Assessment of Pollution Load on the Kenyan Catchment of Lake Victoria Basin using GIS Tools

A dissertation submitted in partial fulfillment of the requirements for the degree of DOCTOR OF ENGINEERING

by

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Abstract

Lake Victoria is a freshwater lake in East Africa and has surface and basin areas of 68,800 km^2 and 194,000 km^2 respectively. The lake is located at an altitude of 1,134 m asl and its average depth is 40 m while volume is 2,760 km^3. It is the second largest freshwater lake by surface area in the world and the largest in Africa. The lake is an economic zone to the three riparian countries, namely, Kenya, Tanzania and Uganda and also a lifeline source of water supply to dry downstream countries. Lake Victoria basin also extends to Burundi and Rwanda. The lake's shoreline is convoluted enclosing numerous small and shallow bays and inlets in which most are swamps and wetlands. The main gulfs/bays are Winam Gulf on the Kenyan side and Speke Gulf on the side of Tanzania. The only outlet from the lake, River Nile, flows down all the way to Egypt. River Sondu is the third largest by flow volume among the main six rivers on the Kenyan side of Lake Victoria basin and its watershed has the largest forest cover rate. Intensive natural and human activities compounded by ever growing population, poor livelihoods and less investment in sanitation; have accelerated environmental degradation through deforestation, siltation, fishing malpractices, wetland destruction and direct disposal of sewage into the lake. Parts of Sondu catchment have recently been reforested: Koguta hill and Mau forest. Sedimentation limits river carrying capacity and fills irrigation channels/canals with silt deposits and cause flooding downstream. Increased inflow of nutrients has enriched the lake. Lake deterioration is being driven by excessive pollution load: sediments and nutrients (total nitrogen - TN & total phosphorous - TP).

Estimation of pollution load to Lake Victoria has been carried out by several studies in the past. Estimation of pollution load has always been hampered by scarcity of data which adversely affects the accuracy and reliability of results. The methods used borrowed nutrient export coefficients (UAL) to estimate pollution load. The borrowed coefficients were not adjusted to fit local conditions because of lack of relevant data and information. There is need to develop criteria of adjusting borrowed coefficients and or estimating local coefficients based on observed water quality and quantity data. Simulation of hydrology, sediment and nutrients as well as watershed management plans provides useful insights to watershed or lake manager especially on amount of pollution load and effectiveness of various watershed interventions.

This study was conducted with the main goal to improve pollution load estimation framework and to assess pollution load on the Kenyan side of Lake Victoria by incorporating Geographical Information System (GIS) and Remote Sensing technologies. First, estimation methods of pollution load in Lake Victoria in past studies were reviewed to highlight their strengths and weaknesses in tandem with advancement in technology in watershed modelling. Second, nutrient export coefficients for three land covers on the Kenyan side of Lake Victoria basin were derived using a model equation with land use and rainfall-runoff coefficient as main variables. The land covers are cropland, forest and vegetation/grassland/shrubland. Third, hydrology sediments and nutrients (TN & TP) as well as their spatial-temporal distribution in Sondu watershed were simulated using Soil Water Assessment Tool (SWAT) to identify sediment and nutrients source hot spots. And finally, effectiveness of three watershed management plans aimed at curbing environmental degradation and sediment erosion in Sondu watershed was assessed using SWAT for both space and time distributions. The plans are: maintaining the existing situation, application of 1 m filters on agricultural land covering 54 % of the watershed and 11.2 % addition of forest cover through reforestation.

Past studies on estimation of pollution load to Lake Victoria have different estimates of pollution load which makes it difficult to determine which estimates are reliable and accurate. It demonstrates that in situations of inadequate data varying methods give different results. Estimates show that atmospheric deposition contributes significantly (30 – 80 %) to the total nitrogen and total phosphorous loads to the lake. Total annual nutrient municipal load of 548 t/yr - TN and 301 t/yr - TP are estimated to be flowing to the Lake from the main six river watersheds on the Kenyan side of the basin. Pit latrines and septic tanks were considered as sources of urban diffuse pollution. The model equation estimated the export coefficients with satisfactory performance for the three land-covers both at validation phase and when matched with those in literature. Nyando watershed had relatively high river nutrient concentration with low rainfall-runoff depth. It suggests that driving factors other than land use and rainfall-runoff coefficient which include loose soil characteristics. However, positive solutions for nutrient export coefficient demonstrated that land use and rainfall-runoff coefficient have significant influence and are usually available and useful variables to explain runoff load.

The SWAT model performance was satisfactory at both phases of stream flow and sediment simulations with scarce observed data notwithstanding. High sediment yield periods were

February-April and November-January and directly correlated with high rainfall seasons. Average annual sediment yield from Sondu watershed is 106,200 tons/yr over the 2005 – 2007 calibration periods while TN & TP are 3,388 tons/yr & 312 tons/yr respectively. The nutrients peak periods lagged behind sediments’ by one to two months on average. Sediments and nutrients are mainly generated from agricultural crop areas at downstream, central (Sondu) and upstream West (lower Kisii/Nyamira) area of the watershed while the high water runoff yielding areas are upstream (Kericho/Kisii/Kericho) areas. Application of filters on agricultural HRUs reduced the yield from the baseline annual yield of 106,200 tons by 17 % at basin level while addition of 11.2 % forest cover reduced the yield by 28 %. Both filter and reforestation plans were more effective in wetter months of the year. Months of April-May and November-December which are beginning of high rainfall seasons had high sediment reduction rates for reforestation and filter plans. Reforestation plan consistently ranked higher with respect to sediment yield reduction in all months of the year as monitored at basin outlet. Reforestation was relatively effective in reducing sediment at most upstream sub basins while filters had more impact at most downstream sub basins of the watershed. Sediment yield in sub basins did not show a distinctive pattern whether located upstream or downstream but sediment yield amount corresponded to size of agriculture cover.

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CHAPTER 1: INTRODUCTION

This Chapter provides the background and general information on Lake Victoria and followed by introduction of study areas. The challenges facing the basin ecosystem and ecology of the Lake are introduced. The need for research is underscored in the Chapter. Finally the four objectives of this study are listed and graphical structure of the study is presented.

1.1Background

Lake Victoria is the second largest freshwater lake in the world and largest in Africa by surface area and is a shared resource amongst its basin countries. The basin lies within territories of Burundi, Kenya, Rwanda, Tanzania and Uganda. It stretches from north to south between latitudes 0°30'N and 3°12'S, and from west to east between longitudes 31°37' and 34°53'E (Fig. 1.1). The lake's basin covers a surface area of 194,000 Km^2 while the lake's surface area is 68,800 Km^2. The areas translate to ratio of basin area to that of the lake of about 1:3. The ratio of lake area is relatively large when compared to other lakes in Africa region and beyond. For example, the corresponding ratio for Lake Nakuru in Kenya is 1:60, Lake Tanganyika's is 1:7 and Lake Biwa in Japan has a ratio of 1:6. The average depth of the lake is 40 m and maximum depth is 79 m, volume is 2,760 Km^3 and it's located at an altitude of 1,134 m (Scheren et al., 2000; Muyodi et al., 2010; Kayombo and Jorgensen, 2005). The lake is fairly shallow as compared to other great African lakes and thus its volume is only 15 % that of Lake Tanganyika because of differences in depth despite the huge surface area of Lake Victoria (LVEMP, 2005).

The climate of Lake Victoria basin is equatorial climate with varying temperatures due to its varying topography. The temperatures range from 10°C to over 35°C while annual rainfall range is from 1,000 mm to over 2,500 mm (LVEMP, 2005). The high rainfall periods are March-May and short rains in October-December. There is wide spatial variation of rainfall in the basin. Upstream areas receive relatively higher rainfall than downstream and most parts of the Tanzania watershed receive least rainfall. The rainfall is controlled by the movement of the Inter Tropical Convergence Zone (ITCZ) (LVEMP, 2005; COWI, 2002). The soil types of Lake Victoria basin are Cambisols, planasols, vertisols, regosols, aeronosols, gleysols and ferrasols in which gleysols are on the low lying areas downstream covered by swamps while planosols are associated with agricultural land for its soil fertility (Faith, 2005; LVEMP, 2005).

Lake Victoria is a source of fish, freshwater supply, and hydroelectric power and also provides routes for transportation. Lake Victoria basin supports about 40 million people, whose livelihoods are mainly dependent on the resources in the basin, thereby attracting intensive multiple human activities. Intensive natural and human activities compounded by ever growing population, poor livelihoods and less investment in sanitation; have accelerated environmental degradation through deforestation, siltation, fishing malpractices, wetland destruction and direct disposal of sewage into the lake. This has resulted in increased pollution of the lake to the extent of compromising its ecosystem integrity. Lake pollution has led to deterioration of water quality, as manifested by algal blooms and periodic massive fish kills caused by oxygen depletion (Ochumba, 1988).

Increased inflow of nutrients has enriched the Lake as a result of population growth and associated land use change such as conversion of forest to agricultural land. Also soil erosion is being driven by loss of soil cover and rainfall and subsequently deposited in the bottom of rivers and the lake. Sediment deposition lowers the water holding capacity of the lake and the river channel especially at downstream low lying and plain areas. Eutrophication adversely affects the lake ecosystem and estimation of sediment and nutrient loadings is necessary to address the problem. Also continuous monitoring and simulation of stream flow, sediments and nutrients is useful for lake management. Total nitrogen and total phosphorus are important indicators for eutrophication.

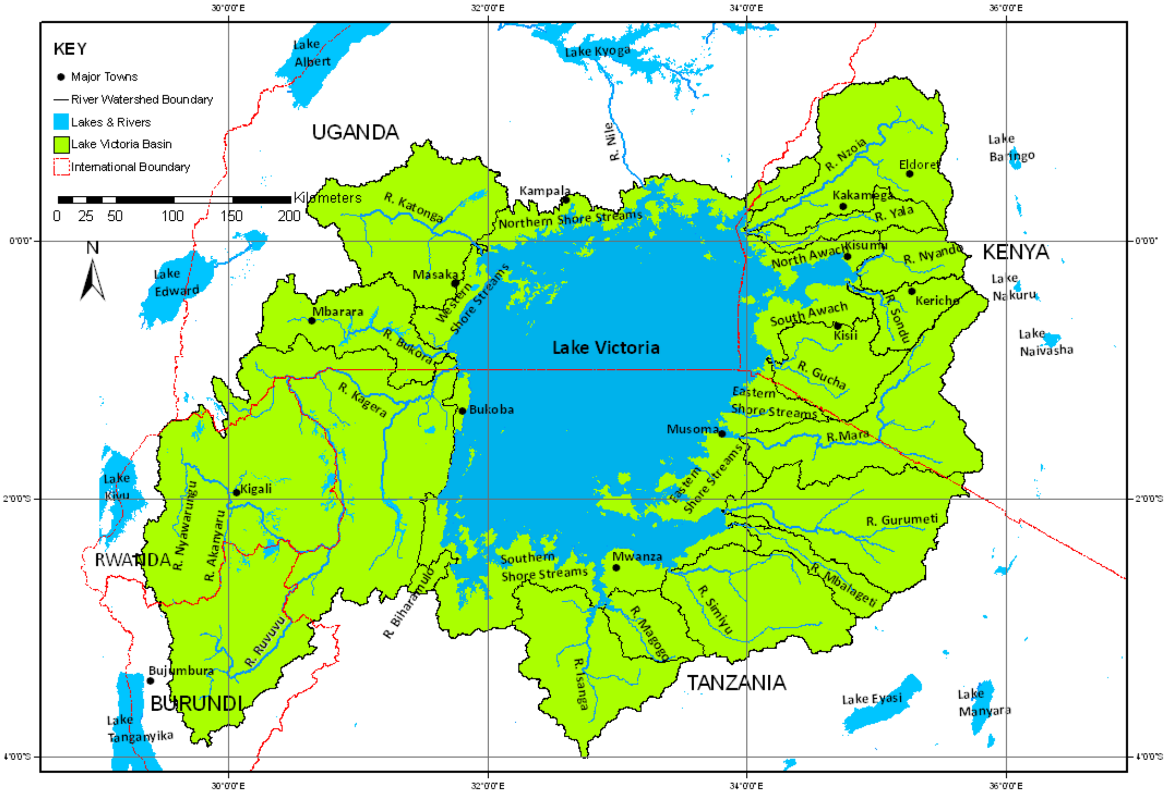


Fig.1.1 Lake Victoria basin in East Africa

The lake and its ecosystem show evidence of dramatic changes with infestation by water hyacinth being one of the major concerns in the lake in recent years. Threats facing the lake have adversely affected efforts to improve livelihoods of the population dependent on the lake (Kayombo and Jorgensen, 2005). Recently, floating water hyacinth often driven by wind waves has trapped and held hostage fishermen offshore several times. To address these challenges, several studies and projects have been implemented, focusing both within the lake and the basin. The Lake Victoria Environmental Management Project, Phase II (LVEMPII, 2009 - 2017) is one of the major ongoing interventions on the lake being implemented by all the five basin countries.

Estimation of pollution load to the lake has always been hampered by limited data and has thus not been comprehensively done. Pollution loads that threaten the lake's ecosystem are sediments, nutrients (Total Nitrogen, TN and Total Phosphorous, TP), pathogens, organic matter and heavy metals. Lake Victoria Environmental Management Project, Phase I (LVEMP, 1995 - 2005) made a detailed attempt to quantify pollution load to the lake (COWI, 2002; LVEMP, 2005) with respect to sediments, organic matter (Biochemical Oxygen Demand, BOD), TN and TP. Similar studies on pollution load estimation have been done by Calamari et al. (1995), Scheren et al. (1995, 2000), Africa Water Network (AWN, 1998) and Scheren (2003, 2005), among others. Methodologies used in these studies vary, mainly due to limitation of available data and resources.

Water hyacinth at Winam Gulf, Kisumu (Cheruiyot, 2011)

Water hyacinth at Winam Gulf, Kisumu (Kimathi N., 2009)

Water hyacinth at Winam Gulf (NTV, 2010)

Water hyacinth at Winam Gulf (NTV, 2010)

Fig. 1.2 Water hyacinth infestation in Lake Victoria

1.2 Overview of Lake Victoria basin

The lake has several enclosed islands and a shoreline of about 3,460 Km long (Kayombo and Jorgensen, 2005; COWI, 2002). The shoreline is convoluted enclosing numerous small and shallow bays and inlets in which most are swamps and wetlands (LVEMP, 2005). The main gulfs/bays are Winam Gulf on the Kenyan side and Speke Gulf on the side of Tanzania while the main islands include Rusinga island of Kenya and Kalangala and Ukerewe islands of Uganda and Tanzania respectively.

The lake and the basin is a trans-boundary and shared resource. Tanzania has the biggest share of the basin while Burundi has the least while significant share of the lake surface area is in Tanzania (49 %) and Uganda (45 %) (Table 1.1). The only lake outlet, River Nile, flows down all the way to Egypt. The lake is an important resource to all countries within the Nile river basin. The river at Owen falls in Uganda generates 260 MW of hydro-power (Kayombo and Jorgensen, 2005). The Nile waters downstream support economies through water supply for domestic and irrigation uses especially in Egypt where irrigation is extensive.

Table 1.1 Share of Lake Victoria and basin areas by countries

Country	Basin area (Km^2)	Basin area (%)	Lake area (Km^2)	Lake area (%)
Tanzania	85,360	44 %	33,700	49 %
Kenya	42,680	22 %	4,100	6%
Uganda	31,040	16 %	31,000	45 %
Rwanda	21,340	11 %	-	-
Burundi	13,580	7 %	-	-
Total	194,000	100 %	68,800	100 %

The lake receives surface inflow water from 17 perennial river watersheds and 6 offshore stream catchments (Fig. 1.1). River Kagera watershed which extends all the way to Burundi is the largest while River Nyashishi's is the smallest watershed by surface area (Fig. 1.1). In terms of water balance, surface water inflow constitutes 18 % and the significant remaining 82 % is by direct rainfall on the lake surface due to large ratio of lake surface area to basin area while the outflow is significant through evaporation (76 %) and River Nile (24 %) (COWI, 2002; LVEMP, 2005) (Table 1.2).

Table 1.2 Average water inflows and outflows in Lake Victoria

Inflow (outflow)	Flow (m^3/s)	Share (%)
Rain over the Lake	3,631	82 %
River flow	778	18 %
(Evaporation)	-3,330	76 %
(River Nile)	-1,046	24 %

Source: COWI (2002)

Besides fishing, the basin favors agricultural (crop) economic activities because it is endowed with high precipitation and fertile soils. Livestock farming is also practiced. The basin is home to urban settings ranging from small rural settlements to large administrative towns.

These economic activities generate raw materials such as tea, sugarcane, coffee, livestock, and fish, among others. Raw materials have attracted and promoted growth of various industries due to strategic proximity to the resources and available market within the basin and beyond.

Investment in sanitation infrastructure is low and not all main towns have sewerage systems. The connection is low where available; Kampala city has 13% of population connected to sewerage system while that of Kisumu city is 28% (Letema et al., 2008). They are the major towns with comprehensive sewerage systems. Alternative sanitation systems are onsite treatment systems such as septic tanks and pit latrines. Open defecation (flying toilet) is practiced in informal settlements (KNBS, 2010). Pit latrines are the most common and affordable to most households. Towns on Tanzania’s side of Lake Victoria have no sewerage systems with exception of Mwanza (COWI, 2002). Septic tanks and pit latrines are used in the towns.

The capital cost of putting up conventional sewerage systems such as stabilization ponds is relatively expensive for low income countries. The average capital cost per capita of sewerage system, for low income countries, is estimated to be greater than 39% of Gross National Income per capita (GNI/capita) and for high income countries is lower than 1.6% of GNI/capita, (Muhandiki et al., 2008). Such prohibitive costs partly explain why capital costs for most sewer systems in low income countries and by extension the same in Lake Victoria basin are funded with external assistance. Some of the existing sewerage systems are old, dating back to colonial government regimes. For example Kisat sewage treatment plant in Kisumu city was constructed in 1958 by the British colonial government, but since then, its expansion has always lagged behind urban population growth. The treatment capacity for the plant is still inadequate. Investment in sanitation infrastructure is not only expected to reduce pollution load to the lake but also bring about improvement in public health and living environment in general.

1.3 Study areas

1.3.1 Kenyan side of Lake Victoria basin and Winam Gulf

Lake Victoria is a significant source of fish production in Kenya. Even though Kenya's share of Lake Victoria is only 6 %, the lake is estimated to contribute about 95 % of fish produced in Kenya of which the majority is Nile Perch (Calamari et al., 1995; LVEMP, 2005). Nile perch is mainly for commercial exports and therefore the Lake plays a role in contribution to Kenya's Gross Domestic Product (GDP) as foreign currency exchange earner and provides a source of livelihood to communities around the Lake. Human population living on the Kenyan basin as per 1999 census was 12 million with a fast population annual growth rate of 3 % thus putting pressure on the basin resources.

The Kenyan catchment of Lake Victoria has an elevation range of 1,100 m to 3,000m asl. The topography of the area around the lake shore is low lying and flat allowing satellite lakes and wetlands to exist and unfortunately making some areas prone to frequent floods. These areas are plain fields of Budalangi, Nyando and Kano plains. The wetlands and small lakes play important roles to the lake ecosystem through filtering stream flow, breeding ground for fish, food for wildlife and source of building materials for communities. The shoreline hosts scenic beaches which attract tourism and boost the economy of the area.

The watershed network is defined by elevated areas to the east by the great eastern rift valley running north to south and Nandi hills and to the north by Mount Elgon and Cheraganyi hills hence the rivers flow generally westwards and southwards. Sondu, Nzoia, Sio, Yala, Nyando and Gucha are the main 6 perennial river watersheds on the Kenyan side of Lake Victoria basin. There are smaller shore catchments and seasonal streams flowing to the Lake from the Kenyan side (North and South Awach). River Nzoia has the largest discharge while Sio has the least. Mara watershed originates from Kenya and traverse through Tanzania but bigger part of the watershed is on the Kenyan side (Table 1.3). The headstreams of the rivers are from Kenyan highlands where they are predominantly covered by agriculture and partly forests. The catchment on the Kenyan side has huge potential for hydro-power generation which remains underutilized with only development in Sondu watershed (Calamari et al., 1995; LVEMP, 2005).

As the rivers flow downstream to the lake the waters get polluted by wastewater from urban areas and industries and bad land practices in the watersheds. The main urban areas are Kisumu, Eldoret, Kakamega, Kericho and Kisii (Fig. 1.3). Industries in the area are mostly sugar and tea industries: Muhoroni, Chemelil, Mumias, Sony and Western Kenya sugar industries and several agro-chemicals industries within environs of Kisumu and Homa Bay towns.

Table 1.3 Kenyan river flows and as % of total flow from Kenya basin and whole basin

River	Flow (m^3/s)	% Kenya basin	% Whole basin
Sio	11.4	3.5	1.5
Nzoia	115.3	35.0	14.8
Yala	37.6	11.4	4.8
Nyando	18.0	5.5	2.3
North Awach	3.7	1.1	0.5
Sondu	42.2	12.8	0.8
South Awach	5.9	1.8	5.4
Gucha-Migori	58.0	17.6	7.5
Mara	37.5	11.4	4.8
Total	778.3	100	42.4

Source: LVEMP (2005)

The surface area of the lake on the Kenyan side is 4,100 Km^2 while the catchment area that flows to the Kenyan side of the lake is 29,795 km^2. The unique shape of the lake has some of its parts protruding inland such as Winam Gulf on the Kenyan side of Lake Victoria as described above. The gulf is long, slender, shallow, semi-enclosed and bottlenecked at the point of connection to the main lake. It has a surface area of 1,400 km^2 and an average depth of 10 m (Calamari et al., 1995) and connects to the main lake at Rusinga channel (Fig. 1.3). The gulf is a source of fish, freshwater supply and also provides routes for transportation. The catchment of Winam Gulf is entirely on the Kenyan side of Lake Victoria basin.

The 1:3 ratio of lake to basin geometric characteristic makes the lake susceptible to significant atmospheric pollution from long range airborne nutrients relative to land based nutrients and sediments (COWI, 2002; Scheren, 2003). Also the large lake surface area is reflected in water balance in which 82 % of water inflows come from direct rainfall and 18 % from river systems. When water balance is narrowed down to Winam Gulf, 8.1 billion m^3

(46 %) of water come from direct rainfall and 9.2 billion m^3 (54 %) come from inflowing rivers (LVEMP, 2005; COWI, 2002). Studies done in the past to estimate pollution load to the lake have indicated that more than 65% of total non-point pollution comes from atmospheric deposition. This has been attributed to the large ratio of the lake surface area to basin area but the situation is different for Winam Gulf. As elaborated above, the direct rainfall vs river inflow in percentage terms is 82/18 for the whole lake while for Winam Gulf is 46/54. Atmospheric load is deposited uniformly over the lake unlike river-driven (land runoff) load whose deposition is concentrated within river mouths. The concentrated deposition from rivers is worse for Winam Gulf which is like a small pond with less mixing with the main lake. Therefore information on river driven pollution load is important to ecological health of Winam Gulf.

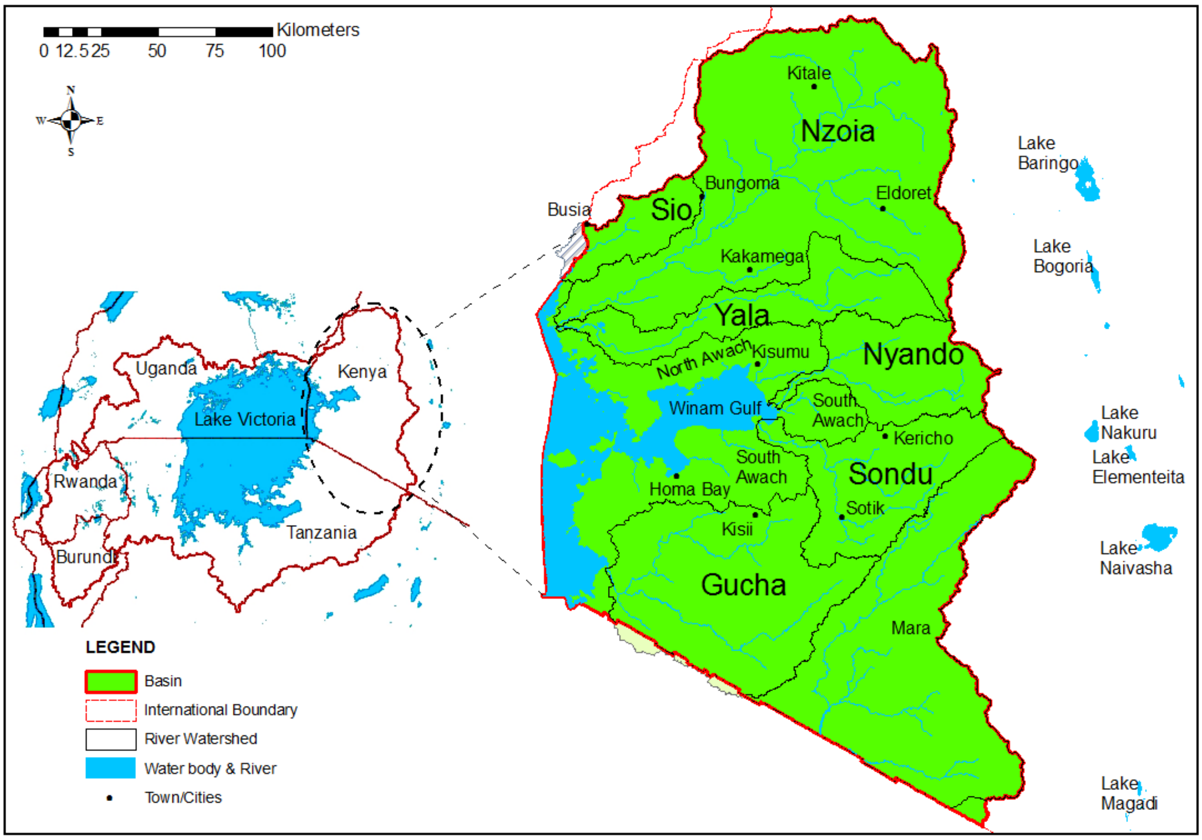


Fig. 1.3 Winam Gulf and the Kenyan catchment of Lake Victoria

1.3.2 Sondu river watershed

River Sondu originates from the Mau forest complex and has a watershed area of 3,508 km^2. It is the third largest by flow volume among the main six rivers on the Kenyan side of Lake Victoria basin and its watershed has the largest forest cover rate (COWI, 2002). It flows through a narrow gorge, penetrating the Odino falls flowing through the flood plains of

Nyakwere and Sango and thereafter pours its waters to Lake Victoria at Winam Gulf (Fig. 1.4). The watershed supports a human population of about 1.1 million (LVEMP, 2005) and has an elevation range of 1,134-2,930 m above sea level. The watershed receives average annual rainfall of 1,000-2,500 mm, with upstream parts (Kericho, Molo, Kisii) receiving higher rainfall than downstream areas (Fig. 1.4). There is a wide variation in average daily temperatures which range from 10^0C to 31^0C. According to LVEMP (2005), high temperatures are experienced downstream and around the lakeshore. Major land covers (land use) in the watershed are agriculture and forest in which forest is mainly the Mau forest complex.

Forested areas are mainly upstream while the dominant agriculture enjoys even distribution across the watershed and rice irrigation is practiced downstream. The Mau forest is the largest indigenous mountain forest in East Africa and is also an important ecosystem resource for not only Sondu watershed but for many other neighboring Kenyan rivers. The forest had earlier been encroached for human settlement but it is now under rehabilitation. Changes in forest cover and other aspects of the watershed would have adverse impact on development at both the watershed and within the lake.

The Sondu watershed is a source of water supply for domestic and irrigation uses and powers the Japanese Government funded 80 MW Sondu-Miriu hydropower station located downstream. Land sediment loss and subsequent flow carry along nutrients into the lake resulting in adverse impacts on water resources development on both the aquatic and terrestrial social-economic activities. Sediment erosion leads to loss of soil cover and subsequently results in adverse impacts on agricultural production, lake's ecosystem integrity and watershed hydrology.

Sedimentation also reduces the storage capacity of Sondu-Miriu hydropower dam at the water intake point and causes clogging of turbines. Sediments are swept downhill, due to steep gradient and poor farming methods upstream, during wet seasons into the river channels that feed the power station, occasionally the blocks roll down and block the channels (Ministry of Energy and Petroleum - Kenya, 2014). The responsible ministry has recently forested Koguta hill which is part of Sondu catchment to curb siltation Sondu-Miriu hydro-power dam. Additionally, sedimentation limits river carrying capacity and fills irrigation channels/canals with silt deposits. During high precipitation seasons, the river regularly bursts its banks downstream and causes flooding at Nyakach and Rachuonyo North districts. Excessive sedimentation not only leads to lake pollution, high operation costs of desilting irrigation channels and dredging of hydropower dams and reduced river capacity but also loss of lives and livelihood and human displacement.

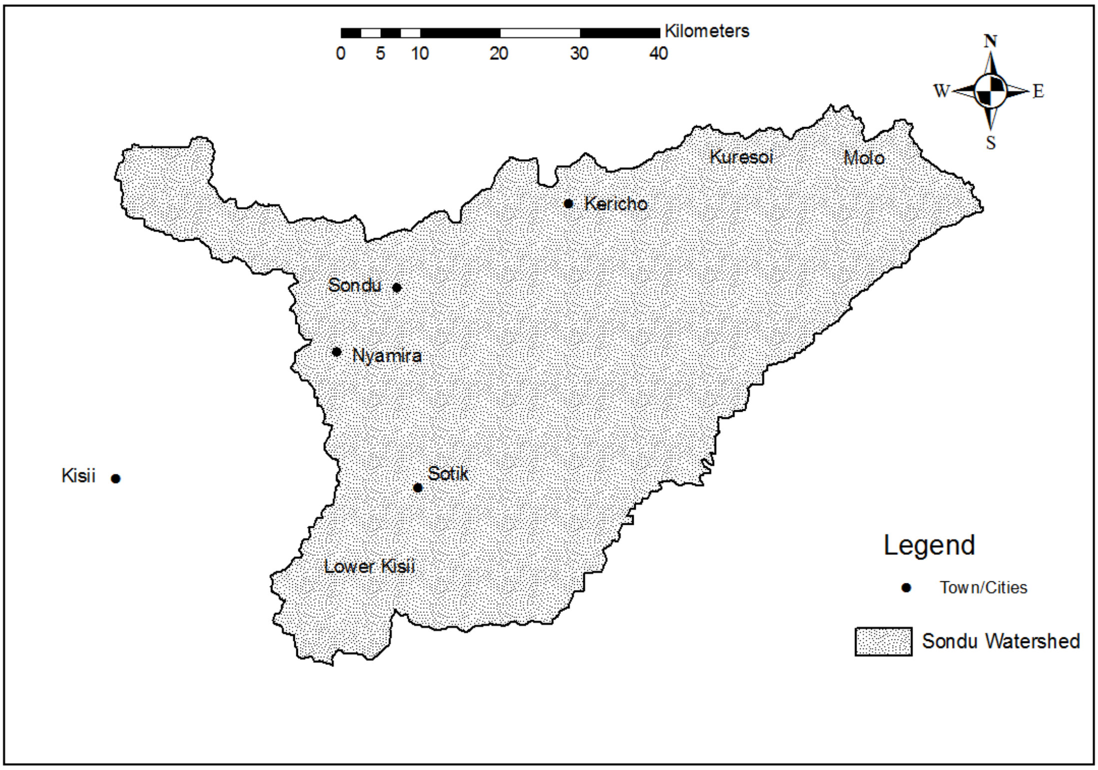


Fig. 1.4 Sondu river watershed and major towns

1.4 Need for research

Estimation of pollution load to Lake Victoria has been carried out by several studies in the past. Estimation of pollution load has always been hampered by scarcity of data which adversely affects the accuracy and reliability of results. The choice of simplistic methods was informed by data scarcity. The studies have different estimates of pollution load which makes it difficult to determine which estimates are reliable and accurate. There is need to review and consider possible methods based on GIS modelling tools for future improvement. The Lake Victoria basin is geographically enormous and incorporation of remote sensing and GIS mapping technology has potential to improve reliability and accuracy of the estimates.

Also in the past studies, rapid assessment methods were used in estimation of pollution load in Lake Victoria. The approach uses nutrient export coefficients commonly referred to as

Unit Area Load (UAL) to estimate pollution load but the UALs were borrowed from other regions. Local export coefficients are in inexistent for Lake Victoria. The borrowed nutrient export coefficients were not adjusted to fit local conditions because of lack of relevant data and information. A critique of this approach is that borrowed export coefficients may not be representative of local conditions. For example, borrowed UAL for cropland from a wet watershed would not reflect the actual situation if used in a less wet watershed. Estimated local UAL facilitate analysis of impacts of various management plans applied on a watershed with respect to spatial sources with the aim of reducing pollution load. The local UALs are useful in improving method of estimation of pollution load compared with the current methods which use borrowed coefficients.

Simulation of hydrology, sediment and nutrients as well as impacts of watershed management practices provides useful insights to watershed or lake manager especially on mitigation of adverse impacts. Assessment of management practices done at watershed outlet gives a clearer understanding of temporal dynamics while at sub watershed level provides information on spatial distribution. A simulation of temporal-spatial characteristics of a watershed aids its management through identification of hot spot areas and time periods and resource needs which are useful for informed decision making.

Atmospheric load is deposited uniformly over the lake as compared to riverine (land runoff) load whose deposition is concentrated within river mouths. The gulf is like a small pond with little mixing with the main lake due to its unique characteristics. Whereas lake area to basin area ratio is 1:3 for the whole lake, that of Kenyan side is 1:8. These features make the gulf to be significantly susceptible to runoff pollution load. Subsequently, the adverse changes that befall the gulf are mainly attributed to runoff load relative to atmospheric load and therefore there is need to focus on this part of the Lake.

1.5 Research objectives

The broad goal of this research is to improve pollution load estimation framework and to assess pollution load on the Kenyan side of Lake Victoria by incorporating Geographical Information System (GIS) and Remote Sensing technologies with the following specific objectives:

1. To review estimation methods of pollution load in Lake Victoria in past studies, their strengths and weaknesses in tandem with advancement in technology in watershed modelling;
2. To improve estimation framework of static models by estimating local nutrient export coefficients for land covers on the Kenyan side of Lake Victoria basin;
3. To simulate hydrology, sediments, total nitrogen and total phosphorous and their spatial-temporal distribution in Sondu watershed using Soil Water Assessment Tool (SWAT) to identify soil loss hot spots;
4. To model and assess effectiveness of three watershed management plans (existing situation, use of filters on agricultural land and reforestation) aimed at curbing environmental degradation and sediment erosion in Sondu watershed.

1.6 Outline of the thesis

The thesis is composed to flow step by step in six chapters to achieve the above objectives and within the specified scope. The thesis structure is described below and summarized in Fig. 1.5.

Chapter 1: Introduction. The chapter describes the background and existing environmental challenges in the study area and introduction of research topic. The chapter also introduces the need for research and list research objectives.

Chapter 2: Literature review. The chapter introduces existing static and dynamic runoff models, their relevance and weaknesses in simulation of hydrology and pollution load. The existing studies and estimation methods of pollution load to Lake Victoria are reviewed. The estimation methods of point and non-point pollution load are described to identify limitations and areas needing improvement. The Chapter informs: the structure of this study, formulation of the objectives, expected challenges in pursuance of the objectives and methodology in Chapter 4 to be used to attain the objectives (The chapter addresses the first objective).

Chapter 3: Data description and processing. The chapter describes specifications of remote and non-remote sensing data which were used in the study, including their sources. The Chapter also describes the processing done on the data using GIS and other tools to prepare them for use in model development. The GIS processes of generating watersheds and sub watersheds for the study are described.

Chapter 4: Models development and methods. The Chapter elaborates the design of two models developed in this study (runoff model using export coefficients and SWAT model). The models are for estimating municipal load, export coefficients, nutrients and sediment load. The chapter elucidates the limits of the models, parameters and assessment criteria. Watershed management plans aimed at curbing watershed sediment loss are also described (The chapter provides a methodology for second, third and fourth objectives).

Chapter 5: Results and Discussion. The Chapter presents the outcomes of review of current estimation of pollution load in Lake Victoria, output of models application to estimate nutrient export coefficients, sediment and nutrients and to assess watershed management plans performance in reduction of sediment loss. The Chapter also compares results to other similar studies and highlights model performance in calibration and validation phases.

Chapter 6: Conclusions and Recommendations. The chapter summarizes the findings on review of current studies on estimation of pollution load in Lake Victoria. Also on ways of improvement of static load estimation models and on use of dynamic model (SWAT) to simulate hydrology, sediment and nutrients as well as simulation of watershed management plans. Challenges and suggestions of issues for further research and improvement are also included.

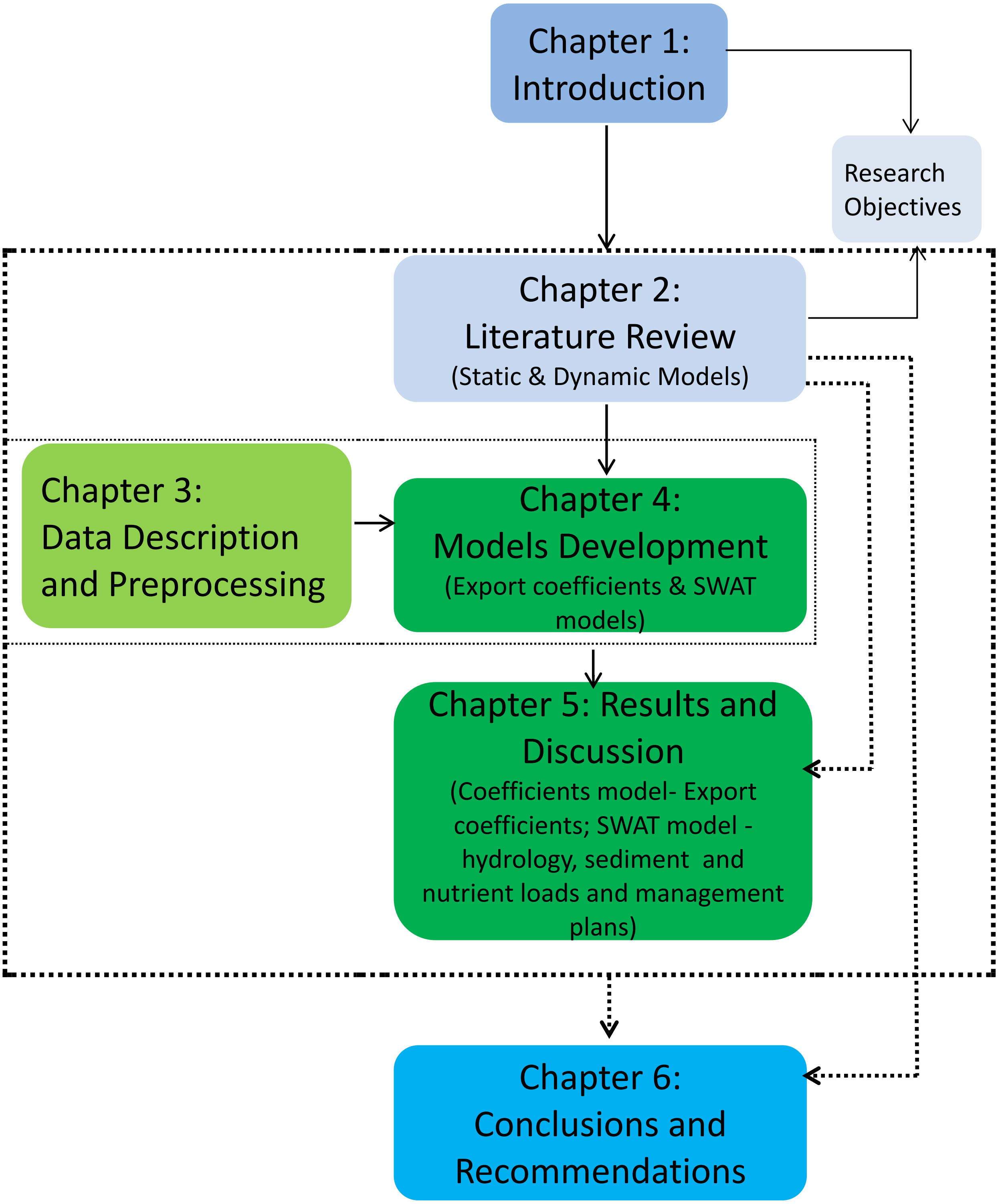


Fig 1.5 Graphical representation of thesis framework

CHAPTER 2: LITERATURE REVIEW

This Chapter introduces some of the relevant current runoff models used to estimate pollution load. On the second part, studies on estimation of pollution load in Lake Victoria are described as well as presentation of the methods they used and their data sources. Finally, the Chapter discusses the studies with interest on the methods used. The discussion brings out the differences in estimates of pollution load, their strengths and weaknesses. It is from the discussion that the basis of the objectives of this study is elucidated. The Chapter addresses the first objective of this study.

2.1 Existing runoff models

Several models have been developed to simulate water runoff hydrology, sediments and nutrients generation and transport mechanisms. In this section, some of the existing runoff models are described below.

2.1.1 Constant concentration model

Spreadsheet based models are used to estimate pollution load by making assumptions to: simplify and fit in a spreadsheet. For example, a specified nutrient concentration in a river is assumed to be constant throughout the year. Total annual nutrient load is derived by multiplying the annual river discharge with annual river concentration using spreadsheets. Data input required include: river (stream) flow, river water quality, rainfall water quality and area of water surface. The model has limitation in simulation of water quality parameters which are rainfall driven events and continuously changing in concentration.

2.1.2 AGNPS model

Agricultural Non-Point Source (AGNPS) model was developed by United States Department of Agriculture – Agricultural Research Service (USDA – ARS) (1980). It is a computer model that estimates non-point source pollution load from a river watershed. The model estimates runoff load for a single storm event or for a continuous simulation (Young et al., 1987). The modified universal soil loss equation (MUSLE) is used to predict soil erosion and unit hydrograph is used to simulate hydrology flow. Input data required include: digital elevation information, soils, land cover and rainfall data. The model calculates runoff water quality of single rainfall event in a watershed and application area is limited to about 200 Km^2 hence its limitation (Aisha Akter, 2005).

