Building a dynamic water quality evaluation system for Lake Naivasha (Kenya): exploration in the use of DMS

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By

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Dedicado a Mamá

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Abstract

The water quality of Lake Naivasha depends mainly on the quality of the water discharged into it. With the continuous growing of the agricultural industry around the lake, the quality of the water used for the Naivasha town and the farmers themselves is a major concern issue. The Duflow modeling studio is a software program developed by IHE, Delft University of Technology, LUT, STOWA and others, to supply the Dutch water authorities with a set of tools capable of performing unsteady flow computations in networks of open courses. DMS also includes a precipitation runoff module RAM to calculate the supply of rainfall to the surface flow and more complex water quality processes. DMS was used to model the Lake as a network of open channels trying to assess the applicability of the tool in the evaluation of the impact in the water quality of the lake from point and non point pollution sources. This model is based on the Slibmeer example developed by G.Blom and J. Icke and included in the DMS user's manual. [STOWA, 1999]

Despite of the difficulty of creating a conceptual flow model of a lake in terms of open channels (sometimes resulting in unstable flow conditions); DMS is able to represent the water balance of the lake in a dynamic concept. This allows the application of the advection-dispersion equation in order to assess the fate of contaminants from the simple physical point of view. The model showed a correlation factor (R-square) of 72% with the observed lake water levels based for a long period of 32 years (1968-1990) and 99% for a short period of 10 months (1999-2000) including the estimated abstraction of the lake (approximately 1.5 m^3/s). The model is highly dependent on the quality of the large amount of needed input data, particularly in the RAM calculations that require a rather wide knowledge of the soil properties involved in the precipitation-runoff process. The wind plays an important role in the completely mixed status of a shallow water body as Lake Naivasha, the change in the directions of the superficial flow of the water over some of the sections in the network, clearly shows its effect in the flow patterns. The impact of the non-point pollution sources over the lake was analyzed with some experimental values, the result is the remarkable incidence in terms of water quantity and quality although these values must be assessed in the field in order to calibrate the model (fine tuning).

Chapter 1

1. Introduction

Lake Naivasha represents one of the most important natural resources for the people living close to its shores, farmers, visitors and the Kenyan people in general, due to its biodiversity and economic potential as a source of water for horticultural production and tourism development.

Some studies have been conducted to assess the quantity of water in the lake, but it is also necessary to evaluate its quality and the effects of the actual exploitation system of the natural resources associated with the lake. This study area requires pollution sources to be identified and the more rational way to do it is using the point and non point source pollution concept.

“Non point source” (NPS) pollution, unlike pollution from industrial and sewage treatment plants, comes from many diffuse sources. Rainfall or snowmelt moving over and through the ground causes NPS pollution. As the runoff moves, it picks up and carries away natural and human-made pollutants, finally depositing them into lakes, rivers, wetlands, coastal waters, and even in our underground sources of drinking water. These pollutants include:

- Excess fertilizers, herbicides, and insecticides from agricultural lands and residential areas
- Oil, grease, and toxic chemicals from urban runoff and energy production
- Sediment from improperly managed construction sites, crop and forestlands, and eroding streambanks
- Salt from irrigation practices and acid drainage from abandoned mines
- Bacteria and nutrients from livestock, pet wastes, and faulty septic systems
- Atmospheric deposition and hydromodification are also sources of non point source pollution. [EPA, 1996]

The use of numerical models based on GIS has demonstrated its potential as a tool in the assessment of the pollution risks, response of the ecosystems to accidental discharges and as a predictor of some effects or impacts caused by human activities in the environment.

The Duflow Modeling Studio (DMS) is a computer package developed by the STOWA (Stichting Toegepast Onderzoek Waterbeheer) that allows performing unsteady flow computations in networks of open watercourses and is also useful in simulating the transportation of substances in free surface flow.

This study assess the feasibility of using DMS as a modeling tool in the evaluation of the impacts on the water quality of lake Naivasha from point and non point pollution sources represented by some farms and the Naivasha town.

1.1 Importance of the study

The lake Naivasha is located in the Kenya rift valley and is the only fresh water lake in a semi arid region. The inhabitants of the region depend on it for drinking water, fishery, recreation and irrigation water, because of that the demand on the resource is increasing dramatically with the associated consequences of pollution over the exploited resource. The analysis of the impact on the water quality of the lake by the pollution sources (using the point and non-point approach), can help to identify the risk factors in the over demand of the resource and the essential aspects to tackle in the sustainability scheme adopted by the LNROA (Lake Naivasha Riparian Owners Association) and the Kenyan government. The Lake has no surface outflow and the groundwater flow patterns are changing frequently because of the increasing of the pumping rates from the big farms. Therefore is important to count with some tools to identify the influence of the pollutants over the water quality of the lake, which is highly significant in the economical development of the region.

1.2 Research Objective

The objective of the research is to evaluate the use of DMS as a modeling tool for the assessment of the water quality of the lake. The model of the lake has to be able to describe in some extent the actual conditions in order to predict the consequences of the discharges and some possible spills in normal and extreme scenarios.

