.79	1.28	48	19.3	102.8	31.8	12.6	0.76	0.99	19	2.2	167	201	25	0.41
Mean	795	2040	278	433	7.72	0.73	64	10.3	90.1	31.22	6.25	0.27	1.67	24	2.9	184	228	22	0.46
StDev	464	1462	131	203	0.38	0.24	59	4.27	29.2	1.6	2.86	0.21	0.6	17	1.02	87	105	17	0.17

Wonji

	Turb	TS	TDS	EC	P^H	NH_3	Na	K	TH	Ca	Mg	TotFe	F	Cl	NO_3-	Alkal	HCO_3-	SO_4-	PO_4-
2005	400	774	193	296	8.09	0.24	32	6.3	87.3	28.3	4.04	0.07	1.98	13	2.76	123	141	9	0.2
2006	151	410	189	312	8.25	0.43	33	6.29	80.5	28.81	3.94	0.12	1.89	14	1.72	126	144	7	0.28
2007	257	539	180	267	8.47	0.74	26	6.43	91.2	29.92	4	0.3	1.4	12	0.91	116	129	8	0.2
2008	249	503	219	330	10.6	0.54	41	6.49	92.2	29.7	4.64	0.25	1.9	17	2.8	148	174	6	0.52
2009	257	537	225	342	7.71	0.42	38	7.16	88.8	28.2	6.12	0.09	1.42	17	5.1	152	175	13	0.36
2010	179	381	260	403	7.88	0.43	57	8.45	88.9	27.04	5.13	0.11	1.74	22	2.7	175	213	10	1.14
2011	224	512	211	323	8.19	0.83	34	6.95	96.8	29.3	5.54	0.59	1.02	16	5.51	132	155	23	0.73
2012	182	420	205	324	7.76	0.79	32	7.75	98.8	26.43	7.86	0.26	1.01	16	5.26	131	254	19	0.48
2013	198	334	178	302	7.37	1.42	32	6.56	93.6	29.26	7.09	0.49	1.03	13	4.96	118	138	22	0.56
Mean	233	490	207	322	8.25	0.65	36	6.93	90.9	28.55	5.37	0.25	1.49	16	3.52	135	169	13	0.5
StDev	69	122	24	35	0.87	0.33	9	0.7	5.1	1.12	1.33	0.17	0.38	3	1.61	18	39	6	0.28

Appendix 2: Two years' water quality data (Oromia water office)