2.1.3 AnnAGNPS model

Annualized Agricultural Non-Point Source (AnnAGNPS) model was also developed by USDA – ARS (1990). It simulates runoff, sediment and nutrient loads from watersheds and evaluates conservation programs. The model is applied on in level of small watersheds in which the watershed can be delineated to accommodate land use and soil variation and conservation practices and remaining computationally feasible (Yongpin et al., 2011). The model routes the loads for a single day event and point sources are limited to constant loading. The model is limited by absence of pesticides consideration mass balance calculations.

2.1.4 CMSS and Bayesian models

Catchment Management Support System (CMSS) is a simple unit area load model. CMSS estimates pollution load (TN & TP) from land runoff and allows for natural reduction (attenuation). Natural reduction is expressed as a function of river length, river channel depth and catchment area. The needed input data include: land cover types and areas of river watershed, length of river channel, slope of river, depth of river channel, and generation rates of land cover (Unit Area Load - UAL).

The CMSS model can be used in a Bayesian framework as done by Broad and Corkey (2011) in Tasmara, Southern Island State of Australia. Bayesian approach allows incorporation of uncertainty in the estimates in a natural way. All data are considered simultaneously and in this respect uncertainty is propagated through the model. In a Bayesian framework, CMSS can be used to calculate generation rates when you have observed pollution parameters. The river watershed is sub divided into sub catchments and CMSS model is applied to determine land cover generation rates (a case where you have all input parameters listed above with exception of generation rates).

2.1.5 SWAT model

Soil Water and Assessment Tool is a GIS interface model. SWAT is a continuous model and operates on a daily frequency. It simulates watershed hydrology, sediment and nutrients transport. SWAT is a comprehensive hydrological model with capability to analyze land and water management for agriculture and water quality (Arnold *et al*., 1998). The model was developed by researchers Jeff Arnold of USDA-ARS, Texas, and Raghavan Srinivasan of Texas A & M University (1993). The main threes steps are: partitioning watershed and input information and simulation Hydrology in land phase and water or routing phase (Fig. 2.1 and Fig. 2.2). Required data are: elevation information, soils, land cover and weather data (rainfall, humidity, wind speed, temperature, etc).

The runoff hydrology is based on Curve Numbers (CN) by United States Soil Conservation Service (SCS). The model could be used to assess several watershed phenomena, for example to assess the impact of land cover change on a lake. Input data required are: elevation information, soils, land cover and weather data (rainfall, humidity, wind speed, temperature, land management practices, etc.).

Hydrologic modelling

The hydrologic cycle as simulated by SWAT is based on the water balance equation (Eq. 2.1)

$$\mathrm{SW_t} = \mathrm{SW_0} + \sum_{i=1}^{t}(\mathrm{R_{day}} - \mathrm{Q_{surf}} - \mathrm{E_a} - \mathrm{W_{seep}} - \mathrm{Q_{gw}}) \qquad (2.1)$$

Where

$\mathrm{SW_t}$ is the final soil water content (mm), $\mathrm{SW_0}$ is the initial soil water content on day I (mm), t is the time (days), $\mathrm{R_{day}}$ is the amount of precipitation on day i (mm), $\mathrm{Q_{surf}}$ is the amount of surface runoff on day i (mm), $\mathrm{E_a}$ is the amount of evapotranspiration on day i (mm), $\mathrm{W_{seep}}$ is the amount of water entering the vadose zone from the soil profile on day i (mm), and $\mathrm{Q_{gw}}$ is the amount of return flow on day i (mm).

The model calculates runoff in each Hydrologic Response Unit (HRU) in small sub basins which sum up to the total runoff for whole watershed. The use of HRUs increases accuracy and gives a much better physical description of the water balance. The surface runoff is simulated using SCS curve number method (Eq., 2.2).

$$Q_{surf} = \frac{(R_{day} - I_a)^2}{(R_{day} - I_a + S)} \qquad (2.2)$$

Where

Q_{surf} is the accumulated runoff or rainfall excess (mmH_2O); R_{day} is the rain fall depth for the day (mmH_2O); I_a is the initial abstractions which includes surface storage, interception and infiltration prior to runoff (mmH_2O); and S is the retention parameter (mmH_2O).

The retention parameter is a function of curve number in which the curve number varies depending on watershed characteristics (for example land use, soil type, and slope) (Eq. 2.3).

$$S = 25.4(\frac{1000}{CN} - 10) \quad (2.3)$$

Where
CN is the curve number for the day.

Manning's equation is used in SWAT to calculate the rate and velocity of flow in water and routing phase (Eq. 2.4 & 2.5).

$$q = \frac{1}{n} AR^{\frac{2}{3}} slp^{\frac{1}{2}} \quad (2.4)$$

$$v = \frac{1}{n} R^{\frac{2}{3}} slp^{\frac{1}{2}} \quad (2.5)$$

Where
q is the rate of flow in the channel (m^3/s); A is the cross-sectional area of flow in the channel (m^2); R is the hydraulic radius for a given depth of flow (m); and *slp* is the slope along the channel length (m/m); n is the Manning's coefficient for the channel; and v is the flow velocity (m/s).

Sediment modelling

Soil erosion caused by rainfall and runoff is simulated with the Modified Universal Soil Loss Equation (MUSLE) (Eq. 2.6).

$$sed = 11.8 \cdot (Q_{surf} \cdot q_{peak} \cdot area_{hru})^{0.56} \cdot K_{USLE} \cdot C_{USLE} \cdot P_{USLE} \cdot LS_{USLE} \cdot CFRG \quad (2.6)$$

where *sed* is the sediment yield on a given day (metric ton); Q_{surf} is the surface runoff volume (mmH_2O/ha); q_{peak} is the peak runoff rate (m3/s); $area_{hru}$ is the area of the HRU (ha); K_{USLE} is the USLE soil erodibility factor (0.013 metric ton m^2); C_{USLE} is the USLE cover and management factor; P_{USLE} is the USLE support practice factor; LS_{USLE} is the USLE topographic factor; and CFRG is the coarse fragment factor.

Nutrient modelling

SWAT models the transformation and movement of nitrogen and phosphorus in the watershed. In the soil, SWAT monitors five different pools of nitrogen, two mineral N pools (NH4+ and NO3-) and three organic N pools (active, stable, and fresh). SWAT also monitors six different pools of phosphorus, three mineral P pools (stable, active, and solution) and three organic P pools (active, stable, and fresh). Nutrients introduced to the main channel are then routed through channel networks.

Description of SWAT model, its conceptual framework is elaborated in detail by Neitsch et al. (2009).

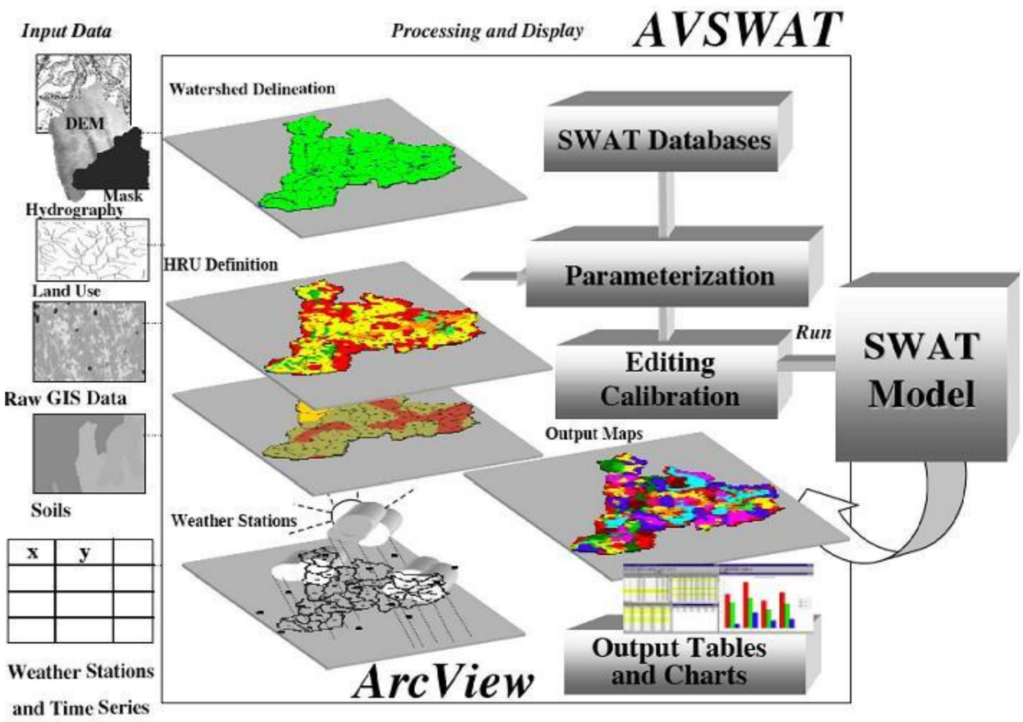


Fig. 2.1 The SWAT model development framework (Arnold et al., 2011)

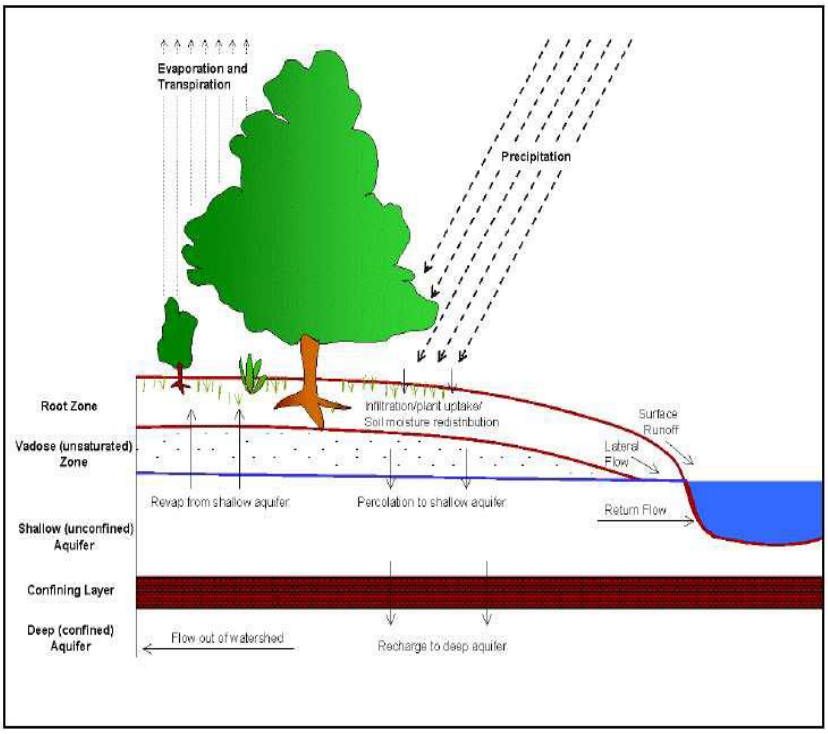


Fig. 2.2 Hydrologic cycle concept in SWAT model (Arnold et al., 2011)

2.2 Existing studies and estimation methods of pollution load

Methods used in past studies were reviewed in order to identify both their strengths and weaknesses in order to inform this study. This was done in consideration of continued expansion of database of Lake Victoria as more projects are being implemented and advancement in GIS and remote sensing technologies with respect to water resources management.

Pollution sources are usually conveniently classified into point and non-point sources. All the studies reviewed classified municipal and industrial sources as point sources while land runoff and atmospheric deposition as non-point sources. However differences emerge among the studies regarding the methods of quantification of pollution load. The different approaches taken by the reviewed studies are discussed below. Studies and projects considered here in detail are Calamari et al. (1995), Scheren et al. (1995, 2000), COWI (2002), LVEMP (2005), Scheren (2003, 2005). The studies reviewed are discussed below and key features summarized in Tables 2.1 and 2.2.

2.2.1 Calamari et al. (1995)

The study conducted pollution risk assessment on river watersheds and shore catchments flowing into Winam Gulf on the Kenyan side of Lake Victoria. The main aim of the study was to identify potential pollutants. Pollution load was estimated from municipal (point load), industrial (point load) and agricultural sources (non-point load). Organic matter (BOD) and TP were estimated in the study but atmospheric deposition was not estimated.

Municipal pollution load

Municipal loads from ten towns were taken into consideration. The towns that were considered are: Ahero, Chemelil, Homa Bay, Kendu Bay, Kericho, Kisumu, Muhoroni, Oyugis, Sondu and Sotik. These are urban areas that had a population of more than 10,000 inhabitants otherwise areas with less population were considered as small and scattered rural settlements which contribute to runoff pollution load. Pollution from solid waste leachate was also estimated using per capita unit loads and population size. Pollution load was expressed as a function of population size (Eq., 2.2).

$$\text{Pollution Load (BOD)} = \textit{Population} \times \text{BOD Leachate per capita} \qquad (2.2)$$

The urban population was categorized into persons using the various sanitations: main sewer, pit latrines and septic tanks. The pollution load was then estimated based on population size using each sanitation and corresponding unit load. The total pollution load was the aggregate sum of estimated load for each sanitation use (Eq., 2.3).

$$\text{PollutionLoad(BOD)} = \sum_{\text{Sanitation}} (\textit{Population} \times \text{BOD per Capita}) \qquad (2.3)$$

The BOD and solid waste leachate unit loads for Eq. (2.2 & 2.3) were sourced from literature on estimation methods by Iwugo (1990). There was no reduction applied. With absence of clarity on reduction, the total pollution load was assumed to be the resultant load that gets to the nearest river course or wetland.

Industrial pollution load

The main sugar millers, agro-chemical and bottling industries were pooled to estimate industrial load. The industries are: Agro-Chemical and Food Company (ACFC), Chemelil, East African Breweries, Equator Bottlers Miwani and Muhoroni, among other miscellaneous industries. BOD parameter was used as a measure of organic matter in discharged wastewater from the industries. Pollution load estimates were derived from industrial production and industrial unit loads (waste load factors) (Eq., 2.4). Estimation was done for individual industries and later aggregated to get the total load. The waste load factors (unit loads) were sourced from guidelines outlined by World Health Organization (WHO, 1989). Penetration was applied to account for reduction by treatment facilities. However, how the penetration factors were arrived at was not elaborated.

$$\text{PollutionLoad(BOD)} = \sum_{\text{Industry}} (\textit{Production} \times \text{WasteLoadFactor} \times \text{Penetration}) \tag{2.4}$$

Non-Point pollution load

Unit Area Load (UAL) concept was adopted to estimate TP. Landuse was classified into two categories: cultivated and non-cultivated land. Rural settlements (inhabitants) and livestock were considered separately as generators of non-point load (TP) and derived using a per capita load. The estimates from the aforementioned sources were summed up to get the ultimate load (Eq., 2.5). The coefficients were sourced from literature.

$$\begin{aligned} &\text{Pollution Load (TP)} = \{ \sum_{\text{Landuse}} \textit{Land Area} \times \text{export Coefficients} \} + \\ &\{ \textit{Inhabitants} \times \text{Load/Capita} \} + \{ \textit{Cattle} \times \text{Load/Capita} \} + \{ \textit{Sheep} \times \text{Load/Capita} \} \end{aligned} \tag{2.5}$$

The study acknowledged difficulty in selecting coefficients (export coefficient) appropriate for Winam Gulf catchment. To select the applicable coefficient from the pool sourced from literature they were guided by the fact that less phosphorous is released from the soil under tropical areas relative to temperate zones. Only phosphorous from runoff was estimated because, according to the study, the nutrient was considered as the main limiting nutrient for primary production in the lake.

2.2.2 Scheren et al. (1995, 2000) and Scheren (2003, 2005)

Taking note of limitation of data rapid assessment methods were used by the studies. The studies came up with inventories of pollution data they considered adequate for their methodology based on extensive literature review and field visits. Municipal and industrial sources were classified as point sources while land runoff and atmospheric deposition as non-point sources. BOD, TN and TP were estimated for point sources while only TN and TP for non-point sources were estimated.

Municipal pollution load

Municipal load was deduced from wastewater generated from urban areas. Rural settlements (rural towns with less than 10,000 persons) were accounted for under land runoff as a non-point load. Unlike rural settlements, urban populations are in most cases in close proximity to the lake and river systems in Lake Victoria basin. Rural settlements are scattered over the basin. The studies came up with a range of typical per capita loads (pollution intensity) sourced from literature.

The range consisted of three values: the lowest and the highest unit loads that had been reported elsewhere, and a most likely value which was regarded as the best guess. Where data existed, the most likely value was sourced from a location with close characteristics as much as possible to those of Lake Victoria. The urban population was classified into sewered and unsewered population. The unsewered population comprised of people using septic tanks, pit latrines and others. Pollution load was expressed with respect to population size, Eq. (2.6).

$$\begin{aligned} \text{PollutionLoad(TN,TP\&BOD)} &= \textit{Population}\text{(sewered/unsewered)} \\ &\times \text{Load/Capita} \times \text{Reduction(sewered/unsewered)} \end{aligned} \quad (2.6)$$

The urban population data were sourced from central government departments and annual urban growth rate of 5 - 10% was applied to calculate current population. Penetration factors of artificial treatment facilities, rated from 30 - 70% efficiency, were applied. Reduction by rivers (BOD) as a function of distance while for natural wetlands (nutrients) was factored as a function of loading rate. The reduction factors for artificial facilities and wetlands were sourced from literature and field visits.

BOD breakdown in rivers was described as a first order decay process (Eq., 2.7). Error analysis was applied to determine reliability intervals occasioned by adopted (literature) unit loads and penetration factors of wastewater treatment facilities, rivers and wetlands. Variability is based on the logic that, unit loads sourced from literature may not be the actual values.

$$\text{Reduction Efficiency} = e^{\left(-K\frac{D}{86.4v}\right)} \quad (2.7)$$

Where K, D and v are decay rate, distance and flow velocity respectively.

Industrial pollution load

The studies estimated BOD load while TN and TP from industrial sources were not considered. Industrial database was assembled through field visits with assistance from government institutions and literature review. The data of industrial production and type of products produced were collected. Industries were grouped as per International Standard Industrial Classification (ISIC). ISIC group similar industries guided by the products they produce, for example fish group, dairy group of industries, among others. ISIC industrial grouping guided determination of corresponding unit loads of BOD. The pollution intensities for BOD (unit loads) were sourced from literature (World Health Organization, WHO, 1982).

The unit loads were considered as average industrial unit loads for industries globally. Although the unit loads adopted for a group of industries may be biased, it was assumed that estimation for large batches (production by the group of industries) is accurate and therefore error estimation was considered not necessary. For each individual group, pollution load was estimated as a product of production (functional variable) and pollution intensity (BOD load per unit product). Loads from individual groups were then tallied to get total industrial load (Eq., 2.8).

$$\mathrm{PollutionLoad(BOD)} = \sum_{\mathrm{Industrial group}} Production \times \mathrm{PollutionIntensity} \quad (2.8)$$

Runoff pollution load

The studies used UAL concept to estimate rainfall runoff load. Landuse was classified into cultivated and non-cultivated land. Ranges of UAL (nutrient export coefficients) were borrowed from literature and most likely values (best guess) were borrowed from studies in conditions similar to or close as much as possible to those of Lake Victoria. The most likely values that were adopted were sourced from study on Lake Malawi by Bootsma *et al*. (1996). However, due to dense population density they were regarded to be on a lower side and thus adopted as a first estimate.

UAL is a function of several characteristics including: precipitation, soil texture, type of land cover, slope, among others. In this regard, UAL borrowed from the case of Lake Malawi was based on assumption that they have close characteristics to those of Lake Victoria basin. Total runoff load was derived by matching land use area with export coefficients (Eq., 2.9).

Error estimation was considered to determine possible variability of UAL from most likely value and to explain the uncertainity.

$$\text{PollutionLoad(TN\&TP)} = \sum_{\text{Cultivated}}^{\text{Non cultivated}} \textit{Land Cover Area} \times \text{ExportCoefficient} \qquad (2.9)$$

Atmospheric pollution load

Atmospheric pollution load was modeled as a product of unit area deposition rates and lake area (Eq., 2.10). The study referred to literature for unit deposition rates with acknowledgement of absence of reliable data. The unit deposition rates for non-populated areas in Lake Malawi were adopted as the most likely value. The data available which were measured on shores of Lake Victoria were considered substantially high relative to literature values reported in other remote tropical regions. The data were thus considered not representative for Lake Victoria. The variance was attributed to large interference by effects of human activities around the shores of Lake Victoria. The full range of values reviewed defined upper and lower boundaries.

$$\text{PollutionLoad(TN\&TP)} = \sum_{\text{Wet}}^{\text{Dry}} \textit{Lake Area} \times \text{Atmospheric Deposition per unit Area} \qquad (2.10)$$

2.2.3 Lake Victoria Environmental Management Project (COWI, 2002; LVEMP, 2005)

The studies under Lake Victoria Environmental Management Project (LVEMP), Phase I (1995 - 2005) made a detailed attempt to quantify pollution load to the lake from both measured (taken from field) and estimated (approximated) data. LVEMP was a project co-funded by World Bank and the three riparian countries (Kenya, Tanzania and Uganda) aimed at improvement of environmental status of Lake Victoria.

Point pollution load comprised of municipal effluent discharged from towns (with more than 10,000 persons) and wet industries. Non-point pollution load comprised of diffuse runoff and atmospheric deposition. Rural settlements were accounted for as non-point pollution. Point load (municipal and industrial loads) from towns in Kenya, Tanzania and Uganda were estimated. Point loads from Rwanda and Burundi which are part of the basin were not estimated but non-point pollution load estimation covered the whole basin.

Municipal pollution load

Urban population was grouped by mode of waste disposal (discharge system – sanitation type). The discharge systems considered are: main sewer, pit latrines, septic tanks and direct disposal to wetland and/or river. Actual measurements and estimations were used to identify size of population using a given mode of disposal. Urban population size was derived using country censuses, 1988 (Tanzania), 1991 (Uganda) and 1999 (Kenya). Expansion of urban areas was classified into four categories (from least to fast growing): fishing villages, rural expanding, normal expanding and highly expanding towns. Growth of 2 – 4 % was applied to determine current population.

Municipal load was estimated using per capita loads (unit load) for TN, TP and BOD. Standard figures for per capita load were reviewed from literature. Selection of the standard unit figures of unit loads for municipal wastewater was guided by values that reflect population in developing countries with relatively low protein consumption. The total pollution load was derived by matching population, unit loads and reduction factors (Eq., 2.11).

$$\text{PollutionLoad}(\text{TN},\text{TP}\,\&\,\text{BOD}) = \sum_{\text{Sanitation}} \textit{Population} \times \text{Load/Capita} \times \text{Reduction} \qquad (2.11)$$

Only the reduction by artificial treatment systems (main sewer, pit latrine and septic tank) was considered. Reduction by river and natural wetlands was disregarded. This means, the load reported is the resultant estimate of pollution load reaching the nearest water course. Treatment efficiency of discharge systems were determined by both estimation (approximation) and field observations.

Industrial pollution load

Estimates and rough approximations were used to estimate industrial pollution load due to scarce data. The various industries within Lake Victoria basin were identified. This comprised of 68 industries in the database and grouped by their river watershed locations. The pollution load estimation was based on production figures and standard loads per production unit (Eq., 2.12). Reduction of pollution load was treated as for the case of that of municipal origin.

$$\text{Pollution Load (TN, TP and BOD)} = \sum_{\text{Industry}} \textit{Production} \times \text{Load/Unit} \times \text{Reduction} \quad (2.12)$$

Runoff pollution load

Runoff load was deduced from water quality and quantity data measured at downstream river stations. The data were taken at points along the rivers and not necessarily at river mouths. Total runoff load was estimated as a product of load concentration and river discharge (Eq., 2.13).

$$\text{Pollution Load (TN\&TP)} = \sum_{\text{River A}}^{\text{N}} \textit{River Discharge} \times \text{Nutrient Concentration} \quad (2.13)$$

In the method it should be noted that calculated runoff pollution load (TP and TN) includes point loads discharged to the rivers upstream. However, the quantity of point loads in the study was considered negligible as compared to the quantity of pollution load from diffuse runoff. Also, not all river watersheds were gauged. That is, water quality and quantity data were not collected for some river watersheds and shore watersheds. The missing data were borrowed from the neighboring river watersheds.

Atmospheric pollution load

Like runoff load atmospheric pollution was estimated based on measured water quality and quantity data. Atmospheric deposition was derived from laboratory tests on samples collected using an open container for both dry and wet season deposition and ultimately extrapolated to cover the whole lake area. The samples were collected from land based stations within lakeshores of Kenya, Tanzania and Uganda. The lake was subdivided into rain boxes and precipitation data were collected. The precipitation data together with laboratory water quality data for dry and wet deposition were used to estimate atmospheric deposition load over the lake (Eq., 2.14).

$$\text{Pollution Load (TN\&TP)} = \sum_{\text{Wet}}^{\text{Dry}} \textit{Lake Area} \times \text{Atmospheric Deposition/Area} \quad (2.14)$$

Table 2.1 Summary of estimation methods (point sources)

Study			Calamari *et al.* (1995)	Scheren *et al.* (1995, 2000) and Scheren (2003, 2005)	COWI (2002) and LVEMP (2005)
Coverage			Winam Gulf	Lake Victoria Basin	Lake Victoria Basin
Pollution load			BOD	TN, TP, BOD	TN, TP, BOD
Industrial	Generation	Scope	6 Industries	12 Groups of Industries as per ISIC[1] (50 Industries)	68 Wet Industries
Industrial	Generation	Load	Load=Production* pollution intensity[2]* penetration factor[2]	Load=Production* pollution intensity[3]* penetration factor	Load=Production[4]* pollution intensity* penetration factor[4]
Industrial	Generation	Data source: Production	Not specified	Field visits, literature and relevant institutions	Actual measurements and rough estimates
Industrial	Reduction considered		Artificial treatment systems	Artificial treatment systems, rivers and wetlands	Artificial treatment systems
Municipal	Generation	Scope	10 Towns	40 Towns (Rwanda and Burundi included)	87 Towns (Rwanda and Burundi excluded)
Municipal	Generation	Disposal facility	Sewer, Pit latrine and Septic tank	Sewered and Unsewered	Sewer, Pit latrine and Septic tank and open defecation
Municipal	Generation	Load	Load=∑(persons*p.c.l**)	Load=Population* penetration factor* p.c.l**	
Municipal	Generation	p.c.l** for disposal facility	Different p.c.l** for each facility	Same p.c.l** for TN and TP. different p.c.l**BOD for each facility	Same p.c.l** for all facilities
Municipal	Reduction considered		Not considered	Artificial treatment systems, rivers and wetlands	Artificial treatment systems

**Per capita load (TN, TP or BOD); ***Unit Area Load; [1]International Standard Industrial Classification; [2]As per WHO (1989); [3]BOD as per ISIC, TN and TP as per WHO, (1982); [4]Based on measured or estimated data

Table 2.2 Summary of estimation methods (Non-point sources)

Study		Calamari et al. (1995)	Scheren et al. (1995, 2000) and Scheren (2003, 2005)	COWI (2002)
Coverage		Winam Gulf	Lake Victoria Basin	Lake Victoria Basin
Pollution load		TP	TN and TP	TN and TP
Land Runoff	Landuse	Cultivated and Non-cultivated	Cultivated and Non-cultivated	Not classified
	Load	Load={Area*UAL***}+{Population(persons, sheeps, cattle)}*p.c.l**	Load=Area*UAL***	Load=River discharge*Nutrient concentration
	Data source: p.c.l**, UAL*** & Water quality & quantity	Literature	Literature (Range of values was used)	Measured river water quality and quantity (not necessarily restricted to river mouths)
Atmospheric deposition	Load	Not considered	Load=surface area*annual deposition per unit area	Load=(nutrient concentration*precipitation)+(surface area*annual dry deposition per unit area)
	Data source: Annual deposition per unit area and Samples	Not considered	Literature (most likely values borrowed from measured values of unpopulated areas of Lake Malawi)	Actual measurement of samples for dry and wet deposition collected from land based stations

**pcl - Per capita load (TP); ***UAL - Unit Area Load

2.3 Discussion of literature

The sections below highlights useful information conveyed and challenges encountered by the past studies in the preceding literature background. It relooks at the literature against realistic mechanisms of movement of pollution load from point of origin to the lake. The unit loads (unit per capita and unit per unit product) and export coefficients from literature review that inform logical arguments below are summarized in Tables 2.3, 2.4 & 2.5.

2.3.1 Point pollution load

Not all towns and industries considered by the studies within the Lake Victoria basin have sewage treatment facilities. Alternatives such as wetlands, pit latrines and septic tanks are used. For households connected to municipal sewers, it is easy to conceptualize how municipal waste load ends up in the lake through treatment systems then to wetlands and river course or disposed directly from treatment plants to water courses. It is also possible to monitor the effluent quantities and quality with such controlled system (sewerage). Flow quantity and pollution load can be measured and total pollution load deduced with ease for a sewerage system situation. The pollution source from a controlled system is referred as a point source because the source can be identified with clarity.

Pit latrines provide an underground storage of human wastes and in some instances they receive wastewater from bathrooms and kitchens. In an ideal case where there is neither overflow, underflow seepage nor flooding the pollution load from pit latrines would not find their way into the lake. The challenge is how to quantify it where it happens. In extreme cases of overflow, pollution load from pit latrine will be driven by storm water runoff to the lake. In this regard, pit latrines would be simply considered as a diffuse pollution source.

Typical septic tanks do not flow (treated wastewater) directly into water courses but are discharged into either soak pits or vegetation/wetlands. It is also difficult to comprehend the movement mechanism of pollution load from septic tank to the lake. The pollution load flow mechanism of a septic tank could be better approached as a diffuse pollution source as is the case of pit latrines.

Therefore, assuming a less likelihood of extreme case occurrence which occasion load to flow from pit latrines and septic tanks; it is expected that relatively much pollution load should come from the main sewer than pit latrines and septic tanks combined when equal population usage is assumed. The per capita loads for each disposal system (sewer, latrine, septic tank) from the rationale should reflect their relative pollution load contribution.

COWI (2002) used the same per capita load (11 kg/person/yr) for BOD from urban areas for persons using main sewer, septic tanks and pit latrines This means people using pit latrines, septic tanks and main sewers pollute the lake equally. The same case was applied for TN and TP (but with different per capita loads from those for of BOD) (Table 2.3). It may be argued that, if a person living in a town and using a pit latrine pollutes the lake, then the same consideration should apply to a person living in the rural area. In extension this means pollution generated by both persons should be estimated without considering one as a point source and the other a non-point source.

Calamari et al. (1995), Scheren et al. (1995, 2000) and Scheren (2003, 2005) used different per capita loads for each disposal system (Table 2.3). The studies used a higher value for

BOD per capita load for sewered persons (8-20 Kg/person/yr) than those using other systems. This reflected the relative pollution potential by different disposal systems. The flat rate across different sanitations used by COWI (2002) does not represent realistic scenario. Scheren et al. (1995, 2000), Scheren (2003, 2005) and COWI (2002) used a flat rate for TN and TP with respect to all the sanitation systems (Table 2.3). This does not reflect the relative capacities of different sanitation systems to pollute the lake as argued above.

It is necessary to identify all the polluting industries in order to adequately quantify load from industries. The baseline information needs are: annual production, the load concentration (water quality) and quantity (flow) of wastewater discharge and efficiency of treatment facilities and insitu determined unit loads. However, these data are not always complete as acknowledged in reviewed studies because not all industries keep records. Without such data, past studies used standard unit loads from literature and estimates of industrial production; this seems to be the only option available to adopt until industries keep records and make them available. For example, Calamari et al. (1995), Scheren et al. (1995, 2000) and Scheren (2003, 2005) used industrial production as variables. They referred to guidelines by WHO (1982, 1989) for unit loads (TN and TP), and ISIC for BOD unit loads.

Table 2.3 Typical per capita unit loads of BOD, TN and TP (Kg/person/yr) for point pollution load

Study	Calamari et al. (1995)			Scheren et al. (1995, 2000) and Scheren (2003, 2005)		COWI (2002)		
Disposal system	Sewered	Septic tank	Pit latrine	Sewered	Unsewered	Sewered	Septic tank	Pit latrine
TN	-	-	-	Range: 2.2-4.4 Most likely=3.3	Range: 2.2-4.4 Most likely=3.3	1.8	1.8	1.8
TP	-	-	-	Range: 0.2-1.6 Most likely=0.4	Range: 0.2-1.6 Most likely=0.4	0.73	0.73	0.73
BOD	8.4	11	7.3	Range: 8-20 Most likely=16	Range: 7-11 Most likely=8	11	11	11

2.3.2 Non-Point pollution load

COWI (2002) estimated runoff pollution load based on water quality and water quantity data collected from rivers. Sampling was done at various stations for individual river watersheds and data from downstream stations were used to estimate total pollution load. The downstream stations are not completely at river mouths and this leaves out some part of the watershed un-gauged. Most wetlands in the lake basin are located close to the river mouths (downstream). Papyrus wetlands play a big role in the removal of nutrients (Kansiime and Nalubega, 1999; Kiwango, 2007). Their exclusion may influence the accuracy of the final load measured. Therefore water quality not measured at tail end of the river (river mouths) may not give an accurate estimate of nutrient loads. The approach provided useful information the challenges encountered notwithstanding.

The study by COWI (2002) used average river discharge and average nutrient concentration (pollution load) (Table 2.4). This is based on assumption that river water quality (nutrient concentration) is constant throughout the year regardless of level of river discharge to simplify estimation. Of course nutrient concentration to varies with river discharge and through the seasons of the year. It may be prudent to consider in future averages with respect to say four seasons in a year. Furthermore water quality data for 11 river catchments were borrowed from neighbouring catchments due to lack of data occasioned by study limitation. The borrowed river data were consequently used to estimate pollution load for river watersheds with missing data. The borrowed data may not be truly representative which probably creates bias error in the end results.

Calamari et al. (1995), Scheren et al. (1995, 2000) and Scheren (2003, 2005) used UAL concept (Table 2.4). The UALs were sourced from literature because there were no actual UAL values measured for any part of Lake Victoria Basin. UAL is a function of several characteristics (land slope, precipitation, soil texture, land use, among others) (Baginska et al., 2003; Scheren, 2003). UAL values from literature applicable for Lake Victoria basin were borrowed by looking for similarities in these characteristics. In practice it is absolutely hard to get river watersheds with similar characteristics. Therefore transfer of UAL from one region to another creates major uncertainity in the end estimates. However, the studies by Scheren did error analysis to explain the variability in the estimates due to the uncertainity.

Insitu measured UAL is needed for Lake Victoria basin to get better estimates of pollution load using the UAL approach. Estimated runoff pollution load by COWI (2002) for TN was almost two times that estimated by Scheren et al.(1995, 2000) and Scheren (2003, 2005), (TN: 49,509, 26,292 tons/yr respectively). The estimates for TP by both studies were closely equal (TP: 5,693, 5,634 tons/y respectively) (Table 2.5). The studies adopted similar approach to estimate the nutrients but there was variance and closeness in reported results with respect to parameters of pollution load. The variance and closeness in results is linked to choice of UALs and areas of classified land cover. Land cover does not change significantly over time. UAL has a greater sensitivity to influence the estimates relative to land cover change.

To explain further, UAL concept assumes that a unit area of land under a given land use generates a constant quantity of nutrients per year regardless of precipitation. Ideally, UAL is a function of several characteristics (rainfall intensity, slope, soil, watershed geometry etc). These factors vary temporally and spatially and UAL borrowed from a different location may not be in congruence with respect to these characteristics. There is need for further improvement to determine UAL (as a function of precipitation) for Lake Victoria basin.

Atmospheric deposition has consistently been reported by past studies as a significant source of pollution load to Lake Victoria, which seems reasonable when its huge surface area is considered. COWI (2002) collected laboratory samples for wet and dry deposition. The samples were only collected from land based and island stations and none from within the lake. Islands samples were later rejected due to handling and preservation problems in the laboratories arising from limitations such as poor cash flow and inadequate equipment for analytical methods among others. Given the influence by wind dynamics and human activities on atmospheric deposition and expansive nature of Lake Victoria; samples collected only on land based stations and used to estimate atmospheric deposition for the whole lake may not be truly representative. Scheren et al. (1995, 2000) and Scheren (2003, 2005) used annual deposition per unit area borrowed from literature. The limitations and shortcomings on use of atmospheric deposition units are similar to those of UAL.

Given limitations faced by past studies it is appreciated that it was prudent for them to use the methods they adopted. It is also worth to note that to overcome the limitations, huge amounts of data and resources are needed which were not available to the studies.

Table 2.4 Typical runoff/export coefficients (tons/Km^2-yr) and unit per capita loads (Kg/yr) used to estimate runoff load

Study	Calamari et al. (1995)			Scheren et al. (1995, 2000) and Scheren (2003, 2005)		COWI (2002)
Landuse	Cultivated	Non Cultivated	Others (Kg/yr)	Cultivated	Non Cultivated	NA
TN	-	-	-	Range: 0.05-1.2 Most likely=0.14	Range: 0.1-0.7 Most likely=0.14	Water quality and quantity data used
TP	0.04	0.01	Inhabitants=0.2 Cattle=0.95 Sheep=0.15 Goats=0.15	Range: 0.01-0.14 Most likely=0.03	Range: 0.01-0.09 Most likely=0.03	

Load estimates of TP (runoff) by the studies were closely equal while TP (atmospheric) estimated by Scheren et al. (1995, 2000) and Scheren (2003, 2005) were about seven times that of COWI (2002) but their TN (atmospheric) were close (Table 2.5). Considering the similarity in estimation approach and close periods when studies were done, the variations are significant. Despite the limitations, method by COWI (2002) which relied on measurements provides useful information especially for the gauged river watersheds. The shortcomings of the method may be addressed by collecting more samples within the un-gauged river watersheds, the lake and islands to make estimates more representative. The measured data provide basis for preliminary determination of atmospheric deposition load and informs subsequent studies.

Table 2.5 Comparative estimates of pollution load to Lake Victoria (tons/yr)

Study			Calamari et al. (1995)	Scheren et al. (1995,2000), Scheren (2003, 2005)	COWI (2002)
Coverage			Winam Gulf	Lake Victoria Basin	Lake Victoria Basin
Point loads	Municipal	TN	-	7,600*	3,515
		TP	-	920*	1,623
		BOD	3,577	12,800*	17,938
	Industrial	TN	-	-	413
		TP	-	-	342
		BOD	2,600	3,170*	5,606
Non-point loads	Runoff	TN	-	26,292*	49,509
		TP	1,190	5,634*	5,693
	Atmospheric	TN	-	85,513*	102,148
		TP	-	3,647*	24,402
Total load (without Atmospheric)		TN	-	33,892	53,437
		TP	-	6,554	7,658
Total load (with Atmospheric)		TN	-	119,405	155,585
		TP	-	10,201	32,060

*Most likely values; 1 ton = 1,000 Kgs

Use of SWAT in Lake Victoria basin has not found much practice, but few studies have been noted. Kimwaga et al. (2011) investigated pollution load on Tanzania's Simiyu catchment of Lake Victoria using SWAT model to assess impact of land use change on non-point source pollution. The study compared river flow and runoff nutrient (TN, TP) of 1975 and those of 2006 and demonstrated that land use has heavy impact on river runoff and nutrient pollution. Also Jayakrishman et al., (2005) applied SWAT on Sondu river watershed in Lake Victoria basin. The study assessed the impact of change in land use driven by adoption of modern technology for smallholder dairy industry. Although lack of data was the major challenge faced by the studies, more similar studies was recommended for Lake Victoria basin by the studies.

2.3.3 Export coefficients (UAL) in Lake Victoria and literature

A review of past studies on estimation of pollution load to Lake Victoria shows that different methods have been used to estimate runoff load as elaborated in section 2.2 and 2.3. The studies used two methods: 'at point of discharge' refers to use of nutrients and river flow measured at river mouths (COWI, 2002; LVEMP. 2005); and 'at point of generation' is use of nutrient export coefficients commonly referred to as Unit Area Load (UAL) but in the studies, the UAL were borrowed from other regions (Calamari et al., 1995; Scheren et al., 1995; Scheren et al., 2000).

The two methods had several shortcomings: In the 'at point of discharge' method, the in stream data were collected from points at the river mouths and not spread to cover river tributaries. Hence the data provide aggregate load but cannot readily provide information about the spatial distribution of nutrient sources. On the other hand, in the 'at point of generation' method, the borrowed export coefficients were not adjusted to fit local conditions because of lack of relevant data and information. A critique of this method is that borrowed export coefficients may not be representative of local conditions. For example, borrowed UAL for cropland from a wet watershed would not reflect the actual situation if used in a dry watershed.

Young et al. (1996) and Baginska et al. (2003) argue that borrowed coefficients may be adjusted to fit local conditions. However, quantitative adjustment is dependent on availability of information for both the receiving and origin catchments. Adjustment is further limited to few attributes, namely, rainfall intensity, catchment size and factors integrated by runoff volume variation. The information on how other environmental attributes influence nutrient export is too limited to facilitate adjustment on nutrient export coefficients (Young et al., 1996). In other words, the relationship between land use and rainfall-runoff coefficients with nutrient generation and export in a catchment are not only significant relative to other environmental attributes but also their information is usually available.

In summary, generation and transportation of runoff load is significantly influenced by soil-plant system (land use) and rainfall characteristics relative to other environmental attributes (Young et al., 1996; Mulung and Munishi, 2007; Ellis and Revitt, 2008). Land use, as an integrator of several environmental attributes, is the conventional best factor to estimate runoff pollution load (Young et al., 1996; Scheren et al., 2000; Baginska et al., 2003; Broad and Corkey, 2011). Unlike other factors, land use and rainfall data are usually readily available. Rainfall-runoff coefficient of a river watershed which denotes the ratio of amount of rain that falls on the catchment and pours to the lake is a relevant factor to explain export of nutrients.

Young et al. (1996) infer that runoff pollution load have strong correlation with meteorology and hydrology of the catchment. Nutrients in the catchment come from different sources which include: atmospheric deposition and environmental management practices (EMP) such as application of fertilizer for farming and agrochemicals etc. Nutrients have their way into the lake through surface and subsurface flows and wind transport. River driven nutrients (surface transport) is usually relatively most significant.