1.3 Research Questions

- Is DMS a suitable tool for the evaluation of the impact of point and non-point pollution sources around the lake?
- What are the main requirements of DMS from the fieldwork survey in order to model accurately the lake?
- What can be the methodology used to model the water quality of Lake Naivasha?
- Are the farms around the lake affecting its water quality in terms of the balance of Nitrogen and Phosphorus?
- Is it possible to suggest some actions in order to keep the water quality in the lake within acceptable standards?

1.4 Methodology

The development of the work is distributed in four areas: preparation of the fieldwork or pre-fieldwork, fieldwork survey, data analysis and modeling and final assessment.

1.4.1 Pre-fieldwork

This stage includes the literature review, analysis of available and required data, interpretation of existing data, selection and definition of the sample points and variables, analysis of the software program and setup of a system. This system would represent the lake as a unique area with inputs and outputs in quantity terms to calibrate the model based on the known budget.

1.5 Fieldwork

Collection and analysis of water samples, collection of historical data, inputs and outputs update, selection and rank of the proposed scenarios

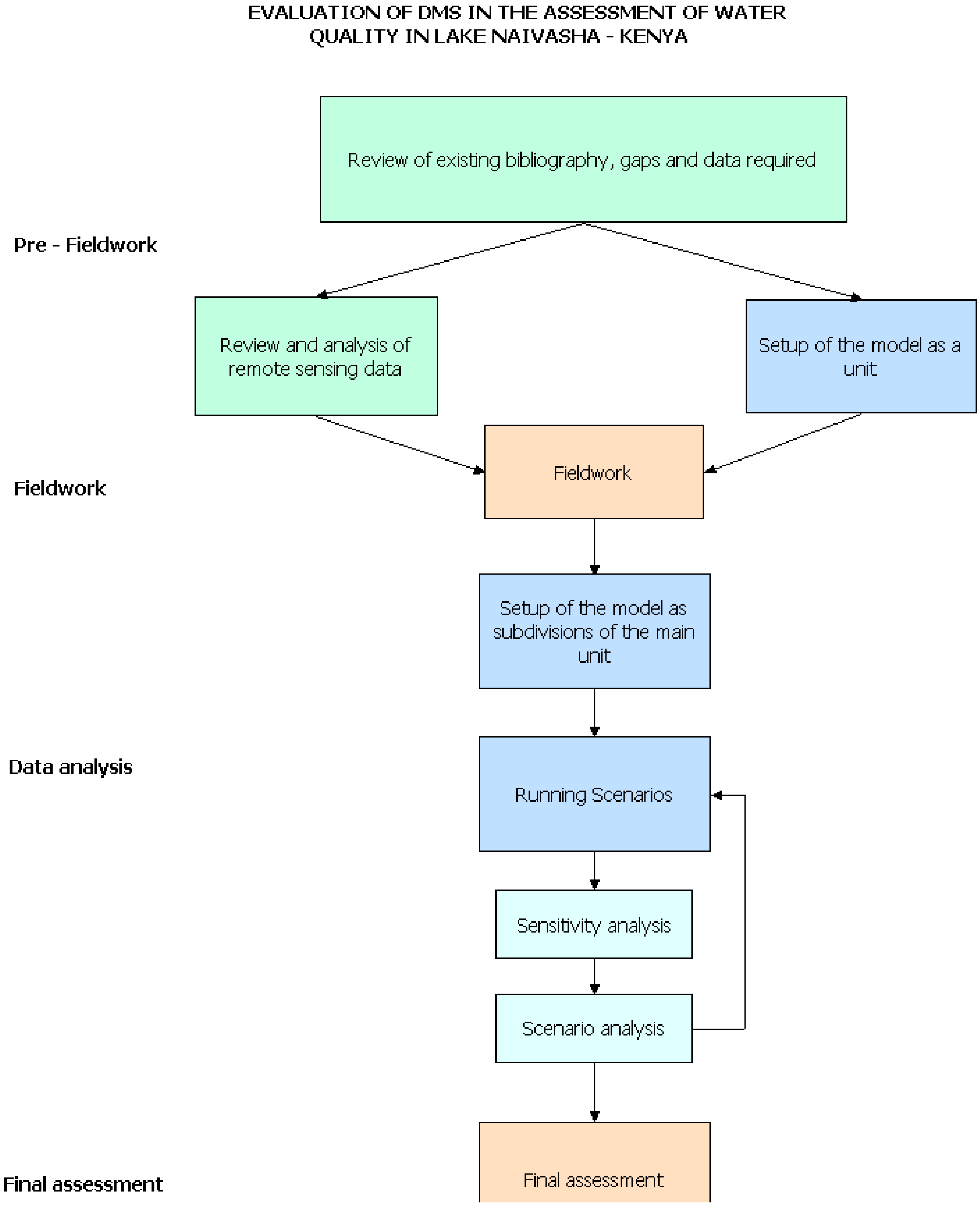
1.5.1 Data analysis

Hydrochemical assessment, data series analysis, historical data comparison, setup of the model as partitioning of the lake to run the selected scenarios, run the model, model calibration, sensitivity analysis and pollution assessment. The partitioning of the model will allow analyzing the geographic distribution of the water quality and the identification of the main processes governing the behavior of the pollutants in the lake.