Rds	Par / Stn	Turb	pH	Temp	TDS	EC	DO	BOD	COD	Pb	Zn	Cr	TN	K+	NO3	NO_2	SO_4	Fe	Mn	F-	NH_3	Cu	Cl2	Cl-	Ca	Mg	TAlk	ECo	TCo
1st	S14	310	7.7	21.6	262	525	3.6	26.1	87	6	0.12	0.01	4.6	12.7	7.04	0.102	23	2.95	0.17	1.56	3.01	2	0.4	10	122	78	170	28	TNTC
	S15	500	8.2	23.3	237	475	5.5	16.6	111	3	0.13	0.01	3.7	9.02	10.1	0.003	25	2.69	0.01	1.65	2.23	2	0.38	24	110	70	123	37	TNTC
	S16	430	7.8	21.4	181	355	2.2	19.4	346	8	0.02	0.05	26.4	8.5	52.8	2.5	23	3.5	0.05	0.98	2.44	15	Nil	24	108	66	110	TNTC	TNTC
	S17	120	8	21.5	300	601	5.8	7.94	71	15	0.02	0.17	6.7	11	7.04	1.16	35	1.56	4.6	1.07	6.75	10	0.33	24	134	38	208	TNTC	TNTC
	S18	176	8.2	23.6	289	577	4.2	6.6	31	1	0.01	0.02	10.7	17.1	0.44	1.39	47	0.22	0.01	0.57	10.6	9	0.13	42	132	26	172	TNTC	TNTC
	S19	1,337	7.8	18.8	81	162	2.4	13	17	5	0.03	0.03	27	0.1	13.6	0.05	10	2.27	0.01	0.4	16.2	6	Nil	38	84	22	130	TNTC	TNTC
2nd	S14	116	6.7	23.7	116	232	4.7	6.15	16	1	0.03	<R	2.7	4.3	47.3	0.08	30	1.89	1.19	0.54	1.34	13	0.05	60	50	166	88	40	TNTC
	S15	116	6.9	23.4	113	227	5.5	4	18	0	0.05	<R	8.3	4.1	12.3	0.09	28	1.12	4.2	0.46	1.14	5	0.02	40	60	100	110	32	TNTC
	S16	725	6.7	21.7	132	264	4.5	9.3	89	3	0.06	<R	5.7	3.2	14.5	0.44	2	4.5	<0.2	<0.02	3.64	25	0.08	5	82	42	156	TNTC	TNTC
	S17	470	7	21.7	316	632	3.7	10.2	117	5	0.01	0.13	11.5	5.6	30.8	0.36	30	2.94	0.3	<0.02	3.7	100	0.76	57	126	26	130	TNTC	TNTC
	S18	52	6.8	20.8	184	369	2.4	K	9	2	0.03	0.01	1.7	6.9	7.04	0.752	24	0.38	0.4	0.22	5.14	2	0.12	54	108	132	136	TNTC	TNTC
	S19	1380	6.9	20.1	79	158	4.6	8.12	60	3	0.2	<R	2.7	0.5	0.44	0.033	2	1.57	0.2	0.05	3.32	2	1.89	28	128	46	120	TNTC	TNTC
3rd	S14	73	7.8	22.7	124	248	4.3	2.85	10	<R	0.1	<R	3.2	5.75	12.2	0.004	58	0.13	1	0.66	1.08	8	0.06	4	58	78	86	37	TNTC
	S15	77	8	23.5	121	242	4.6	2.85	9	<R	0.01	<R	4.1	5.25	15.8	<R	56	0.74	0.2	0.79	0.95	15	0.04	18	92	56	88	49.5	TNTC
	S16	50	7.2	22.2	319	639	3.9	4.74	19	1	<R	<R	6.1	9.8	16.7	1.42	52	0.38	0.8	0.56	0.77	1	0.23	24	250	130	194	TNTC	TNTC
	S17	70	7.1	20.4	597	1196	1.7	6.3	57	0	<R	0.05	13.8	15.4	10.6	0.95	64	0.16	0.6	1.16	14.9	1	0.13	16	278	78	360	TNTC	TNTC
	S18	203	7.2	21.4	470	939	0.3	14.4	688	<R	0.01	<R	15.6	15.5	21.1	0.004	62	4.56	3.4	0.51	24.8	1	0.4	4	112	58	166	TNTC	TNTC
	S19	20	7.6	20.1	217	434	4.3	2.55	12	2	0.01	0.01	1.3	4.2	2.64	0.016	50	0.2	0.4	0.33	0.4	<R	0.05	2	196	32	134	TNTC	TNTC
4th	S14	90	7.6	22.5	156	311	ND	4.8	40	ND	0.02	0.02	1.3	4.6	0	0.033	14	0.57	0.1	0.84	1.14	10	0.07	18	142	46	138	11	51
	S15	178	7.7	22.4	156	312	ND	10	111	ND	0.04	0.02	1.1	4.5	0	0.01	14	0.46	0.1	0.86	1.04	7	0.03	18	158	26	136	8	43
	S16	100	7.4	24.4	344	688	ND	5.3	59	ND	0	0	20	13.5	15.4	0.64	51	0.82	0.2	0.7	1.39	23	0.21	8	240	44	240	TNTC	TNTC
	S17	240	7.7	22	745	1491	ND	32	208	ND	0	0.02	27.4	13	43.1	0.231	36	1.18	0.5	1.34	32.1	41	0.41	18	330	22	518	TNTC	TNTC
	S18	285	7.4	20.6	493	984	ND	25.9	150	ND	0	0	2.3	16.5	16.3	0.158	30	2.2	0.7	ND	51.5x	18	0.45	24	280	80	420	TNTC	TNTC
	S19	35	7.3	20.6	273	546	ND	2	6	ND	0	0.01	0	8.82	0	0.043	12	0.14	0.3	ND	0.49	2	0.21	70	210	70	300	180	TNTC