Comparison of rainfall-runoff coefficients, by watershed, provides information about relative surface runoffs between river catchments. The coefficient is a function of slope, rainfall intensity, land use, soil characteristics and ambient conditions (temperature, moisture, wind conditions, etc.). Ambient conditions greatly influence loss of catchment water through evaporation. The coefficient is considered to best mirror geometric and physical characteristics of a catchment. On the basis of integration of environmental attributes, land use and rainfall-runoff coefficient are considered parameters that best integrate the catchment characteristics and better explain generation and export of runoff load.

2.4 Summary of literature

A review of past studies on estimation of pollution load to Lake Victoria shows that different methods have been used to estimate pollution load. Scarce and scattered data is consistently pointed out as a major limitation in the studies. The methods of estimating point and non-point pollution load as reviewed can be broadly classified into:

1) Use of actual measurement approach; and
2) Rapid assessment approach.

Actual measurement method uses locally measured data to estimate point and non-point pollution load in an estimation framework. For example, use of measured water quality and quantity or UAL to estimate runoff load. On the other hand rapid assessment is applicable where data are scarce. For example, UAL from literature (with similar characteristics with study area) which is considered applicable is used to estimate runoff load.

There is a need to have representative unit loads to effectively use rapid assessment methods to estimate municipal and industrial load. The main baseline data are urban population with their corresponding sanitation system, industrial production, etc. More important is to establish locally improved and applicable per capita unit load and unit load per unit product. The challenges experienced by reviewed studies were pegged on the availability of these data. Population census and sanitation data are collected by regional governments. For example, Kenya conducts population census once in 10 years. Industries are themselves better placed to provide their data if they do keep the relevant pollution records. In the studies reviewed, industrial data are the scarcest and surrounded by much uncertainty.

The alternative to rapid assessment is use of actual measurements of municipal and industrial load; measurement of water quality and quantity of wastewater generated in a controlled system. For this alternative, data of wastewater treatment facilities for both industries and municipal are continuously monitored. Where wastewater does not flow through a control system it is accounted as non-point load. Estimates derived from wastewater treatment plants may be matched with number of persons using the plant to define the per capita load. The same may be done for industries to determine the waste load per unit of production. Treatment plants for industries, households and storm water should be separate for it to be successful. Also data collection should be done over a reasonably long period of time enough to cover extreme cases of load flow fluctuations. Periods of storm runoff and peak production are examples of extreme cases. The information from locally measured data will be useful for future rapid assessment methods.

The UAL and unit deposition rates (unit loads) from literature are used for estimation of runoff and atmospheric load in rapid assessment method. In the literature reviewed, UAL was defined for two types of land use (cultivated and non-cultivated). The classification excluded other significant land uses such as wetlands, urban areas, among others. Limited land use classification for a large basin with multiple human activities may not truly represent the runoff nutrient generation process. Wetlands cover a significant area and play a major role in reduction of nutrients in Lake Victoria (Kiwango, 2007). About 10,235 Km^2 of the basin is dominated by papyrus wetlands (Kiwango, 2007). Bearing in mind that multiple factors influence UAL, land use classification should be reasonably adequate to represent runoff nutrients generation and transport as much as possible.

COWI (2002) used measured river flow and nutrients concentrations to estimate runoff load. However, water quality and quantity measurements in rivers should be done at the tail end of the river just before pouring into the lake. Equally, flow and water quality measurements in treatment plants should be done to monitor municipal and industrial loads (not done for COWI, 2002).

The two methods of estimating pollution load have been applied in Lake Victoria. They are complementary in use for lake management. The trend in the past studies is that rapid assessment was initially used because of scarce data. As more measured data are becoming available, it should be incorporated in the estimation process. This study utilized the useful information from both methods and additional data from GIS and remote sensing in Chapter 3 to enrich the estimation process of pollution load to Lake Victoria.

The differences and at the same time closeness observed in the results of the past studies on estimation of pollution load to Lake Victoria makes it is difficult to determine which estimates are reliable and accurate. However, this demonstrates that in situations of inadequate data varying methods give different results. Reliable estimates are dependent on the quality of data and on use of methods that simulate the actual process dynamics as much as possible. For Lake Victoria, total point loads seem far much less than non-point loads but more accurate estimation of both loads would be important for policy making. Non-point loads come from diffuse sources with characteristics which vary in spatial and temporal dimensions. Estimates show that atmospheric deposition contributes significantly (30 – 80 %) to the TN and TP loads to the lake. Such significant contribution calls for an urgent need to come up with more reliable estimates of atmospheric deposition loads to inform policy making for this very important lake.

Although the past studies provide useful information within the existing constraints, there is a lot of uncertainty in the accuracy and reliability of the estimated pollution loads. The Lake Victoria basin is geographically enormous and incorporation of remote sensing and GIS mapping technology will improve reliability and accuracy of the estimates. The ability to use GIS technology to collect data and predict various scenarios of land use in the quantification of pollutants should reduce the number of errors made when less-exact methods are used. Remote sensing and GIS relate spatial and temporal geographical relationships and reinforce weaknesses noted in the past studies and stand to improve the estimation of pollution load to Lake Victoria especially runoff load.

In summary, the efforts in the past studies on Lake Victoria were mainly hampered by lack of data and hence the choice of the simplistic methods used. Lacking data include management practices in the basin, water flow, water quality, municipal and industrial effluent generation, etc. Continuous time models such as Soil and Water Assessment Tool (SWAT) have not taken root in Lake Victoria. Use of SWAT to simulate pollution load requires diverse data, among, river water quality and quantity and weather data and thus its use has always been limited.

CHAPTER 3: DATA DESCRIPTION AND PREPROCESSING

This Chapter describes GIS, remote sensing and other secondary data that were used to estimate nutrient export coefficients and develop SWAT models. The specifications of the data are presented as well as their sources. The procedure of delineating watersheds is well developed in literature and thus the procedure was explained in brief in this Chapter. The basis of identifying sources of municipal load, identifying pollution load per capita and reduction of municipal and runoff load is also presented in this Chapter.

3.1 GIS and remote sensing data

Remote sensing data types and how they were incorporated in a GIS framework is described under this section. Besides generation of data for model development, the data were used to develop maps used in this study.

3.1.1 SRTM3 data

The 3-arc Shuttle Radar Topography Mission (SRTM3) is a Digital Elevation Model (DEM) data collected by National Aeronautic Space Agency (NASA) and freely downloadable from the link (http://www2.jpl.nasa.gov/srtm/cbanddataproducts.html). The data represents ground elevation and was used in the SWAT model and also to delineate basin of the lake, river watersheds and calculation of river networks to generate watershed maps. Versions 2.1 of SRTM3 in 1^0 by 1^0 tiles collected in the year 2000 were used for this study.

The SRTM3 data come in a raster format whose resolution at the equator is approximately 90 m. The data for some areas have no data values such as areas covered by ice and water bodies. The raw unedited data were downloaded and evaluated on ArcGIS9.3.1 software and used to simulate the ground elevation of Lake Victoria basin. Data should be projected first before input into SWAT. The elevation data was projected using World Geodetic System (1984) reference coordinate system (WGS, 1984) as datum.

3.1.2 SWBD data

SRTM Water Body Dataset (SWBD) is also a product of SRTM mission by NASA. The data come as shape files and shows existing water bodies such as ponds and lakes in their locations within the basin at the time captured by satellites. The mission radar captures water bodies of size, approximately, at least 600 m in length and/or 183 m in width. The raw version 2.1 SWBD data are freely downloadable from the link (http://dds.cr.usgs.gov/srtm/version2_1/SWBD/). The downloaded data was processed in a GIS framework to provide locations and areas of water bodies in Lake Victoria basin and to develop the maps.

3.1.3 Soil data

Harmonized World Soil Database (HWSD) Ver 1.2 (Soil Data, 2007) was sourced from International Institute for Applied Systems Analysis (IIASA), Food Agricultural Organization of the United Nations (FAO). The data are available in both vector and raster formats and were used to generate soil distribution in Lake Victoria as captured by satellite signals. The data is freely downloadable from the link (http://www.iiasa.ac.at/Research/LUC/External-World-soil database/HTML/index.html?sb=1). The soil data was projected using reference (WGS, 1984) coordinate system as datum before input into SWAT.

3.1.4 Land cover

Land cover data were sourced from European Space Agency (ESA; MERIDAS - France). Global cover data were freely downloaded from the link (http://ionia1.esrin.esa.int/). The data were collected from December 2004 to June 2006 and are considered as an average over the period. They are classified using UN Land Cover Classification System (UN-LCCS). The classification system has widely been adopted for harmonized reporting reasons. The data resolution is approximately 300 m at the equator. The data were preprocessed to get individual land coverage (areas) of predefined land cover types and thereafter projected using reference (WGS, 1984) coordinate system as datum ready for use in SWAT.

Data quality checks were done to verify the deduced land uses and their respective areas. Rate of coverage of forest was chosen for verification of land use because it is an easily verifiable parameter. The verification was a two-fold procedure. First, Google Earth was used to check existence and location of main forests in the catchment. It was found that the ESA data captured accurately the main forests such as Mau forest in the Sondu watershed. Secondly, raw ESA data were used to deduce forest land cover for Kenya and Japan as at year 2005 and counterchecked against information from other sources. The choice of the two countries was informed by the locality of study area (Kenya), and Japan which has one of the highest rate of forest cover. As per the ESA data, forest land cover for Kenya and Japan were 8% and 66% of land area, respectively. Secondary sources recorded forest cover of 6.1% for Kenya (FAO, 2010) and 67.4% for Japan (Japan Forest Agency, 2008). The slight discrepancy could be partly attributed to the mode of collecting data and definition of forest. Kenya reports her forest cover to FAO as tree cover with minimum crown cover of 10%, minimum height of 5 m and minimum coverage of 0.5 ha (FAO, 2010) while ESA considers minimum crown cover of 15% and 5 m height. The discrepancy is not significant and ESA land cover data were considered to be representative and were therefore adopted for this study.

3.2 Basin delineation

The DEM data was processed through various stages to generate the basin of Lake Victoria using ArcGIS 9.3.1 software. The no data areas were filled using a spatial analyst extension tools. The elevation values for no data values were set to 0 m. The corrected DEM (DEM with no data areas assigned a value) formed the elevation data to delineate the drainage basin (Lake Victoria basin). The delineated basin or sub basin is an end product of a 3 step process using spatial analyst tools: fill, flow direction and watershed delineation.

River networks were calculated using spatial analyst commands as well. Flow accumulation was run to determine cell by cell flow of water in the DEM. A flow accumulation threshold value of 20,000 was set on a raster calculator to calculate the rivers that flow to Lake Victoria. The stream orders were generated and the raster converted to feature and refined for map output. SWBD shape files were processed and added to the database to represent the water bodies.

The same concept of drainage basin delineation was applied to river watersheds delineation. The calculated rivers guided setting out pour points (river mouths) for individual watersheds. Towns in the basin were retrofitted using their global spatial coordinates. All the information generated using above described data were integrated together in GIS layers and used to develop maps.

3.3 Towns and urban population

Towns on the Kenyan side with developed sewerage system were considered as sources of point (municipal) pollution load. Population data of identified urban areas (towns) were used to estimate municipal load. Towns without sewerage and parts of towns without sewerage were considered as contributing to lake pollution through land runoff. Urban population data for Kenya was sourced from national census of 1999 as compiled by COWI (2002). Fifteen (15) towns in Kenya were identified to have sewerage systems. A conservative population growth rate of 5% was applied to determine urban population at the years 2004 and 2009.

3.4 Pollution unit loads

Unit load refers to municipal pollution per capita load and unit area load - UAL - for runoff load (export coefficient). Municipal pollution per capita (unit load) represents municipal load generated by one person per day while UAL is amount of runoff load (non-point) generated per unit area. Industrial load was not considered due to data scarcity. The per capita loads were derived from observed flow and population data collected from two treatment plants (Kisat and Nyalenda) in Kisumu. They were compared with existing values in the literature and incorporated in estimation of municipal load.

3.5 Artificial and natural reduction

Artificial reduction refers to treatment efficiency by sewerage systems (treatment plants) while natural reduction is treatment efficiency by rivers and wetlands (natural and constructed). Provision for artificial reduction was used to estimate municipal load. Artificial reductions were determined from measured treatment efficiencies and literature values. Average treatment efficiencies for sample treatment plants in the basin were adopted. Natural reduction (degradation) within the river system was modeled to follow first order decay process.

CHAPETR 4: MODELS DEVELOPMENT AND METHODS

This Chapter first describes the framework used to estimate nutrient export coefficients on the Kenyan side of Lake Victoria basin. The basis and need for the export coefficients was introduced in Chapter 2. Export coefficients represents pollution load per unit area and the aim of this study to improve rapid assessment methods of estimating pollution load by estimating the coefficents. The coefficients were estimated using a mathematical equation that expresses runoff load as a product of land cover and export coefficients. Upstream municipal load and industrial load are first deducted from observed runoff load at river mouth. However, only municipal load was considered in this study. Not only is industrial load negligible as compared to runoff load and as reviewed in Chapter 2 but also data on industrial load was not available. Two possible options of deriving export coefficients are explored and description of parameters for model equation is explained in this Chapter. Secondly, SWAT modeling procedure as used in this study is elaborated. SWAT model was used to simulate hydrology sediment and nutrient load in Sondu watershed. Thereafter the model was used to assess three hypothetical management plans aimed at reducing soil erosion in the watershed. The details of the procedures are elaborated below.

4.1 Export coefficients model

4.1.1 Municipal load

Municipal pollution loads are generated from urban settings into river network through treatment systems such as sewerage and septic tanks. Treated wastewater in the study area is disposed to streams which then flow to Lake Victoria. Distinction between municipal load and runoff load is necessary where neither is negligible in terms of total load. However, for Lake Victoria, the aggregate municipal load is significantly less relative to runoff load as per the past studies that were reviewed (Scheren et al., 1995; Scheren et al., 2000; COWI, 2002; Scheren, 2003; LVEMP, 2005). Nevertheless, in this study municipal load was estimated. Municipal pollution load was modeled to be coming from only urban areas with sewerage systems.

Parameters of municipal load

Parameters used to estimate municipal pollution load are unit per capita loads, treatment efficiencies of treatment plants. The parameters are described below.

Municipal unit load

Preliminary municipal unit per capita load (TN) was calculated from laboratory tests on survey of Kisat and Nyalenda treatment plants in Kisumu, Kenya by Ogonda and Jura (2011). Additional information was sourced from reviewed literature (Table 4.1).

Table 4.1 Unit per capita load (TN) estimated from Nyalenda and Kisat plants in Kisumu

Item	Volume (m^3/day)	Average TN (mg/l)	TN (Kg/day)
Nyalenda plant[1]	11,600	35.5	411.8
Kisat[1]	2,200	46.0	101.2
Total load/day[1]	N/A		513.0
Population estimates (2009)[2]	N/A		202,300
Unit load (g/person.day)	N/A		**2.54**

TN loads include only Nitrate (NO_3) and ammonia (NH_3) excludes nitrite (NO_2) [1]Source: Ogonda and Jura (2011); [2]Letema et al. (2008)

The following was assumed when calculating the unit loads in Table 4.1:

1) All wastewater originates from households;
2) Sewerage systems is a separate system from storm water system;
3) There are no significant losses of wastewater as it flows from households to treatment plants.

The assumptions above exclude industrial wastewater and storm water in calculating the unit load. In this regard, any significant variance from these assumptions is bound to equally change significantly the estimated unit loads. Table (4.1) is based on household connection of 28.9% (Letema et al., 2008) and an urban (Kisumu) population size of 700,000 (Ogonda and Jura, 2011). The estimated unit per capita load was compared with those from reviewed literature to utilize and validate the information against the assumptions made (Table 4.2).

Table 4.2 Estimated municipal unit loads of TN and TP (g/person.day) matched with literature values

Pollution Load	This Study (Ogonda & Jura, 2011)	Scheren et al. (1995, 2000) & Scheren (2003, 2005)	COWI (2002)
TN	2.54	6.03 – 12.05	5.0
TP	N/A	0.55 – 4.38	2.0

Observed TN (2.5 g/person/day) was far outside the range (6.03 – 12.05) as reviewed from literature (Chapter 2). Also it was lower than that of COWI (2002). The variation could be attributed to inherent influence by factors ignored in the assumptions made and the fact that measured TN does not include Nitrites. To elaborate further, the variance could be attributed to possible inaccurate sewer connection and/or possible substantial shifts in the assumptions made in calculating the unit loads.

The field observed and literature unit loads in tandem with the assumptions made were evaluated in order to determine the unit loads to be used in this study. The unit loads by COWI (2002) are within the literature range and close to the field observed data and were considered suitable and this study adopted them in estimation of municipal load.

Efficiency of treatment plants

There are several wastewater treatment plants within Lake Victoria basin (30 plants identified in this study). This study could not ascertain the operation treatment efficiencies of all of them. The treatment efficiency field measurements on existing treatment plants within Lake Victoria basin by Ngetich and Sirmat (2008), Ogonda and Jura (2011) and COWI (2002) were reviewed. The study by Ngetich and Sirmat (2008) was done on Moi University main campus stabilization ponds while that of Ogonda and Jura (2011) was done on the two treatment plants in Kisumu (Kisat and Nyalenda) while COWI (2002) covered extensively plants in Kenya and Uganda. The treatment efficiencies are summarized in Table (4.3).

Table 4.3 Average treatment efficiencies (%) of treatment plants in the basin

Study	Plant	TN	TP
Ngetich and Sirmat (2008)	Moi University	N/A	N/A
Ogonda and Jura (2011)	Nyalenda	50	N/A
Ogonda and Jura (2011)	Kisat	70	N/A
COWI (2002)	Kenya and Uganda	60	45
Mean treatment efficiency (adopted in this Study)		**60**	**45**

The averages of the treatment efficiencies of the sample plants were adopted for sewerage systems in this study to estimate municipal pollution load.

Estimation of municipal load

The list of sewerage systems available in towns within the basin were matched with corresponding size of population using it. The sewerage usage estimates were done as at the year 2009. Town population was matched with unit per capita loads, treatment plant efficiencies and decay within the river system to estimate municipal pollution load. Resultant municipal load reaching the river was calculated using Eq. (4.3 & 4.4).

$$TN\,(Kg/day) = \sum_{Plant,1}^{20} \text{Persons using plant} \times \frac{TN\,p.e}{1000} \times \alpha \qquad (4.3)$$

Where:

TN p.e is TN per capita (5 g/person.day)

α is efficiency of wastewater treatment plant (60%)

$$TP\,(Kg/day) = \sum_{Plant,1}^{20} \text{Persons using plant} \times \frac{TP\,p.e}{1000} \times \alpha \qquad (4.4)$$

Where:

TP p.e is TP per capita (2 g/person.day)

α is efficiency of wastewater treatment plant (45%)

Table 4.4 Population estimates of sewerage usage in the study watersheds

Watershed	Town	Population 1999	2009*	Sewage treatment system
Yala	Siaya	1,500	2,443	Siaya district hospital
Yala	Kapsabet	35,000	57,011	Kapsabet treatment works
Gucha-Migori	Kisii	57,797	94,145	Kisii Municipal council treatment works
Gucha-Migori	Kisii	-	1,532	Kisii high school treatment works
Gucha-Migori	Migori	400	652	Migori Institutional (Hospital)
Nzoia	Kakamega	19,458	31,695	Kakamega, Shirere treatment works
Nzoia	Kakamega	5,040	8,210	Scheme treatment works
Nzoia	Bungoma	30,000	48,867	Old treatment works (Bungoma)
Nzoia	Mumias	500	814	Artisan.Mumias-sugar company domestic
Nzoia	Mumias	1,000	1,629	Central sugar company domestic
Nzoia	Mumias	10,000	16,289	Mumias town treatment works
Nzoia	Webuye	38,794	63,191	Webuye town treatment works
Nzoia	Kitale	25,885	42,164	Kitale matisi treatment works
Nzoia	Kitale	25,885	42,164	Kitale bidii treatment works
Nzoia	Eldoret	2,500	4,072	Chepkoilel campus
Nzoia	Eldoret	50,000	81,445	Conventional wastewater treatment (Eldoret)
Nzoia	Eldoret	117,273	191,025	Waste stabilization ponds
Nzoia	Eldoret	5,000	8,144	Moi university main campus
Sondu	Kericho	20,000	32,578	Kericho municipal treatment works
Sondu	Kericho	1,800	2,932	Kericho T.T.C treatment works
Sio	Busia	11,980	19,514	Busia municipal council treatment works

*5% growth rate applied

4.1.2 Export coefficients

Export coefficients are used together with land cover in static runoff models. This study estimated local nutrient export coefficients for three land uses in six main watersheds on the Kenyan side of Lake Victoria basin. Sondu, Nzoia, Sio, Yala, Nyando and Gucha river watersheds were the six focal areas (Fig. 4.2).

The data for river flow and nutrients measured at river mouths collected under Lake Victoria Environment Management Project (LVEMP, 1997-2005) were utilized. Nutrient export coefficients were estimated by distributing back the direct measured runoff load across the three land uses. The model used links the land use and the watershed's rainfall-runoff coefficient (as explanatory parameters) to the measured nutrients at the river mouth. The model is based on the assumptions that export coefficient for each land use is distinct irrespective of location, that water in the rivers comes from rainfall runoff process, and that extraneous variables do not have much influence on generation of nutrients. This approach has been criticized that it could lead to less reliable and counter intuitive information (Young et al., 1996). To the contrary, for a situation such as that of Lake Victoria basin where export coefficients are inexistent for the catchment, the estimated export coefficients from this approach are useful. Again the export coefficient estimates are not meant to be exact but to indicate a possible range of rate of nutrient generation. Factors that drive export of nutrients in the watersheds were also assessed on how they influence nutrient load that get to the lake. The information should facilitate analysis of impacts of various management plans in Winam Gulf with respect to spatial sources with the aim of reducing pollution load.

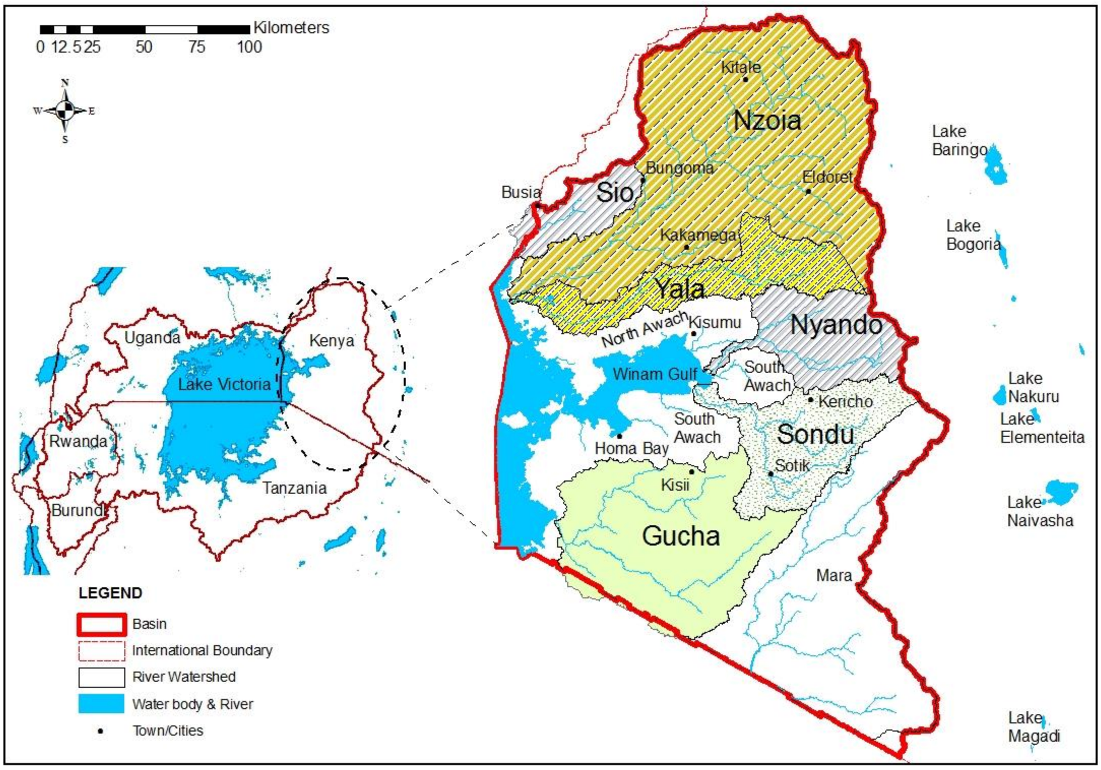


Fig. 4.2 Winam Gulf and six main river watersheds on the Kenyan catchment of Lake Victoria

Concept on estimation of export coefficients

Export coefficients can be derived from water quality and water quantity measured at river mouths by linking with classified land cover and measured river flow. This is pegged on the basis that land cover and precipitation are major (strong) variables of runoff load while extraneous variables are less sensitive to explain runoff load (Eq. 4.5).

$$\text{Runoff Load} = \alpha\, f(\text{Landcover}) + \varepsilon \qquad (4.5)$$

Where:

ε represents extraneous variables

α is precipitation weight factor of river watershed

Extraneous variables are taken to be not having much influence on runoff load $(\varepsilon = 0)$. Extraneous variables in this case are factors such as:

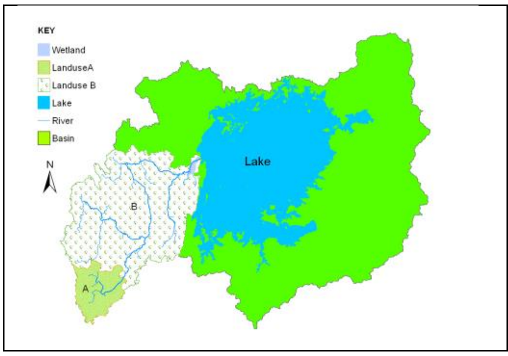
1) Soil characteristic;
2) spatial variability of precipitation across the watershed;
3) Human activities other than land cover: human settlements, livestock farming;
4) Underground water flow to rivers;
5) Land slope, among others.

The concepts which can be used to derive export coefficients for illustration purpose can be elaborated as:

1) Single watershed multiple periods concept;
2) Multiple watersheds single period concept.

Single watershed multiple periods concept

This is a case applicable when there is a single watershed and measured water quality and quantity data over multiple periods of time and their corresponding land cover. For example, a single river watershed with two types of land use (A and B) and wetland in a basin with observed water quality and quantity over three consecutive periods (period X, Y and Z) (Fig. 4.3a, b & c).



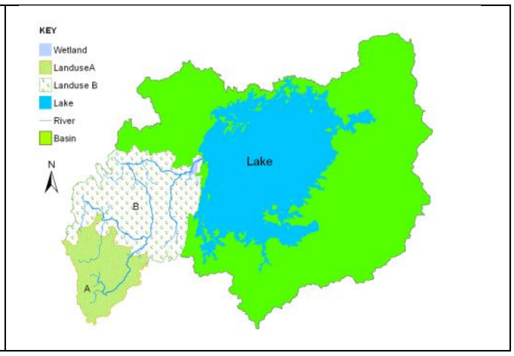


Fig. 4.3a River watershed with land use A and B and wetland in period X

Fig. 4.3b River watershed with land use A and B and wetland in period Y

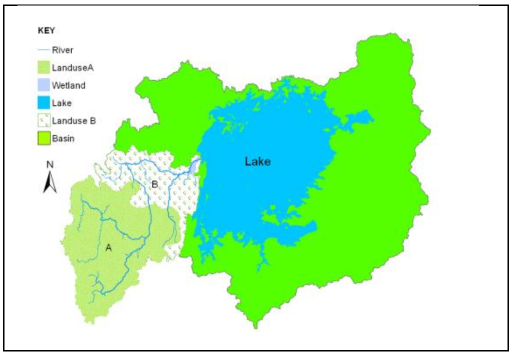


Fig. 4.3c River watershed with land use A and B and wetland in period Z

Runoff pollution load is expressed as a function of land cover area (land use A, B and wetland) and predetermined point pollution load as a constant in the runoff model.

Runoff load during periods X, Y and Z are expressed in Eq. (4.6a, b & c):

$$A_{AX}\alpha_X R_A + A_{BX}\alpha_X R_B - A_{wX}\alpha_X R_W = RL_X - PL_X \quad (4.6a)$$

$$A_{AY}\alpha_Y R_A + A_{BY}\alpha_Y R_B - A_{wY}\alpha_Y R_W = RL_Y - PL_Y \quad (4.6b)$$

$$A_{AZ}\alpha_Z R_A + A_{BZ}\alpha_Y R_B - A_{wZ}\alpha_Z R_W = RL_Z - PL_Z \quad (4.6c)$$

Where:

A_{Ai} is area of land use A in period *i* (*i* = Period X, Period Y and Period Z)

A_{Bi} is area of land use B in period *i* (*i* = Period X, Period Y and Period Z)

A_{wi} is area of wetland in period *i* (*i* = Period X, Period Y and Period Z)

α_i is precipitation weight factor relative for the period (base year/period, $\alpha_X = 1$)

R_j is export coefficient for landuse *j* (landuse A and B)

R_w is reduction efficiency of wetland

RL_i is runoff load in period *i* (*i* = Period X, Period Y and Period Z)

PL_i is total point load discharged upstream in period *i* (*i* = Period X, Period Y and Period Z)

Eq. (4.6a, b & c) are three (3) simultaneous equations and can be equally expressed in a matrix form (Eq. 4.7a, b & c).

$$\begin{bmatrix} \alpha_X A_{AX} & \alpha_X A_{BX} & -\alpha_X A_{WX} \\ \alpha_Y A_{AY} & \alpha_Y A_{BY} & -\alpha_Y A_{WY} \\ \alpha_Z A_{AZ} & \alpha_Z A_{BZ} & -\alpha_Z A_{WZ} \end{bmatrix} \begin{Bmatrix} R_A \\ R_B \\ R_W \end{Bmatrix} = \begin{Bmatrix} RL_X - PL_X \\ RL_Y - PL_Y \\ RL_Z - PL_Z \end{Bmatrix} \tag{4.7a}$$

$$[\text{Area}][\text{Runoff Coefficient}] = [\text{Pollution Load}] \tag{4.7b}$$

$$[\text{Independent Variables}][\text{Parameters}] = [\text{Explained Variables}] \tag{4.7c}$$

Eq. (4.7a) is a set of three simultaneous equations with three unknown parameters (export coefficients – R_A, R_B and R_w). The independent and explained (dependent) variables are known. Cramer's rule of solving simultaneous equations is one of the options to solve the equations (Eq. 4.7d & e).

$$\begin{Bmatrix} R_A \\ R_B \\ R_W \end{Bmatrix} = \begin{bmatrix} \alpha_X A_{AX} & \alpha_X A_{BX} & -\alpha_X A_{WX} \\ \alpha_Y A_{AY} & \alpha_Y A_{BY} & \alpha_Y A_{WY} \\ \alpha_Z A_{AZ} & \alpha_Z A_{BZ} & \alpha_Z A_{WZ} \end{bmatrix}^{-1} \begin{Bmatrix} RL_X - PL_X \\ RL_Y - PL_Y \\ RL_Z - PL_Z \end{Bmatrix} \tag{4.7d}$$

$$\begin{Bmatrix} R_A \\ R_B \\ R_W \end{Bmatrix} = \frac{1}{\det(\text{variable matrix})} \begin{bmatrix} \alpha_X A_{AX} & \alpha_X A_{BX} & -\alpha_X A_{WX} \\ \alpha_Y A_{AY} & \alpha_Y A_{BY} & -\alpha_Y A_{WY} \\ \alpha_Z A_{AZ} & \alpha_Z A_{BZ} & -\alpha_Z A_{WZ} \end{bmatrix}^{T} \begin{Bmatrix} RL_X - PL_X \\ RL_Y - PL_Y \\ RL_Z - PL_Z \end{Bmatrix} \tag{4.7e}$$

Solution to the above export coefficient model equations are subject to the following assumptions:

1) Runoff coefficients are unique for each land use irrespective of spatial distribution;
2) Runoff load is measured over a period long enough to cover flow lag time of the watershed;
3) Land use is superior variable to explain runoff load;
4) Wetland is a sink of pollution load and not a source;
5) Precipitation spatial distribution is uniform;
6) Precipitation is directly (positive) proportional to runoff load.

Iterations

The initially predetermined point load (PL_i) used in Eq. (4.7e) was not subjected to reduction by wetlands. R_w, is determined among other coefficients after solving Eq. (4.7e) wetland reduction. Wetland reduction efficiency (%) is then deduced and PL_i is then subjected to R_w (%). Eq. (4.7e) is solved again for several iterations until when change in export coefficients (R_i) is minimal. For a case where PL_i is of small quantity relative to runoff load (RL_i), the number of iterations is expected to be less or may be ignored as negligible.

Multiple watersheds single period concept

Multiple watersheds single period concept is applicable when there are multiple watersheds and measured water quality and quantity data for only one period of time and land cover information for the period is available.

The three watersheds (watershed 1, 2 & 3) with two land uses (landuse A & B) in the same basin are used as an example to elaborate on the concept (Fig. 4.4).

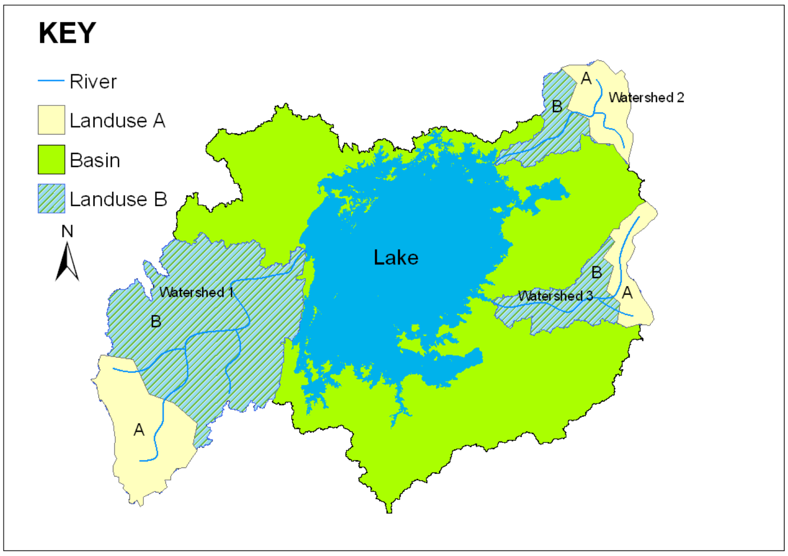


Fig. 4.4 Three watersheds with land uses A and B

This is a case where runoff load is measured downstream of the watersheds and point load are estimated/measured for one single period. Two watersheds at a time are considered to solve for export coefficients. For example, watershed 1 and 2 are first considered to express runoff load and to determine the first set of possible values of export coefficients (Eq., 4.8a, b).

$$A_{1A}\alpha R_A + A_{1B}\alpha R_B = RL_1 - PL_1 \quad (4.8a)$$

$$A_{2A}\alpha R_A + A_{2B}\alpha R_B = RL_2 - PL_2 \quad (4.8b)$$

Where:

A_{1A} & A_{2A} is area of land use A in watershed 1 and 2 respectively

A_{1B} & A_{2B} is area of land use B in watershed 1 and 2 respectively

α is precipitation weight factor for watershed (α = 1 for base year)

RL_1 & RL_2 is measured runoff load for watershed 1 and 2 respectively

PL_1 & PL_2 is estimated/measured point load in watershed 1 and 2 respectively

Eq. (4.8a, b) are solved for export coefficients (R_A and R_B) subject to the conditions that:

1) Watershed 1 and 2 are compatible. For example, export coefficients of land use A in watershed 1 is equal to export coefficient of land use A in watershed 2.
2) Assumptions above for - single watershed multiple periods concept - also apply.

Watersheds Compatibility

Ideally factors such as land use, land slope and soil characteristics for a huge basin vary with spatial distribution. These factors have significant influence on runoff (Mulung and Munishi, 2007; Broad and Corkrey, 2011). For example, grassland covers in Simiyu and Sondu watersheds in the basin of Lake Victoria have varying characteristic. Simiyu is flat relative to Sondu (Fig. 4.5a, b). These factors are more profound in calculation of export coefficients which is a basis of watersheds compatibility for - multiple watersheds single period concept.

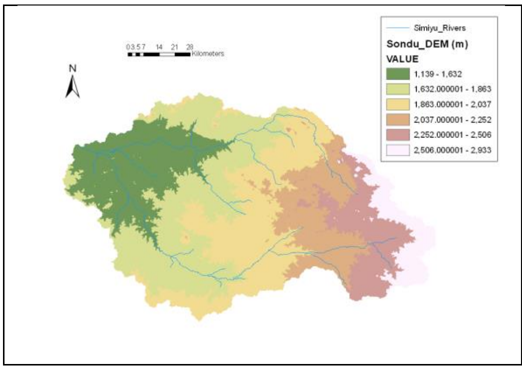


Fig. 4.5a Terrain elevation (m) of Simiyu watershed

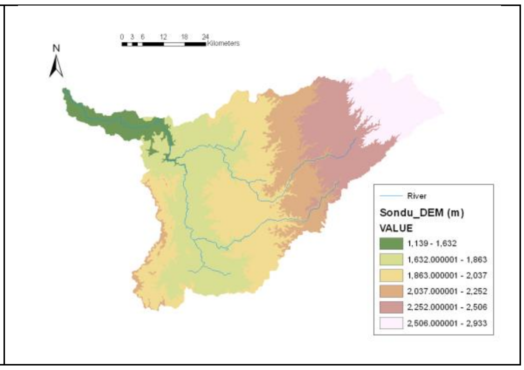


Fig. 4.5b Terrain elevation (m) of Sondu watershed

Calculated export coefficients (R_A and R_B) by solving simultaneously Eq. (4.8a) and Eq. (4.8b) are expected to return positive export coefficients (i.e. land cover are generators of pollution load and not sinks like treatment systems). However due to inherent factors explained above, solving Eq. 4.8a and Eq. 4.8b may return negative coefficients. Return of a negative coefficient means watershed 1 and 2 are not compatible to solve for the coefficients. Several watershed combinations are run and coefficients solved in the concept. Combinations which return positive coefficients are adopted and such watersheds are considered compatible. Multiple watersheds single period concept was applicable in this study.

The two other combinations (set of simultaneous equations) for this illustration are Eq. (4.8c, d, e & f):

Combination 2

$A_{1A}\alpha R_A + A_{1B}\alpha R_B = RL_1 - PL_1$ (4.8c)

$A_{3A}\alpha R_A + A_{3B}\alpha R_B = RL_3 - PL_3$ (4.8d)

Combination 3

$A_{2A}\alpha R_A + A_{2B}\alpha R_B = RL_2 - PL_2$ (4.8e)

$A_{3A}\alpha R_A + A_{3B}\alpha R_B = RL_3 - PL_3$ (4.8f)

Where:

A_{3A} is area of land use A in watershed 3

A_{3B} is area of land use B in watershed 3

RL_3 is measured runoff load in watershed 3

PL_3 is measured point load in watershed 3

Other symbols are as described in Eq. (4.8a, b)

The number of possible combinations is calculated using Eq. (4.9) and within the constraint of Eq. (4.10).

$$^{\text{No. of Watersheds}}C_{\text{No. of Runoff Coefficients}} \rightarrow {}^{3}C_{2} = 3 \text{ Combinations} \quad (4.9)$$

$$\text{No. of watersheds} \geq \text{No. of export coefficients} + 1 \quad (4.10)$$

Model parameters

Export coefficients for the Kenyan side of Lake Victoria basin were calculated based on the -multiple watersheds single period concept. Data input into the model comprised of land use, river flow, river nutrients and individual watershed rainfall-runoff coefficient for the six river watersheds. The data were collected and analyzed as described below. The conceptual approach of the model used in this study is illustrated by Fig. 4.6 and Fig. 4.7.

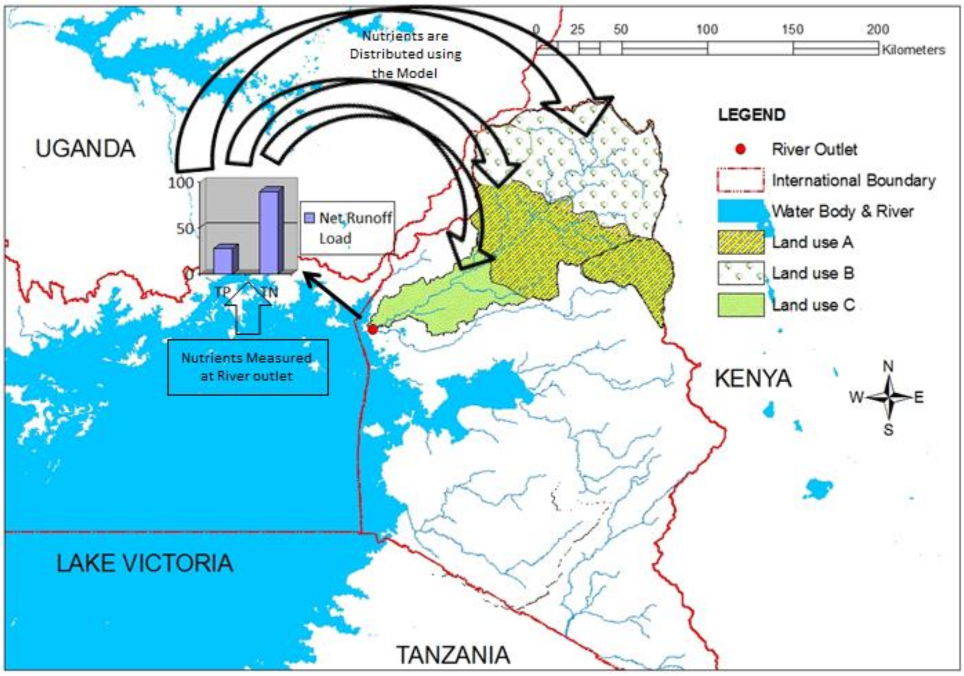


Fig. 4.6 An Illustration of distribution of nutrients measured at river mouths across various land uses

Land cover

Land cover data were sourced from the European Space Agency (ESA) as elaborated in Chapter 3. The data were analyzed using ArcGIS 9.3 software to deduce land cover areas using the basin parameters derived when basin was delineated. Land covers were reclassified into three classes, namely, cropland (agricultural), grassland/shrubland/vegetation and forests (Table 4.5).