1.5.2 Final assessment

Analysis of results maps elaboration, conclusions and recommendations. The figure 1 presents the research methodology in a flow chart.

Figure 1. Research methodology flowchart



1.6 Expected Results

- Dynamic simulation of Lake Naivasha behavior in terms of water quantity and quality; i.e. dynamic evaluation of effects of boundary conditions (river inflows, rainfall, evaporation, runoff, abstraction, groundwater outflows, nutrient and matter inputs and fate) on the water status of the lake.

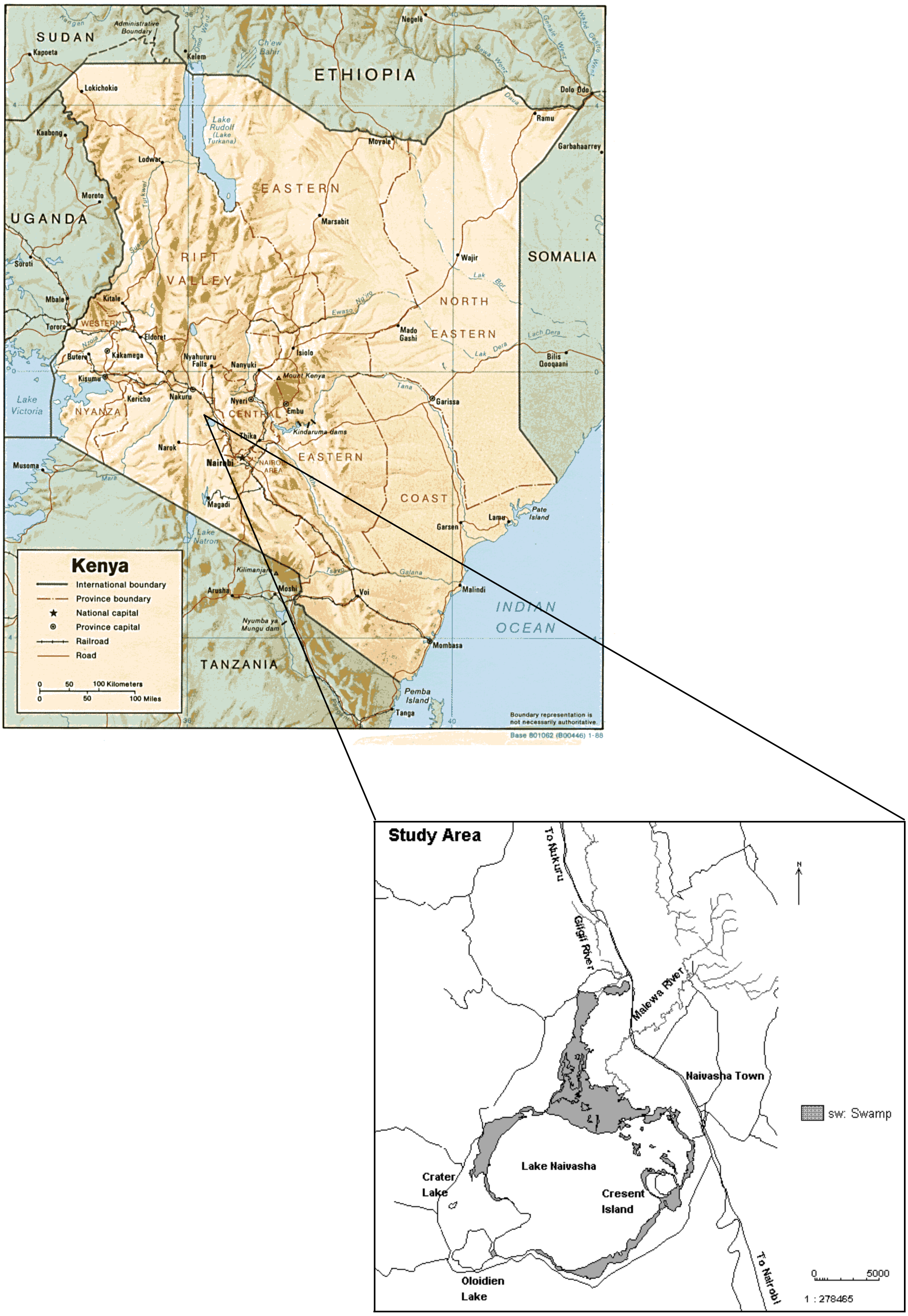
- Examination of potential of Duflow-DMS (pro's and drawbacks) for water system modeling of this tropical environment.
- Model of the water quantity of the lake based on DMS
- Analysis and recommendations based on the obtained results for the lake water quality management
- Analysis of the effect of some climatic variables on the mass balance of the lake
- Response of the lake applying the advection-dispersion equation to some potential spills of pollutant substances.