5th	S14	230	7.2	23.5	244	488	4	2.1	29	ND	0.01	<R	ND	6.2	6.6	0.01	20	1.44	<R	0.7	2.89	<R	0.04	32	99	75	184	ND	51
	S15	220	7.5	25.6	219	436	5.4	1.6	25	ND	0.03	<R	ND	5.9	5.28	0.036	16	1.45	<R	0.96	2.78	<R	0.01	10	110	64	186	ND	43
	S16	350	7.3	25.1	234	469	2.9	6.4	49	ND	0.04	<R	ND	7	18.5	0.867	16	1.55	0.1	0.34	4.9	<R	0.03	22	118	67	146	TNTC	TNTC
	S17	600	8.1	25.9	748	1495	0	45.6	914	ND	<R	0.15	ND	8.75	7.38	0.42	124	1.37	1.1	0.49	2.3	4	0.15	40	174	98	214	TNTC	TNTC
	S18	172	7.4	25	591	1180	5.4	26.1	406	ND	<R	0.01	ND	8.75	13.7	0.148	59	1.56	1.7	0.62	22.3	18	0.22	<R	380	94	408	TNTC	TNTC
	S19	560	7.3	21.9	157	314	1.3	7	81	ND	<R	<R	ND	4.8	4.78	0.145	<R	6.49	<R	<R	7.54	<R	0.06	<R	122	68	168	180	TNTC
6th	S14	136	7	26.3	122	243	4.4	7.4	ND	ND	0.01	0.03	ND	5	1.84	0.198	13	1.13	0	0.21	1.68	<R	0.12	14	99	75	184	192	TNTC
	S15	124	7	25.2	135	252	3.6	10.5	ND	ND	0.01	0.02	ND	5.1	2.33	0.013	12	1	0	0.27	1.54	<R	0.14	16	110	64	186	223	147
	S16	2050	6.5	22.4	121	243	2.1	42.8	ND	ND	0.01	<R	ND	3.7	1.3	0.83	10	5.63	0	0.37	1.17	<R	0.04	11	118	67	146	TNTC	TNTC
	S17	1350	7.2	25.4	240	479	3.7	25.5	ND	ND	0.04	0.02	ND	5.1	1.08	0.78	23	1.57	0	1.07	2.69	<R	0.06	14	118	54	214	TNTC	TNTC
	S18	44	6.4	24.7	176	353	4.5	5.09	ND	ND	0.2	0.05	ND	7	8.36	2.97	23	0.53	0.01	<R	5.69	0.4	11	10	286	54	266	260	TNTC
	S19	3200	8	22.1	54	109	5.7	57.2	ND	ND	<R	<R	ND	2	1.19	0.099	30	5.8	0	<R	4.11	<R	0.07	10	122	68	168	TNTC	TNTC
7th	S14	87.4	6.8	19.6	160	321	ND	Nil	Nil	ND	0.04	0.02	1.12K	8.2	5.28	0.053	18	0.65	0	0.48	1.43	3	0.06	4	122	32	154	TNTC	203
	S15	81.2	6.9	20	159	318	ND	Nil	Nil	ND	0.07	0.02	1.96K	5.1	6.6	0.083	15	0.62	0	0.58	1.23	15	0.09	4	86	34	134	170	151
	S16	190	6.9	22.9	200	400	ND	Nil	Nil	ND	0.02	Nil	0.84K	11.5	17.2	0.792	20	1.46	0.3	<R	1.5	12	0.14	6	224	70	268	TNTC	TNTC
	S17	34.5	7.6	21.5	832	1673	ND	Nil	40	ND	0.02	0.02	1.96K	16.5	5.72	0.109	59	0.35	0.4	1.09	27.4	1	0.18	10	271	65	528	TNTC	TNTC
	S18	819	7.2	20.1	776	960	ND	120	200	ND	<R	0.1	2.52K	25.5	0.14	0.33	90	2.84	3.2	Nil	39.6	<R	0.25	4	290	50	408	TNTC	TNTC
	S19	165	7.1	19.2	314	626	ND	Nil	Nil	ND	0.13	0.06	1.12K	7.75	1.06	0.017	24	0.15	0.08	0.85	0.3	14	0.74	2	206	50	270	TNTC	TNTC

Rds: rounds, S14: Awash River after Lake Koka, S15: Lake Koka at Koka Dam, S16: Awash River before Lake Koka, S17: Mojo River before Lake Koka, S18: Akaki River after Lake Aba Samuel, S19: Awash River at Awash MelkaKuntire, Stn: station, Par: parameter, ECo: E. coli, TCo: Total coliform, R=0.01, K=10^-3