Table 4.5 Classification and reclassification of land use

Land Cover Classification System (LCCS)		Reclassification (This Study)
Value	Global Globcover Legend	
11	Irrigated croplands	Cropland
14	Rainfed croplands	
20	Mosaic cropland (50-70%)/Vegetation (20-50%)	
30	Mosaic vegetation (50-70%) /Cropland (20-50%)	
40	Closed to open (>15%) broadleaved evergreen or semi-deciduous forest (>5 m)	Forest
50	Closed (>40%) broadleaved deciduous forest (>5 m)	
60	Open (15-40%) broadleaved deciduous forest/woodland (>5m)	
70	Closed (>40%) needleleaved evergreen forest (>5 m)	
90	Open (15-40%) needleleaved deciduous or evergreen forest (>5 m)	
100	Closed to open (>15%) mixed broadleaved and needleaved forest (<5 m)	
110	Mosaic forest or shrubland (50-70%) /Grassland (20-50%)	
120	Mosaic grassland (50-70%) /Forest or shrubland (20-50%)	Grassland, Shrubland and Vegetation
130	Closed to open (>15%) (broadleaved or needleleaved, evergreen or deciduous shrubland (<5 m)	
140	Closed to open (>15%) herbaceous vegetation (grassland, savannas, or lichens/mosses)	
150	Sparse (<15%) vegetation	

River flow and nutrients

River nutrient concentration (TN & TP) and river flow data collected by LVEMP (2005) were used to set up the model. Frequency of river flow and nutrients data collection was through the year 2003 on daily basis and reflected the four seasons of the year. The stream flow was collected two times per day. The observed river flow was used together with rainfall data to derive watershed rainfall-runoff coefficient. River nutrient concentrations were measured concurrently with river flows at points close to river mouths and designed to cover seasonal variations. Annual volumetric weighted mean concentration for nutrients were determined for each river watershed. The data for the year 2003 were used because they had good temporal coverage (Table 4.6). On the other hand, the river flow and nutrient concentration data collected in September 2001 by COWI (2002) were used to validate the model (Table 4.7). This was part of the water quality data collected under LVEMP (1997-2005) in Lake Victoria. However, data collection was limited to only one month due to limitations such as inadequacy of laboratory equipment.

Municipal Load

Estimates of municipal load as elaborated above were deducted from the total load measured at the river mouths before inputting the net runoff load into the model.

Table 4.6 Summary of model inputs for model set-up

	Land use Areas (2004 - 2006) in Km^2 & Coverage (%)					*Mean Daily Discharge		Runoff Coefficient factor	*Nutrient Mean Concentration (2003)	
River	Cropland (A_c) (%)	Forest (A_f) (%)	Vegetation, Grass & Shrubland (A_{gs}) (%)	Urban (A_T) (%)	Total	m^3/s (2003)	*Runoff Coefficient	Relative to **Gucha's	TN (mg/L)	TP (mg/L)
Sio	1,354 (98.5)	1 (0.1)	17 (1.2)	3(0.2)	1,375	11.4	0.0063	1.07	0.85	0.13
Nzoia	11,797 (92.5)	564 (4.4)	384 (3.0)	14(0.1)	12,759	115.0	0.0088	1.49	1.09	0.12
Yala	2,928 (93.9)	58 (1.9)	132 (4.2)	1(0.0)	3,119	34.9	0.0142	2.41	1.06	0.09
Nyando	2,187 (78.4)	345 (12.4)	255 (9.1)	4(0.1)	2,791	18.0	0.0060	1.02	1.90	0.40
Sondu	2,428 (69.1)	1,048 (29.9)	31 (0.9)	5(0.1)	3,512	42.2	0.0119	2.02	1.22	0.12
Gucha	5,578 (82.9)	1,106 (16.4)	39 (0.6)	6(0.1)	6,729	59.1	0.0059	1.00	1.36	0.32
Total	26,272 (86.8)	3,122 (10.3)	858 (2.8)	33 (0.1)	30,285					

Table 4.7 Model validation data

River	Annual Mean Discharge (m^3/s)	*Nutrient Concentration (2001) TN (mg/l)	TP (mg/l)
Sio	12.10	0.65	0.124
Nzoia	118.00	0.90	0.254
Yala	27.40	1.16	0.118
Nyando	14.70	1.12	0.377
Sondu	40.30	1.08	0.250
Gucha	62.70	1.44	0.143

*Source. COWI (2002)

Watershed geometry parameters

Mean slope, flow length and area parameters were derived using ArcGIS 9.3 software tools for the export coefficient model (Eq. 4.12, 4.13 & 4.14).

Model description, calibration and validation

The model equation explains measured nutrients at the river mouth using land use and rainfall-runoff coefficient with consideration of reduction of nutrients within the river system. The model estimates nutrient export coefficients which are the only unknowns in the model. The model and its components are described below.

Baseline model

Runoff pollution load for each of the six watersheds (Fig. 4.2) was expressed as illustrated by Eq. (4.11) using parameters described above and with consideration to municipal (point) load discharged upstream

$$\mathrm{RL} - \mathrm{PL} = \mathrm{r}\left(A_c\,\mathrm{R_c} + A_{gs}\,\mathrm{R_{gs}} + A_f\,\mathrm{R}_f\right)\exp(\text{-kt}) \quad (4.11)$$

Where

RL is measured load at river mouth (t/year); PL is estimated point load generated in the watershed (t/year); A_i represent areas of respective three land uses in the watershed (c for cropland, gs for grassland and f for forest) (Km^2); R_i is nutrient export coefficient ($t/Km^2/year$); r is watershed relative rainfall-runoff coefficient (dimensionless); and $\exp(-kt)$ represents nutrient reduction within the river system (dimensionless) (k and t are sourced from Eq 4.13 & 4.14).

Relative rainfall-runoff coefficient (r)

As elaborated in Section 2.3.3, rainfall-runoff coefficient integrates environmental attributes of the watershed. Rainfall-runoff coefficient varies across river watersheds. The relative rainfall-runoff coefficient factors for each watershed were derived using Gucha watershed as a base watershed because it has the least runoff depth (Table 4.6). The factors were used as precursor factor to nutrient export coefficients in the model (Eq. 4.11). This ensures that model output (nutrient export coefficients) takes into account the varying runoff depths across watersheds.

Nutrient reduction within the river system

Nutrient load that gets to the lake is lower than the load generated in the catchment because nutrients are depleted within the river and wetland systems. Nutrient degradation was assumed to follow first order decay process as per Eq. (4.12) (Scheren et al., 2000; Broad and Corkey, 2011). The choice of a first order decay was because it is simple and easier to numerically solve for model constants in a situation of limited data

$$\frac{d(L)}{d(L_R)} = -k(L) \tag{4.12}$$

Where

L is the net (residual) nutrient load; L_R is main river length; and k is the decay rate.

Integration of Eq. (4.12) and boundary solutions would require field data on the decay of nutrients with respect to river length which were not available in this study. The first order decay model (Eq. 4.13) for Catchment Management Support System (CMSS) which simulates nutrient decay with time was adopted (Broad and Corkey, 2011)

$$L_t = L_o \exp(-kt) \tag{4.13}$$

Where L_t is the load at time t (tons); L_o is the initial load (tons); k is the decay rate (1/days) and t is the retention time of runoff water and nutrients as it traverse the catchment (days).

Nutrient sources are spatially distributed in the catchment and thus distance and time taken by nutrients to exit the catchment vary. Average retention time for a watershed was calculated using Bransby-Williams formula (Eq. 4.14) for the purpose of accounting for nutrient reduction (Broad and Corkey, 2011)

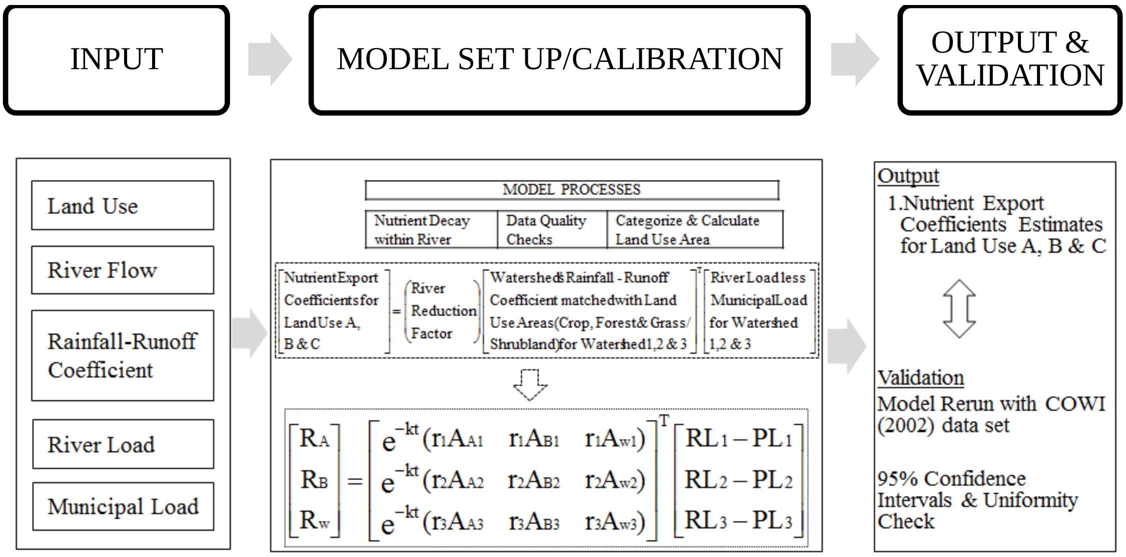
$$t = (0.042 \times L)/(S^{0.2} \times A^{0.2}) \tag{4.14}$$

Where t is the average retention time of watershed (days); L is the length of river channel (km); S is the slope (m/km); and A is the catchment area (ha). The value of k is taken as 0.0302 for river channel depth greater than 4 m. Flow depth for the six watersheds were assumed to be deeper than four meters.

Model set-up and validation

The model was set-up with the parameters elaborated above and as put together in Eq. (4.11) and illustrated in Fig. (4.7). One equation for each of the six watersheds yielded a total of six independent equations. The model equation (Eq. 4.11) enables determination of export coefficients (R_i) which are the only unknowns. Sets of three equations each were formulated by combining three watersheds at a time. The six equations yielded twenty different sets of equations. The nutrient export coefficients were determined by solving simultaneously the sets (of three equations with three unknowns) using Cramer's rule in an excel spreadsheet. Ranges of estimated export coefficients of the three land uses were determined at 95% confidence interval.

The above procedure was done using the two sets of data. The first set (Table 4.6) was used to set-up the model while the second set (Table 4.7) was used to validate the model. Validation criterion was based on checking the overlap of the 95% confidence interval of estimated nutrient export coefficients.



$$\begin{bmatrix} R_A \\ R_B \\ R_w \end{bmatrix} = \begin{bmatrix} e^{-kt}(r_1A_{A1} & r_1A_{B1} & r_1A_{w1}) \\ e^{-kt}(r_2A_{A2} & r_2A_{B2} & r_2A_{w2}) \\ e^{-kt}(r_3A_{A3} & r_3A_{B3} & r_3A_{w3}) \end{bmatrix}^T \begin{bmatrix} RL_1 - PL_1 \\ RL_2 - PL_2 \\ RL_3 - PL_3 \end{bmatrix}$$

Fig. 4.7 Export coefficient estimation model framework

4.2 SWAT model

The basic concept of the model is to subdivide a basin into sub basins and further combine land cover, soil and slope to get unique units (Hydrologic Response Unit – HRU). Currently, with the development of Geographical Information System (GIS) interface, it has become a significant model in water resources management (Arnold et al., 1998).

This study modeled temporal and spatial distribution of hydrolofy, sediment loss and nutrients in Sondu river watershed using SWAT model on daily basis by incorporating remote sensing data into scarce water quantity and quality data. Effectiveness of three watershed management plans aimed at curbing environmental degradation and sediment erosion were also assessed. The management plans are: maintaining existing situation, use of filters on part of agricultural land and reforestation. Comparative assessment was done at both watershed outlet (basin) and sub watershed (sub basin) levels. The model parameters, model performance assessment and watershed management plans are elaborated below. Fig. 4.8 shows Sondu river watershed and model parameters details.

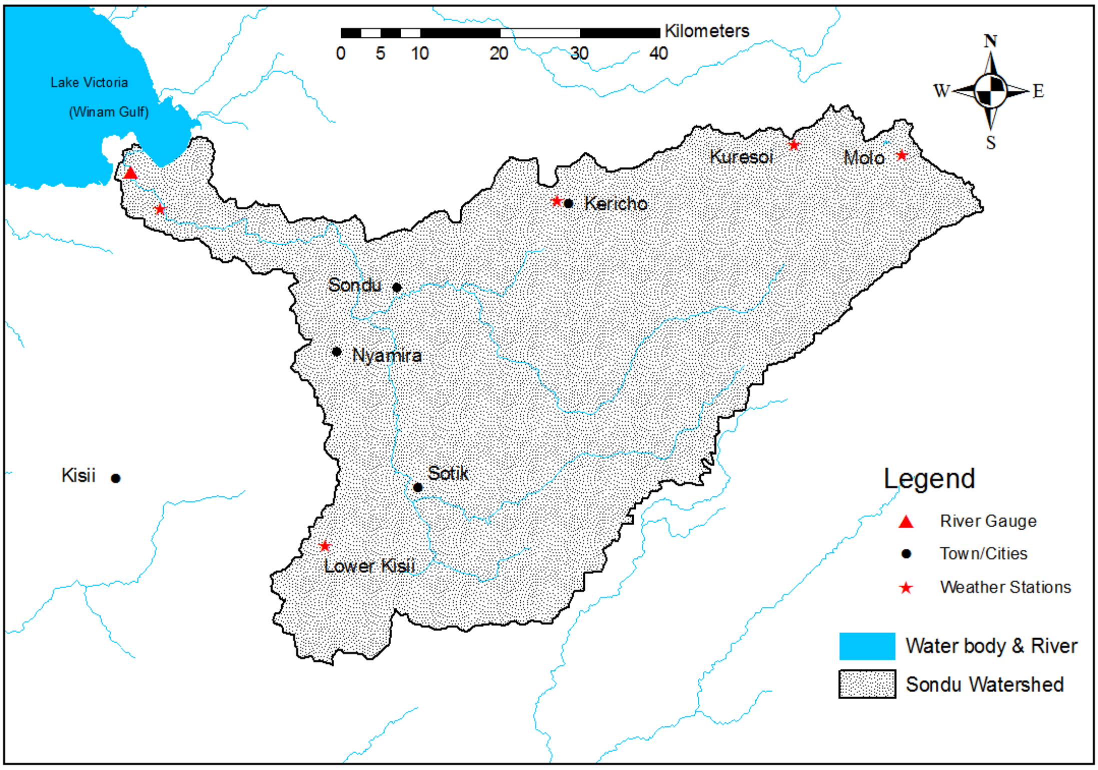


Fig. 4.8 Sondu river watershed on the Kenyan side of Lake Victoria basin

4.2.1 Model Parameters

The SWAT model requires detailed and extensive data inputs. Data collection in Lake Victoria especially on water quality is low. There is deliberate effort to improve the situation through projects such as the ongoing LVEMP taking cognizance of the data scarcity for management of the Lake. The main data inputs required in the SWAT model are elevation, land cover, soil data, hydro-meteorology and observed flow and water quality data for the study area.

DEM and Land Cover

Digital Elevation Model (DEM) represents elevation of the watershed (Fig. 4.9). This study used the Shuttle Radar Topography Mission (SRTM3) elevations as introduced Chapter 3. The data were processed in ArcGIS 9.3 to combine individual tiles and convert them into useable format in SWAT model. The Globcover Ver. 2.3 (land cover data of 2005-2006) introduced in Chapter 3 was used as well. The data were originally classified in UN Land Cover Classification System (UNLCCS) and were therefore reclassified to SWAT model categories guided by accompanying literature describing the land cover types (Table 4.8 and Fig. 4.10).

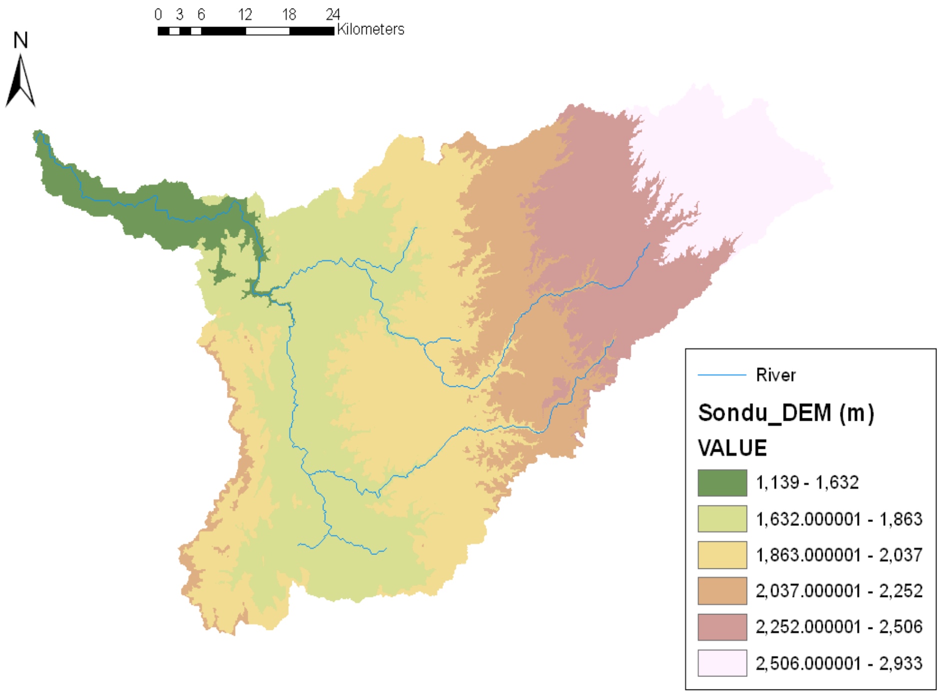


Fig.4.9 Elevation (DEM) map for Sondu watershed

Table 4.8 Land cover for Sondu watershed, reclassification in SWAT and their coverage (%)

Original land cover classification as sourced	Land cover reclassified in SWAT	Cover rate (%)
Rain fed croplands	Agriculture – close grown - AGRC	54.39
Mixed cropland (50-70%) and vegetation (20-50%)	Agriculture – row crops - AGRR	0.03
Mixed vegetation (50-70%) and cropland (20-50%)	Agriculture – land generic - AGRL	13.54
Mixed forest	Forest mixed - FRST	4.42
Broadleaved deciduous forest (>5 m)	Forest deciduous - FRSD	22.05
Mixed broadleaved deciduous forest/woodland (>5m)	Coffee/Tea - COFF	2.13
Evergreen forest (>5 m)	Forest evergreen - FRSE	2.36
Mixed grassland (50-70%) /forest/shrubland (20-50%)	Pasture - PAST	0.01
Mixed broadleaved/evergreen/deciduous/shrubland (<5 m)	Coffee/tea/orange - ORAN	0.94
Residential medium density	Urban - URMD	0.12
Water bodies	Water - WATR	0.01

SWAT classes are described in SWAT (2009)documentation (Arnold et al., 2011)

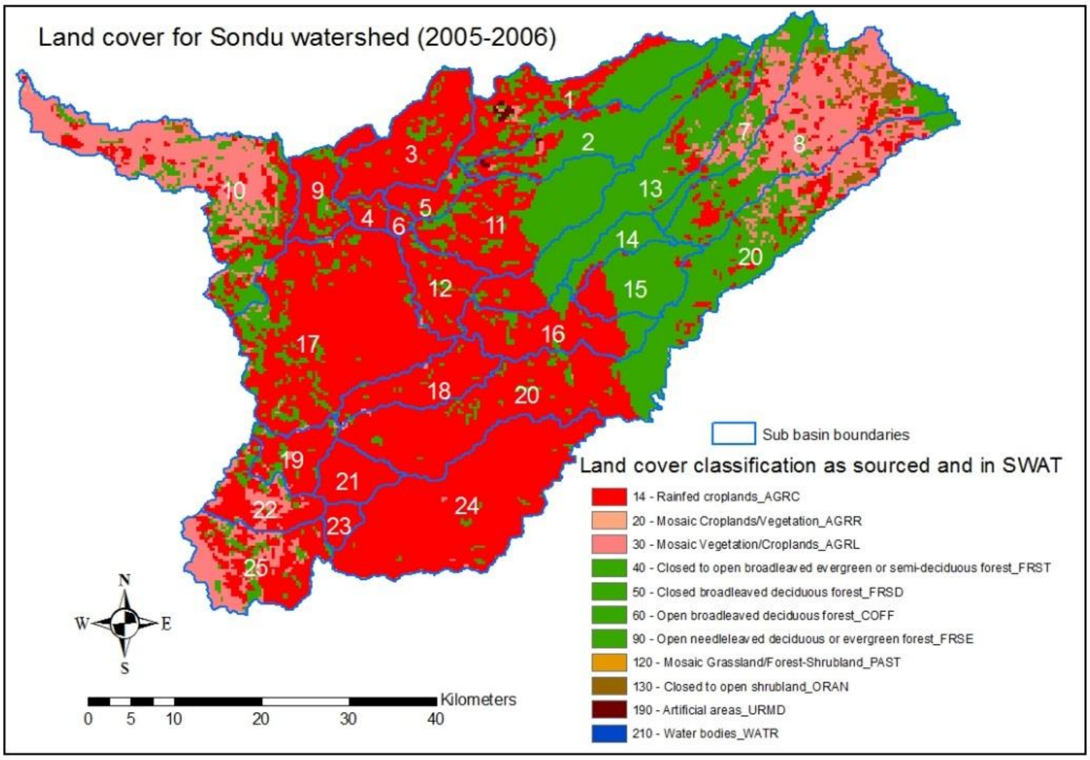


Fig. 4.10 Sub basins, land cover classification as sourced and as classified in SWAT

Soil data

Soil data (HWSD) described in Chapter 3 was clipped out to get soil for Sondu watershed and used as part of model inputs in SWAT modeling process (Fig. 4.11). The soils are in two layers with 0.3 m depth for top layer as while the lower layer is 1.0 m. The soil was sourced because existing soils in accompanying SWAT database are mainly US soils. The properties of soil required in the model are listed in Table 4.9. The HWSD data description in the accompanying documentation does not have all soil parameters as required in SWAT model. In particular the missing parameters were four: soil hydrologic group (HYDGRP), saturated hydraulic conductivity (SOL_K), moist soil albedo (SOL_ALB) and soil erodibity K factor (USLE_K). The Soil Plant Atmosphere Water (SPAW) software was used to get SOL_K. Universal Soil Loss Equation (USLE) was used to calculate USLE-K. The parameter is a product of soil erodibility factors of coarse-sand, clay-silt and organic-carbon soils. The parameters were compiled and appended into soil database using ArcGIS tools.

Table 4.9 Soil properties for user soil input in SWAT model: Sample for top layer of soil 17316

Property	Value	Definition
HYDGRP	D	Soil hydrologic group (A, B, C or D).
SOL_ZMX	1000	Maximum rooting depth of soil profile (mm).
SOL_Z	300	Depth from soil surface to bottom of layer(mm)
SOL_BD	1.1	Moist bulk density(mg/m^3 or g/cm^3)
SOL_AWC	0.15	Available water capacity of the soil layer (mm H_2O/mm soil)
SOL_K	1.27	Saturated hydraulic conductivity(mm/hr)
SOL_CBN	3.33	Organic carbon content(% soil weight)
SOL_CLAY	45	Clay content (% soil weight)
SOL_SILT	25	Silt content (% soil weight)
SOL_SAND	30	Sand content (% soil weight)
SOL_ROCK	0	Rock fragment content (% total weight)
SOL_ALB	0.01	Moist soil albedo
USLE_K	0.20	USLE equation soil erodibity (K) factor

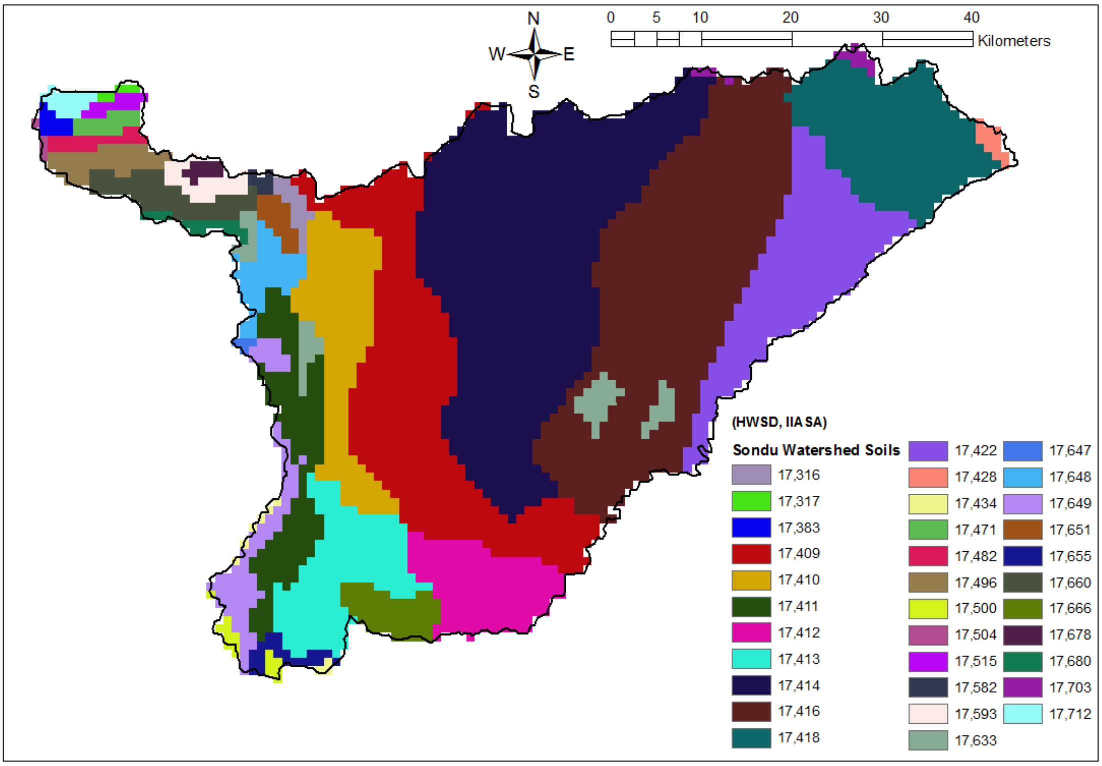


Fig. 4.11 Soil types of Sondu watershed as sourced from IIASA

Missing soil parameters

Saturated hydraulic conductivity (SOL_K)

Soil Plant Atmosphere Water (SPAW) software was used to get SOL_K. The software calculates SOL_K with input of sand, clay, silt and gravel percentages content of the soil.

Soil erodibity K factor (USLE_K)

Universal Soil Loss Equation (USLE) equation was used to calculate USLE-K. The equation is illustrated below (Eq., 4.15).

$$K_{USLE} = f_{csand} * f_{cl-si} * f_{orgc} * f_{hisand} \quad (4.15)$$

Where

f_{csand} is a parameter that gives low soil erodibility for soils with highcoarse-sand contents and high values for soils with little sand, f_{cl-si} is a parameter that gives low soil erodibility factors for soils with high clay to silt ratios, f_{orgc} is a parameter that reduces soil erodibility for soils with high organic carbon content, and f_{hisand} is a parameter that reduces soil erodibility for soils with extremely high sand contents. The calculation of parameters is elaborated below (Eq., 4.16, 4.17, 4.18 & 4.19):

$$f_{csand} = \left\{0.2 + 0.3 * exp\left[-0.256 * m_s * \left(1 - \frac{m_{silt}}{100}\right)\right]\right\} \quad (4.16)$$

$$f_{cl-zi} = \left(\frac{m_{silt}}{m_c + m_{silt}}\right)^{0.3} \quad (4.17)$$

$$f_{orgc} = \left[1 - \frac{0.25 * c_{org}}{c_{org} + exp(3.72 - 2.95 * c_{org})}\right] \quad (4.18)$$

$$f_{hisand} = \left\{1 - \frac{0.7 * (1 - \frac{m_S}{100})}{\left(1 - \frac{m_S}{100}\right) + exp\left[-5.51 + 22.9 * (1 - \frac{m_S}{100})\right]}\right\} \quad (4.19)$$

Where

m_s is the percent sand content (0.05-2.00 mm diameter particles), m_{silt} is the percent silt content (0.002-0.05 mm diameter particles), m_c is the percent clay content (< 0.002 mm diameter particles), and c_{org} is the percent (%) organic carbon content of the layer.

Soil hydrologic group (HYDRGP) and Soil albedo (SOL_ALB)

The HYDRGP and SOL_ALB parameters were determined by studying the description of soil characteristics in SWAT (2009) documentation (Arnold et al, 2011) and HWSD literature.

Weather data

Precipitation, temperature, solar radiation, humidity, and wind speed are the five weather parameters required in SWAT model. These data were obtained from responsible institutions in Kenya (Kenya Meteorological Department - KMD) for five weather stations with exception of solar radiation (Kisumu meteorological station, Kericho hail research station, Molo forest station, Kuresoi forest station and Kisii meteorological station) (Fig. 4.8). Weather data input in SWAT were done on daily frequency. Precipitation statistics, for the purpose of SWAT inbuilt weather generator, were calculated using pcpSTAT program (Stefan Liersch, 2003) while for the other parameters such as average maximum and minimum temperature were calculated manually using excel spreadsheets to get simple monthly averages (Table 4.10).

The data period of interest was from 1990 to 2010; however, not all data days were available. Rainfall and temperature data had fairly better coverage as compared to other weather parameters. The years (2005-2007; 2010) had matching water quality data hence were used for modeling (Table 4.11). In this study, weather generator which is an inbuilt algorithm was used to fill/interpolate data gaps in the observed weather parameters and to simulate solar radiation parameter which was not available from the field. The missing weather data statistics for weather generator were sourced from the National Centers for Environmental Prediction (NCEP), Climate Forecast System Reanalysis (CFRS) which provides global weather data for SWAT. The data is available through the link: http://globalweather.tamu.edu/

Table 4.10 Statistics for weather parameters for user weather stations in SWAT: Sample for Kericho station for January

Statistic	quantity	Description	parameter
TMPMX	25.46	Average or mean daily maximum air temperature for the month	Temperature
TMPMN	11.03	Average or mean daily minimum air temperature for the month	
TMPSTDMX	7.36	Standard deviation for daily maximum air temperature in the month	
TMPSTDMN	6.10	Standard deviation for daily minimum air temperature in the month	
PCPMM	122.83	Average or mean total monthly precipitation	Precipitation
PCPSTD	10.53	Standard deviation for daily precipitation in the month	
PCPSKW	5.02	Skew coefficient for daily precipitation in the month	
PR_W1	0.23	Probability of a wet day following a dry day in the month	
PR_W2	0.23	Probability of a wet day following a wet day in the month	
PCPD	11.52	Average number of days of precipitation in the month	
RAINHHMX	34.07	Maximum 0.5 hour rainfall in entire period of record for the month	
SOLARAV	20.20	Average daily solar radiation for month	Solar radiation
DEWPT	0.64	Average daily dew point temperature for each month or relative humidity	Humidity
WNDAV	1.85	Average daily wind speed in the month	Wind speed

Observed river flow, sediments and nutrients (TN & TP)

Observed daily river (stream) flow data and limited observed daily total nitrogen, total phosphorous and sediment concentration were sourced from Water Resources Management Authority (WRMA) in Kenya. The data was collected at Sondu-Miriu bridge station (Table 4.11 and Fig. 4.8). Simulation of sediment load in the SWAT model was based on observed total suspended solids (TSS) and was input into the model as concentration. TN is composed of Organic nitrogen (ORGN), Nitrate (NO_3), Ammonium (NH_4) and Nitrite (NO_2) while TP is composed of Organic phosphorous (ORGP) and Mineral phosphorous (MINP). Daily observed nutrients are highly variable (as reported in literature) and therefore nutrients simulations were done on monthly time step. Monthly observed nutrient values were derived from observed daily values by direct extrapolation. Modeling period was guided by observed data distribution. There is low monitoring of water quality data at stream gage as compared to weather stations in Sondu watershed over the target period. Weather data had better coverage hence modeling period was mainly guided by stream flow and the water quality data coverage. The periods 2005 – 2007 and 2010 and had most of the observed data overlapping hence were used for calibration and validation respectively (Table 4.11). It was observed that the highest recorded stream flow is 60 m^3/s. When the highest flow mark is recorded there is a data gap thenceforth. This could be that the limit of the gauge station is 60 m^3/s or the river bursts the banks or overflows at stream flow of above 60 m^3/s.

Table 4.11 Observed daily data: percentage of available data days

Parameter	Station	Coordinates	1990 - 2010 (%)	2005 - 2007 (%)	2010 (%)
Rainfall	Kisumu	0.100S, 34.750E	99.6	100.0	99.7
	Kericho	0.367S, 35.267E	99.2	100.0	99.5
	Molo	0.283S, 35.750E	69.8	33.3	0.0
	Kuresoi	0.283S, 35.533E	58.3	66.6	0.0
	Kisii	0.683S, 34.783E	98.1	100.0	99.4
Temperature	Kisumu	0.100S, 34.750E	91.5	96.4	96.4
	Kericho	0.367S, 35.267E	88.1	91.9	99.7
	Kisii	0.683S, 34.783E	78.8	96.8	98.6
Relative humidity	Kericho	0.367S, 35.267E	84.4	24.8	0.0
	Kisumu	0.100S, 34.750E	17.7	57.1	0.0
Wind speed	Kisumu	0.100S, 34.750E	5.1	0.0	0.0
Stream flow	Sondu Miriu	0.335S, 34.787E	20.6	25.0	35.3
Sediments	Sondu Miriu	0.335S, 34.787E	0.5	0.9	1.1
Total nitrogen	Sondu Miriu	0.335S, 34.787E	0.2	0.5	1.1
Total phosphorous	Sondu Miriu	0.335S, 34.787E	0.2	0.5	1.1

4.2.2 SWAT modeling process

A study by Manoj et al. (2004) assessed and recommended appropriate threshold level of watershed subdivision to sub watersheds for simulation of stream flow, sediment and nutrients. It determined threshold number of sub watersheds in which further subdivision yield little effect on stream flow, sediment or nutrient simulations. The findings relevant to this study were two-fold: stream flow - level of sub division had negligible effect; sediment - recommendation a minimum sub watershed area of 3 % of total watershed area. The 3 % threshold translates to about 25 to 35 sub watersheds depending on watershed elevation distribution. Sub division above 35 sub watersheds has little effect on sediment simulation (and stream flow).

The SWAT model was set up in the conventional three step procedure: watershed partition, information input and simulation (Fig. 4.12). The study watershed was first partitioned into 25 sub watersheds based on the findings of Manoj et al. (2004). Hydrologic Response Units (HRUs) were created and finally, weather data input and the model was run.

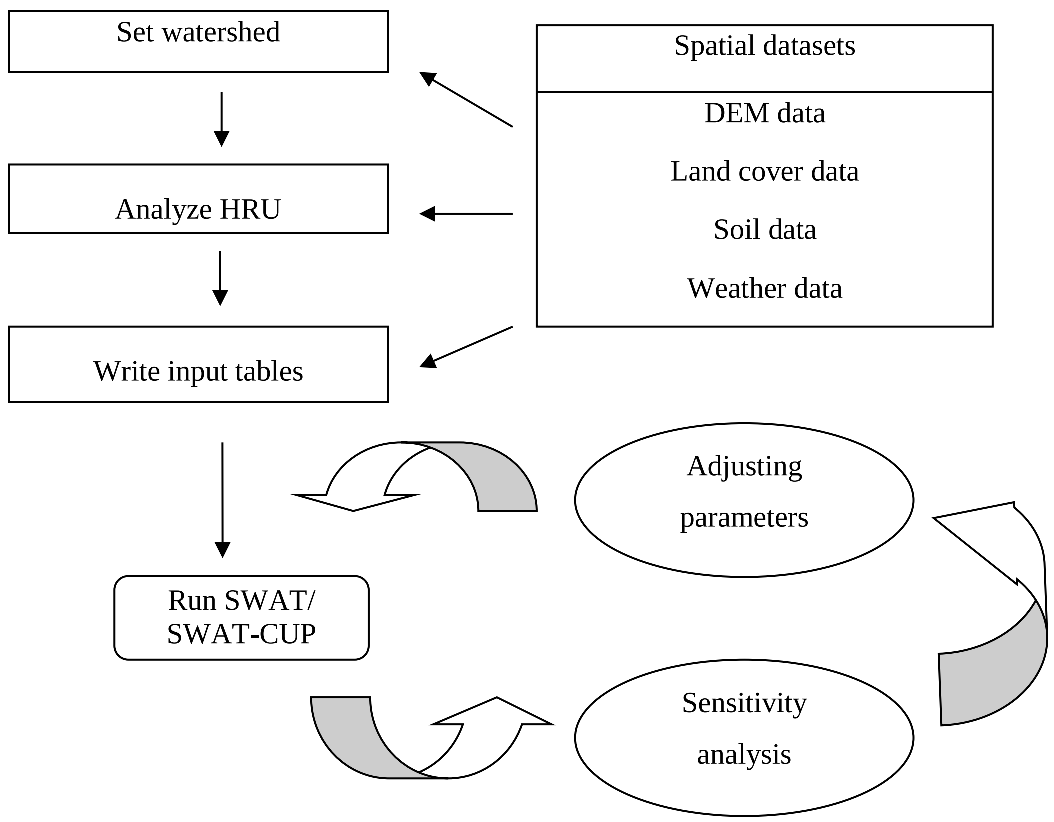


Fig. 4.12 Schematic diagram for SWAT modeling process

4.2.3 Sensitivity, calibration and validation

The ArcSWAT (2009) was used to run sensitivity analysis with and without observed data for inbuilt 42 model parameters for stream flow, sediment and nutrient. The sensitivity analysis was run using the method of Latin Hypercube - One factor At a Time (LH-OAT). The basis of sensitivity is to mainly guide the calibration process. There exists so many model parameters and thus there is need to select a few that are relevant and useful. The parameter sensitivity is useful in the selection process and subsequently calibration in that regard.

The choice of modeling periods (2005-2007; 2010) was based on level of data availability, especially observed river flow, nutrients and sediment concentration as explained above. The scarce weather and water quality data (Table 4.11) resulted in limited latitude on the length of calibration and validation periods.

The SWAT Calibration and Uncertainity Program (SWAT-CUP) was used to calibrate and validate the model on a daily time step. Calibration was done step by step, (river flow first and then both flow and sediment concentration). SWAT-CUP is a complementary program to ArcSWAT and was preferred for calibration/validation process because it is faster as compared to inbuilt automated calibration in ArcSWAT. Sequential Uncertainty Fitting Ver. 2 (SUFI2) optimization algorithm option was used for the calibration/validation analysis of the model.

Latin Hypercube One factor At a Time (LH-OAT) sensitivity analysis

Latin hypercube (LH) sampling is a sophisticated approach of random sampling for robust analysis with minimal runs. It divides the distribution of each parameter into n ranges each with probability of occurrence of 1/n. The parameter values are randomly sampled such that each range is sampled only once and model is run n times. The LH concept is based on Monte Carlo simulation but uses stratified sampling (McKay et al., 1979; McKay, 1988).

One factor At a Time (OAT) sampling is a case where one parameter is changed for each run. The change in output is thus unambiguously attributed to the change in the parameter. For example if you have p parameters then you will have (p+1) model runs to get partial effect for each parameter. It is an example of an integration of a local to a global sensitivity method.

LH-OAT sensitivity analysis combines LH and OAT sampling methods. In this study parameter ranges was divided into 10 (n = 10) and there were 42 parameters (p = 42) populated for sensitivity analysis hence 430 model runs - n*(p+1).

4.2.4 Model performance and evaluation

The four model performance factors for SUFI2 program (p-factor, r-factor, coefficient of determination-R^2 and Nash-Sutcliff efficiency-NS) were used to guide the calibration and validation processes. The statistics indicate how well or poor the model simulation has performed in calibration and validation phases. The model can be used for further analysis of the watershed if the performance is considered satisfactory or acceptable.

The p-factor is the percentage of data bracketed by the 95 % prediction uncertainty (95 PPU) band while the r-factor is the average thickness of the 95 PPU band divided by standard deviation of observed data (Karim, 2012). The p-factor ranges from 0 to 1.0 (0 – 100 %), with a value of 0 indicating 0 % of simulated values are within the bracket range of 95 PPU while a value of 100 means 100 % are bracketed. The r-factor ranges from 0 to infinity (0 - ∞). An ideal or perfect model simulation has a p-factor of 1.0 and r-factor of 0 (Karim, 2012).

The NS and R^2 define goodness of fit between observations and simulations. NS measures how well the simulated values are representative of the observed. The NS values are between negative infinity and 1.0 (-∞ – 1.0) in which a value of 1.0 means a perfect prediction of observed while a value of 0 and less means poor prediction. The R^2 statistic is an indicator of how well the regression line of simulation and observed is approaching the ideal match. Its range is between 0 and 1.0 (0 – 1.0) where 0 means no correlation while 1.0 simulated values equals observed values.

Karim (2012) recommends a p-factor of 0.7 and r-factor of around 1.0 as acceptable. According to Moriasi et al. (2007), model simulation can be judged as satisfactory if NS>0.5 and acceptable if NS is 0≥1 for stream flow while Santhi et al. (2001) recommends R^2>0.5 as acceptable (Table 4.12). However, Harmel et al. (2006) argue that uncertainty of measured data, which is characterized by measurement conditions, missing data days etc, be considered in model evaluation. That is to say, model evaluation for high certainty data should be stricter but relaxed in a case of low certainty data. Also Legates and McCabe (1999) argue that NS and R^2 are over sensitive to high extreme values (outliers) and less sensitive to close values between simulations and observed. This means NS and R^2 are better statistics in a situation of a lot of data points than in a case of scarce data. The statistics were used in this study but by taking note of the limitations because of scarce data.