Chapter 2

2. Description of the study area

The highest of the Rift Valley lakes, Naivasha (Figure 2) lies at about 1880 masl (meters above sea level) the lake level varies quite considerably - in 1926 it was reported to be 6 m higher. Eons ago it was higher than that and its waters gushed through Njorowa gorge, which is located now above the lake and forms the entrance to Hell's Gate National Park. Lakes in the Rift Valley are normally saline unless water can escape through an outlet, however there is now no visible outlet to the Naivasha Lake. The supposition is that there are underground seepage maintaining the movement of fresh water brought into the lake by the Gilgil and Malewa rivers in the north [Beth Bliss, 1994].The Naivasha basin is situated in the East African Rift Valley, about 80 km north west of Nairobi. The basin is located approximately between 0° 00' to 1° 00' S and 36° 00' to 36° 45' E. This part of the Rift Valley covers the three lakes of Nakuru, Elementeita and Naivasha to the south. [Hamadudu, 1998].

Figure 2. Location of the study area. [Beth Bliss, 1994]



2.1 Lake

The Lake ecosystem consists of the main lake, at present, a small separated lake Oloidien and a smaller Crater Lake Sonachi. The main lake (water surface) is approximately 120-150 km^2 plus 12 - 18 km^2 of swamp. [LNROA, 1996] reported that the lake has a mean depth of 4.7 m, with the deepest part at the Oloidien Bay (9 m) and around Crescent Island (17 m). In 1997 the mean depth of the lake was calculated at 3.8 m [Donia, 1998]. Lake levels fluctuate between 1880-1890 meters amsl (above mean sea level, similar to those of the groundwater around the lake itself [Clarke, 1990]. Crescent Island is the highest part of the lake displaying a crater/cone feature. Water inputs to the lake include rainfall, inflow from surrounding rivers, runoff and underground water from the catchment. Outputs include direct evapotranspiration, water abstraction and groundwater outflow. The total catchment of the lake is approximately 3200 km^2. [Morgan, 1998]. According with the pollution sources inventory [Donia, 1998], the industrial (leading business) sector is the main point source of pollution in the area accompanied by the Naivasha sewage treatment works.

2.2 Water Quality

The major problem of the lake is the risk of eutrophication due to the high nutrient content. Streams carry sand, silt, clay, organic matter and other chemicals into the lake from the surrounding watershed. These materials settle out once they reach quieter waters, silting up the bottom with gradually thickening sediment layer. It is necessary to quantify and qualify the input from these rivers via establishing a model to simulate and predict the future influence of any activity in the watershed on the water quality. From the hydrochemical assessment, poor water quality for drinking water purposes was indicated from the range of fluorides. The groundwater is rhyolitic in composition resulting from silicate weathering as indicated from the source rock deduction analysis [Donia, 1998]. Generally speaking, the water quality of Lake Naivasha is in a good condition for irrigation purposes and when is compared with the irrigation guidelines, only $NO_3 – N$ slightly exceeds the guideline value. [Tang, 1999].

2.3 Hydrogeology

The Lake Naivasha sub-catchment is the most important of the Rift valley floor because of its fresh water status and its hydrochemical potential. It is most complex hydrogeologically speaking due to the rift floor geometry and tectonics. Young volcanic sediments cover the floor of the rift valley, which is a continuous unconfined aquifer with high permeability. It consists of reworked volcanic sediments and forms the major part of the Naivasha area. Estimated hydraulic conductivity averaged 10 m/d and a well yield on average of 3 l/s/m (liters per second per meter of depth) [Clarke, 1990].

Groundwater systems in the area are thought to be faulting controlled [Clarke, 1990]. In general faults facilitate groundwater flow as high permeability channels, in particular along the rift axis they create barriers to flow offsetting high permeability channels across the rift.

The Lake Naivasha catchment has an internal drainage system but no surface outlet; this is typical of Eastern Rift valley lakes where extensive volcanic activity disrupted the drainage system, creating these shallow lakes. The underground water inflow and outflow (seepage) accounts for the lake fresh water status. [Morgan, 1998].

2.4 Climate

The climate of the area is warm and semi arid (East African Meteorological Dept. 1964). Air temperatures moderate with monthly means varying little from 5.9 to 18.5 ° C. Seasonal variations in water temperature are also light ranging from 19.5 to 23 °C. at the surface and from 19.2 to 21.5 °C. near the bottom. The combination of moderate temperature, low relative humidity and low rainfall make January, February the months with highest evaporation.[Donia, 1998]

The wind is generally calm with velocities between 11 and 15 km/h, but there are some records showing the velocity can reach 21 km/h between August and October. Violent storms are also a common phenomenon and often lead to serious water movement in the lake. The wind direction is mainly from the southeast and the northwest depending on the season. Some strong winds have been reported along the rift valley especially through the window between Longonot and Kinangop hills. [Hamadudu, 1998]

2.5 Water budget and drainage

The drainage is characterized by an internal system without surface outlets. It has underground water inflows and outflows. The water budget studies show that the potential evaporation is close 2-3 times the amount of the annual precipitation over the lake [Ase, 1987]. There are a number of rivers around the lake but the two most important are the Malewa and Gilgil. The two rivers together constitute about 90% of the total river flow into the lake. The Malewa River has an annual mean discharge of 153 E+06 m^3 and the Gilgil 24 E+06 m^3 meanwhile the third largest river the Karati contributes only 2.1 E+06 m^3/year. The preliminary water budget for the area included in the lake management plan is showed in the Tables 1 and 2.