Appendix 3: Summary of the weather data used as userwgn in setting up the model

STN	WLAT	WLONG	WELEV	RAIN_YRS	TMXAv	TMNAv	TSDMXAv	TSDMNAv	PCPMMAv	PCPSDAv	PCPSKWAv	PR_W1_Av	PR_W2_Av	PCPDAv	RAINHHMXAv	SOLARAv	DEWPTAv	WNDAv
Ayisha	10.76	42.58	721	21	33.7	21	1.18	1.03	17.76	2.32	9.41	0.12	0.66	8.57	5.92	22.46	16.59	3.35
Asaita	11.53	41.53	430	21	37.16	23.61	1.49	1.95	14.37	2.5	12.04	0.08	0.51	4.64	4.79	22.13	18.72	2.2
Dubti	11.72	41.01	376	21	37.71	22.83	1.23	1.41	16.98	2.76	11.8	0.06	0.72	5.12	5.67	22.47	20.79	1.55
Melkasa	8.4	39.32	1540	21	28.91	13.56	0.94	1.97	72.62	6.07	5.79	0.2	0.61	8.91	24.21	22.17	15.42	4.88
Metahara	8.86	39.92	944	21	33.88	17.95	0.96	1.27	41.43	4.17	7.16	0.17	0.43	6.6	13.81	23.27	17.63	1.63
Nazaret	8.55	39.28	1622	21	27.95	15.06	0.95	1.01	75.18	6.17	6.58	0.21	0.51	8.34	25.06	21.08	13.85	2.6
Shewaro	10.01	39.89	1277	21	27.26	12.07	2.51	1.9	57.25	4.58	7.47	0.21	0.73	13.25	19.09	25.5	9.91	2.32
Sholageb	9.22	39.55	2500	21	23.01	9.67	2.9	1.38	48.47	3.32	5.87	0.2	0.68	11.3	16.16	22.73	8.15	2.2
Addis	9.02	38.75	2386	21	22.27	10.25	0.73	0.8	101.75	6.01	5.46	0.29	0.71	12.99	33.91	20.48	9.53	0.55
Gewane	10.15	40.63	568	21	37.38	22.04	2.03	1.47	40.15	4.69	7.97	0.14	0.55	6.44	13.38	22.45	13.29	2.16
Abomsa	8.47	39.82	1630	21	28.06	15.49	0.97	0.63	75.11	6.12	5.7	0.24	0.6	10.52	25.03	20.15	13.9	1.54
Dire	9.97	42.53	1180	21	32.59	18.96	0.96	0.87	55.48	5.6	7.85	0.18	0.58	8.39	18.5	20.9	15.86	1.72
Majete	10.5	39.85	2000	21	28.66	14.67	0.92	0.94	99.77	6.95	5.35	0.23	0.68	11.5	33.24	21.11	14.71	1.09
Mile	11.43	40.77	487	21	36.11	22.1	1.31	1.77	35.22	3.52	8.63	0.17	0.72	12.08	11.74	23.01	13.85	0.29
D/Zeit	8.73	38.95	1900	21	26.59	7.98	0.71	0.91	73.11	5.08	6.28	0.22	0.75	11.93	24.37	24.68	10.8	2.2
Hombol	8.37	38.77	1743	21	27.11	9.88	1.58	1.7	67.15	4.22	5.53	0.16	0.85	15.85	22.43	23.76	11.89	3.52
AwShel	9.33	40.25	737	21	36.38	18.51	2.13	3.24	39.01	3.61	8.95	0.09	0.88	14.56	13.05	21.74	15.63	1.86
Teji	8.83	38.37	2091	21	24.53	9.58	2.89	2.14	78.01	4.81	5.48	0.26	0.69	12.41	25.99	22.34	10.42	1.68
Cheffa	10.84	39.81	1466	21	30.08	13.34	1.99	2.84	78.18	4.17	6.94	0.17	0.9	19.88	26.12	22.14	19.73	1.99
Erer	9.58	41.36	1065.3	21	30.61	15.71	2.14	2.01	17.06	2.47	9.68	0.16	0.64	9.22	5.69	24.03	11.87	2.8[3]

[3] The suffix **Av** in column headings from **TMXAv** to **WNDAv** refers to their respective 12 months' average value.

Appendix 4: Observed average monthly flow data used for calibration and validation of SWAT model simulation at Dubti