Table 4.12 Model performance and evaluation rating using NS index

Model	Value	Performance rating	Modeling phase	Reference
SWAT	>0.65	Very good	Calibration and Validation	Saleh et al. (2000)
SWAT	0.54 – 0.65	Adequate	Calibration and Validation	Saleh et al. (2000)
SWAT	>0.5	Satisfactory	Calibration and Validation	Santhi et al. (2001)
SWAT and HSPF	>0.65	Satisfactory	Calibration and Validation	Singh et al. (2004)

Compiled by Moriasi et al. (2007)

4.2.5 Watershed management plans

Watershed management plans represent interventions aimed at reducing the sediment loss and environmental degradation. There are several choices of interventions in literature; however, the options should be based on local conditions and how realistic they are to implement in the watershed. Existing literature on use of SWAT model to assess management plans were reviewed to guide on selection of reasonable management plans (Betrie et al., 2011; Hurni, 1983; Santhi et al., 2006; Hengsdijk et al., 2005). In this study three management plans were assessed and were considered realistic and reasonably comparable and as compared with similar studies in literature. The management plans are illustrated in Table 4.13.

Option 1 is the baseline which represents existing watershed conditions (a case of business as usual) (Table 4.13).

Option 2 is the use of 1 m filter strips on all agricultural HRUs covering 54 % of the watershed (Table 4.13). The choice of filter width of 1 m was informed by similar studies in the region (Betrie et al., 2011; Hurni, 1985; Herweg and Ludi, 1999). A filter is a dense of vegetative strip, embankment like, located to intercept and filter pollutants flowing downslope and is widely used as a watershed conservation practice. The filter structure is conceptualized in SWAT model and user defines the breadth and the land cover to be applied on. Its crest breadth was provided as 1.0m. The filter works by sieving sediment in the water runoff hence it prevents sediment from leaving agricultural unit to waterways. The option was modeled by introducing filter parameter (FILTERW) in SWAT-CUP and applied on agricultural HRUs (AGRC) and a width range of 0.9 to 1.0 m was provided.

Option 3 is reforestation of agricultural areas. This has an effect of reducing overland flow and rainfall erosivity (Betrie et al., 2011). It was considered impractical to convert all agricultural land into forests. Reforestation was modeled by converting part of the areas under agriculture into evergreen forest in the SWAT model and agricultural land generic (AGRL) as referred to in SWAT was used for the purpose. This had the effect of increasing the forest cover by 11.2 % to a total cover of 42 % (Table 4.13 & 4.14).

Table 4.13 Land cover distribution for the three management plans

Baseline and Filters	Reforestation	Coverage (%)
Agriculture – close grown – AGRC*	Agriculture – close grown - AGRC	54.39
Agriculture – row crops - AGRR	Agriculture – row crops - AGRR	0.03
Agriculture – land generic - AGRL	**Forest evergreen - FRSE**	**13.54**
Forest mixed - FRST	Forest mixed - FRST	4.42
Forest deciduous - FRSD	Forest deciduous - FRSD	22.05
Coffee/Tea - COFF	Coffee/Tea - COFF	2.13
Forest evergreen - FRSE	**Agriculture – land generic - AGRL**	**2.36**
Pasture - PAST	Pasture - PAST	0.01
Coffee/tea/orange - ORAN	Coffee/tea/orange - ORAN	0.94
Urban - URMD	Urban - URMD	0.12
Water - WATR	Water - WATR	0.01

SWAT classes are described in SWAT (2009) documentation (Arnold et al., 2011); *1 m filters were applied on AGRC

Table 4.14 Land cover distribution (%) by sub basin for the three management plans

Sub basin	Area (Km^2)	Baseline/Filters			Reforestation		
		Agriculture	Forest	Others	Agriculture	Forest	Others
1	161.03	46.63	51.67	1.70	45.64	52.67	1.69
2	140.95	21.02	78.13	0.85	20.28	78.87	0.85
3	128.48	89.47	10.52	0.01	89.46	10.53	0.01
4	16.90	93.81	6.19	0.00	93.81	6.19	0.00
5	33.21	77.13	22.87	0.00	76.10	23.90	0.00
6	7.30	92.49	7.51	0.00	92.49	7.51	0.00
7	90.02	41.77	57.06	1.17	16.16	82.66	1.18
8	263.89	60.58	30.28	9.14	19.55	71.31	9.14
9	64.02	83.03	16.97	0.00	82.49	17.51	0.00
10	285.65	76.50	22.73	0.77	27.81	71.43	0.76
11	179.11	47.04	52.96	0.00	47.04	52.96	0.00
12	67.11	90.44	9.56	0.00	89.94	10.06	0.00
13	188.56	25.71	74.29	0.00	23.55	76.45	0.00
14	36.76	5.62	94.38	0.00	2.62	97.38	0.00
15	84.72	22.83	77.17	0.00	22.83	77.17	0.00
16	105.92	75.11	24.89	0.00	70.11	29.89	0.00
17	369.45	86.84	13.16	0.00	85.66	14.34	0.00
18	78.51	96.45	3.42	0.13	95.58	4.29	0.13
19	54.95	84.50	15.50	0.00	82.41	17.59	0.00
20	471.77	62.89	36.04	1.07	54.38	44.57	1.05
21	45.79	100.00	0.00	0.00	100.00	0.00	0.00
22	71.99	88.31	11.69	0.00	63.12	36.88	0.00
23	17.56	99.56	0.44	0.00	99.56	0.44	0.00
24	297.07	98.54	1.46	0.00	98.30	1.70	0.00
25	134.73	86.81	13.19	0.00	54.01	45.99	0.00
Total	3,395.45	67.96	30.96	1.08	56.55	42.37	1.08

CHAPTER 5: RESULTS AND DISCUSSIONS

This chapter presents results of: review of estimation of pollution load as done by the studies, estimation of nutrient export coefficients on the Kenyan catchment of Lake Victoria, estimates of simulation of hydrology, sediments and nutrients in Sondu watershed using SWAT and finally SWAT simulation of effectiveness of three hypothetical watershed management plans aimed at reducing sediment loss in Sondu watershed. The review of past studies was extensively covered in Chapter 2 and only the main points are presented in this chapter. Both municipal and industrial load are needed to facilitate estimation of nutrient export coefficients but only municipal load was considered in this study. The amount of industrial pollution load is negligible as a component of non-point load and also data on industrial load was not available.

5.1 Estimation of pollution load in Lake Victoria

5.1.1 Current estimation models

There are several models but the main and common models that are used to estimate and or simulate hydrology and pollution load (organic matter, sediments and nutrients) were reviewed. There are static models used for rapid assessment such as Unit Area Load (UAL) method, and dynamic models such as AGNPS, AnnAGNPS and SWAT models. Use of UAL has limitation in situations where water quality parameters are varying a lot as a result of characteristic of rainfall (intensity, depth and seasons) and pollution load reduction by artificial and natural treatments are not considered. CMSS model covers some of the limitations of UAL method. The model allows for natural reduction of pollution load within river system. AGNPS model is limited in application area (about 200 Km^2) and works for only single rainfall events while AnnAGNPS is an improvement of AGNPS but does not predict impact of land management practices. The SWAT model was developed to address the limitations.

5.1.2 Methods in similar past studies

Existing similar studies in Lake Victoria classified pollution into point and non-point. The studies are Calamari et al. (1995), Scheren et al. (1995, 2000), COWI (2002), LVEMP (2005), Scheren (2003, 2005). They classified municipal and industrial sources as point sources while land runoff and atmospheric deposition as non-point sources of pollution load. That is the shared similarity but their methods differ as you proceed beyond classification. The differences in methods are defined by data availability and maneuvering data collection.

For example, the studies considered municipal load from urban areas with a threshold of at least a population of 10,000 persons and they classified population by the type of sanitation they use. However, the number of classes differs as well as unit per capita loads applied. Calamari et al., (1995) included solid waste leachate as source of municipal (point) load and domestic animals as source of runoff (non-point) load while the other studies did not. Also Scheren et al., (2000) classified municipal load into sewered and unsewered population and went further to provide for reduction (degradation) of the load (organic matter) within the river systems as function of river length – first order decay process, and nutrients reduction by wetland systems. The methods are summarized in Chapter 2 and specifically by Eq. 2.2 all through to Eq. 2.14 and Tables 2.1 to Table 2.5.

5.1.3 Estimates of pollution load in similar past studies

Total point loads are far much less than non-point loads. Atmospheric load is the main source of pollution load, nitrogen in particular. More than 65 % of non-point load comes from atmospheric sources (Table 2.5). Estimated runoff pollution load by COWI (2002) for TN was almost two times that estimated by Scheren et al.(1995, 2000) and Scheren (2003, 2005), (TN: 49,509, 26,292t/yr respectively). The estimates for TP by both studies were closely equal (TP: 5,693, 5,634t/y respectively) (Table 2.5). Load estimates of TP (runoff) by the studies were closely equal while TP (atmospheric) estimated by Scheren et al. (1995, 2000) and Scheren (2003, 2005) were about seven times that of COWI (2002) but their TN (atmospheric) were close (Table 2.5).

The estimates of pollution load by the similar studies done in the past had varying figures. The differences and at the same time closeness observed in the results of the past studies on estimation of pollution load to Lake Victoria makes it is difficult to determine which estimates are reliable and accurate. In comparing the figures the methods used and scarce data availability is appreciated. Lacking data include management practices in the basin, water flow, water quality, municipal and industrial effluent generation, etc. The estimation approach had similarities and studies were done at close periods but the variations are significant. The approach by COWI (2002) which relied on measurements provides useful information especially for the gauged river watersheds. The shortcomings of the method may be addressed by collecting more samples within the un-gauged river watersheds, the lake and islands to make estimates more representative.

Reliable estimates are dependent on the quality of data and on use of methods that simulate the actual process dynamics as much as possible. Continuous time models such as Soil and Water Assessment Tool (SWAT) have not taken root in Lake Victoria. Use of SWAT to simulate pollution load requires diverse data, among, river water quality and quantity and weather data and thus its use has always been limited.

5.1.4 Export coefficients in estimation of runoff load

The existing similar studies on Lake Victoria used either monitoring of water quality at river mouths to estimate pollution load (COWI, 2002; LVEMP. 2005) or export coefficients as a function of land use (Unit Area Load -UAL) but UAL were borrowed from other regions (Calamari et al., 1995; Scheren et al., 1995; Scheren et al., 2000). The monitoring at river mouth isn't continuous in terms of time and doesn't provide information on spatial distribution while use of borrowed export coefficients need to localized (adjusted to local conditions). For example, borrowed UAL for cropland from a high precipitation region would not be representative if used in a watershed with less precipitation. The challenge is how to adjust borrowed export coefficients to fit local conditions. Young et al. (1196) and Baginska et al. (2003) are of the opinion that quantitative adjustment is dependent on available and measurable information at both origin and receiving watersheds. The main watershed characteristics are: rainfall intensity, catchment size and runoff volume. Information on how other environmental attributes influence runoff load generation is too limited to facilitate adjustment.

Apart from land use, rainfall-runoff coefficient of a watershed was singled out from literature that can best represent watershed characteristics holistically. The coefficient is a function of slope, rainfall intensity, land cover, soil and ambient conditions of a watershed. A combination of land use and rainfall-runoff coefficient is considered the best integrators of watershed characteristics and explains better the generation and export of runoff load. Thus the two attributes should form the basis of use and adjustment of export coefficients (UAL) and more importantly to improve the current rapid assessment methods as used in Lake Victoria. It is against this background that this study used the monitored load at river mouth and the concept of UAL load method to estimate nutrient export coefficients for the Kenyan part of Lake Victoria basin.

5.2 Export coefficients model

Municipal load was first estimated to facilitate estimation of export coefficients on the Kenyan side of Lake Victoria basin. Therefore, municipal load estimates are first presented and then followed by the output of export coefficient model equation.

5.2.1 Municipal load estimates

Municipal load discharged from identified sewerage facilities were estimated as at the year 2009 using the method described in Section 4.1 of Chapter 4. The load generated based on unit per capita loads was reduced to correct for treatment by wastewater treatment plants. Table 5.1 summarizes the estimates of municipal load in the target watersheds.

Table 5.1 Estimates of net municipal load (tons/yr)

River watershed	TN	TP
Yala	43.40	23.87
Gucha Migori	70.32	38.68
Nzoia	393.99	216.69
Sondu	25.92	14.26
Sio	14.25	7.83
Nyando	N/A	N/A
Total (tons/yr)	547.88	301.33

The population in Lake Victoria basin is sparsely distributed in rural areas and dense in towns. Not all towns are connected with municipal sewerage systems. Estimates of sewerage usage indicate that about 1.2 million persons on the Kenyan side of Lake Victoria basin are connected to municipal sewer system (Table 4.4). Majority of population in towns in the catchment use pit latrines followed by sewer and septic tanks in that order. Total annual nutrient municipal load of 548 tons/yr - TN and 301 tons/yr. - TP are estimated to be flowing to the Lake Victoria from the main six river watersheds on the Kenyan side of the basin.

Despite varying reductions load reduction by natural systems, load estimates from river watersheds reflected the relative number of persons connected to the sewerage (Table 4.4 and Table 5.1).

5.2.2 Export coefficient estimates

The combinations of watershed model equations with model inputs yielded estimates of export coefficients for three land uses. Table 5.2 summarizes the estimates of export coefficients and it shows that vegetation/grassland/shrubland generates more nutrients per unit area annually while cropland generates the least with respect to both TN and TP. The land use also has relatively wider range. However, cropland is the main source of nutrients in terms of aggregate load due to its dominant coverage. The high coverage of land use under cropland in the catchment is explained by dominant tea, maize and sugarcane plantations in the study area. These are the main livelihood activities of the resident population. Collection of water quality data in Lake Victoria is still very limited and current efforts by regional governments to address the situation will be useful in improving estimation of the nutrient export coefficients.

Table 5.2 Estimates of nutrient export coefficients (Kg/ha/yr)

Nutrient		Statistics	Cropland	Forest	Vegetation/ grassland/ shrubland
TN		Minimum	0.643	3.123	12.862
		Mean	1.412	14.426	27.800
		Maximum	2.048	29.625	45.880
		Stdv*	0.543	10.902	33.032
	95% Confidence interval	Margin of error	0.238	4.778	5.232
		Low	1.174	9.648	22.569
		High	1.650	19.204	33.032
TP		Minimum	0.185	0.045	2.639
		Mean	0.257	1.958	5.611
		Maximum	0.296	5.778	11.423
		Stdv*	0.062	3.308	5.033
	95% Confidence interval	Margin of error	0.027	1.450	2.206
		Low	0.230	0.508	3.405
		High	0.284	3.408	7.817

*Standard Deviation

The 95% confidence intervals of nutrient export coefficients estimates based on the two data sets (2001 and 2003) with a view of validating the model are represented in Fig. 5.1 a & b. They show overlap of the model estimates and consequently how well the model can estimate nutrient export coefficients. There was 100 % overlap with respect to nutrient export coefficients for TP while for TN only estimates for cropland overlapped. The gap between the intervals of forest and vegetation/grassland/shrubland land uses should be looked at with consideration of the challenge in integrating the multiple factors that influence nutrient export and limited water quality data in Lake Victoria as well as taking note of ranges in literature which are wider such as those compiled by Letcher et al. (1999).

Since model set-up and validation is based on the same study area but different sets of data, factors other than the watershed's physical characteristics could be attributed to the gap. These are factors such as hydro-meteorological and land management practices. With foregoing explanation, the model is considered able to estimate ranges of nutrient export coefficients based on monitored river information.

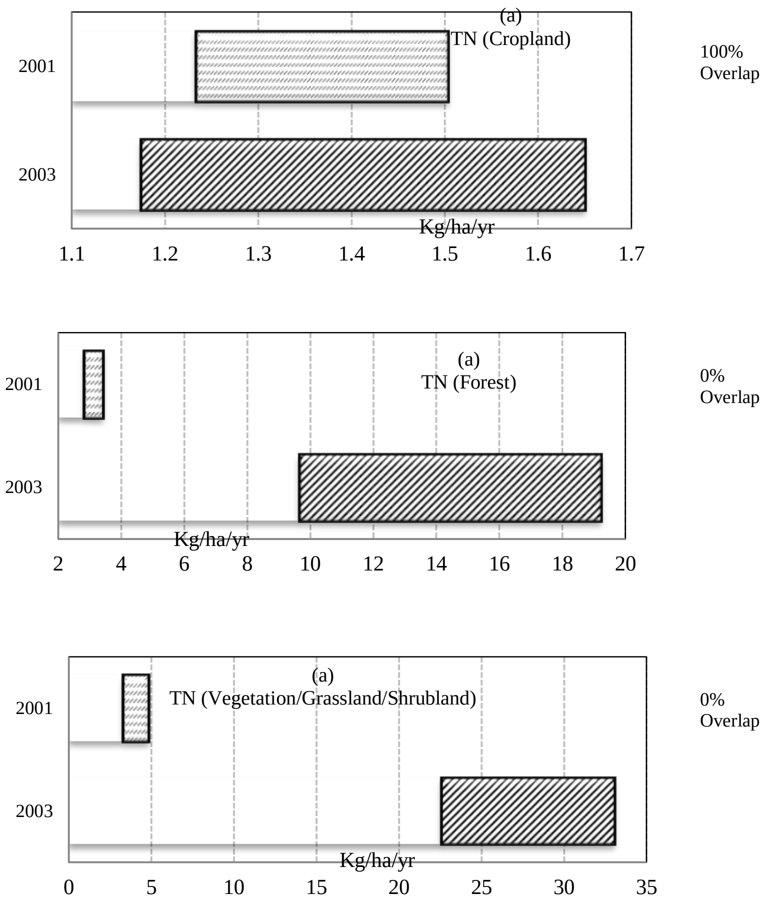


Fig. 5.1a The 95% confidence interval estimates of TN nutrient export coefficients derived using 2001 and 2003 datasets

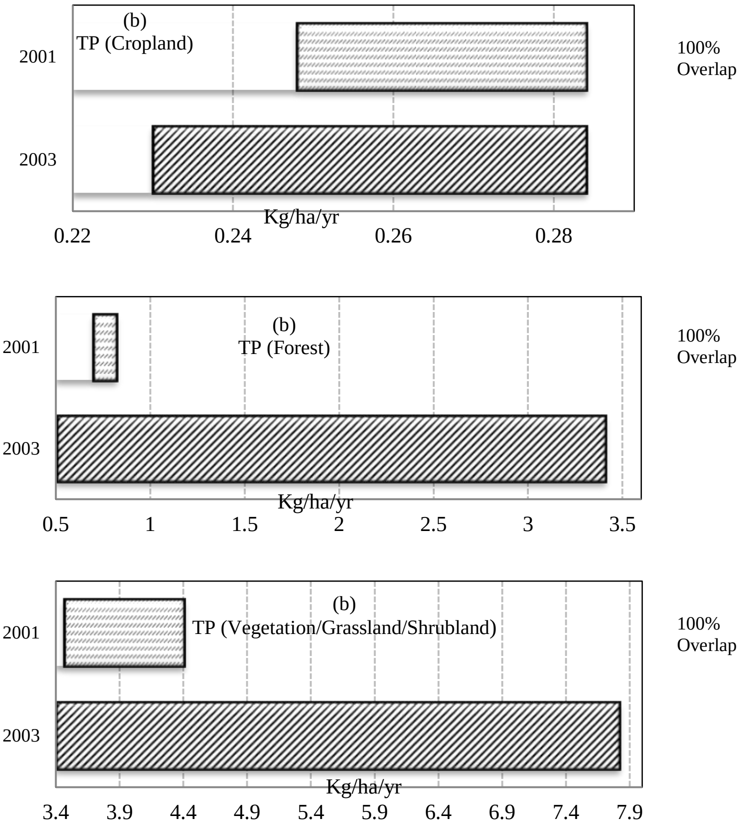


Fig. 5.1b The 95% confidence interval estimates of TP nutrient export coefficients derived using 2001 and 2003 datasets

As shown in Table 4.6, cropland in the study area is the main land use which covers 87 % while forest and vegetation/grassland/shrubland cover 10.3 % and 2.8 % respectively of the total area. Built-up area (towns) which occupies less than 1 % is the least. Land use distribution within watersheds varies but cropland/agricultural activities remain dominant. The large forest coverage (30 %) for Sondu watershed is attributed to Mau forest which is located upstream. Satellite images by ESA poorly capture built up areas (towns) because of their low resolution (300 m). Most highly built up areas in the catchment have at least one dimension less than 300 m and hence less likely to be captured as urban areas. It is for this reason that urban land use was not considered for the estimation of export coefficients in this study.

Simultaneous solutions to the sets of equations (Eq. 4.11) returned positive values while some returned negative values of export coefficients. Ideally, watersheds with similarity in respect of factors influencing nutrient generation and export are expected to return positive solutions. Since it was not possible to determine the similarity of watersheds with respect to all parameters, all possible sets of watersheds were formulated and solved simultaneously.

The amount of river-driven nutrients is a product of nutrient export coefficients and area of land use (Calamari et al., 1995; Scheren et al., 2000). However, the export coefficient is a function of several environmental and management attributes. The relevant environmental attributes are land use, rainfall parameters (rainfall intensity, depth and frequency), slope, catchment size, drainage density, soil type and rainfall erosivity factor (Young et al., 1996; Baginska et al., 2003). On the other hand, management attributes refer to variables meant to reduce nutrient input and output in the catchment such as installation of treatment facilities in urban areas, use of eco-friendly fertilizer substitutes (organic farming), considerate use of inorganic fertilizers, construction of artificial wetlands and maintenance of natural wetlands and so forth (Scheren et al., 2000; Broad and Corkrey, 2011).

Therefore, a negative solution is an indication of incompatibility of watersheds in a set i.e. not closely similar, while a positive solution is considered to be a case of watersheds with close similarity. The estimated export coefficients from a positive solution represent the average and not exact values. Watershed incompatibility is attributed to inherent environmental and management attributes of the watersheds as elaborated in Chapter 2. For example, significant areas of forests in all watersheds are located upstream but other factors such as elevation/slope, geometric shape and soil parameters are not necessarily similar. Complete similarity of watershed characteristics is an ideal case and such a scenario would be rare.

Table 4.6 shows Yala watershed has the highest conversion of rainfall into runoff and subsequent proportion of rainfall that gets to the lake. Yala watershed's rainfall-runoff coefficient is 2.4 times relative to that of Gucha which is the least. This is attributed mainly to their differences in hydrometeorology, soil, land use, drainage density, slope and geometrical characteristics among other environmental attributes of the watersheds. The relative rainfall-runoff coefficient (r) was incorporated because watersheds have different depths of rainfall-runoff coefficient. Nutrient export coefficients for the same land use type in watersheds with unequal rainfall-runoff coefficient would not be equal assuming other parameters are constant. It is in this regard the relative coefficient (r) was used in the model to equate export coefficients in different watersheds.

5.2.3 Correlation: Rainfall runoff and nutrients

The relationships between river nutrient concentrations with rainfall-runoff coefficient based on the data in Table 4.6 are represented in Fig. 5.2. The relationship helps to understand the role which watershed characteristics play in runoff load generation. The general relationship shows that river watersheds with high rainfall-runoff coefficient have low concentration of nutrients in rivers. However, the relationship is not linear as indicated by the low correlation coefficient R (0.36 for TN; 0.69 for TP) (Fig. 5.2).

The weak relationship shows that other factors beyond rainfall characteristics have influence. These are factors such as non-uniform distribution of land use across the six watersheds (Table 4.6), soil characteristics and management practices among others and as described in Chapter 2. A close look at Gucha, Nyando and Sio watersheds (circled in Fig. 5.2) brings out another aspect. The watersheds have equal rainfall-runoff coefficients. Nyando and Gucha have close uniform land use distribution within the watersheds (Table 4.6) but the levels of nutrient concentrations in the rivers vary significantly (Fig. 5.2). This could be mainly attributed to the loose soil characteristic of the watershed. This implies that nutrient generation in a watershed is not only influenced by land use but also that the other factors have influence in an integrated manner.

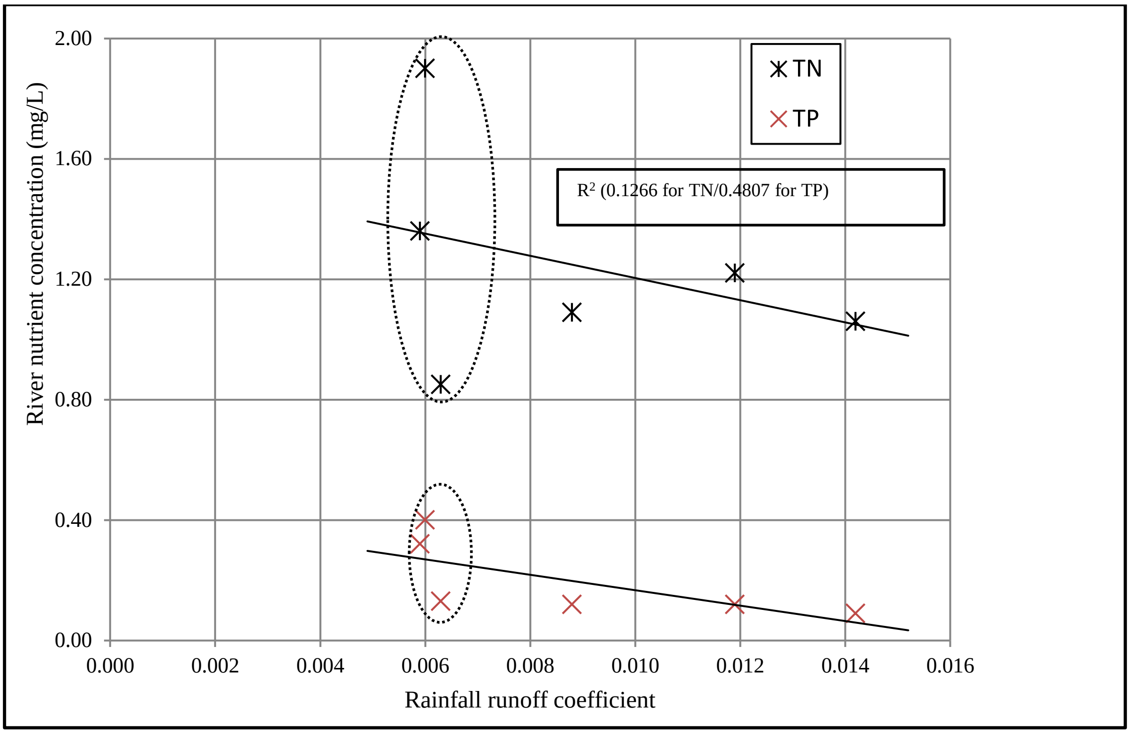


Fig. 5.2 Correlation between rainfall runoff coefficient and river nutrient concentration

5.3 SWAT model

Several iterations were run to arrive at reasonable simulation values for the two variables (stream flow, sediments and nutrients – TN & TP). The main land covers are agriculture and forest (67 % & 30 % respectively). The forested areas are spatially distributed in the watershed. However, the main forest is the Mau forest, located upstream and to the South East of the watershed. In spite of the scarce data, sediments simulation fitted into observed values with reasonable model performance. The subsections below elaborate in detail the model results.

5.3.1 Sensitivity analysis and Calibration parameters

The initial SCS curve number for moisture condition II (Cn2) parameter and linear parameter for calculating the maximum amount of sediment that can be re-entrained during channel sediment routing (Spcon) were the most sensitive. Less sensitive parameters such as available water capacity of the soil layer (SOL_AWC) and Soil evaporation compensation factor (ESCO) were useful in calibrating peak stream flows (Table 5.3a & b).

Table 5.3a Parameter sensitivity based on run with observed data: stream flow and sediment

Rank	River flow		Sediment	
1	Cn2	Initial SCS curve number for moisture condition II	Spcon	Linear parameter for calculating the maximum amount of sediment that can be re-entrained during channel sediment routing
2	Alpha_Bf	Baseflow alpha factor - days	Ch_K2	Effective hydraulic conductivity in main channel alluvium
3	Rchrg_Dp	Deep aquifer percolation fraction	Ch_N2	Manning's n value for the main channel
4	Ch_K2	Effective hydraulic conductivity in main channel alluvium	Cn2	Initial SCS curve number for moisture condition II
5	Ch_N2	Manning's n value for the main channel	Spexp	Exponent parameter for calculating sediment re-entrained in channel sediment routing
6	Esco	Soil evaporation compensation factor	Alpha_Bf	Baseflow alpha factor - days

Sensitivity decreases down the Table; Parameter symbols as used in SWAT (2009) (Arnold et al., 2011)

Table 5.3b Parameter sensitivity based on run without observed data: stream flow and sediment

Rank	River flow		Sediment	
1	Cn2	Initial SCS curve number value	Spcon	Linear parameter for calculating the maximum amount of sediment that can be re-entrained during channel sediment routing
2	Rchrg_Dp	Deep aquifer percolation fraction	Ch_N2	Manning's n value for the main channel
3	Esco	Soil evaporation compensation factor	Ch_K2	Effective hydraulic conductivity in main channel alluvium
4	Canmx	Maximum canopy storage - mm H_2O	Cn2	Initial SCS curve number for moisture condition II
5	Blai	Maximum potential leaf index	Spexp	Exponent parameter for calculating sediment re-entrained in channel sediment routing
6	Sol_Awc	Available water capacity of the soil layer - mmH_20/soil	Usle_p	USLE equation support practice factor

Sensitivity decreases down the Table; Parameter symbols as used in SWAT (2009) (Arnold et al., 2011)

Table 5.3c Parameter sensitivity based on run with observed data: TN and TP

Rank	TN		TP	
1	Nperco	Nitrogen percolation coefficient	Biomix	Biological mixing efficiency
2	Cn2	Initial SCS curve number value	Surlag	
3	Blai	Maximum potential leaf area index	Usle_P	USLE equation support practice factor
4	Biomix	Biological mixing efficiency	Canmx	Maximum canopy storage
5	Rchrg_Dp	Deep aquifer percolation fraction	Cn2	Initial SCS curve number value
6	Usle_P	USLE equation support practice factor	Ch_K2	Channel effectiveness hydraulic conductivity

Sensitivity decreases down the Table; Parameter symbols as used in SWAT (2009) (Arnold et al., 2011)

Table 5.3d Parameter sensitivity based on run without observed data: TN and TP

Rank	TN		TP	
1	Nperco	Nitrogen percolation coefficient	Biomix	Biological mixing efficiency
2	Blai	Maximum potential leaf area index	Surlag	Surface runoff lag time
3	Cn2	Initial SCS curve number value	Cn2	Initial SCS curve number value
4	Rchrg_Dp	Deep aquifer percolation fraction	Usle_P	USLE equation support practice factor
5	Biomix	Biological mixing efficiency	Ch_K2	Channel effectiveness hydraulic conductivity
6	Gwqmn	Threshold depth of water in the shallow aquifer	Blai	Maximum potential leaf area index

Sensitivity decreases down the Table; Parameter symbols as used in SWAT (2009) (Arnold et al., 2011)

Initial iteration was run using the five most sensitive stream flow parameters, but subsequent improvement led to replacement and addition of other parameters. Twenty eight (28) parameters were used for the final calibration and validation iterations. Additional filter (FILTERW) parameter was added for filter management plan simulation (Table 5.4).

Table 5.4 Final calibration parameters and their ranges as used in SWAT-CUP

	Parameter	Minimum	Maximum	Variation method*
1	r__CN2.mgt	0.100	0.134	R
2	v__ALPHA_BF.gw	0.100	0.200	V
3	v__GW_DELAY.gw	400	500	V
4	v__GWQMN.gw	1.600	1.610	V
5	v__CH_N2.rte	0.153	0.254	V
6	v__CH_K2.rte	140	240	V
7	v__ESCO.hru	0.974	1.100	V
8	r__SOL_AWC().sol	0.410	0.600	R
9	r__SOL_K().sol	0.090	0.095	R
10	v__GW_REVAP.gw	0.350	0.370	V
11	v__REVAPMN.gw	1.272	1.280	V
12	v__RCHRG_DP.gw	0.500	0.726	V
13	v__SPCON.bsn	0.009	0.010	V
14	v__SPEXP.bsn	1.000	1.500	V
15	v__USLE_P.mgt	1.500	2.000	V
16	v__USLE_C.crop.dat	0.200	0.400	V
17	v__CH_COV1.rte	0.000	0.100	V
18	v__CH_COV2.rte	0.000	0.120	V
19	v__NPERCO.bsn	0.000	0.005	V
20	v__SOL_NO3().chm	0.000	0.050	V
21	v__SOL_ORGN().chm	0.000	0.050	V
22	v__PPERCO.bsn	25	30	V
23	v__SOL_LABP().chm	0.000	0.005	V
24	v__PHOSKD.bsn	250	280	V
25	v__SOL_ORGP().chm	0.000	0.005	V
26	v__BIOMIX.mgt	0.500	0.600	V
27	v__RSDCO.bsn	0.000	0.010	V
28	v__AI1.wwq	0.000	0.020	V
29	**v__FILTERW().hru______AGRC**	**0.950**	**1.050**	**V**

*Variation method: V – means existing parameter value is replaced by a given value while R – means is multiplied by - 1 + a given value

5.3.2 Stream flow calibration and validation

The model simulated stream flow with a p-factor of 0.67 and r-factor of 0.63 over the calibration period and 0.65 and 0.78 respectively for validation period. The calibration simulation had R^2 and NS indices of 0.70 and 0.61 while the values for validation were 0.52 and 0.55 respectively (Table 5.5). The model performance was satisfactory in calibration and validation period and was thereafter used for assessment of management plans. Calibration and validation iterations captured the low and high flow seasons reasonably well and in synchrony with rainfall pattern (Fig. 5.3a, b, c & d). The simulations compared favorably with similar studies on Lake Victoria such as Kimwaga et al. (2011) and Opere and Okello (2011) which run the SWAT model with scarce data and attained R^2 value of 0.24 and lower, limitation of statistic in scarce data situation notwithstanding.

In the calibration period 2005-2007, the high rainfall period was March-May while the high stream flow was from May-July, lagging by about two months (Fig. 5.3a & b). The simulated annual average flow over the calibration period (2005-2007) was 39 m^3/s whereas LVEMP (2005) recorded an average of 42 m^3/s (1.1 times more) although the time periods are different. The LVEMP (2005) finding is based on 2003 observed stream flow which was a relatively wetter year and this partly explains the difference in stream flow.

Table 5.5 Stream flow simulation – model performance based on SWAT-CUP statistic

Statistic	Limits (worse – best)	Calibration	Validation
p-factor	0 to1.0	0.67 - Satisfactory	0.65 - Satisfactory
r-factor	0 to ∞	0.63 - Satisfactory	0.78 - Satisfactory
NS	-∞ to 1.0	0.70 – Very good	0.52 - Satisfactory
R^2	0 to1.0	0.61 - Satisfactory	0.55 - Satisfactory

Model performance assessed as per compilations of Moriasi et al al. (2007) and Karim (2012)

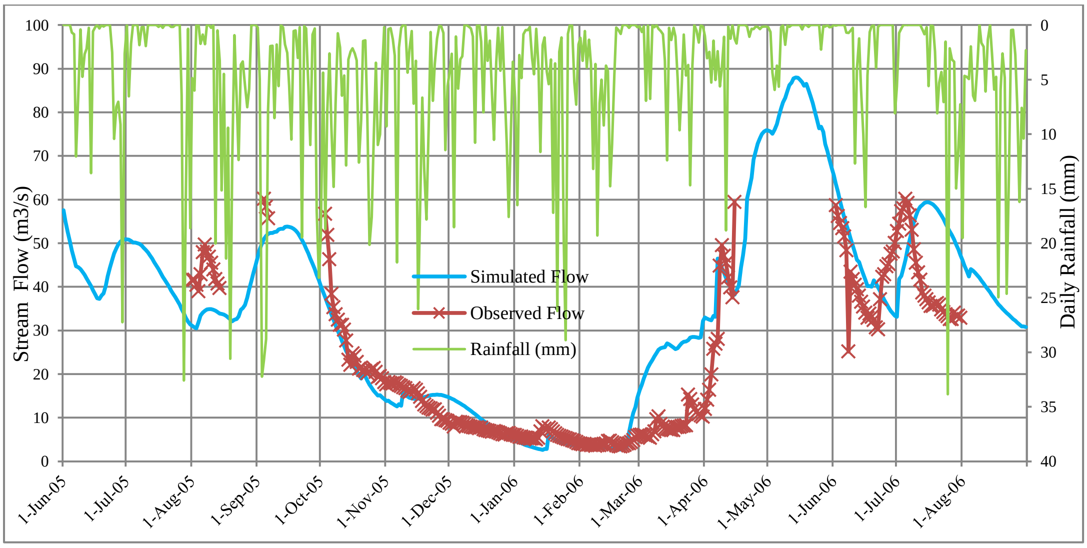


Fig. 5.3a Daily observed and simulated stream flow and rainfall in the calibration period

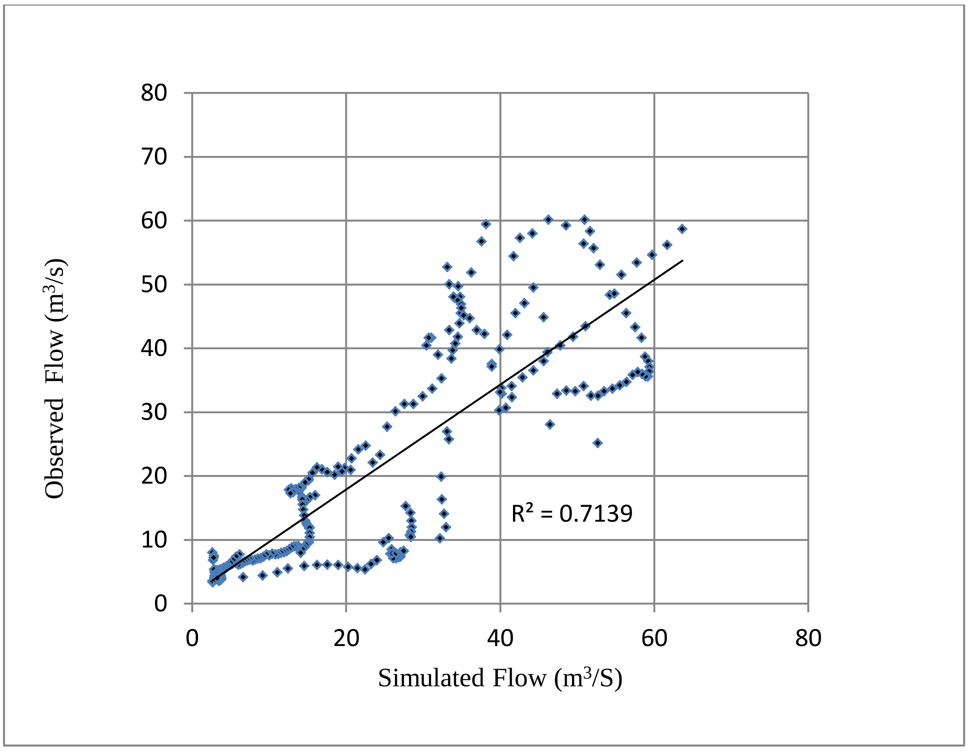


Fig. 5.3b Correlation of observed against simulated stream flow values (Calibration)

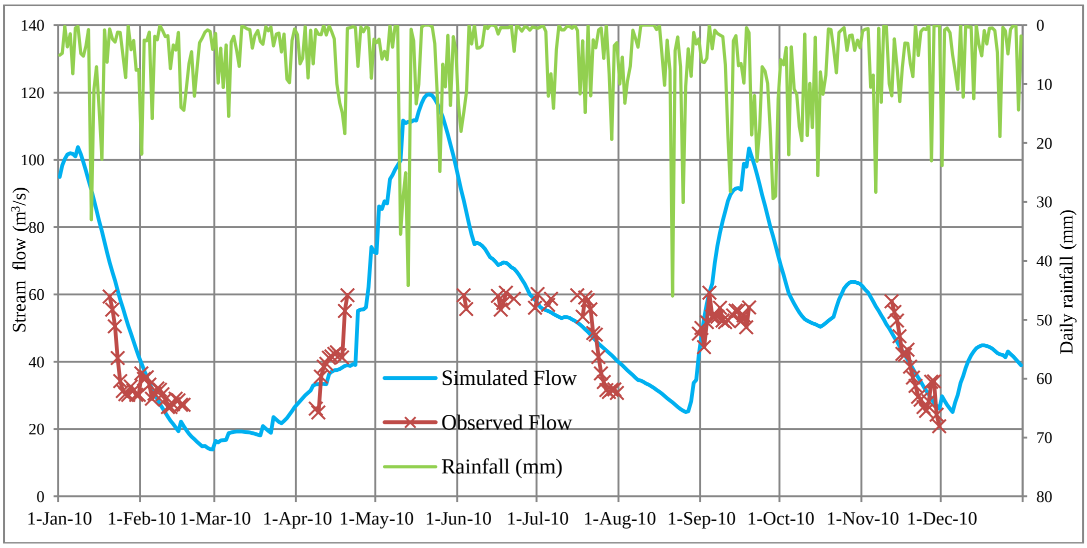


Fig. 5.3c Daily observed and simulated stream flow and rainfall in the validation period

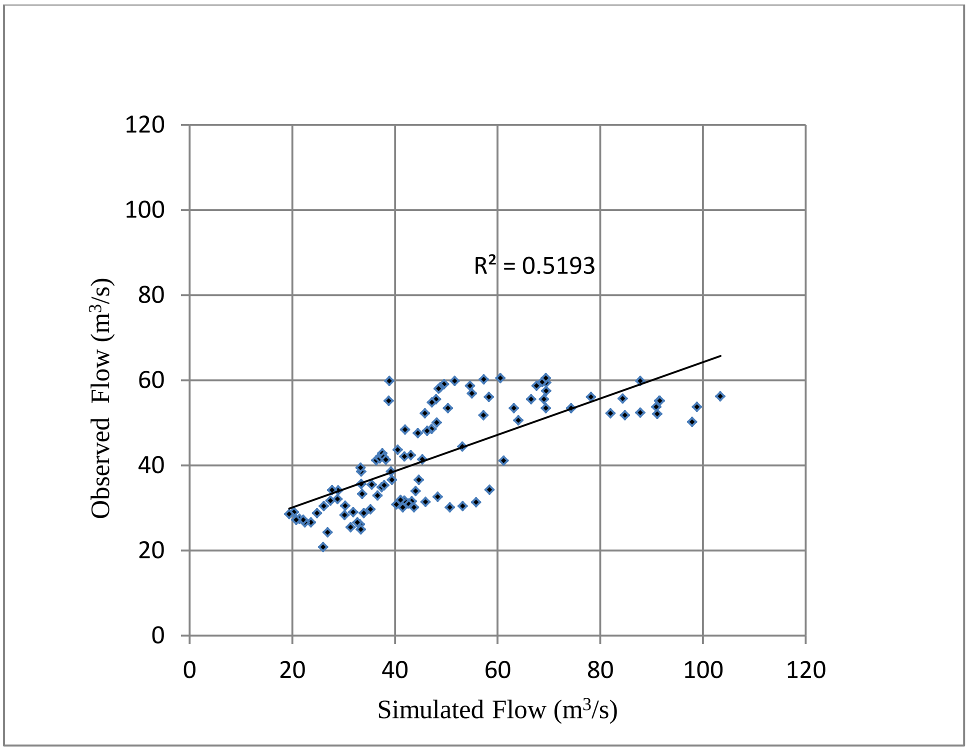


Fig. 5.3d Correlation of observed against simulated stream flow values (Validation)

Spatial and temporal water yield

The year 2006 had relatively higher water yield out of the watershed to Lake Victoria while 2005 had the least during the calibration period. The temporal precipitation had a similar trend. The high water yielding areas are watersheds in the upstream-North (Kericho region), upstream-South and South East (upper Sotik/Kuresoi regions) of the watershed (Fig. 5.4 and 5.5). These high water yielding areas not only receive higher precipitation but also have higher slope and the two characteristics mainly explain the water yield. Some high water yielding areas are mainly covered by agriculture (Sotik/Kericho) and some parts are mainly forested (Kuresoi) (Fig. 5.4 and 5.5). This was the same finding by Betrie et al. (2011) and Opere and Okello (2011) study on neighboring Nzoia river watershed that agricultural areas are significant contributors of water runoff yields.