Table 1. Annual variables used in the water budget. [LNROA, 1996]

Variables	Wet Conditions	Mean Conditions	Dry Conditions
Direct rainfall on the lake	939 mm	608 mm	442 mm
Open water evaporation	1529 mm	1529 mm	1743 mm
Transpiration from swamps	2141 mm	2141 mm	2440 mm
Area of swamps	18 km^2	12 km^2	9 km^2
Area of lake	150 km^2	120 km^2	102 km^2
Lake storage (10^6 m^3)	600	320	50
Average lake level (a.m.s.l)	1888.3	1885	1882.3

Table 2. Preliminary annual water budget in $10^6 m^3$ [LNROA, 1996]

Inputs	Wet Conditions	Mean Conditions	Dry Conditions
Direct rainfall on the lake	140.8	72.9	45
Malewa river	378	153	53
Gilgil river	74	24	3.2
Karati river	6.5	2.1	0.28
Watershed ungauged area	117.8	77.9	34.2
Seepage-in	54	54	32
Total inputs	771.1	383.9	167.7
Outputs	**Wet Conditions**	**Mean Conditions**	**Dry Conditions**
Loss due to transpiration	38.5	26.7	21.9
Evaporation loss	229	183.5	177.8
Seepage out	54	54	32
Abstraction (estimated)	33.8	44.6	53.2
Total outputs	355.3	308.8	284.9
Balance	**+ 415.8**	**+ 75.1**	**-117.2**

This budget was updated by Gitonga based on a long-term analysis (1932-1997), the results are shown in the Table 3.

Table 3. Long term water balance for Lake Naivasha. Units: $10^6 m^3$ [Gitonga, 1999]

Month	Discharge	Precipitation	Ground water flow	Ground water Outflow	Evaporation	Storage change	Level change
January	11.00	4.87	0.0948	4.60	25.4	-14.0	-0.097
February	8.03	5.32	0.272	4.60	24.2	-15.0	-0.103
March	9.19	8.12	0.323	4.60	26.5	-14.0	-0.097
April	21.90	1.69	0.300	4.60	20.8	14.0	0.097
May	34.70	1.16	-0.116	4.60	22.2	19.0	0.131
June	20.10	6.81	-0.339	4.60	20.2	1.80	0.012
July	19.80	5.73	-0.139	4.60	20.3	0.42	0.003
August	24.10	6.79	-0.067	4.60	22.0	4.20	0.029
September	22.10	7.15	-0.125	4.60	23.2	1.60	0.110
October	19.30	7.89	-0.0846	4.60	24.5	-1.90	-0.013
November	19.80	9.22	0.0138	4.60	19.6	4.90	0.034
December	13.00	6.12	-0.0649	4.60	22.3	-7.90	-0.054