	Flow (m^3/s)								
Month\Yr	**1997**	**1999**	**2001**	**2003**	**2005**	**2007**	**2009**	**2011**	**2013**
Jan.	20.7	25.43	27.82	24.89	14.89	19.63	19.86	25.11	55.2
Feb.	10.39	25.19	8.67	21.31	14.27	16.87	17.52	14.66	50.91
Mar.	45.69	35.08	39.91	37.89	20.89	20.47	27.16	47.61	97
Apr.	93.13	29.65	23.84	100	75.07	18.27	33.67	82.46	45.49
May	43.12	20.1	14.49	13.92	14.09	18.75	13.32	66.16	57.67
Jun.	32.41	5.57	57.58	4.45	6.52	5.38	4.19	42.68	36.83
Jul.	67.53	91.13	223.9	12.95	26.76	66.74	61.52	58.04	100.5
Aug.	131.3	250.6	195.3	314.3	166.2	273.7	189	179.7	284
Sep.	87.37	312.5	130.2	133.9	82.16	244.5	186.5	184.7	333.5
Oct.	125.6	199.5	62.27	104.8	48.97	141.8	117.9	153.1	246.6
Nov.	116.8	84.32	39.32	44.86	25.86	79.56	48.4	90.5	72.31
Dec.	118.7	38.32	40.12	48.17	22.07	42.09	33.54	76.74	30.83
Month\Yr	**1998**	**2000**	**2002**	**2004**	**2006**	**2008**	**2010**	**2012**	**2014**
Jan.	75.96	13.83	14.29	15.48	14.65	48.33	24.36	45.72	31.97
Feb.	74.35	8.56	9.86	18.68	13.62	42.37	18.67	46.51	23.21
Mar.	125.7	5.86	19.25	22.54	14.2	85.71	43.76	74.14	58.9
Apr.	69.69	6.89	37.68	112.5	59.67	81.41	29.49	91.08	46.54
May	47.81	17.41	6.55	21.63	19.52	45.46	37.04	34.72	78.37
Jun.	28.76	5.19	2.81	10.22	7.71	30.58	23.86	19.49	48.93
Jul.	129.5	42.35	31.91	21.62	31.98	98.49	51.68	75.53	59.99
Aug.	370.6	296.9	127.3	205	250.9	250.9	162.4	287.8	212.8
Sep.	412.7	176.5	60.49	103.8	140.1	250	157.5	258.2	268.2
Oct.	314.3	84.16	36.25	61.68	72.92	219.9	107.5	188	179.7
Nov.	81.31	74.79	12.49	39.24	57.02	99.06	37.9	60.27	63.75
Dec.	33.79	45.87	28.76	15.39	30.63	76.23	28.32	24.59	31.35

Appendix 5: Temporal variation of TN in each subbasin

Sbn	**TN_1994 (kg)**	**TN_2000 (kg)**	**TN_2014 (kg)**	**2000-1994**	**2014-2000**	**2014-1994**
1	223593.75	212722.41	244692.25	-10871.35	31969.84	21098.49
2	7031731.18	260212.13	275814.22	-6771519.05	15602.09	-6755916.96
3	145009.90	6519350.52	6693364.61	6374340.62	174014.09	6548354.71
4	6686051.60	205298.15	7438611.89	-6480753.46	7233313.75	752560.29
5	509468.66	6278804.40	590575.66	5769335.75	-5688228.74	81107.01
6	1984924.13	499042.84	2256096.89	-1485881.29	1757054.04	271172.75
7	154184.90	1762654.82	167347.50	1608469.92	-1595307.32	13162.60
8	6016901.54	123331.28	6710848.15	-5893570.26	6587516.87	693946.61
9	235050.53	672556.19	698081.83	437505.66	25525.64	463031.30
10	1667778.55	266932.76	1851994.89	-1400845.78	1585062.12	184216.34
11	335790.26	1487319.36	340515.48	1151529.10	-1146803.87	4725.22
12	305299.81	311960.01	535240.87	6660.20	223280.86	229941.06
13	5198780.90	440893.20	5977086.69	-4757887.70	5536193.49	778305.79
14	633526.51	4909417.81	747117.22	4275891.31	-4162300.59	113590.71
15	2037424.02	807916.47	2073835.12	-1229507.55	1265918.65	36411.10
16	1607489.19	1976668.07	1634745.68	369178.88	-341922.38	27256.49
17	620594.66	1466614.28	565903.13	846019.61	-900711.15	-54691.54
18	438310.11	550892.83	492855.03	112582.72	-58037.80	54544.92
19	176559.17	449902.19	203838.38	273343.02	-246063.81	27279.21
20	1187876.75	175697.23	1191871.92	-1012179.53	1016174.70	3995.17
21	4072153.95	1026001.71	4094786.19	-3046152.23	3068784.47	22632.24
22	1294037.81	4007448.79	1470620.64	2713410.98	-2536828.15	176582.83
23	183716.61	1146318.01	236427.34	962601.40	-909890.67	52710.73
24	262083.02	177267.53	270954.97	-84815.49	93687.44	8871.95
25	153741.48	274292.59	289325.92	120551.11	15033.33	135584.44
26	281912.52	342762.52	268017.03	60850.00	-74745.49	-13895.49
27	277981.02	643808.98	330893.10	365827.96	-312915.88	52912.08
28	643115.58	275125.58	675466.43	-367990.00	400340.86	32350.86