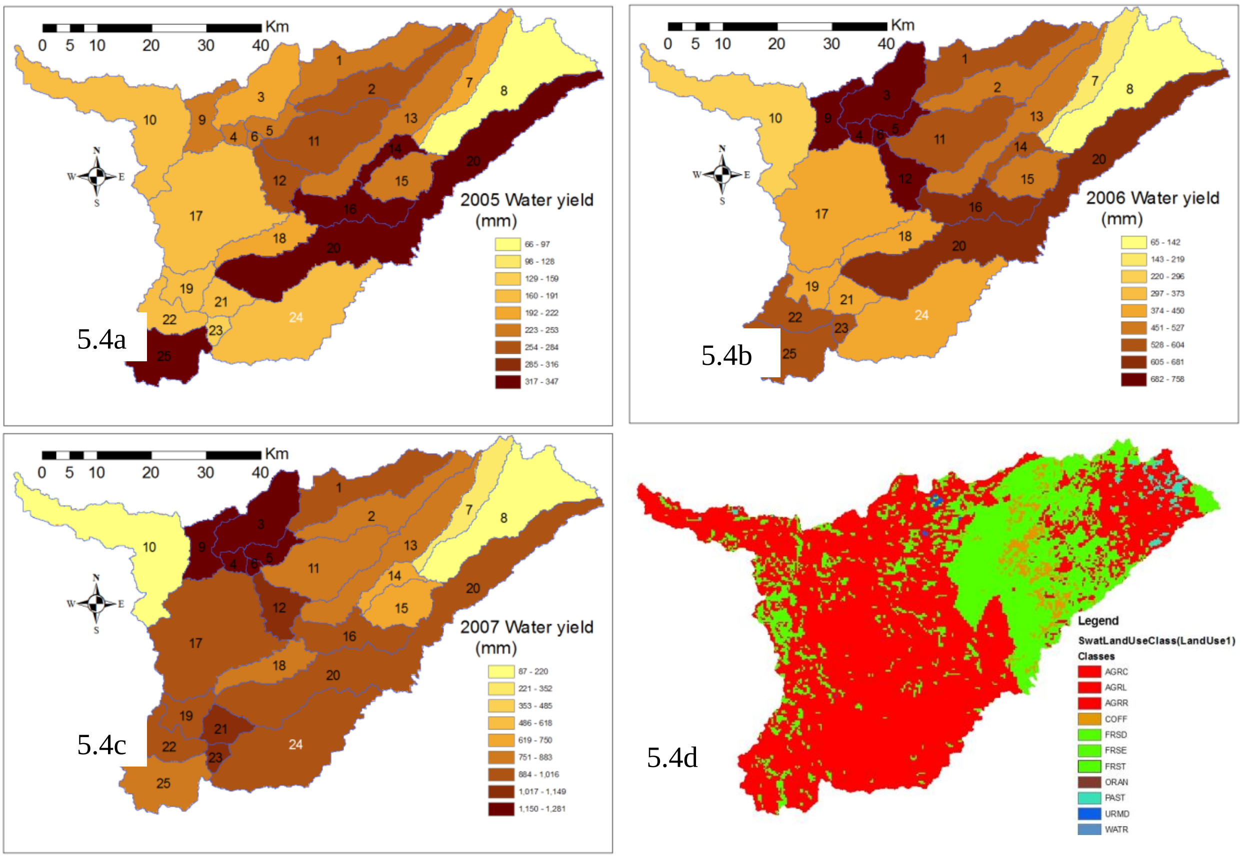


Fig. 5.4 Water yield in the years 2005 (5.4a), 2006 (5.4b), 2007 (5.4c) and Land cover, 2005 (5.4d)

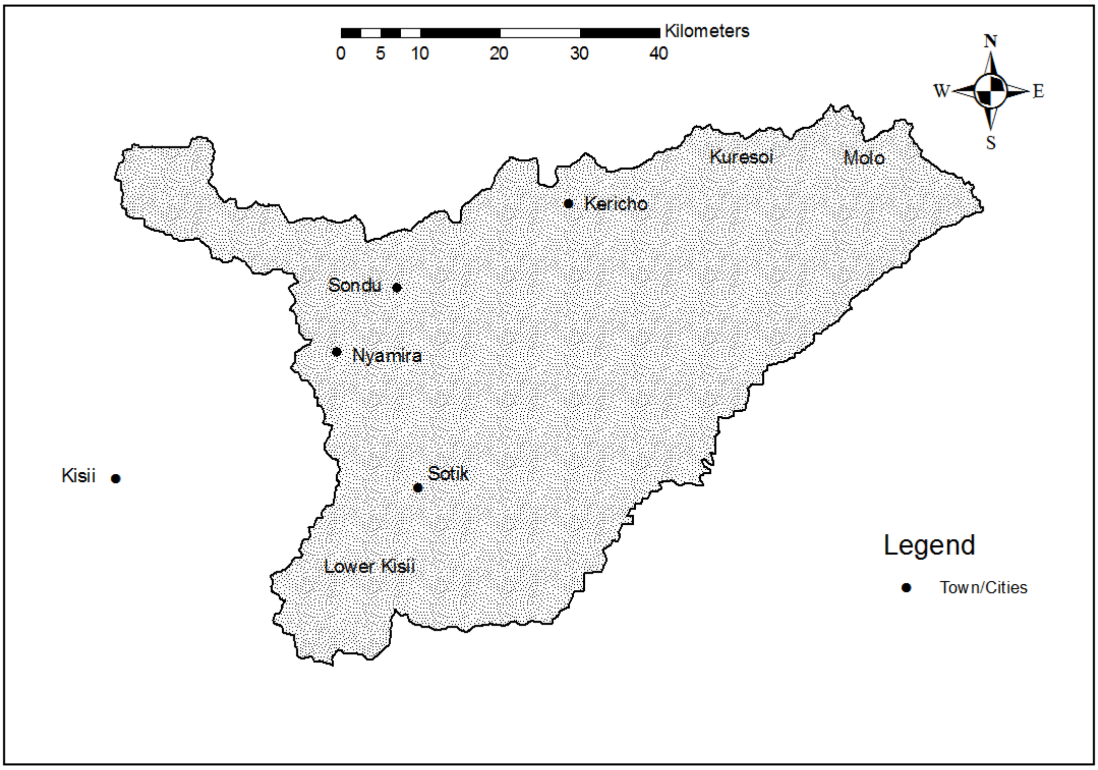


Fig. 5.5 Main sub regions of Sondu watershed

5.3.3 Sediment calibration and validation

The p-factor and r-factor indices for the final calibration iteration were 0.56 and 1.17 while for validation period were 0.45 and 1.6 respectively. The R^2 and NS calibration indices were 0.78 and 0.13 while for validation they were 0.40 and 0.15 respectively (Table 5.6). Based on Moriasi et al. (2007) and Santhi et al. (2001), the model performance was considered satisfactory and within the observations of Harmel et al. (2006) and Legates and McCabe (1999) in a case of scarce observed data.

Table 5.6 Sediment simulation – model performance based on SWAT-CUP statistic

Statistic	Limits (worse – best)	Calibration	Validation
p-factor	0 to1.0	0.56 - Satisfactory	0.45 - Satisfactory
r-factor	0 to ∞	1.17 - Satisfactory	1.6 - Adequate
NS	-∞ to 1.0	0.13 - Adequate	0.15 - Adequate
R^2	0 to1.0	0.78 - Good	0.40 - Satisfactory

Model performance assessed as per compilations of Moriasi et al al. (2007) and Karim (2012)

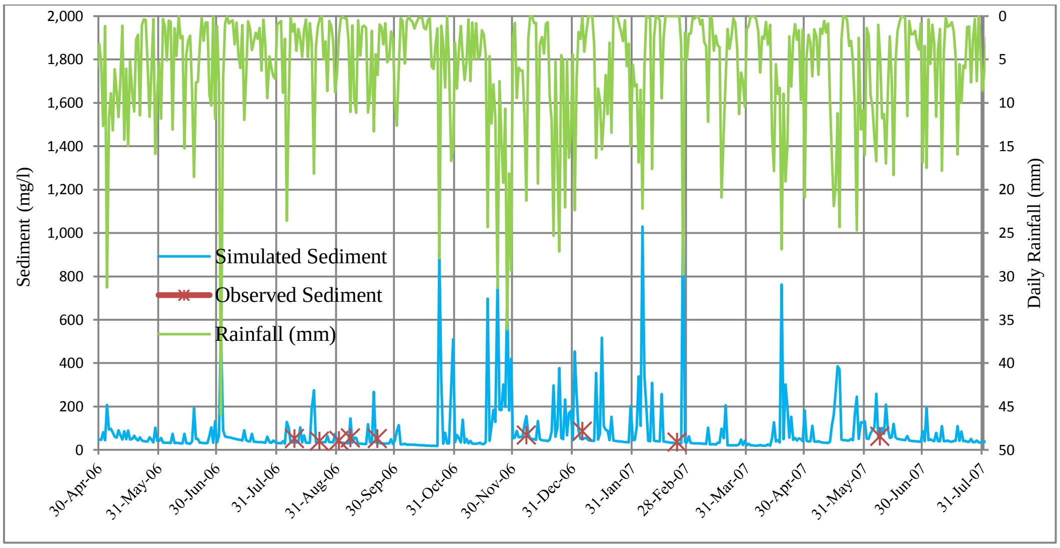


Fig. 5.6a Daily observed and simulated sediment concentration in the calibration period

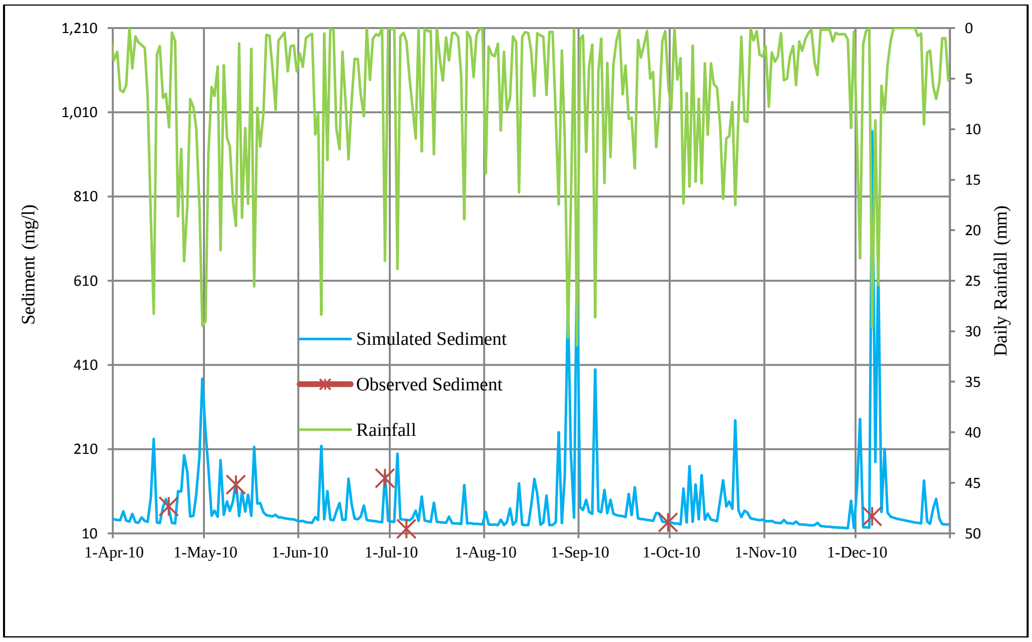


Fig. 5.6b Daily observed and simulated sediment concentration in the validation period

Sediment distribution

Sediment erosion distribution in the watershed was assessed based on the baseline management plan. High sediment yield periods were Feb - May and November - January and they directly correlated with high rainfall seasons (Fig. 5.7). In the simulation period (2005 –

2007), sub basin 24 of the watershed had high sediment yield relative to other sub basins (Fig. 5.8). The sub basin is mainly covered by agriculture (Table 4.12). Ideally not all sediment loss from upstream watersheds ends up in the outlet watershed because some are deposited on the river channels and reservoirs. Upstream sediment loss may not have much impact on water resources development downstream but the resulting environmental degradation negatively impacts agricultural production.

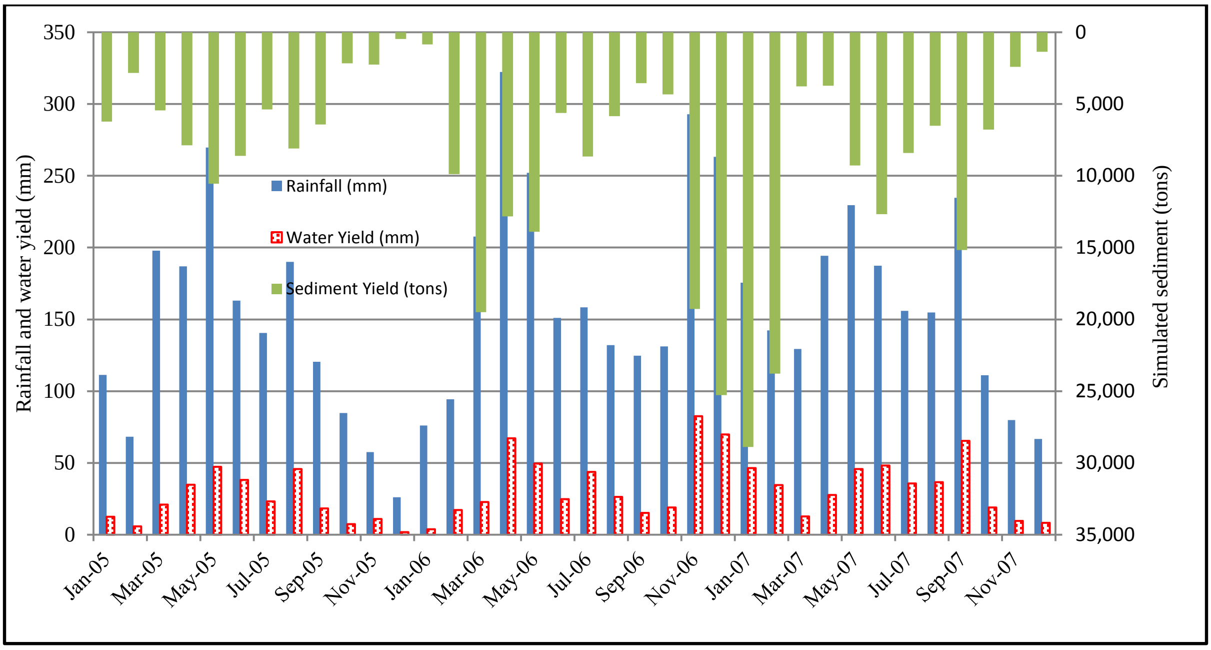


Fig. 5.7 Monthly simulated sediment yield and precipitation against watershed water yield

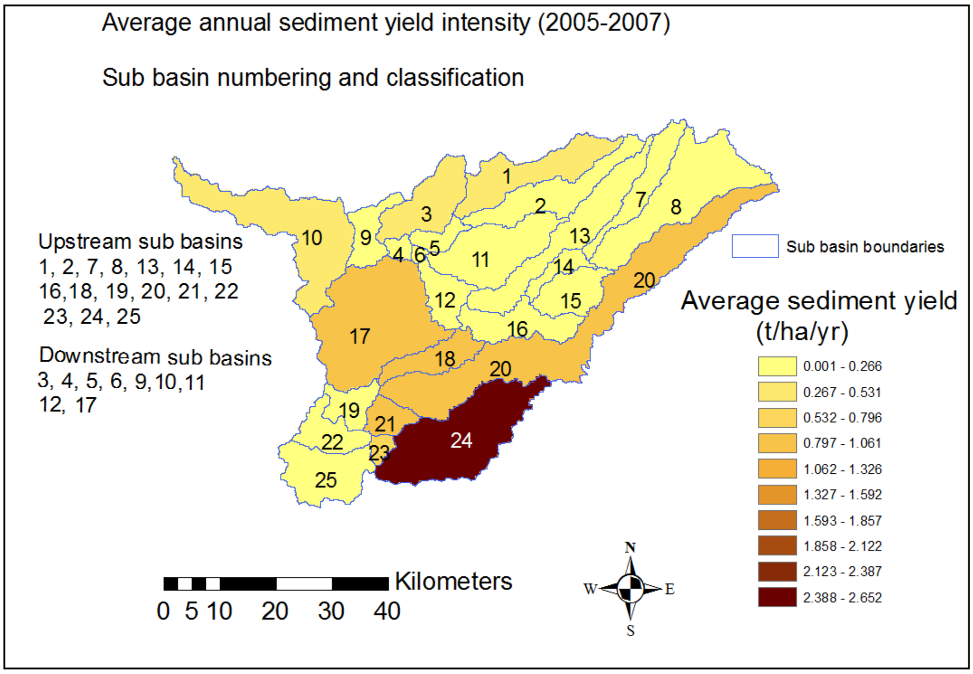


Fig. 5.8 Sub basin numbering and average annual sediment yield for the calibration period (2005-2007)

5.3.4 Nutrient calibration and validation

The p-factor indices for nutrients over the calibration period (TN: 0.71 & TP: 0.50) and validation period (TN: 0.50 & TP: 0.50) were attained. Performance of TP simulation was low on r-factor, NS and R^2 indices. The model performance was considered reasonable (Karim, 2012; Moriasi et al., 2007; Harmel et al., 2006) (Table 5.7). Monitoring of nutrients in Sondu watershed is low and observed data collected from the field were scarce and gave less room for robust calibration. It is good to note that use of observed monthly which is calculated based on skewed daily observed data and such data limitation is appreciated when analyzing the model output (Table 4.11).

Table 5.7a Total Nitrogen (TN) simulation – model performance based on SWAT-CUP statistic

Statistic	Limits (worse – best)	Calibration	Validation
p-factor	0 to1.0	0.71 - Satisfactory	0.50 - Satisfactory
r-factor	0 to ∞	4.05 - Poor	5.13 - Poor
NS	-∞ to 1.0	0.14 - Adequate	-5.20 - Poor
R^2	0 to1.0	0.67 - Good	0.96 - Good

Model performance assessed as per compilations of Moriasi et al al. (2007) and Karim (2012)

Table 5.7b Total Phosphorous (TP) – model performance based on SWAT-CUP statistic

Statistic	Limits (worse – best)	Calibration	Validation
p-factor	0 to1.0	0.50 - Satisfactory	0.50 - Satisfactory
r-factor	0 to ∞	3.06 - Poor	5.10 - Poor
NS	-∞ to 1.0	-5.55 - Poor	-7.58 - Poor
R^2	0 to1.0	0.20 - Low	0.10 - Low

Model performance assessed as per compilations of Moriasi et al. (2007) and Karim (2012)

April - May and October - December are high nutrient (TN & TP) yield seasons with exception of November - December of 2005 and 2010 (Fig. 5.9a & b and Fig. 5.10a & b) which were low rainfall seasons.

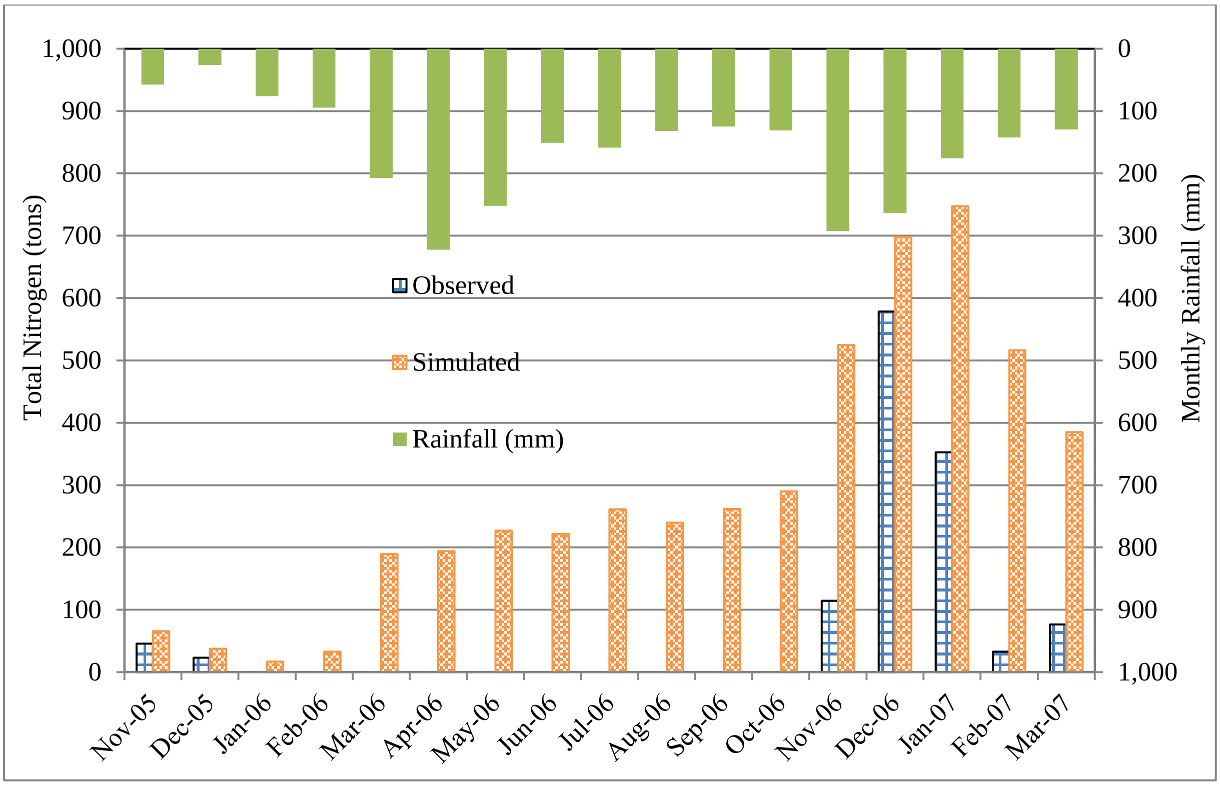


Fig. 5.9a Observed and simulated total nitrogen (TN) during the calibration period

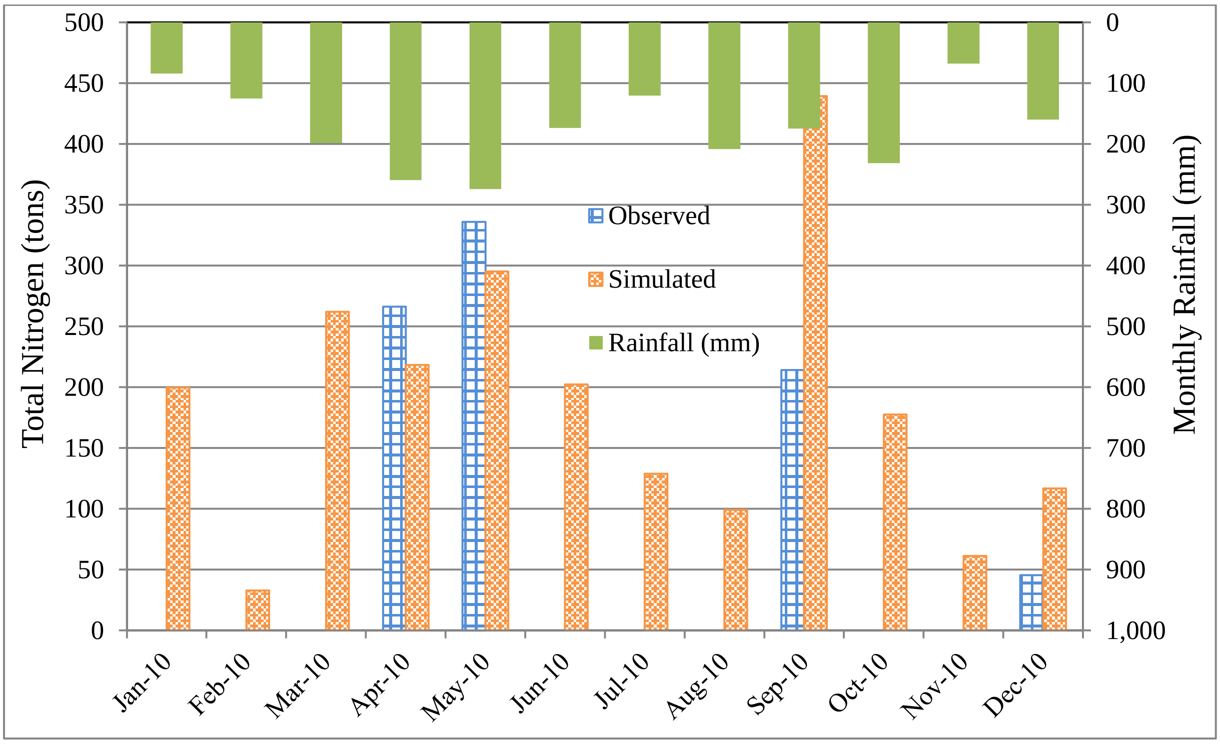


Fig. 5.9b Observed and simulated total nitrogen (TN) during the validation period

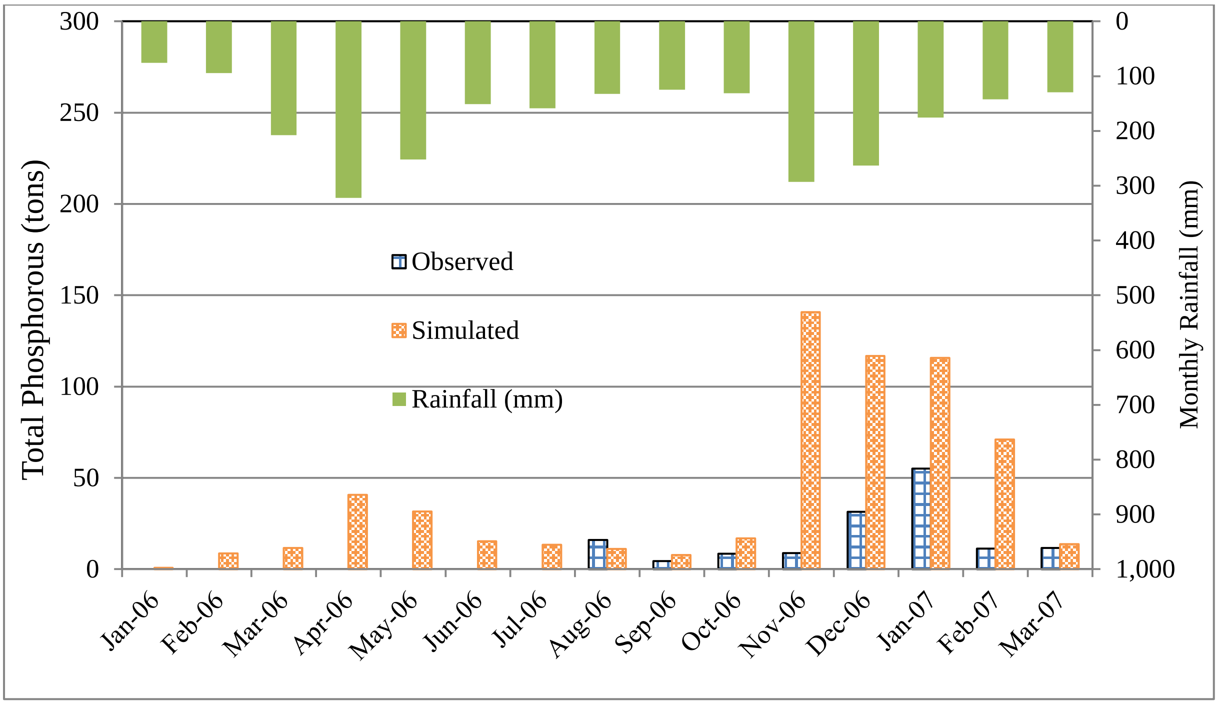


Fig. 5.10a Observed and simulated total phosphorous (TP) during the calibration period

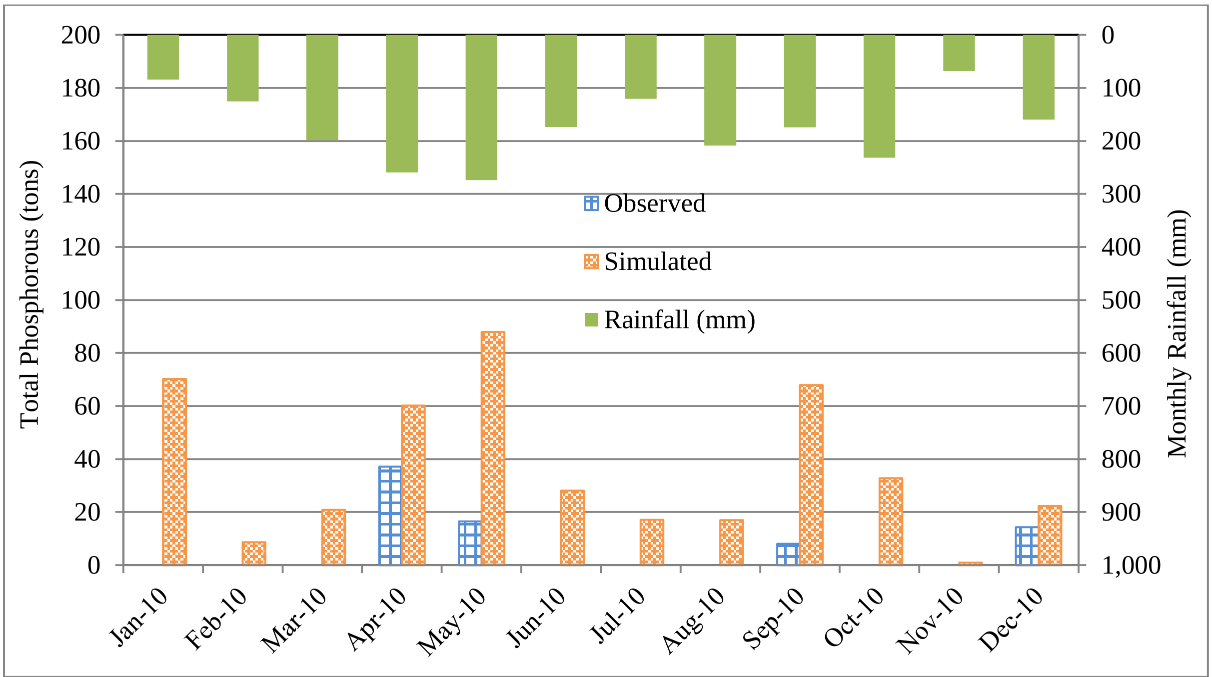


Fig. 5.10b Observed and simulated total phosphorous (TP) during the validation period

Nutrient distribution

The downstream and central (Sotik region) to upstream-West (lower Kisii/Nyamira region) of the watershed are high nutrient yielding zones (Fig. 5.11a, b, c & d; Fig. 5.12a, b, c & d). The regions are agricultural areas while the lower Kisii/Nyamira region is not only covered by agriculture but it is also densely populated. The two land use characteristics explain the relatively high nutrients generation from these areas. There is drastic change in high nutrient yield areas in relative terms through the periods 2005, 2006 and 2007. The pattern could be attributed to, first, the nutrient yield are in small quantities and are bound to be erratic and pose a great challenge to its calibration in a situation of scarce data. Secondly, weather pattern in the downstream part of the watershed is non-uniform. For example the average daily rainfall at Kisumu weather station is 3.17mm, 4.67mm and 3.18mm for the years 2005, 2006 and 2007 respectively with erratic rainfall pattern within the years.

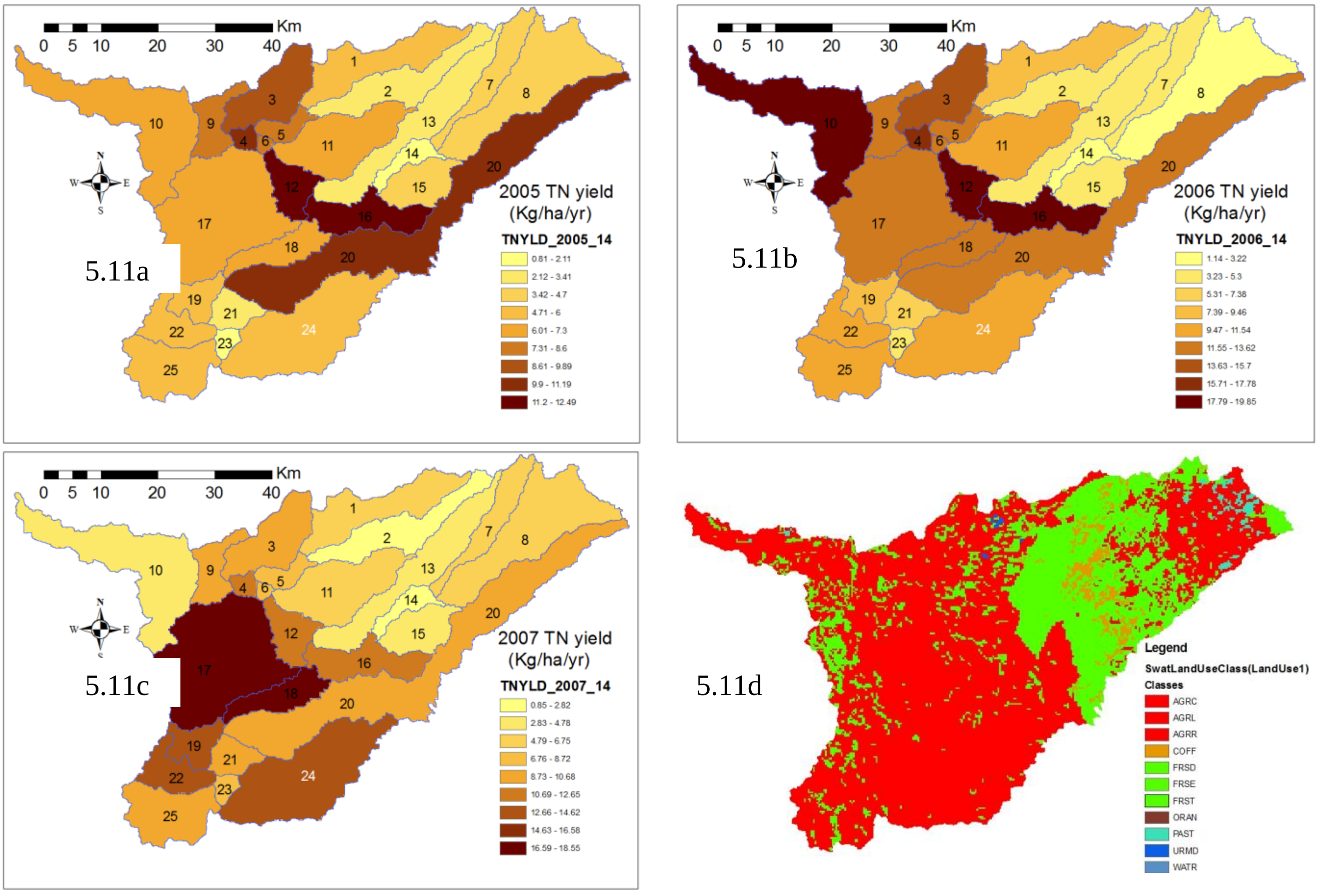


Fig. 5.11 Total nitrogen yield in the year 2005 (5.11a), 2006 (5.11b), 2007 (5.11c) and land cover (5.11d)

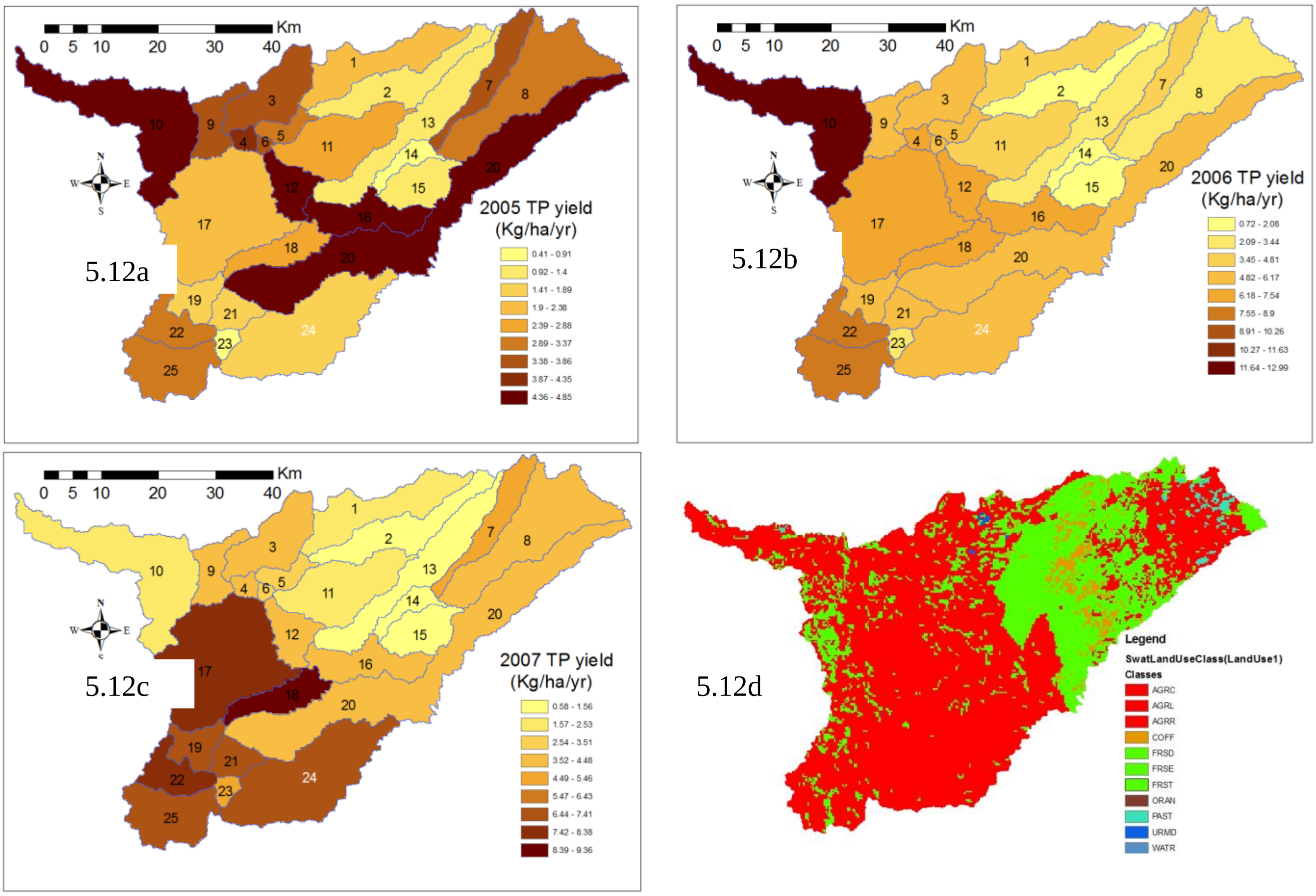


Fig. 5.12 Total phosphorous yield in the year 2005 (5.12a), 2006 (5.12b), 2007 (5.12c) and land cover (5.12d)

5.3.5 Comparative analysis

A comparative analysis with similar studies showed differences in the findings and method characteristics. For example, simulated annual sediment load during the simulation period in the year 2005 was 66,400 tons/yr and was lower as compared to estimates by LVEMP (2005) which was 145,200 tons/yr. The sediment yield by the study is about 2.2 times whereas annual average stream flow was 1.4 times (Table 5.8). LVEMP (2005) study used water quality data collected in the year 2003 which was wetter as compared to the 2005 period but not adequate to explain the significant difference. Further, average surface sediment loading for Sondu watershed in this study is 0.61 t/ha/yr while for LVEMP (2005) is 0.41 t/ha/yr. The discrepancy is explained not only by the fact that LVEMP (2005) was based on monitored data at basin outlet while in this study is based on sub basin basis in which not all sediment load at sub basin outlet gets to the basin outlet. LVEMP (2005) total load as observed at the outlet was directly divided by total basin area to get simple average surface loading while for this study is surface loading of sediment loss as simulated. Also LVEMP (2005) study did not separate sediment originating from land surface and sediment from channel degradation as modeled in SWAT.