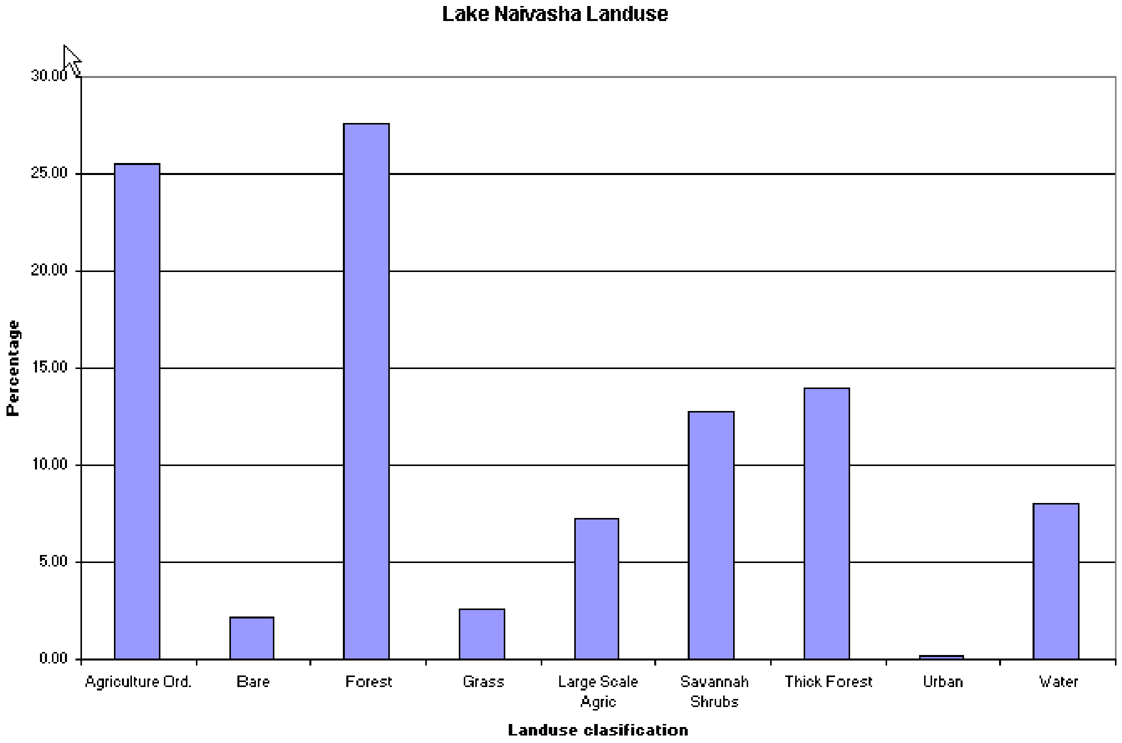
2.6 Soils

The soils around the lake have been developed on sediments from volcanic ashes. They are deep, dark grayish brown to dark brown, firm, saline, sodic and little calcaric, fine gravelly, sandy clay loam to sandy clay with humic topsoil. These soils have a low agricultural fertility and poor workability but give, nevertheless, very high yields due to the irrigation possibilities and good farming management. [Hamadudu, 1998]

2.7 Land Use

Forests and agriculture dominate the area. The forest is dominated mainly by the whistling thorn tree (Acacia seyal) and near the lake the "yellow fever tree" (Acacia xantophloea) is common, other species are the Tarconanthus camphratus, Solanum incanum, and Acacia nilotica. Agriculture is a growing practice around the lake mainly like horticultural farms that have increased in terms of irrigated area from 981.8 ha in 1988 to 7353 ha in 1998. [Tang, 1999]. The following graph presents the landuse of the study area.

Figure 3. Lake Naivasha Landuse (Adapted from Hamadudu).



2.8 Population, settlements

According with the LNROA management plan, there are 250000 people living around Lake Naivasha (often in inadequate housing and unsanitary living conditions) who can be considered as a potential threaten for the lake water quality; this number includes the Naivasha town with 45.000 inhabitants approximately and a 40% sewage covering.

2.9 Main pollution sources

The main pollution sources are:

- Nutrient enrichment and pollution (including pesticides) from agricultural activities in the lake's catchment and surroundings
- Toxins from the resulting ashes of burning Papyrus (Cyperus papyrus)
- The sewage and storm drainage from the urban population around the lake and some illegal settlements
- Unchecked commercial fishing activities are potential pollution sources
- The industrial sector in the area of study is mainly related with dehydration of vegetables dairy products, and wine production. Donia [Donia, 1998] identified 12 pollution sources in the study area with some preliminary chemical analysis.
-

2.10 Fertilizers use around Lake Naivasha

Mostly the soil is unable to provide sufficient nutrients to attain full potential yield. To supplement soil supplies fertilizers are applied. They provide major plant nutrients nitrogen, phosphorus and potassium (N, P and K respectively). Sometimes fertilizers are fortified with trace elements such as boron, magnesium and manganese. There are two types of fertilizers based on the requirements of the crops, straight consisting of a single substance providing one, or occasionally two major nutrients and the compounds that provide two or three major plant nutrients. At present chemicals are used specifically for compounds and total nutrient contents of over 50% are possible. [McConnell, 1976]
The main fertilizers used around the lake are NPK (15:5:30), ammonia sulphate, calnitrate, microsol MAP (commercial name), potassium nitrate and urea as sources of Nitrogen, Phosphorus and Potassium. The microelements correspond to the type of crop and the desired final product (i.e. color of roses).

2.10.1 Nitrogen

Nitrogen is used by plants to synthesize protein and chlorophyll, which utilizes sunlight in the synthesis of carbohydrates. The majority of nitrogenous fertilizers used are water soluble inorganic salts supplying N as nitrate (NO_3) or ammonium (NH_4) or a combination of both. Nitrate, unlike the ammonium form, is not held in the soil and is rapidly leached. The most known forms of nitrogenous fertilizers with its correspondent content of N are ammonium nitrate (34.5%), sulfate of ammonia (21%), nitrate of soda (16%), potash nitrate (15 %), urea (46%), and anhydrous ammonia (82%). [McConnell, 1976]

2.10.2 Phosphorus

Phosphorus encourages healthy root development, and the establishment and full development of crops, its deficiency results in stunted growth and a purple coloration, whilst excess causes premature ripening and loss of yield. Phosphate fertilizers are immobile in soil, being precipitated in forms only slightly soluble. The main inorganic phosphate fertilizers and the content of P_2O_5 are superphosphate (18-22 %), triple superphosphate (47%), ammonium phosphate (48-51%), basic slag (8-22%) and mineral rock phosphates (25-35%). [McConnell, 1976]

2.10.3 Potassium

Potassium is involved with health and efficient functioning of plants, improves resistant to drought and fungal disease. The K_2O is particularly required (a) when a crop is continuously removed, (b) where little farmyard manure is used, (c) where high N dressings are applied, and (d) for crops that make special demand on the nutrient. The most used forms of K_2O and its concentration are muriate of potash (60%), sulfate of potash (48%), kainit and potash salts (12-30%), nitrate of potash or saltpeter (40%).