29	484770.57	408378.07	519785.08	-76392.50	111407.01	35014.51
30	808303.69	713298.23	527315.33	-95005.46	-185982.91	-280988.37
31	354199.90	238191.20	638149.73	-116008.70	399958.53	283949.83
32	354569.01	268326.78	325332.44	-86242.23	57005.66	-29236.57
33	215585.98	143176.19	430863.57	-72409.79	287687.38	215277.59
34	154730.33	179571.52	330722.91	24841.18	151151.39	175992.58
35	148121.28	139810.85	188123.50	-8310.43	48312.65	40002.22
36	3099352.85	3467182.35	3728947.56	367829.50	261765.21	629594.71
37	184088.21	240369.42	720498.92	56281.20	480129.51	536410.71
38	3606930.02	3245527.79	3913646.35	-361402.23	668118.57	306716.34
39	3261052.92	3093015.18	3318197.61	-168037.74	225182.43	57144.69
40	155630.21	104015.08	3131292.35	-51615.13	3027277.27	2975662.14
41	208360.16	143252.94	58515.75	-65107.21	-84737.20	-149844.41
42	290702.86	192744.23	226553.16	-97958.63	33808.93	-64149.70
43	3483299.41	2978551.97	2219148.04	-504747.44	-759403.92	-1264151.37
44	308651.01	191999.65	2927831.34	-116651.36	2735831.69	2619180.33
45	478950.10	398445.18	168604.36	-80504.93	-229840.81	-310345.74
46	2537958.63	2481148.41	2494201.70	-56810.22	13053.29	-43756.93
47	348200.02	293362.93	655713.20	-54837.09	362350.27	307513.18
48	191746.06	441467.78	439595.60	249721.71	-1872.18	247849.54
49	850650.84	675779.72	998802.95	-174871.12	323023.23	148152.11
50	333871.56	317186.49	432234.30	-16685.07	115047.81	98362.73
51	266027.87	261893.44	389739.06	-4134.43	127845.62	123711.19
52	2374103.77	2011123.14	2474271.29	-362980.63	463148.15	100167.52
53	1231258.11	968215.82	1289834.71	-263042.29	321618.88	58576.60

Appendix 6: Temporal variation of TP in each subbasin

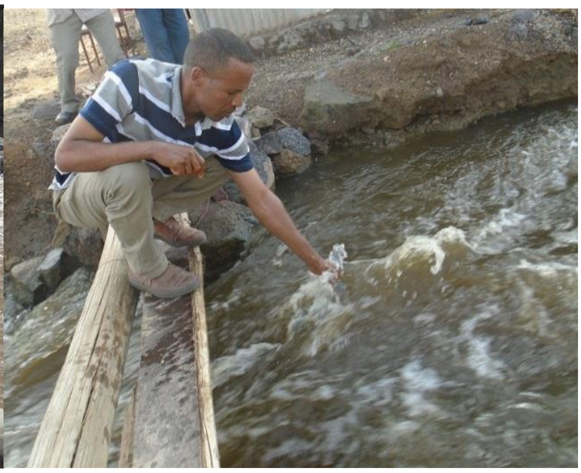
Sbn	TP_1994(kg)	TP_2000(kg)	TP_2014(kg)	2000-1994	2014-2000	2014-1994
1	79485.552	76636.301	83292.813	-2849.25	6656.511	3807.261
2	2295568.9	74563.167	76716.633	-2221006	2153.466	-2218852
3	54588.305	2218719.7	2233618	2164131	14898.35	2179030
4	2156187.6	74532.457	2161853.3	-2081655	2087321	5665.694
5	156005.41	2149101.4	171129.21	1993096	-1977972	15123.8
6	526826.71	154697.38	601671.98	-372129	446974.6	74845.27
7	55162.594	495662.14	60004.711	440499.5	-435657	4842.117
8	1975017.7	44409.764	1983079.6	-1930608	1938670	8061.897
9	83209.883	1954176.6	67210.754	1870967	-1886966	-15999.1
10	429663.37	91936.538	478751.7	-337727	386815.2	49088.33
11	80211.215	406896.35	82632.958	326685.1	-324263	2421.743
12	77890.343	74575.44	54787.853	-3314.9	-19787.6	-23102.5
13	1696993.8	106214.43	1684081	-1590779	1577867	-12912.7
14	156951.22	1686140.9	166525.58	1529190	-1519615	9574.366
15	620595.34	194348.17	620464.29	-426247	426116.1	-131.046
16	513729.38	574823.64	522352.52	61094.25	-52471.1	8623.133
17	159396	468629.77	136849.67	309233.8	-331780	-22546.3
18	136234.51	137639.36	154407.78	1404.853	16768.42	18173.27
19	60585.902	138707.33	71431.182	78121.43	-67276.1	10845.28
20	379435.74	65659.881	369988.98	-313776	304329.1	-9446.75
21	1481256.2	331749.43	1447334.5	-1149507	1115585	-33921.6
22	338658.06	1432575	384531.54	1093917	-1048043	45873.49
23	59774.903	323512.44	69767.192	263737.5	-253745	9992.289
24	75733.741	56832.122	75382.661	-18901.6	18550.54	-351.08
25	51276.086	73053.668	83041.096	21777.58	9987.428	31765.01
26	82504.973	100125.59	54096.999	17620.62	-46028.6	-28408
27	95826.451	202211.5	87085.438	106385.1	-115126	-8741.01
28	199514.67	91336.642	202411.76	-108178	111075.1	2897.084
29	140748.4	123478.74	83621.452	-17269.7	-39857.3	-57126.9