The simulated annual average TN and TP over the calibration period (2005-2007) was 3,388 t/yr and 312 t/yr respectively. The estimates by COWI (2002) and LVEMP (2005) from the field observations done in the year 2001 and 2003, found annual average range of TN & TP as 1,374-1,821 t/yr and 183-318 t/yr respectively. The TP findings compared favorably with this study while TN was on a higher side (Table 5.8). Aggregate loads need to be assessed on the background of higher uncertainity of observed data when modeling of nutrients in an environment of scarce data as is the case in Sondu watershed similar to sediments.

Table 5.8 Comparative annual sediment, total phosphorous and total nitrogen yield estimates in Sondu Watershed

Study/	COWI (2002)	LVEMP (2005)	This Study		
Year	2001	2003	2005	2006	2007
Flow (m^3/s)	42.2	41.8	29.6	40.5	48.1
Sediment (tons)	-	145,192	66,400	129,509	122,747
Total nitrogen (tons)	1,374	1,821	1,335	3,157	5,673
Total phosphorous (tons)	318	183	154	416	370

Watershed elevation and rainfall characteristics have significant influence on sediment erosion. For example, similar studies by Hurni (1983) and Betrie et al. (2006), done in Nile catchment - Ethiopia - which covers Lake Victoria basin, reported surface loadings as high as 150 t/ha/yr which is significantly high as compared to the maximum of 2.65 t/ha/yr reported in this study (Fig. 5.8). Descriptions of the catchments in Ethiopia are in the nature of rivers originating from the Ethiopian plateau and are very steep unlike Sondu watershed. The catchments receive rainfall of between 900 mm and 2,200 mm range which is comparable to that of Sondu watershed. However, about 80% of the Ethiopian rainfall is concentrated between July and October while other months barely receive rainfall (Betrie et al., 2011). Therefore the significant difference in surface loading is attributed to high slope and concentrated rainfall intensity.

The estimates of average nutrient yield by the export coefficient model compared favorably with estimates by LVEMP (2005) and COWI (2002) for both TN and TP notwithstanding the different time periods of the studies (Table 5.9). The simulation estimates by SWAT were on a higher side when compared with estimates by the coefficient model, LVEMP (2005) and COWI (2002). Higher estimation by SWAT model is expected because first, the estimates represent the load at point of origin before natural reduction within the river system and secondly, the nutrients may be reduced due to deposition together with sediments before it gets to the Lake. It is notable that the difference in TP is significant and may reflect that TP from municipal sources is a significant component of total load. In future SWAT modeling the observed TP at river outlet should account for nutrients from municipal and land runoff (Table 2.5 & 5.1).

Table 5.9 Annual average nutrient surface loading (yield) estimates in Sondu Watershed as compared with other studies

Study/	LVEMP (2005)	COWI (2002)	Coefficient model	SWAT model		
Year	2003	2001	2003	2005	2006	2007
Total nitrogen (Kg/ha/yr)	5.19	3.92	4.91	6.41	10.76	9.31
Total phosphorous (Kg/ha/yr)	0.52	0.91	0.52	3.01	5.71	4.51

5.3.6 Management plans analysis

The three management plans were compared on their effectiveness in reducing sediment loss in the watershed. This illustrates which plan is effective where and when and how much effective. This was done using simulated sediment yields at watershed outlet (basin) and sub watershed outlets (sub basin) levels to cover both temporal and spatial aspects. Performance of filters and reforestation on percentage reduction of sediment yield based on the baseline plan was done for 36 months (2005 – 2007) and for the 25 sub basin basis.

The annual average simulated sediment yield at the watershed outlet, for the baseline management plan as reported above, was 106,200 tons. Introduction of filters on agricultural HRUs reduced the yield to 87,900 tons which is equivalent to 17 % decrease. Addition of 11.2 % forest cover (reforestation) reduced the yield to 77,000 tons which is equivalent to 28 % decrease.

Temporal analysis

The filter and reforestation plans were more effective in wetter months of the year. There were higher relative sediment reductions in the months of April-May and November-December for both reforestation and filter options (Fig. 5.13). The months are the onset of rainfall seasons and during the periods the baseline simulation predicted higher sediment yields. Although both reforestation and filter plans resulted in reduced sediment yields, the reforestation plan consistently ranked higher with respect to sediment reduction in all the months of the year (Fig. 5.13). Higher sediment yield was generated in the year 2006 for all the three management plans while 2005 was the least in the three plans (Fig. 5.14). The pattern followed the same trend as water yield in which the year 2006 was highest and 2005 the least.

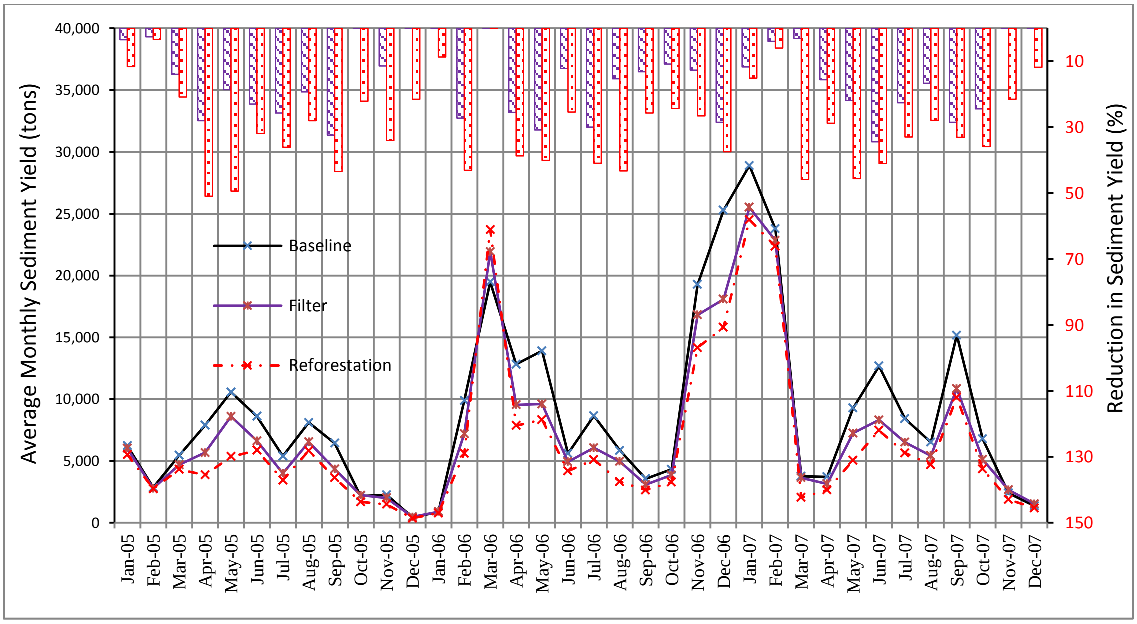


Fig. 5.13 Average monthly sediment yield at watershed outlet for the three management plans and their percentage reduction of sediment

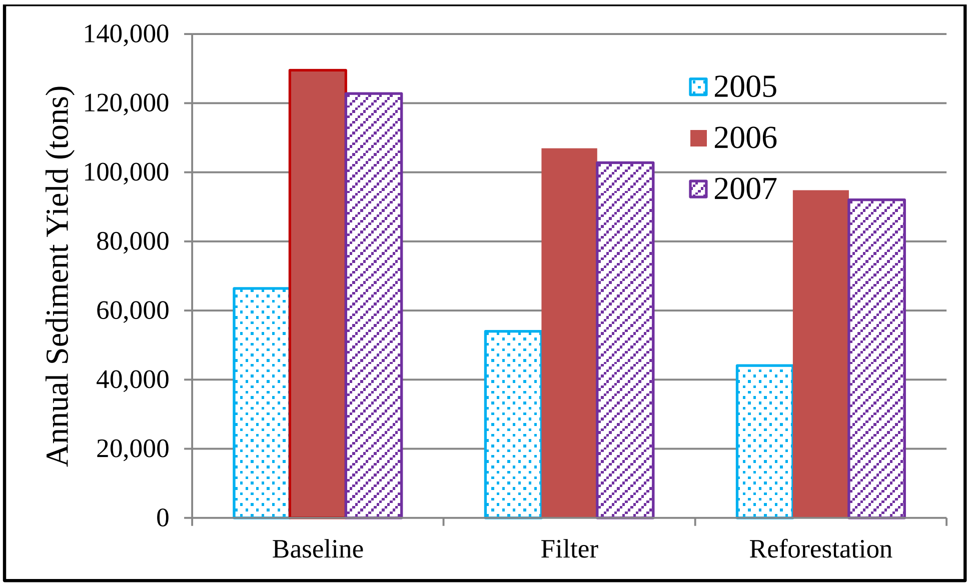


Fig. 5.14 Annual sediment yield for the three management plans

Spatial analysis

At sub basin level, reforestation plan had lower sediment reduction than filter plan in four sub basins (2, 5, 13 and 15) (Table 5.10). The effect of management plans showed a wider spatial variability of sediment reduction in percentage terms. Sub basins 7, 8 and 14 had significant sediment reduction impact (91 %, 99 % and 92 % respectively) due to reforestation while the same sub basins 7 and 8 had low impact with introduction of filters (9 % and 6 % respectively) (Fig. 5.8, Fig. 5.15 and Table 5.10). Reforestation on sub basin 8, which is an upstream sub basin, would increase total forest cover from 30 % to 71 % and it mainly explains the significant reduction in sediment yield out of the sub basin (Table 4.12).

This findings are similar to those of Betrie et al. (2011) (Ethiopian catchment) and Santhi et al. (2006) (USA, Texas catchment) which recorded sediment reduction impacts of 75 % - 99 % at sub basin level and 1 % - 2 % reduction at basin level. Betrie et al. (2011) applied additional 8 % forest cover at basin/sub basin levels while Santhi et al. (2006) applied several management plans at sub basin/farm level aimed at reducing sediment and nutrient losses.

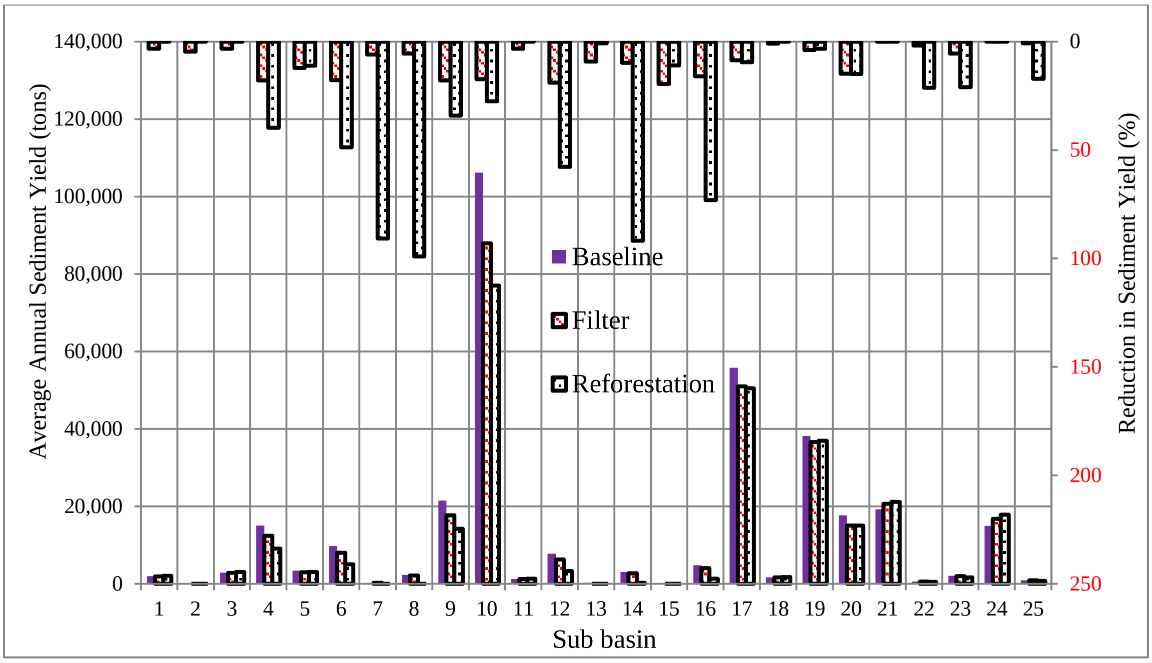


Fig. 5.15 Average sub basin sediment yield for the three management options and their percentage reduction (Sub basin 10 is the watershed outlet)

Table 5.10 ranks sub basins with respect to amount of sediment yield (baseline plan) and their subsequent reduction rates when filters and reforestation plans are applied. The analysis of ranking highlights the effect of sub basin location and application area of each management plan on reduction of sediment yields in the sub basins.

Sub basin 24 in the case of baseline option with 1.5 % forest and 98 % agriculture covers has the highest sediment yield intensity while sub basin 14 with 94 % forest cover and 6 % agriculture had lowest sediment yield of 0.001 t/ha/yr. Sub basin sediment yield ranking from highest to lowest does not show a clear pattern in terms of whether located upstream or downstream but the intensity of sediment yield is mainly driven by land cover distribution in the sub basin (Table 4.12, Table 5.10 and Fig. 5.16).

Application of filters had highest impact on sub basin 15 on which filters were applied on part of agriculture covering 22 % of the sub basin. Sediment yield reduced by 20 %. Least reduction impact of filters was on upstream sub basin 21 on which filters were applied on part of agriculture covering 4 % of the sub basin and resulted in 1 % sediment reduction. On the other hand, application of reforestation on sub basin 8, an upstream sub basin where forest cover was increased from 30 % to 71 %, gave highest sediment reduction rate of 99 % whereas least reduction was on sub basin 2 where forest cover was increased marginally from

78 % to 79 % and reduced sediment yield by 1 % (Table 4.11, Table 4.12, Table 5.10 and Fig. 5.16). The amount of reduction of sediment yield in the sub basins had direct relationship with the application area of filters and reforestation. It is expected that introduction of Filters and Reforestation would reduce sediment yield but that was not the case in some sub basins such as 21 and 24. In sub basins 21 and 24, Filters covered 100 % and 98.3 % of the sub basins respectively while additional forest cover (reforestation) was negligible 0 % and 0.2 % respectively. The negative effect and low effectiveness is observed when filters are applied on significant part of the watershed, it becomes counterproductive when used excessively. Also for reforestation when applied for sub basin insignificant coverage has not effect. This could be a limitation in the conceptual structure of the SWAT model as well.

Ranking of sub basins in Table 5.10 shows that reforestation was more effective in sediment yield reduction at most upstream sub basins while filters had more impact at most downstream sub basins relative to those located upstream of the watershed (Fig. 5.16).

Table 5.10 Ranking of sub basins based on sediment yield intensity and subsequent reduction rate when management plans are applied

	Baseline		Filters			Reforestation		
Rank	Sub basin	Sediment yield (t/ha)	Sub basin	Sub basin location	% Reduction	Sub basin	Sub basin location	% Reduction
1	24	2.652	15	Upstream	-19.48	8	Upstream	-99.08
2	17	1.057	12	Downstream	-18.93	14	Upstream	-91.78
3	18	1.004	4	Downstream	-17.95	7	Upstream	-90.82
4	21	0.850	9	Downstream	-17.93	16	Upstream	-73.04
5	20	0.838	6	Downstream	-17.76	12	Downstream	-57.78
6	23	0.608	10	Downstream	-17.24	6	Downstream	-48.72
7	3	0.491	16	Upstream	-17.24	4	Downstream	-39.73
8	10	0.344	20	Upstream	-16.02	9	Downstream	-34.11
9	1	0.268	5	Downstream	-14.73	10	Downstream	-27.54
10	22	0.265	14	Upstream	-12.14	22	Upstream	-27.54
11	25	0.228	13	Upstream	-9.75	23	Upstream	-21.29
12	12	0.207	17	Downstream	-9.16	25	Upstream	-21.03
13	11	0.151	7	Upstream	-8.60	20	Upstream	-17.15
14	5	0.149	8	Upstream	-6.00	5	Downstream	-14.88
15	19	0.144	23	Upstream	-5.53	15	Upstream	-11.17
16	8	0.095	2	Upstream	-5.46	17	Downstream	-11.01
17	16	0.077	19	Upstream	-4.58	19	Upstream	-9.55
18	4	0.077	1	Upstream	-3.95	13	Upstream	-3.25
19	9	0.075	11	Downstream	-3.33	2	Upstream	-0.85
20	6	0.042	3	Downstream	-3.32	3	Downstream	3.49
21	7	0.024	22	Upstream	-3.29	1	Upstream	4.64
22	13	0.024	18	Upstream	-1.86	11	Downstream	4.72
23	2	0.011	25	Upstream	-0.87	18	Upstream	4.75
24	15	0.003	21	Upstream	-0.80	21	Upstream	7.24
25	14	0.001	24	Upstream	7.21	24	Upstream	9.80

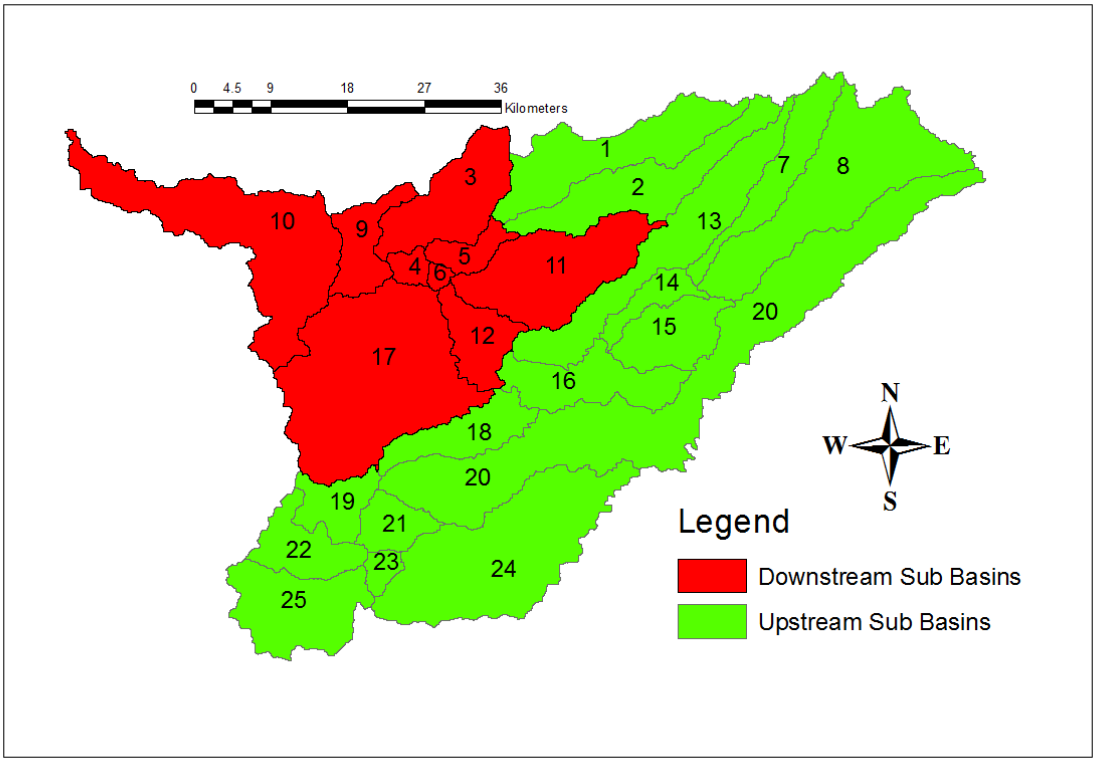


Fig. 5.16 Classification of upstream and downstream sub basins

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

This chapter summarizes the findings on review of current existing studies on estimation of pollution load in Lake Victoria. The conclusions on estimation of nutrient export coefficients are also presented. Also on ways of improvement of static load estimation and use of dynamic model (SWAT) in simulation of hydrology, sediments and nutrients and assessment of watershed management plans on their effectiveness in reducing sediment loss. Challenges and suggestions of issues to be considered in future research are also included in this Chapter.

6.1 Conclusions

6.1.1 Estimation of pollution load in Lake Victoria

The differences and at the same time closeness observed in the results of the past studies on estimation of pollution load to Lake Victoria makes it is difficult to determine which estimates are reliable and accurate. However, this demonstrates that in situations of inadequate data varying methods give different results. Reliable estimates are dependent on the quality of data and on use of methods that simulate the actual process dynamics as much as possible. Estimates show that atmospheric deposition contributes significantly (30-80%) to the TN and TP loads to the lake.

Although the past studies provide useful information within the existing constraints, there is a lot of uncertainty in the accuracy and reliability of the estimated pollution loads. The Lake Victoria basin is geographically enormous and incorporation of remote sensing and GIS mapping technology has potential to improve reliability and accuracy of the estimates. The capacity of GIS tools to collect data and predict various scenarios of management in estimation of pollution load reduces uncertainty when less-exact methods are used. Remote sensing and GIS relate spatial and temporal geographical relationships and reinforce weaknesses noted in the past studies and stand to improve the estimation of pollution load to Lake Victoria especially runoff load.

6.1.2 Export coefficients

Municipal load

Municipal load was estimated from urban areas with sewerage systems only. Municipal unit per capita loads were calculated from two sample treatment plants in Kisumu and compared with literature values but shortcomings were noted and unit loads were considered unrepresentative. The calculated unit per capita loads were found to be low as compared with ranges available in literature. Comparison of calculated unit loads and literature values was made and there were significant variances hence unit per capita load values that reflected the population in developing countries with low protein intake (COWI, 2002) were adopted. The estimated municipal load was less as compared to the estimates by previous studies. Estimates of sewerage usage indicate that about 1.2 million persons on the Kenyan side of Lake Victoria basin are connected to municipal sewer system. Total annual nutrient municipal load of 548 t/yr - TN and 301 t/yr. - TP are estimated to be flowing to the Lake from the main six river watersheds on the Kenyan side of the basin. Pit latrines and septic tanks were considered as sources of urban diffuse pollution.

Municipal load sources should not only be looked as a threat to lake's ecosystem but more importantly as also a threat to human and public health. A reduction of municipal load means cleanliness of towns and public health in general. Installation of proper sanitation systems such as solid waste management systems and sanitation systems such as sewerage systems in urban areas will not only improve public health but also reduce runoff pollution load through reduced urban runoff pollution.

Nutrient export coefficients

Runoff nutrient export is mainly influenced by the watershed's environmental attributes (land use, rainfall and soil characteristic, land slope, drainage density, etc.). Land use and rainfall characteristics are easily measureable and their relationship with nutrient generation is not complex. Rainfall-runoff coefficient influences the export of nutrients to the extent of their linear correlation. The model equation estimated the export coefficients with satisfactory performance both at validation phase and when matched with those in literature. The relatively high river nutrient concentration with low rainfall-runoff depth of Nyando watershed suggests that driving factors other than land use and rainfall-runoff coefficient which include loose soil characteristics. However, positive solutions for nutrient export coefficient demonstrated that land use and rainfall-runoff coefficient have significant influence and are usually available and useful variables to explain runoff load.

The estimated nutrient export coefficients are sufficient for large-scale rapid assessment of pollution load for a situation such as that of Lake Victoria where borrowed export coefficients are often used due to data scarcity. The estimated export coefficients represent the average values and not exact values due to spatial and inherent nature of environmental attributes across the catchment. The usage of estimated export coefficients elsewhere is subject to adjustment relative to rainfall-runoff coefficient of Gucha watershed. Rainfall-runoff coefficient is an appropriate variable to adjust the nutrient export coefficients from other areas to fit local conditions because it integrates other watershed factors or parameters.

Agricultural activities cover a significant part of the Kenya catchment (87%) and are the major contributor to the total load that gets to the lake. Strategies towards reduction of total runoff load to Lake Victoria should target agricultural activities. Best Management Practices (BMPs) or watershed management plans with respect to farming are the key to sound management of the lake which could be boosted by the protection of natural wetlands.

6.1.3 SWAT: Stream flow, sediment and nutrient simulations

The main land covers in Sondu watershed are agriculture (67 %) and forest (30 %). The forested areas are spatially distributed in the watershed and biased to upstream. The initial SCS curve number for moisture condition II (Cn2) parameter and linear parameter for calculating the maximum amount of sediment that can be re-entrained during channel sediment routing (Spcon), Nperco (nitrogen percolation coefficient) and Biomix (biological mixing efficiency) parameters were the most sensitive. However other parameters were useful in model calibration. Twenty eight (28) parameters were used for the final calibration and validation iterations and additional filter (FILTERW) parameter was added for filter management plan simulation.

The model performance was satisfactory at both phases of stream flow and sediment simulations with scarce observed data notwithstanding. The p-factor and r-factor indices for stream flow in the final calibration iteration were 0.56 and 1.17 while for validation period were 0.45 and 1.6 respectively. The R^2 and NS calibration indices were 0.78 and 0.13 while for validation they were 0.40 and 0.15 respectively. Model performance for stream flow, sediment and nutrients simulations were satisfactory for in consideration of the circumstances of low observed data and guiding literature on evaluation of model performance. Modeling of stream flow was comprehensive and had a lot of flexibility in parameter calibration because it had better data coverage but robust calibration for nutrients were constrained by scarce data. Although the model simulation of nutrients did not perfectly fit into observed values, it captured the patterns of low and high seasons.

Annual average aggregate simulated sediment runoff load to Lake Victoria from Sondu watershed is 106,200 t/yr and is composed of mainly silt, annual stream flow is 39 m^3/s while total nitrogen and total phosphorous loads are 3,388 t/yr & 312 t/yr respectively. The pollution load estimates are reasonably within range of findings by COWI (2002) and LVEMP (2005).

High sediment yield periods were February - April and November - January and directly correlated with high rainfall seasons. Average annual sediment yield from Sondu watershed is 106,200 tons over the 2005 – 2007 calibration periods. April - May and October - December are high nutrient yield seasons with exception of November - December of 2005 and 2010 which were low rainfall seasons. February - April is land preparation and crop planting season in the watershed and this partly explains the peak in sediment and nutrients. The sediment peaked while nutrient closely lagged behind by one to two months on average. Sediment yield ranking by sub basins of the baseline management plan does not show a clear pattern with respect to upstream or downstream location but it has correlation with land cover distribution with agriculture driving up the sediment yield while forest slowed down sediment loss.

The high water yielding areas are steep, slopy and agricultural dominant areas in the upstream (Kuresoi/Kisii/Kericho regions) of the watershed. Sediments are relatively highly generated from agricultural areas at downstream (Sondu region), central (Sotik region) and upstream West side (Lower Kisii/Nyamira region) of the watershed. These high water yielding areas not only receive higher precipitation but also have higher slope and the two characteristics mainly explain the water yield. Also the upstream West of the watershed, characterized by dense human population, is a relatively high yielding zone for nutrients and not for sediments. Some high water yielding areas are mainly covered by agriculture and some parts are forested/agriculture mixed (Kuresoi).

6.1.4 SWAT: Watershed management plans

Application of filters on agricultural HRUs reduced the yield from the baseline annual yield of 106,200 tons by 17 % at basin level while addition of 11.2 % forest cover reduced the yield by 28 %. Both filter and reforestation plans were more effective in wetter months of the year. Months of April-May and November-December which are beginning of high rainfall seasons had high sediment reduction rates for reforestation and filter plans. Higher sediment yield was generated in the year 2006 for all the three management plans while 2005 was the least in the three plans. The pattern followed the same trend as water yield in which the year 2006 was highest and 2005 the least and precipitation had the same pattern. Reforestation plan consistently ranked higher with respect to sediment yield reduction in all months of the year as monitored at basin outlet. Reforestation was relatively effective in reducing sediment at most upstream sub basins while filters had more impact at most downstream sub basins of the watershed. Sediment yield in sub basins did not show a distinctive pattern whether located upstream or downstream but sediment yield amount corresponded to size of agriculture cover.

6.2 Recommendations

Estimates of pollution load in Lake Victoria in past studies show that atmospheric deposition contributes significantly (30 – 80 %) to the TN and TP loads to the lake. Such significant contribution calls for an urgent need to come up with more reliable estimates of atmospheric deposition loads to inform policy making for this very important lake.

Municipal unit per capita loads were derived but shortcomings were noted and the unit loads were considered unrepresentative. Insitu wastewater quality and quantity monitoring in treatment plants should be done to determine applicable unit per capita load and unit production load for towns and industries respectively. Sewerage connection data should be yearly updated. This will yield more representative unit per capita loads.

The export coefficients were calculated based on 2005/06 average land cover data and observed water quality and quantity by LVEMP (2005) which collected weather water quality and quantity data over only one year (2003 period). To further improve export coefficients, it should be derived using consistently collected river water quality and flow data measured over the seasons of the year with corresponding land cover. Also Catchment assessment at small-scale level would give more precise results as it would reduce the variance of environmental characteristics. Further investigation of the influence of factors other than land use and rainfall-runoff coefficient will be considered in the successive studies.

Weather and water quality data used in developing SWAT model had missing data days with water quality worst affected. Industrial load was not estimated due to inadequate data and resource constraints. Weather data should be collected consistently and currently non-working weather stations brought back on board. Collection of river water quality data in Lake Victoria is still very low and it was also reported that water quality data collected in the past was lost to arson. Efforts to address the situation and make the data easily accessible will be useful in improving estimation of pollution load.

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APPENDIX

Table A8.1a Land cover distribution on the Kenyan catchment of Lake Victoria basin(2005/06) (Km^2)

Code	Land cover/Watershed	Gucha	Gurumeti	Nyando	Nzoia	Sio	Sondu	Yala	Basin
14	Rainfed Croplands	1,383.87	59.35	497.47	261.10	0.00	1,737.97	3.51	10,265
20	Mosaic Croplands/Vegetation	0.00	0.00	1,523.28	8,584.91	1,141.90	81.43	1,310.82	15,218
30	Mosaic Vegetation/Croplands	4,349.09	3,432.72	846.55	2,084.89	229.52	746.07	1,880.79	103,877
40	Closed to open broadleaved evergreen or semi-deciduous forest	34.12	0.00	149.72	564.62	0.00	121.24	63.80	1,673
50	Closed broadleaved deciduous forest	827.79	183.97	181.14	0.00	0.00	635.90	0.00	9,371
60	Open broadleaved deciduous forest	10.96	2,084.71	80.34	310.28	0.00	31.40	14.72	18,493
70	Closed needleleaved evergreen forest	-	-	-	-	-	-	-	9
90	Open needleaved deciduous or evergreen forest	10.97	0.00	0.00	0.00	0.00	74.85	0.00	268
100	Closed to open mixed broadleaved and needleaved and needleaved forest	0.00	0.00	0.00	0.00	0.00	0.00	0.00	5
110	Mosaic Forest - Shrubland/Grassland	0.00	174.11	19.97	657.82	0.00	0.00	0.00	1,396
120	Mosaic Grassland/Forest - Shrubland	0.00	0.00	0.00	30.93	0.00	0.00	0.00	113
130	Closed to open shrubland	42.17	1,742.01	310.69	306.80	0.00	39.96	42.13	14,770
140	Closed to open grassland	0.00	4,869.80	5.49	0.00	0.00	16.47	0.00	16,412
150	Sparse Vegetation	-	-	-	-	-	-	-	5
160	Closed to open broadleaved forest regularly flooded (Fresh - brackish water)	0.00	184.72	0.00	0.00	0.00	0.00	0.00	1,734
170	Close broadleaved forest permanently flooded (saline - brackish water)	-	-	-	-	-	-	-	11
180	Closed to open vegetation regularly flooded	0.00	53.41	0.00	-5.00	1.00	0.00	15.00	289
190	Artificial area	5.48	0.00	1.00	3.51	1.00	1.00	2.00	220
200	Bare areas	-	-	-	-	-	-	-	18
210	Water bodies	9.16	0.00	3.75	0.00	0.00	5.48	5.48	69,128
Total area		6,674	12,785	3,619	12,800	1,373	3,492	3,338	263,276

Table A8.2a Soil properties – Layer 1

SNAM	CMPPCT	NLAYERS	HYDGRP	SOL_ZMX	ANION_EXCL	SOL_CRK	TEXTURE	SOL_Z1	SOL_BD1	SOL_AWC1	SOL_K1	SOL_CBN1	CLAY1	SILT1	SAND1	ROCK1	SOL_ALB1	USLE_K1	SOL_EC1
17316	100	2	D	1,000	0.5	0.5	SIL-UWB	300	1.100	0.150	1.270	3.330	45	25	30	0	0.010	0.203	0.0
17317	100	2	C	300	0.5	0.5	SIL-UWB	300	1.380	0.150	43.688	0.340	4	4	92	0	0.010	0.087	0.0
17383	100	2	D	1,000	0.5	0.5	SIL-UWB	300	1.260	0.141	3.531	0.570	51	19	30	0	0.010	0.235	0.0
17409	100	2	D	1,000	0.5	0.5	SIL-UWB	300	0.920	0.150	1.778	2.860	46	25	29	0	0.010	0.204	0.0
17410	100	2	D	1,000	0.5	0.5	SIL-UWB	300	1.190	0.150	4.572	2.370	70	20	10	0	0.010	0.213	0.0
17411	100	2	D	1,000	0.5	0.5	SIL-UWB	300	1.200	0.150	1.016	1.140	45	25	30	0	0.010	0.241	0.0
17412	100	2	D	1,000	0.5	0.5	SIL-UWB	300	1.160	0.150	2.794	0.510	31	35	34	0	0.010	0.302	0.0
17413	100	2	D	1,000	0.5	0.5	SIL-UWB	300	1.480	0.138	6.604	1.170	37	23	41	0	0.010	0.228	0.2
17414	100	2	D	1,000	0.5	0.5	SIL-UWB	300	1.170	0.150	3.899	2.190	51	28	21	0	0.010	0.230	0.0
17415	100	2	D	1,000	0.5	0.5	SIL-UWB	300	1.260	0.150	1.092	0.980	57	19	24	0	0.010	0.238	0.0
17416	100	2	D	1,000	0.5	0.5	SIL-UWB	300	1.170	0.150	4.450	2.190	51	28	21	0	0.010	0.230	0.0
17418	100	2	D	1,000	0.5	0.5	SIL-UWB	300	0.960	0.150	9.347	3.010	43	38	19	0	0.010	0.251	0.0
17422	100	2	D	1,000	0.5	0.5	SIL-UWB	300	0.980	0.150	46.126	3.520	18	42	40	0	0.010	0.261	0.0
17428	100	2	D	1,000	0.5	0.5	SIL-UWB	300	1.100	0.150	4.318	3.670	43	27	30	0	0.010	0.209	0.0
17434	100	2	D	1,000	0.5	0.5	SIL-UWB	300	1.100	0.150	1.524	4.200	49	25	26	0	0.010	0.207	0.0
17471	100	2	D	1,000	0.5	0.5	SIL-UWB	300	1.200	0.146	23.279	1.180	22	20	58	0	0.010	0.204	0.0
17482	100	2	C	1,000	0.5	0.5	SIL-UWB	300	1.210	0.105	47.600	0.430	16	8	76	0	0.010	0.131	0.0
17496	100	2	D	1,000	0.5	0.5	SIL-UWB	300	1.250	0.150	1.981	0.700	20	23	57	0	0.010	0.236	0.0
17500	100	1	D	1,000	0.5	0.5	SIL-UWB	300	1.440	0.050	5.842	2.400	31	20	49	0	0.010	0.176	0.0
17504	100	2	C	1,000	0.5	0.5	SIL-UWB	300	1.380	0.150	98.552	0.340	4	4	92	0	0.010	0.087	0.0
17515	100	2	D	1,000	0.5	0.5	SIL-UWB	300	1.240	0.150	1.829	1.310	36	25	39	0	0.010	0.222	0.0
17582	100	1	D	1,000	0.5	0.5	SIL-UWB	300	1.310	0.150	0.622	0.780	49	24	27	0	0.010	0.261	0.0

Table A8.2a Soil properties – Layer 1 continued

SNAM	CMPPCT	NLAYERS	HYDGRP	SOL_ZMX	ANION_EXCL	SOL_CRK	TEXTURE	SOL_Z1	SOL_BD1	SOL_AWC1	SOL_K1	SOL_CBN1	CLAY1	SILT1	SAND1	ROCK1	SOL_ALB1	USLE_K1	SOL_EC1
17593	100	2	D	1,000	0.5	0.5	SIL-UWB	300	1.230	0.150	0.254	1.130	55	12	33	0	0.010	0.182	0.0
17633	100	2	D	1,000	0.5	0.5	SIL-UWB	300	1.130	0.150	5.080	2.540	30	29	41	0	0.010	0.208	0.0
17647	100	2	D	1,000	0.5	0.5	SIL-UWB	300	0.900	0.150	27.584	4.010	65	25	10	0	0.010	0.227	0.0
17648	100	2	D	1,000	0.5	0.5	SIL-UWB	300	1.100	0.150	6.858	2.400	62	31	7	0	0.010	0.252	0.0
17649	100	2	D	1,000	0.5	0.5	SIL-UWB	300	1.080	0.150	9.487	2.250	31	46	23	0	0.010	0.270	0.0
17651	100	2	D	1,000	0.5	0.5	SIL-UWB	300	1.130	0.150	2.540	2.630	54	22	24	0	0.010	0.198	0.0
17655	100	1	D	1,000	0.5	0.5	SIL-UWB	300	1.260	0.137	3.073	2.210	47	32	21	0	0.010	0.238	0.0
17660	100	2	D	1,000	0.5	0.5	SIL-UWB	300	1.210	0.150	4.369	1.980	43	38	19	0	0.010	0.262	0.0
17666	100	2	D	1,000	0.5	0.5	SIL-UWB	300	1.230	0.150	4.470	1.330	37	23	40	0	0.010	0.213	0.4
17678	100	1	D	1,000	0.5	0.5	SIL-UWB	300	1.200	0.150	5.588	1.170	64	10	26	0	0.010	0.177	0.0
17680	100	2	D	1,000	0.5	0.5	SIL-UWB	300	1.270	0.150	1.346	1.870	48	24	28	0	0.010	0.206	0.0
17703	100	2	D	1,000	0.5	0.5	SIL-UWB	300	1.130	0.150	25.908	3.330	22	38	40	0	0.010	0.235	0.0

Table A8.2b Soil properties – layer 2

SNAM	CMPPCT	NLAYERS	HYDGRP	SOL_ZMX	ANION_EXCL	SOL_CRK	TEXTURE	SOL_Z2	SOL_BD2	SOL_AWC2	SOL_K2	SOL_CBN2	CLAY2	SILT2	SAND2	ROCK2	SOL_ALB2	USLE_K2	SOL_EC2
17316	100	2	D	1,000	0.5	0.5	SIL-UWB	1,000	1.170	0.150	2.286	1.330	37	26	37	0	0.130	0.226	0.0
17317	100	2	C	300	0.5	0.5	SIL-UWB	1,000	1.530	0.150	36.830	0.200	4	5	91	0	0.080	0.094	0.0
17383	100	2	D	1,000	0.5	0.5	SIL-UWB	1,000	1.350	0.141	10.109	0.260	48	14	38	0	0.100	0.213	0.0
17409	100	2	D	1,000	0.5	0.5	SIL-UWB	1,000	1.070	0.150	3.556	1.820	65	17	18	0	0.130	0.195	0.0
17410	100	2	D	1,000	0.5	0.5	SIL-UWB	1,000	1.270	0.150	2.540	1.100	83	10	7	0	0.130	0.210	0.0
17411	100	2	D	1,000	0.5	0.5	SIL-UWB	1,000	1.340	0.150	1.524	0.490	38	30	32	0	0.130	0.285	0.0
17412	100	2	D	1,000	0.5	0.5	SIL-UWB	1,000	1.280	0.150	0.508	0.540	51	25	24	0	0.050	0.275	0.0
17413	100	2	D	1,000	0.5	0.5	SIL-UWB	1,000	1.540	0.138	0.635	0.500	49	19	33	0	0.090	0.238	0.2
17414	100	2	D	1,000	0.5	0.5	SIL-UWB	1,000	1.240	0.150	1.181	0.910	66	15	18	0	0.100	0.228	0.0
17415	100	2	D	1,000	0.5	0.5	SIL-UWB	1,000	1.330	0.150	0.813	0.530	65	13	23	0	0.120	0.225	0.0
17416	100	2	D	1,000	0.5	0.5	SIL-UWB	1,000	1.220	0.150	2.515	0.970	62	17	21	0	0.100	0.227	0.0
17418	100	2	D	1,000	0.5	0.5	SIL-UWB	1,000	0.990	0.150	4.674	1.440	41	34	24	0	0.070	0.260	0.0