Chapter 3

Description of collected data during the fieldwork

The data required to fulfil the proposed objectives consist of aerial photos, satellite images, topographic maps, water quality analysis, climatological data, and information collected from the ITC database and during the fieldwork survey. This field campaign took 4 weeks from September 6 – October 3, 2000 at Naivasha town like operations center. The area has been studied extensively in the past, therefore a number of reports, documents and thesis are available at the ITC library. The field trip broadening the perspective of the area giving the real context of the problems, general relief, topography, climatologic conditions, location and characteristics of the pollution sources. Based on the map of the study area, the field task consisted basically in the recognition of the town, farms, sewage treatment plant and main industries around the lake. Water and soil samples were collected in some of the drainage points from the main settlements, farms, the Malewa River and specific interest points at the lake. The fieldwork was developed during one of the driest seasons in Kenya, additionally the soil in the area is particularly permeable therefore the observed runoff was minimal, only during some sporadic rains was possible to collect water samples in the mentioned settlements. Patrick Gitaghe from the LNROA provided some of the samples taken during eventual rains around the lake. The description of the samples location and results are included in the Table 4, 5 and 6. The map in the Figure 4 shows the location of the sampling points around the lake.

Table 4. Summary of water samples and analysis carried out

Sample No.	Location	Date	Total Phosphorus [mg/l]	Kjeldahl Nitrogen [mg/l]	Observations
63	West side of the lake	210900	0.36	1.7	Aquatic vegetation and hippos
Malewa	Mouth of the northern swamp	210900	0.59	1.3	Aquatic vegetation and hippos
62	Mouth of the Malewa river	210900	0.14	1.4	
61	Open channel discharging the wastewater treatment plant and surrounding agricultural areas	210900	0.10	1.4	
Bh Village	Borehole in a neighborhood of Naivasha	290900	0.32	<1.0	
Sulmac 1	Sulmac Farm	140900	3.4	3.8	
Naiv. TownG	Runoff from the Naivasha town	260700	1.1	7.0	Taken by Gitaghe (LNROA)
Karagita Village	Runoff from the Karagita village	270900	3.1	12	
KaragitaG	Runoff from the Karagita village	240600	7.4	37	Taken by Gitaghe (LNROA)
LongonotG	Runoff from the Longonot farm	270900	0.94	3.9	Taken by Gitaghe (LNROA)

The soil samples were collected trying to identify the behavior of main nutrients in the subsurface and the chance to reach the lake via the groundwater flow. During the sampling program the moisture content was analyzed with a Thetaprobe soil moisture meter, the results are presented in the Table 5.

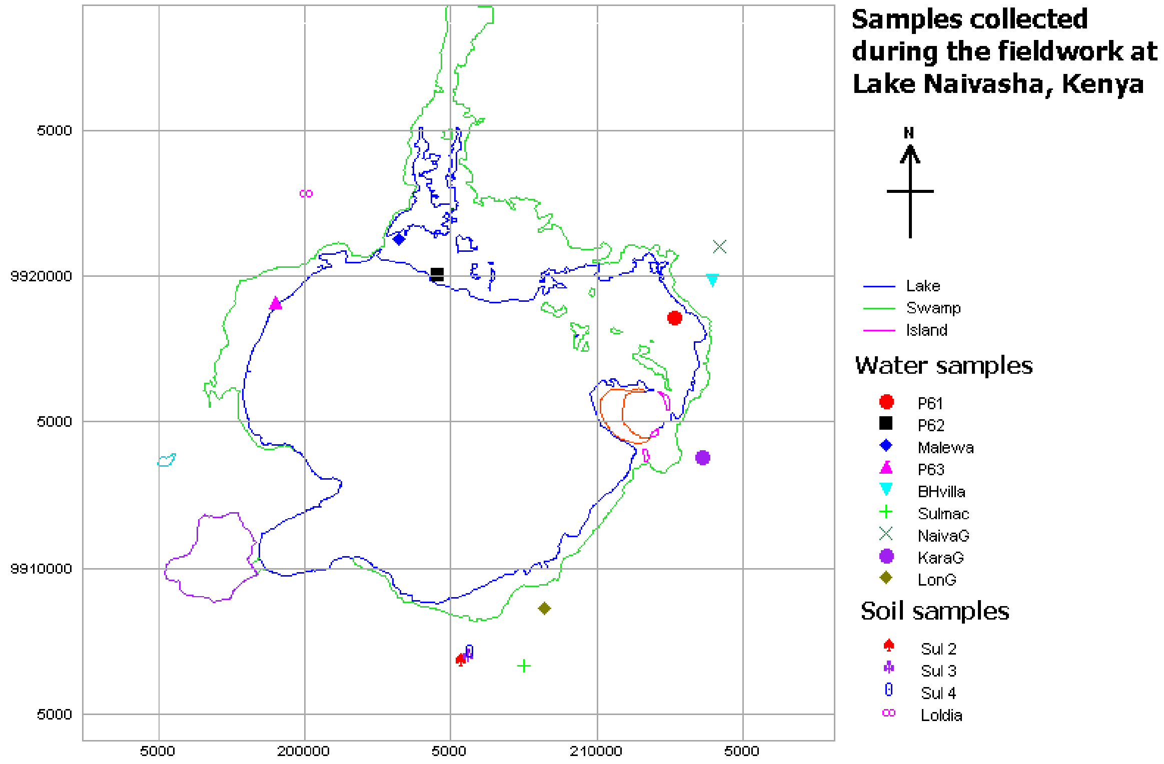
Table 5. Soil moisture content (m3/m3) of the samples taken around the lake