30	218515.09	206118.05	155032.86	-12397	-51085.2	-63482.2
31	111581.63	76184.026	257435.47	-35397.6	181251.4	145853.8
32	119637.32	55628.597	105969.18	-64008.7	50340.58	-13668.1
33	69309.576	42945.837	115763.38	-26363.7	72817.54	46453.8
34	43766.143	40893.716	75253.975	-2872.43	34360.26	31487.83
35	49575.828	40474.622	53137.699	-9101.21	12663.08	3561.871
36	275285.98	1188624.5	118017.39	913338.5	-1070607	-157269
37	61667.181	46155.714	1222586.2	-15511.5	1176430	1160919
38	1077826.8	990918.31	103229.26	-86908.5	-887689	-974598
39	988320.79	928647.29	985345.31	-59673.5	56698.03	-2975.48
40	58246.188	41074.661	922039.18	-17171.5	880964.5	863793
41	80021.07	55562.672	23381.121	-24458.4	-32181.6	-56639.9
42	95091.258	67551.095	104008.9	-27540.2	36457.81	8917.646
43	912913.78	877704.07	67235.21	-35209.7	-810469	-845679
44	92034.838	60260.724	841649.01	-31774.1	781388.3	749614.2
45	113153.03	98297.429	40258.13	-14855.6	-58039.3	-72894.9
46	748651.46	729355.39	118180.54	-19296.1	-611175	-630471
47	117660.61	80574.751	675108.85	-37085.9	594534.1	557448.2
48	66300.82	118481.67	110898.42	52180.85	-7583.26	44597.6
49	228736.56	165427.53	307864.31	-63309	142436.8	79127.76
50	92780.668	88366.025	67283.381	-4414.64	-21082.6	-25497.3
51	87068.998	82301.472	95146.414	-4767.53	12844.94	8077.416
52	605902.8	604887.78	526334.49	-1015.02	-78553.3	-79568.3
53	323441.7	286843.33	409249.3	-36598.4	122406	85807.6

Appendix 7: Water quality sampling and onsite analyses of some sites

Dubti

Adaitu



Awash fall

Beseka

Ziway road

Mojo

Samples in the laboratory

Appendix 8: Acronyms

AAEPA	-Addis Ababa Environmental Protection Authority
AET	-Actual Evapotranspiration
AGNPS	-AGricultural NonPoint Source
AGWA	-Automated Geospatial Watershed Assessment Tool
AHC	-Agglomerative Hierarchical Clustering
Alk.	-Alkalinity
ANN	-Artificial Neural Networks
AnnAGNPS	-Annualized AGricultural Non-Point Source
ANSWERS	-Aerial Nonpoint-Source Watershed Environmental Response Simulation
APHA	-American Public Health Association
AQUATOX	-Simulation Model for Aquatic Systems
ARB	-Awash River Basin
AwBA	-Awash Basin Authority
BASINS	-Better Assessment Science Integrating point and Nonpoint Sources
BCM	-Billion Cubic Meter
BMP’s	- Best Management Practices