Table A8.2b Soil properties – layer 2 Continued

SNAM	CMPPCT	NLAYERS	HYDGRP	SOL_ZMX	ANION_EXCL	SOL_CRK	TEXTURE	SOL_Z2	SOL_BD2	SOL_AWC2	SOL_K2	SOL_CBN2	CLAY2	SILT2	SAND2	ROCK2	SOL_ALB2	USLE_K2	SOL_EC2
17422	100	2	D	1,000	0.5	0.5	SIL-UWB	1,000	1.010	0.150	35.839	1.580	22	38	41	0	0.050	0.256	0.0
17428	100	2	D	1,000	0.5	0.5	SIL-UWB	1,000	0.910	0.150	0.762	1.830	50	20	30	0	0.130	0.192	0.0
17434	100	2	D	1,000	0.5	0.5	SIL-UWB	1,000	1.170	0.150	1.778	3.610	50	22	28	0	0.130	0.195	0.9
17471	100	2	D	1,000	0.5	0.5	SIL-UWB	1,000	1.280	0.146	17.348	0.810	24	16	61	0	0.200	0.060	0.1
17482	100	2	C	1,000	0.5	0.5	SIL-UWB	1,000	1.260	0.105	35.154	0.230	19	10	71	0	0.130	0.159	0.1
17496	100	2	D	1,000	0.5	0.5	SIL-UWB	1,000	1.370	0.150	8.547	0.480	22	23	56	0	0.050	0.243	0.0
17500	100	1	D	1,000	0.5	0.5	SIL-UWB	1,000	1.170	0.050	2.286	1.330	37	26	37	0	0.050	0.226	0.0
17504	100	2	C	1,000	0.5	0.5	SIL-UWB	1,000	1.530	0.150	97.790	0.200	4	5	91	0	0.080	0.094	0.0
17515	100	2	D	1,000	0.5	0.5	SIL-UWB	1,000	1.320	0.150	0.508	0.600	49	22	29	0	0.130	0.254	0.3
17582	100	1	D	1,000	0.5	0.5	SIL-UWB	1,000	1.170	0.150	2.286	1.330	37	26	37	0	0.130	0.226	0.0
17593	100	2	D	1,000	0.5	0.5	SIL-UWB	1,000	1.130	0.150	0.254	0.930	60	15	25	0	0.130	0.216	0.0
17633	100	2	D	1,000	0.5	0.5	SIL-UWB	1,000	1.150	0.150	5.080	0.870	30	27	43	0	0.050	0.253	0.0
17647	100	2	D	1,000	0.5	0.5	SIL-UWB	1,000	1.010	0.150	1.880	1.210	49	26	25	0	0.130	0.249	0.0
17648	100	2	D	1,000	0.5	0.5	SIL-UWB	1,000	1.100	0.150	4.318	1.510	65	28	7	0	0.130	0.262	0.0
17649	100	2	D	1,000	0.5	0.5	SIL-UWB	1,000	1.170	0.150	5.334	1.210	30	46	25	0	0.050	0.312	0.0
17651	100	2	D	1,000	0.5	0.5	SIL-UWB	1,000	1.230	0.150	2.286	1.660	59	24	17	0	0.130	0.232	0.0
17655	100	1	D	1,000	0.5	0.5	SIL-UWB	1,000	1.170	0.150	2.286	1.330	37	26	37	0	0.130	0.226	0.0
17660	100	2	D	1,000	0.5	0.5	SIL-UWB	1,000	1.250	0.150	1.422	1.350	45	18	37	0	0.110	0.200	0.0
17666	100	2	D	1,000	0.5	0.5	SIL-UWB	1,000	1.320	0.150	3.150	0.820	44	17	39	0	0.100	0.219	0.3
17678	100	1	D	1,000	0.5	0.5	SIL-UWB	1,000	1.290	0.150	0.000	0.950	54	8	38	0	0.130	0.163	0.0
17680	100	2	D	1,000	0.5	0.5	SIL-UWB	1,000	1.400	0.150	0.584	0.820	55	22	23	0	0.130	0.252	0.0
17703	100	2	D	1,000	0.5	0.5	SIL-UWB	1,000	1.230	0.150	14.224	1.400	20	45	35	0	0.050	0.285	0.0
17422	100	2	D	1,000	0.5	0.5	SIL-UWB	1,000	1.010	0.150	35.839	1.580	22	38	41	0	0.050	0.256	0.0
17428	100	2	D	1,000	0.5	0.5	SIL-UWB	1,000	0.910	0.150	0.762	1.830	50	20	30	0	0.130	0.192	0.0

Table A8.3a Weather data parameters for weather generator – Average monthly maximum temperature

STATION	WLATITUDE	WLONGITUDE	WELEV	RAIN_YRS	TMPMX1	TMPMX2	TMPMX3	TMPMX4	TMPMX5	TMPMX6	TMPMX7	TMPMX8	TMPMX9	TMPMX10	TMPMX11	TMPMX12
Kuresoi	-0.304	35.534	2,652	20.000	27.371	28.539	27.988	26.617	25.846	25.491	25.343	25.986	26.980	26.913	26.295	26.817
Kisii	-0.683	34.783	1,982	10.000	26.309	27.580	26.914	25.761	25.146	24.737	24.660	25.216	26.171	26.047	25.219	25.686
Kisumu	-0.100	34.750	1,241	20.000	30.344	31.516	30.997	29.547	27.746	28.535	28.652	29.407	30.465	30.557	29.923	30.192
kericho	-0.367	35.267	2,107	20.000	25.462	26.520	26.052	24.544	23.644	23.200	22.716	23.338	24.303	24.134	23.744	24.574
Nandi	0.070	35.230	2,048	10.000	30.340	31.520	31.000	29.550	28.750	28.540	28.650	29.410	30.470	30.560	29.860	30.190
Molo	-0.283	35.750	2,712	20.000	27.371	28.539	27.988	26.617	25.846	25.491	25.343	25.986	26.980	26.913	26.295	26.817
Siret	0.113	35.230	1,512	10.000	32.050	33.270	32.700	31.100	30.260	30.030	30.160	30.950	32.160	32.250	31.500	31.870

Table A8.3b Weather data parameters for weather generator – Average monthly minimum temperature

STATION	WLATITUDE	WLONGITUDE	WELEV	RAIN_YRS	TMPMN1	TMPMN2	TMPMN3	TMPMN4	TMPMN5	TMPMN6	TMPMN7	TMPMN8	TMPMN9	TMPMN10	TMPMN11	TMPMN12
Kuresoi	-0.304	35.534	2,652	20	14.756	14.928	15.080	15.253	15.066	14.556	14.174	14.351	14.409	14.744	14.805	14.643
Kisii	-0.683	34.783	1,982	10	15.956	16.368	16.047	15.966	15.800	15.229	14.770	15.000	15.353	15.612	15.496	15.610
Kisumu	-0.100	34.750	1,241	20	17.281	17.434	17.924	18.102	17.781	16.970	16.639	16.846	16.996	17.606	17.644	17.379
kericho	-0.367	35.267	2,107	20	11.030	10.982	11.268	11.689	11.618	11.470	11.114	11.207	10.876	11.013	11.276	10.941
Nandi	0.070	35.230	2,048	10	17.280	17.430	17.920	18.100	17.780	16.970	16.640	16.850	17.000	17.610	17.640	17.380
Molo	-0.283	35.750	2,712	20	14.756	14.928	15.080	15.253	15.066	14.556	14.174	14.351	14.409	14.744	14.805	14.643
Siret	0.113	35.230	1,512	10	18.240	18.470	18.790	19.050	18.630	17.740	17.420	17.840	17.940	18.670	18.530	18.370

Table A8.3c Weather data parameters for weather generator – Standard deviation for daily maximum air temperature in month

STATION	LATITUDE	LONGITUDE	WELEV	RAIN_YRS	TMPSTDMX 1	TMPSTDMX 2	TMPSTDMX 3	TMPSTDMX 4	TMPSTDMX 5	TMPSTDMX 6	TMPSTDMX 7	TMPSTDMX 8	TMPSTDMX 9	TMPSTDMX1 0	TMPSTDMX1 1	TMPSTDMX1 2
Kuresoi	-0.304	35.534	2,652	20	7.360	6.940	6.470	4.740	3.980	3.410	3.270	3.380	4.440	5.320	6.190	6.470
Kisii	-0.683	34.783	1,982	10	7.360	6.940	6.470	4.740	3.980	3.410	3.270	3.380	4.440	5.320	6.190	6.470
Kisumu	-0.100	34.750	1,241	20	7.360	6.940	6.470	4.740	3.980	3.410	3.270	3.380	4.440	5.320	6.190	6.470
kericho	-0.367	35.267	2,107	20	7.360	6.940	6.470	4.740	3.980	3.410	3.270	3.380	4.440	5.320	6.190	6.470
Nandi	0.070	35.230	2,048	10	2.250	2.310	2.270	1.530	1.280	1.220	1.520	1.680	1.750	1.730	1.730	2.080
Molo	-0.283	35.750	2,712	20	7.360	6.940	6.470	4.740	3.980	3.410	3.270	3.380	4.440	5.320	6.190	6.470

Table A8.3d Weather data parameters for weather generator – Standard deviation for daily minimum air temperature in month

STATION	LATITUDE	LONGITUDE	WELEV	RAIN_YRS	TMPSTDMN 1	TMPSTDMN 2	TMPSTDMN 3	TMPSTDMN 4	TMPSTDMN 5	TMPSTDMN 6	TMPSTDMN 7	TMPSTDMN 8	TMPSTDMN 9	TMPSTDMN1 0	TMPSTDMN1 1	TMPSTDMN1 2
Kuresoi	-0.304	35.534	2,652	20	6.100	5.580	5.590	4.630	3.720	2.760	2.060	2.240	3.960	5.060	5.420	5.510
Kisii	-0.683	34.783	1,982	10	6.100	5.580	5.590	4.630	3.720	2.760	2.060	2.240	3.960	5.060	5.420	5.510
Kisumu	-0.100	34.750	1,241	20	6.100	5.580	5.590	4.630	3.720	2.760	2.060	2.240	3.960	5.060	5.420	5.510
kericho	-0.367	35.267	2,107	20	6.100	5.580	5.590	4.630	3.720	2.760	2.060	2.240	3.960	5.060	5.420	5.510
Nandi	0.070	35.230	2,048	10	1.590	1.680	1.510	1.050	1.120	1.300	1.450	1.420	1.320	1.340	1.270	1.310
Molo	-0.283	35.750	2,712	20	6.100	5.580	5.590	4.630	3.720	2.760	2.060	2.240	3.960	5.060	5.420	5.510

Table A8.3e Weather data parameters for weather generator – Average or mean total monthly precipitation

STATION	LATITUDE	LONGITUDE	WELEV	RAIN_YRS	PCPMM1	PCPMM2	PCPMM3	PCPMM4	PCPMM5	PCPMM6	PCPMM7	PCPMM8	PCPMM9	PCPMM10	PCPMM11	PCPMM12
Kuresoi	-0.304	35.534	2,652	20	90.700	71.820	112.830	170.340	160.490	162.710	192.680	200.290	113.770	85.430	81.430	52.150
Kisii	-0.683	34.783	1,982	10	115.430	118.710	204.590	285.220	260.670	182.020	130.780	232.660	165.260	172.110	197.490	142.170
Kisumu	-0.100	34.750	1,241	20	98.150	59.200	171.820	209.620	167.160	85.360	57.210	84.520	103.510	98.220	126.420	114.450
kericho	-0.367	35.267	2,107	20	122.830	95.040	167.550	238.670	246.670	160.700	158.510	175.770	158.860	195.610	156.460	108.750
Nandi	0.070	35.230	2,048	10	110.060	99.840	153.730	204.030	171.680	132.700	148.040	145.650	125.250	141.630	142.520	134.760
Molo	-0.283	35.750	2,712	20	45.860	38.140	91.260	131.480	130.140	95.330	129.280	130.720	56.310	71.170	84.140	57.160

Table A8.3f Weather data parameters for weather generator – Standard deviation for daily precipitation in month

STATION	LATITUDE	LONGITUDE	WELEV	RAIN_YRS	PCPSTD1	PCPSTD2	PCPSTD3	PCPSTD4	PCPSTD5	PCPSTD6	PCPSTD7	PCPSTD8	PCPSTD9	PCPSTD10	PCPSTD11	PCPSTD12
Kuresoi	-0.304	35.534	2,652	20	6.690	6.350	8.610	9.050	8.400	8.190	7.740	8.030	7.630	4.830	5.820	4.480
Kisii	-0.683	34.783	1,982	10	8.190	9.620	12.590	14.130	14.080	12.330	8.780	17.220	8.900	10.190	9.540	8.670
Kisumu	-0.100	34.750	1,241	20	9.190	6.720	13.360	12.420	11.620	7.900	5.770	6.880	8.110	7.790	10.260	9.960
kericho	-0.367	35.267	2,107	20	10.530	7.630	11.130	10.840	11.140	7.760	9.100	9.030	8.330	10.790	9.180	9.070
Nandi	0.070	35.230	2,048	10	5.900	4.730	9.140	9.540	9.180	7.210	6.760	7.000	5.820	5.920	7.540	7.120
Molo	-0.283	35.750	2,712	20	4.280	3.840	7.070	8.340	7.950	5.370	7.620	7.410	3.730	4.110	5.100	5.190

Table A8.3g Weather data parameters for weather generator – Skew coefficient for daily precipitation in month

STATION	LATITUDE	LONGITUDE	WELEV	RAIN_YRS	PCPSKW1	PCPSKW2	PCPSKW3	PCPSKW4	PCPSKW5	PCPSKW6	PCPSKW7	PCPSKW8	PCPSKW9	PCPSKW10	PCPSKW11	PCPSKW12
Kuresoi	-0.304	35.534	2,652	20	5.700	3.830	3.820	2.390	2.470	2.060	1.810	2.050	3.220	2.850	4.430	5.220
Kisii	-0.683	34.783	1,982	10	3.780	4.480	5.080	4.310	4.740	6.090	4.450	4.050	2.660	4.090	2.510	3.830
Kisumu	-0.100	34.750	1,241	20	4.370	6.010	3.500	2.630	3.950	4.590	4.860	4.060	3.690	4.110	4.420	4.370
kericho	-0.367	35.267	2,107	20	5.020	3.240	3.210	1.980	2.830	2.050	3.770	2.570	2.700	4.500	3.300	4.790
Nandi	0.070	35.230	2,048	10	4.180	6.240	4.100	3.180	5.960	4.130	4.100	3.780	4.330	3.030	4.510	7.420
Molo	-0.283	35.750	2,712	20	4.800	4.210	4.230	3.420	3.260	3.000	3.920	4.360	3.260	3.380	3.600	7.020

Table A8.3h Weather data parameters for weather generator – Probability of a wet day following a dry day in the month

STATION	LATITUDE	LONGITUDE	WELEV	RAIN_YRS	PR_W1_1	PR_W1_2	PR_W1_3	PR_W1_4	PR_W1_5	PR_W1_6	PR_W1_7	PR_W1_8	PR_W1_9	PR_W1_10	PR_W1_11	PR_W1_12
Kuresoi	-0.304	35.534	2,652	20	0.150	0.110	0.140	0.190	0.300	0.390	0.410	0.450	0.170	0.130	0.120	0.110
Kisii	-0.683	34.783	1,982	10	0.260	0.280	0.370	0.560	0.500	0.420	0.340	0.450	0.440	0.450	0.480	0.360
Kisumu	-0.100	34.750	1,241	20	0.210	0.180	0.310	0.460	0.420	0.310	0.260	0.350	0.350	0.400	0.340	0.220
kericho	-0.367	35.267	2,107	20	0.230	0.190	0.310	0.490	0.490	0.540	0.550	0.540	0.520	0.570	0.360	0.210
Nandi	0.070	35.230	2,048	10	0.140	0.130	0.200	0.390	0.290	0.300	0.390	0.420	0.290	0.320	0.230	0.170
Molo	-0.283	35.750	2,712	20	0.070	0.080	0.190	0.260	0.200	0.220	0.320	0.270	0.190	0.260	0.270	0.130

Table A8.3j Weather data parameters for weather generator – Probability of a wet day following a wet day in the month

STATION	LATITUDE	LONGITUDE	WELEV	RAIN_YRS	PR_W1_1	PR_W2_1	PR_W2_2	PR_W2_3	PR_W2_4	PR_W2_5	PR_W2_6	PR_W2_7	PR_W2_8	PR_W2_9	PR_W2_10	PR_W2_11
Kuresoi	-0.304	35.534	2,652	20	0.150	0.730	0.700	0.670	0.770	0.680	0.590	0.740	0.730	0.680	0.770	0.770
Kisii	-0.683	34.783	1,982	10	0.260	0.650	0.650	0.740	0.810	0.740	0.680	0.600	0.630	0.720	0.690	0.800
Kisumu	-0.100	34.750	1,241	20	0.210	0.500	0.430	0.570	0.670	0.620	0.470	0.410	0.420	0.540	0.550	0.540
kericho	-0.367	35.267	2,107	20	0.230	0.570	0.640	0.670	0.810	0.820	0.720	0.650	0.740	0.730	0.760	0.730
Nandi	0.070	35.230	2,048	10	0.140	0.850	0.890	0.820	0.850	0.840	0.780	0.800	0.770	0.810	0.820	0.850
Molo	-0.283	35.750	2,712	20	0.070	0.750	0.710	0.660	0.730	0.750	0.740	0.730	0.820	0.640	0.690	0.710

Table A8.3k Weather data parameters for weather generator – Average number of days of precipitation in the month

STATION	LATITUDE	LONGITUDE	WELEV	RAIN_YRS	PCPD1	PCPD2	PCPD3	PCPD4	PCPD5	PCPD6	PCPD7	PCPD8	PCPD9	PCPD10	PCPD11	PCPD12
Kuresoi	-0.304	35.534	2,652	20	11.890	7.670	10.440	15.110	15.670	15.330	20.440	20.670	11.670	12.560	11.670	7.560
Kisii	-0.683	34.783	1,982	10	13.690	13.130	19.230	23.400	21.290	17.830	14.850	17.690	18.940	19.290	21.980	17.750
Kisumu	-0.100	34.750	1,241	20	9.620	7.240	13.430	18.240	17.240	11.620	10.000	12.050	13.430	15.100	13.380	10.620
kericho	-0.367	35.267	2,107	20	11.520	10.240	15.380	22.520	24.140	20.710	19.670	21.380	21.050	22.860	18.330	11.810
Nandi	0.070	35.230	2,048	10	16.620	18.240	17.900	23.050	21.950	18.860	21.760	21.190	20.050	21.570	20.330	21.520
Molo	-0.283	35.750	2,712	20	7.810	6.560	11.440	15.940	15.560	15.190	17.630	20.000	11.440	15.380	15.130	10.060

Table A8.3m Weather data parameters for weather generator – Maximum 0.5 hour rainfall in entire period of record for the month

STATION	LATITUDE	LONGITUDE	WELEV	RAIN_YRS	RAINHHMX1	RAINHHMX2	RAINHHMX3	RAINHHMX4	RAINHHMX5	RAINHHMX6	RAINHHMX7	RAINHHMX8	RAINHHMX9	RAINHHMX10	RAINHHMX11	RAINHHMX12
Kuresoi	-0.304	35.534	2,652	20	24.200	15.733	19.000	20.000	17.733	17.733	14.767	15.500	17.433	10.000	16.000	14.467
Kisii	-0.683	34.783	1,982	10	24.700	38.400	66.700	66.767	70.133	62.667	41.733	45.100	25.133	45.167	21.333	26.733
Kisumu	-0.100	34.750	1,241	20	30.833	29.100	33.400	25.600	39.367	21.800	14.933	20.967	22.467	21.700	32.933	28.233
kericho	-0.367	35.267	2,107	20	34.067	17.300	27.300	20.133	32.767	16.676	30.533	20.667	18.767	43.667	26.500	32.900
Nandi	0.070	35.230	2,048	10	17.330	21.170	26.330	26.670	4.330	22.000	21.330	20.670	20.000	15.330	22.000	33.000
Molo	-0.283	35.750	2,712	20	11.600	9.600	20.467	20.567	19.533	13.600	25.133	20.767	10.167	12.267	13.867	21.733

Table A8.3n Weather data parameters for weather generator – Average daily solar radiation for month

STATION	LATITUDE	LONGITUDE	WELEV	RAIN_YRS	SOLARAV1	SOLARAV2	SOLARAV3	SOLARAV4	SOLARAV5	SOLARAV6	SOLARAV7	SOLARAV8	SOLARAV9	SOLARAV1 0	SOLARAV1 1	SOLARAV1 2
Kuresoi	-0.304	35.534	2,652	20	20.195	22.527	22.134	20.188	20.235	16.672	15.398	16.394	19.956	20.242	19.860	19.659
Kisii	-0.683	34.783	1,982	10	22.263	24.633	23.836	21.214	21.252	19.563	18.796	19.069	19.949	18.940	19.134	20.724
Kisumu	-0.100	34.750	1,241	20	22.263	24.633	23.836	21.214	21.252	19.563	18.796	19.069	19.949	18.940	19.134	20.724
kericho	-0.367	35.267	2,107	20	20.195	22.527	22.134	20.188	20.235	16.672	15.398	16.394	19.956	20.242	19.860	19.659
Nandi	0.070	35.230	2,048	10	16.630	17.670	17.960	17.300	16.500	15.920	16.620	17.900	19.020	18.300	16.690	15.920
Molo	-0.283	35.750	2,712	20	20.195	22.527	22.134	20.188	20.235	16.672	15.398	16.394	19.956	20.242	19.860	19.659

Table A8.3p Weather data parameters for weather generator – Average daily dew point temperature for each month or relative humidity

STATION	LATITUDE	LONGITUDE	WELEV	RAIN_YRS	DEWPT1	DEWPT2	DEWPT3	DEWPT4	DEWPT5	DEWPT6	DEWPT7	DEWPT8	DEWPT9	DEWPT10	DEWPT11	DEWPT12
Kuresoi	-0.304	35.534	2,652	20	0.640	0.603	0.650	0.736	0.764	0.779	0.785	0.758	0.701	0.676	0.672	0.633
Kisii	-0.683	34.783	1,982	10	0.640	0.603	0.650	0.736	0.764	0.779	0.785	0.758	0.701	0.676	0.672	0.633
Kisumu	-0.100	34.750	1,241	20	0.630	0.636	0.641	0.738	0.719	0.620	0.531	0.643	0.576	0.604	0.665	0.656
kericho	-0.367	35.267	2,107	20	0.640	0.603	0.650	0.736	0.764	0.779	0.785	0.758	0.701	0.676	0.672	0.633
Nandi	0.070	35.230	2,048	10	0.630	0.610	0.660	0.730	0.740	0.730	0.710	0.690	0.640	0.630	0.660	0.640
Molo	-0.283	35.750	2,712	20	0.640	0.603	0.650	0.736	0.764	0.779	0.785	0.758	0.701	0.676	0.672	0.633

Table A8.3q Weather data parameters for weather generator – Average daily wind speed in the month

STATION	LATITUDE	LONGITUDE	WELEV	RAIN_YRS	WNDAV1	WNDAV2	WNDAV3	WNDAV4	WNDAV5	WNDAV6	WNDAV7	WNDAV8	WNDAV9	WNDAV10	WNDAV11	WNDAV12
Kuresoi	-0.304	35.534	2,652	20	1.850	1.660	1.900	1.560	1.290	1.510	1.405	1.390	1.470	1.310	1.420	1.580
Kisii	-0.683	34.783	1,982	10	1.850	1.660	1.900	1.560	1.290	1.510	1.405	1.390	1.470	1.310	1.420	1.580
Kisumu	-0.100	34.750	1,241	20	1.850	1.660	1.900	1.560	1.290	1.510	1.405	1.390	1.470	1.310	1.420	1.580
kericho	-0.367	35.267	2,107	20	1.850	1.660	1.900	1.560	1.290	1.510	1.405	1.390	1.470	1.310	1.420	1.580
Nandi	0.070	35.230	2,048	10	9.600	10.200	9.800	8.000	7.500	7.100	7.600	8.400	8.200	8.500	9.000	9.800
Molo	-0.283	35.750	2,712	20	1.850	1.660	1.900	1.560	1.290	1.510	1.405	1.390	1.470	1.310	1.420	1.580

Table A8.4 Estimates of net municipal load (tons/yr)

Watershed	Town	Population		Influent (kg/day)		Connection (%)		Reduction (%)		Net Load (kg/day)		Net Load (t/yr)	
		1999	2009	TN	TP	Sewerage	Wetlands	TN	TP	TN	TP	TN	TP
Yala	Siaya	1,500	2,443	12.22	4.89	100	0	60	45	4.89	2.69	1.78	0.98
Yala	Kapsabet	35,000	57,011	285.06	114.02	100	0	60	45	114.02	62.71	41.62	22.89
Gucha-Migori	Kisii	57,797	94,145	470.73	188.29	100	0	60	45	188.29	103.56	68.73	37.80
Gucha-Migori	Kisii	-	1,532	7.66	3.06	100	0	60	45	3.06	1.69	1.12	0.62
Gucha-Migori	Migori	400	652	3.26	1.30	100	0	60	45	1.30	0.72	0.48	0.26
Nzoia	Kakamega	19,458	31,695	158.48	63.39	100	0	60	45	63.39	34.86	23.14	12.73
Nzoia	Kakamega	5,040	8,210	41.05	16.42	100	0	60	45	16.42	9.03	5.99	3.30
Nzoia	Bungoma	30,000	48,867	244.33	97.73	100	0	60	45	97.73	53.75	35.67	19.62
Nzoia	Mumias	500	814	4.07	1.63	100	0	60	45	1.63	0.90	0.59	0.33
Nzoia	Mumias	1,000	1,629	8.14	3.26	100	0	60	45	3.26	1.79	1.19	0.65
Nzoia	Mumias	10,000	16,289	81.44	32.58	100	0	60	45	32.58	17.92	11.89	6.54
Nzoia	Webuye	38,794	63,191	315.96	126.38	100	0	60	45	126.38	69.51	46.13	25.37
Nzoia	Kitale	25,885	42,164	210.82	84.33	100	100	60	45	84.33	46.38	30.78	16.93
Nzoia	Kitale	25,885	42,164	210.82	84.33	100	0	60	45	84.33	46.38	30.78	16.93
Nzoia	Eldoret	2,500	4,072	20.36	8.14	0	100	60	45	8.14	4.48	2.97	1.64
Nzoia	Eldoret	50,000	81,445	407.22	162.89	100	0	60	45	162.89	89.59	59.45	32.70
Nzoia	Eldoret	117,273	191,025	955.13	382.05	100	0	60	45	382.05	210.13	139.45	76.70
Nzoia	Eldoret	5,000	8,144	40.72	16.29			60	45	16.29	8.96	5.95	3.27
Sondu	Kericho	20,000	32,578	162.89	65.16	100	0	60	45	65.16	35.84	23.78	13.08
Sondu	Kericho	1,800	2,932	14.66	5.86	100	0	60	45	5.86	3.23	2.14	1.18
Sio	Busia	11,980	19,514	97.57	39.03	100	0	60	45	39.03	21.47	14.25	7.83
												547.88	**301.33**

Table A8.5a Ranking of parameter sensitivity: flow and sediment

Parameter	Description	With observed data		Without observed data	
		Flow	Sediment	Flow	Sediment
Alpha_Bf	Baseflow alpha factor (days)	2	6	10	10
Biomix	Biological mixing efficiency	19	22	17	14
Blai	Maximum potential leaf index	9	11	5	8
Canmx	Maximum canopy storage (mm H_2O)	8	10	4	13
Ch_Cov	Channel cover factor	42	42	42	42
Ch_Erod	Channel erodibility factor	42	42	42	42
Ch_K2	Effective hydraulic conductivity in main channel alluvium	4	2	7	3
Ch_N2	Manning's n value for the main channel	5	3	18	2
Cn2	Initial SCS curve number for moisture condition Ⅱ	1	4	1	4
Epco	plant uptake compensation factor	18	20	16	20
Esco	Soil evaporation compensation factor	6	8	3	11
Gw_Delay	Groundwater delay time (days)	12	16	15	21
Gw_Revap	Groundwater "revap" coefficient	14	17	8	22
Gwqmn	threshold depth of water in the shallow aquifer required for return flow to occur (mmH2O)	16	21	12	24
Nperco	Nitrate percolation coefficient	22	18	23	17
Phoskd	Phosphorus soil partitioning coefficient	42	28	42	26
Pperco	Phosphorus percolation coefficient	25	26	42	27
Rchrg_Dp	Deep aquifer percolation fraction	3	7	2	7
Revapm	threshold depth of water in the shallow for revap or percolation to the deep aquifer to occur (mmH2O)	24	27	20	28
Sftmp	Snowfall temperature (℃)	42	42	42	42
Shallst_N	Initial concentration of nitrate in shallow aquifer (mgN/L or ppm)	42	42	42	42
Slope	Slope (%)	17	12	13	12
slsubbsn	Average slope length (m)	15	15	21	15
Smfmn	Melt factor for snow on December 21 (mmH2O/℃-day)	42	42	42	42
Smfmx	Melt factor for snow on June 21 (mmH2O/℃-day)	42	42	42	42
Smtmp	Snow melt base temperature	42	42	42	42

The parameter ranked 1 is the most sensitive while 41 is the least sensitive. Rank 42 means the parameter is not sensitive/not ranked

Table A8.5a Ranking of parameter sensitivity: flow and sediment - continued

Parameter	Description	Without observed data		With observed data	
		Flow	Sediment	Flow	Sediment
Sol_Alb	Moist soil albedo	21	24	19	25
Sol_Awc	Available water capacity of the soil layer (mmH_20/soil)	10	14	6	18
Sol_K	Saturated hydraulic conductivity (mm/hr)	13	23	11	23
Sol_Labp	Initial labile P concentration in the soil layer (mgP/kg soil or ppm)	42	42	42	42
Sol_NO_3	Initia NO_3 concentration in the soil layer (mgN/kg soil or ppm)	42	42	42	42
Sol_Orgn	Initia organic N concentration in the soil layer (mgN/kg soil or ppm)	42	42	42	42
Sol_Orgp	Initia organic P concentration in the soil layer (mgP/kg soil or ppm)	42	42	42	42
Sol_Z	depth from soil surface to bottom of layer	11	19	9	19
Spcon	Linear parameter for calculating the maximum amount of sediment that can be re-entrained during channel sediment routing	42	1	42	1
Spexp	Exponent parameter for calculating sediment re-entrained in channel sediment routing	42	5	42	5
Surlug	Surface runoff lag coefficient	7	13	14	9
Timp	Snow pack temperature lag factor	42	42	42	42
Tlaps	Temperature lapse rate (℃/km)	42	42	42	42
Usle_C	Minimum value for the cover and management factor for the land use	23	25	24	16
Usle_P	USLE equation support practice factor	20	9	22	6

The parameter ranked 1 is the most sensitive while 41 is the least sensitive. Rank 42 means the parameter is not sensitive/not ranked

Table A8.5b Ranking of parameter sensitivity: TN and TP

Parameter	Description	With observed data		Without observed data	
		TN	TP	TN	TP
Alpha_Bf	Baseflow alpha factor (days)	15	12	12	10
Biomix	Biological mixing efficiency	4	1	5	1
Blai	Maximum potential leaf index	3	7	2	6
Canmx	Maximum canopy storage (mm H_2O)	10	4	13	12
Ch_Cov	Channel cover factor	42	42	42	42
Ch_Erod	Channel erodibility factor	42	42	42	42
Ch_K2	Effective hydraulic conductivity in main channel alluvium	9	6	10	5
Ch_N2	Manning's n value for the main channel	19	8	19	8
Cn2	Initial SCS curve number for moisture condition Ⅱ	2	5	3	3
Epco	plant uptake compensation factor	14	16	21	17
Esco	Soil evaporation compensation factor	12	13	14	13
Gw_Delay	Groundwater delay time (days)	20	20	20	20
Gw_Revap	Groundwater "revap" coefficient	17	21	15	20
Gwqmn	threshold depth of water in the shallow aquifer required for return flow to occur (mmH2O)	8	24	6	25
Nperco	Nitrate percolation coefficient	1	19	1	19
Phoskd	Phosphorus soil partitioning coefficient	24	18	24	16
Pperco	Phosphorus percolation coefficient	25	22	26	23
Rchrg_Dp	Deep aquifer percolation fraction	5	10	4	7
Revapm	threshold depth of water in the shallow for revap or percolation to the deep aquifer to occur (mmH2O)	26	26	25	26
Sftmp	Snowfall temperature (℃)	42	42	42	42
Shallst_N	Initial concentration of nitrate in shallow aquifer (mgN/L or ppm)	42	42	42	42
Slope	Slope (%)	16	11	17	11
slsubbsn	Average slope length (m)	21	15	20	14
Smfmn	Melt factor for snow on December 21 (mmH2O/℃-day)	42	42	42	42
Smfmx	Melt factor for snow on June 21 (mmH2O/℃-day)	42	42	42	42
Smtmp	Snow melt base temperature	42	42	42	42

The parameter ranked 1 is the most sensitive while 41 is the least sensitive. Rank 42 means the parameter is not sensitive/not ranked

Table A8.5b Ranking of parameter sensitivity: TN and TP - continued

Parameter	Description	Without observed data		With observed data	
		TN	TP	TN	TP
Sol_Alb	Moist soil albedo	22	23	23	24
Sol_Awc	Available water capacity of the soil layer (mmH_20/soil)	13	14	9	15
Sol_K	Saturated hydraulic conductivity (mm/hr)	18	17	18	18
Sol_Labp	Initial labile P concentration in the soil layer (mgP/kg soil or ppm)	42	42	42	42
Sol_NO_3	Initial NO_3 concentration in the soil layer (mgN/kg soil or ppm)	42	42	42	42
Sol_Orgn	Initial organic N concentration in the soil layer (mgN/kg soil or ppm)	42	42	42	42
Sol_Orgp	Initial organic P concentration in the soil layer (mgP/kg soil or ppm)	42	42	42	42
Sol_Z	depth from soil surface to bottom of layer	7	9	11	9
Spcon	Linear parameter for calculating the maximum amount of sediment that can be re-entrained during channel sediment routing	42	42	42	42
Spexp	Exponential parameter for calculating sediment re-entrained in channel sediment routing	42	42	42	42
Surlag	Surface runoff lag coefficient	11	2	7	2
Timp	Snow pack temperature lag factor	42	42	42	42
Tlaps	Temperature lapse rate (℃/km)	42	42	42	42
Usle_C	Minimum value for the cover and management factor for the land use	23	25	22	22
Usle_P	USLE equation support practice factor	6	3	8	4

The parameter ranked 1 is the most sensitive while 41 is the least sensitive. Rank 42 means the parameter is not sensitive/not ranked

Table A8.6 Simulated annual water and nutrient yields at sub basin level for the years 2005, 2006 & 2007

Sub basin	AREA km2	WYLD mm (2005)	WYLD mm (2006)	WYLD mm (2007)	TN Kg/h (2005)	TN Kg/h (2006)	TN Kg/h (2007)	TP Kg/h (2005)	TP Kg/h (2006)	TP Kg/h (2007)
1	161	229.348	551.696	967.118	5.737	8.843	5.7	2.331	3.817	2.191
2	141	254.698	465.769	761.584	2.793	4.146	2.783	1.153	1.883	1.189
3	128	216.449	757.556	1,281.216	9.134	14.439	9.298	3.813	6.157	3.647
4	17	229.322	729.108	1,270.398	10.468	16.202	11.055	4.026	6.202	4.064
5	33	247.490	705.654	1,148.754	8.212	12.711	8.224	3.337	5.472	3.142
6	7	240.310	758.354	1,244.703	8.586	13.256	8.668	3.493	5.762	3.32
7	90	192.569	213.919	278.048	4.608	4.326	6.42	3.847	3.778	5.224
8	264	65.534	65.480	86.828	3.952	2.582	5.453	3.121	2.407	4.333
9	64	223.475	727.159	1,197.623	8.49	13.078	8.986	3.614	5.588	3.639
10	286	164.719	267.794	136.602	6.401	19.855	3.615	4.846	12.991	2.232
11	179	269.591	558.049	873.660	6.738	10.14	6.615	2.63	4.237	2.457
12	67	279.478	698.034	1,105.691	12.079	18.212	11.961	4.603	7.364	4.3
13	189	250.370	461.844	788.055	3.342	4.921	3.326	1.344	2.163	1.393
14	37	347.057	556.791	749.723	0.81	1.145	0.851	0.414	0.717	0.585
15	85	252.477	455.492	737.405	3.436	4.908	3.472	1.299	2.064	1.34
16	106	320.669	622.673	939.572	12.489	18.113	12.475	4.419	6.855	4.269
17	369	172.197	448.996	902.351	6.309	11.839	16.807	2.275	6.96	7.92
18	79	202.676	446.642	864.193	7.284	12.848	18.548	2.426	7.14	9.358
19	55	171.608	437.790	924.389	4.717	9.235	13.47	1.748	5.737	7.37
20	472	323.092	649.863	895.453	10.137	13.228	10.676	4.638	5.74	4.41
21	46	165.690	426.834	1,040.144	3.215	7.322	10.559	1.399	5.105	6.87
22	71	183.441	600.700	915.064	4.84	10.967	12.858	2.933	7.853	7.495
23	18	146.706	582.203	1,041.857	1.781	4.588	6.962	0.823	3.339	4.824
24	297	178.596	437.219	989.801	5.142	10.48	14.536	1.783	5.744	6.912
25	135	320.722	602.217	873.234	4.729	11.056	10.617	3.134	7.653	7.019

Table A8.7a Simulated sediment yield (tons) for baseline management plan

Month	YR_2005	YR_2006	YR_2007	Average
1	8,104	5,854	6,511	11,992
2	6,433	3,557	15,171	12,171
3	2,167	4,328	6,772	9,568
4	2,260	19,277	2,403	8,142
5	458	25,285	1,360	11,249
6	8,104	5,854	6,511	8,965
7	6,433	3,557	15,171	7,485
8	2,167	4,328	6,772	6,823
9	2,260	19,277	2,403	8,387
10	458	25,285	1,360	4,423
11	8,104	5,854	6,511	7,980
12	6,433	3,557	15,171	9,034
Mean	66,399	129,509	122,747	106,218

Table A8.7b Simulated sediment yield (tons) for filters management plan

Month	YR_2005	YR_2006	YR_2007	Average
1	6,016	901	25,515	10,810
2	2,770	7,195	22,838	10,934
3	4,690	21,925	3,643	10,086
4	5,671	9,546	3,141	6,119
5	8,592	9,612	7,249	8,484
6	6,629	4,929	8,309	6,622
7	4,004	6,054	6,513	5,524
8	6,543	4,955	5,423	5,641
9	4,345	3,087	10,843	6,092
10	2,233	3,857	5,117	3,736
11	2,002	16,820	2,651	7,158
12	473	18,084	1,532	6,696
Mean	53,967	106,963	102,773	87,901

Table A8.7c Simulated sediment yield (tons) for reforestation management plan

Month	YR_2005	YR_2006	YR_2007	Average
1	5,509.84	775.95	24,517.50	10,268
2	2,747.90	5,624.99	22,355.13	10,243
3	4,316.66	23,719.75	2,034.28	10,024
4	3,869.52	7,861.13	2,650.96	4,794
5	5,344.25	8,333.70	5,052.89	6,244
6	5,860.46	4,186.23	7,474.31	5,840
7	3,444.32	5,105.77	5,643.44	4,731
8	5,828.12	3,320.85	4,689.88	4,613
9	3,636.83	2,643.22	10,148.30	5,476
10	1,688.98	3,272.79	4,341.93	3,101
11	1,490.25	14,161.78	1,885.05	5,846
12	359.36	15,806.10	1,198.25	5,788
Mean	44,096.49	94,812.26	91,991.92	76,967

Table A8.8a Mean monthly basin simulated sediment yield (tons) and subsequent reduction (%) by management plans

Month	Baseline	Filter	Reforestation	Reduction (%)	
				Filter	Reforestation
1	11,992	10,810	10,268	10	14
2	12,171	10,934	10,243	10	16
3	9,568	10,086	10,024	5	5
4	8,142	6,119	4,794	25	41
5	11,249	8,484	6,244	25	44
6	8,965	6,622	5,840	26	35
7	7,485	5,524	4,731	26	37
8	6,823	5,641	4,613	17	32
9	8,387	6,092	5,476	27	35
10	4,423	3,736	3,101	16	30
11	7,980	7,158	5,846	10	27
12	9,034	6,696	5,788	26	36
Mean	106,218	87,901	76,967	17	28

Table A8.8b. Sub basin mean simulated sediment yield (tons) and subsequent reduction (%) by management plans

Sub Basin	Area (Km^2)	Baseline	Filter	Reforestation	Reduction (%)	
					Filter	Reforestation
1	161	1,994	1,927	2,088	3	5
2	141	75	71	77	5	3
3	128	2,905	2,810	3,040	3	5
4	17	15,047	12,346	9,068	18	40
5	33	3,398	2,985	3,019	12	11
6	7	9,738	8,009	4,994	18	49
7	90	230	216	21	6	91
8	264	2,282	2,156	21	6	99
9	64	21,512	17,655	14,175	18	34
10	286	106,218	87,901	76,967	17	28
11	179	1,272	1,229	1,332	3	5
12	67	7,728	6,265	3,263	19	58
13	189	199	180	197	9	1
14	37	3,011	2,717	247	10	92
15	85	10	8	9	19	11
16	106	4,771	4,007	1,287	16	73
17	369	55,765	50,969	50,441	9	10
18	79	1,649	1,634	1,768	1	7
19	55	38,142	36,636	36,901	4	3
20	472	17,651	15,051	15,024	15	15
21	46	19,254	20,642	21,141	7	10
22	72	585	574	460	2	21
23	18	2,079	1,966	1,642	5	21
24	297	14,934	16,792	17,808	12	19
25	135	922	915	764	1	17

Table A8.8c. Monthly basin simulated sediment yield (tons) and subsequent reduction (%) by management plans

Date	Baseline	Filter	Reforestation	Reduction (%)	
				Filter	Reforestation
Jan-05	6,233	6,016	5,510	3	12
Feb-05	2,843	2,770	2,748	3	3
Mar-05	5,454	4,690	4,317	14	21
Apr-05	7,885	5,671	3,870	28	51
May-05	10,562	8,592	5,344	19	49
Jun-05	8,612	6,629	5,860	23	32
Jul-05	5,387	4,004	3,444	26	36
Aug-05	8,104	6,543	5,828	19	28
Sep-05	6,433	4,345	3,637	32	43
Oct-05	2,167	2,233	1,689	3	22
Nov-05	2,260	2,002	1,490	11	34
Dec-05	458	473	359	3	22
Jan-06	850	901	776	6	9
Feb-06	9,890	7,195	5,625	27	43
Mar-06	19,488	21,925	23,720	13	22
Apr-06	12,818	9,546	7,861	26	39
May-06	13,899	9,612	8,334	31	40
Jun-06	5,612	4,929	4,186	12	25
Jul-06	8,651	6,054	5,106	30	41
Aug-06	5,854	4,955	3,321	15	43
Sep-06	3,557	3,087	2,643	13	26
Oct-06	4,328	3,857	3,273	11	24
Nov-06	19,277	16,820	14,162	13	27
Dec-06	25,285	18,084	15,806	28	37
Jan-07	28,893	25,515	24,518	12	15
Feb-07	23,780	22,838	22,355	4	6
Mar-07	3,760	3,643	2,034	3	46
Apr-07	3,723	3,141	2,651	16	29
May-07	9,286	7,249	5,053	22	46
Jun-07	12,671	8,309	7,474	34	41
Jul-07	8,416	6,513	5,643	23	33
Aug-07	6,511	5,423	4,690	17	28
Sep-07	15,171	10,843	10,148	29	33
Oct-07	6,772	5,117	4,342	24	36
Nov-07	2,403	2,651	1,885	10	22
Dec-07	1,360	1,532	1,198	13	12