BOD	-Biochemical Oxygen Demand
CA	-Cluster analysis
CCME	-Canadian Council of Ministers of the Environment
CFSR	-Climate Forecast System Reanalysis
CIA	-Central Intelligence Agency
COD	-Chemical Oxygen Demand
CREAMS	-Chemicals, Runoff, and Erosion from Agricultural Management Systems
DDT	-DichloroDiphenylTrichloroethane
DEM	-Digital Elevation Model
DN	-Digital Number
DO	-Dissolved Oxygen
EC	-Electrical Conductivity
ECo	-Escherichia Coli
EFDC	-Environmental Fluid Dynamic Code
EPIC	-Environmental Impact Policy Climate
EROS	-Earth Resources Observation and Science
ET	-Evapo-Transpiration
ETM+	-Enhanced Thematic Mapper Plus
FDI	-Foreign Direct Investment
FTU	-formazine turbidity unit
GIS	-Geographic Information System
GLCF	-Global Land Cover Facility
GLEAMS	-Groundwater Loading Effects of Agricultural Management Systems
GloVis	-Global Visualization Viewer
GloVis	-Global Visualization Viewer
GPS	-Global Positioning System
GWLF	-Generalized Watershed Loading Function
GWP	-Global Water Partnership
HRU	-Hydrologic Response Unit
HSPF	-Hydrological Simulation Program – FORTRAN
IDW	-Inverse Distance Weighting
IRBM	-Integrated River Basin Management
IT	-Information Technology
ITCZ	-Inter-Tropical Convergence Zone
IWRM	-Integrated Water Resources Management
KINEROS2	-Kinematic Erosion and Runoff
LS	-LandSat
LS TM	-Landsat Thematic Mapper
LU/LC	-Land Use/Land Cover
MCM	-Million Cubic Meter

MER -Main Ethiopian Rift
MoH -Ministry of Health
MoWIE -Ministry of Water, Irrigation and Energy
MUSLE -Modified Universal Soil Loss Equation
MW -Megawatt
NCEP -National Centers for Environmental Prediction
NMSA -National Meteorological Service Agency
NSF -National Sanitation Foundation
NTU -Nephelometric Turbidity Unit
OWQI -Overall Water Quality Index
PAH -Polycyclic Aromatic Hydrocarbons
PCA -Principal Component Analysis
PCBs -Poly Chlorinated Biphenyl
PCP -Precipitation
PCs -Principal Components
PET -Potential Evapo-transpiration
POC -Particulate Organic Carbon
QA/QC -Quality Assurance/Quality Control
QUAL2E -Enhanced Stream Water Quality Model
RE -Relative Error
ROTO -Routing Outputs To Outlet
RSC -Residual Sodium Carbonate
SA -Sensitivity Analysis
SAR -Sodium Adsorption Ratio
SCS CN -Soil Conservation Service curve number
SNNP -Southern Nations Nationalities and Peoples
SPAW -Soil Plant Air Water hydrology
SRTM -Shuttle Radar Topography Mission
SUFI2 -Sequential Uncertainty FItting Version 2
SWAT -Soil and Water Assessment Tool
SWAT-CUP -SWAT Calibration and Uncertainty Programs
SWRRB -Simulator for Water Resources in Rural Basins
TC -Total Coliform
TCU -True Color Unit
TDS -Total Dissolved Solids
TH -Total Hardness
TM -Thematic Mapper
TMDL -Total Maximum Daily Load
TN -Total Nitrogen
TP -Total Phosphorus

TS -Total Solids
TSS -Total Suspended Solids
UNEP -United Nations Environment Program
UNESCO - United Nations Educational, Scientific and Cultural Organization
UNFAO -United Nations Food and Agricultural Organization
UNICEF -United Nations Children's Fund
USDA SCS -United States Department of Agriculture Soil Conservation Service
USDA-ARS- United States Department of Agriculture's Agricultural Research Service
USGS -United States Geological Survey
USLE -Universal Soil Loss Equation
WASP -Water Quality Analysis Simulation Program
WHO -World Health Organization
WQD -Water Quality Dynamics
WQI -Water Quality Index
WQMS -Water Quality Monitoring and Surveillance
WWC -World Water Council
WWDSE -Water Works Design and Supervision Enterprise
WWFS -World Water Forum Secretariat

Personal and Ethical statements

No specific permits were required for the described field studies. This is because the sampling, onsite analysis, travelling in the study area and other activities conducted during the field trip did not cause any disturbances to the environment or to the protected species.

Declaration

I, Amare Shiberu Keraga, declare that this thesis is my original work and has not been presented for a degree in any other university, and that all sources of material used for the thesis have been duly acknowledged.

Submitted by: Amare Shiberu Keraga ______________________________________