Sample No.	Date	Moisture content (m3/m3) at specified depth (m)								
		0.00	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00
Sulmac 1	150900									
Roses 6	280900						0.2			0.35
Roses 7	280900	0.21		0.16		0.16			0.27	0.34
Roses 16	280900	0.22	0.17	0.17	0.19	0.24	0.26	0.28	0.36	0.38
Loldia	280900	0.26	0.29	0.25	0.26	0.3	0.32	0.35	0.4	0.38

Table 6. Field observations of the soil samples

Sample No.	Location	Observations
Sulmac 1	Discharge ditch at Sulmac Farm	
Roses 6	Inside greenhouse at Sulmac	
Roses 7	Inside greenhouse at Sulmac	Very sandy at 1.00, at 1.75 is a white clay
Roses 16	Inside greenhouse at Sulmac	Change of color from light brown to yellowish at 1.00, very wet at 1.25 and the color is whitish at 1.5
Loldia	Cultivated field at Loldia Farm	

Figure 4. Location of the samples collected during the fieldwork survey



The table 7 shows the main fertilizers applied in two of the largest farms around the lake.

Table 7. Summary of fertilizers applied in Sulmac and Oserian farms by type of crop

SULMAC	**N**	**P2O5**	**K2O**	**Ca**	**MgO**	**B**	**Fe**	**Mn**	**Zn**	**Cu**	**Mo**	**HNO_3 (60%)**	**S**	**C. Area (Ha)**
Roses	29.3	16.6	108.9	62.0	21.2								75.6	43.7
Carnations	44.9	37.58	26.9	35.4	5.6								16.2	6
Gypsophilla	38.7	10.5	37.6	15.2	5.4								19.8	1.5
Hypericum	0.1	0.02	0.1	0.1	0.02	0.5	1.2	0.4	0.2	0.1	0.1	3.6		19.0
French beans	43.7	15.56	11.0	30.6	8.95	0.7	0.1	0.2	0.4	0.2	0.0		42.8	
Mange and Sugarsnaps	30.6	12.98	11.0	26.9	8.89	0.7	0.0	0.2	0.3	0.2	0.0		41.2	
Runner beans	39.3	11.10	23.0	27.5	6.75	0.6	0.0	0.3	0.2	0.2	0.0		38.4	
Squash	33.0	19.87	27.8	39.7	4.66	0.6	0.0	0.0	0.2	0.2	0.0		36.9	
Salads	38.1	20.80	23.6	0.0	1.07	0.0	0.0	0.2	0.1	0.0	0.0		2.4	
Total														**170.2**
OSERIAN														
Roses	43.7	0.2	56.9		16.1							16.1	29.6	60
Carnations					5.0	10.6							7.8	50
Gypsophilla	7.2		37.0		6.7							12.2	10.4	20
Total														**130**

Units: Kg/Ha/month

C. Area: cultivated area as reported by the correspondent manager, the totals refer to the whole-cultivated area in the farm.

The information is not easily accessible because of the character of some special fertilizers preparations used to get different results on similar products from competing farms, and also the programs are not continuous in time because of the market needs. The farms are adaptable systems to change crops very easily so the cultivated areas are estimated on a regular basis that can be variable.

The climatological information is not complete because was collected mainly at two farms, Oserian and Sulmac from a conventional station and an automatic station respectively. In the last case the station was installed in October last year and therefore, although the information is collected with high frequency (every 10 minutes), the data does not cover one full year. It collects data of humidity, precipitation, wind and temperature. Hereby the information about wind velocity and direction is only available from Sulmac farm and unfortunately there is no information available for the same period to compare the accuracy of the data. The wind direction is not correspondent with the prevailing reported direction from other sources and the accuracy of this information must be carried out in order to increase the precision of the model. The summary of the collected wind direction and velocity is presented in the Figures 5 and 6, the histograms were calculated from the arithmetic media average of the data available (November 1999 – September 2000).

Figure 5. Wind direction histogram derived from Sulmac farm data

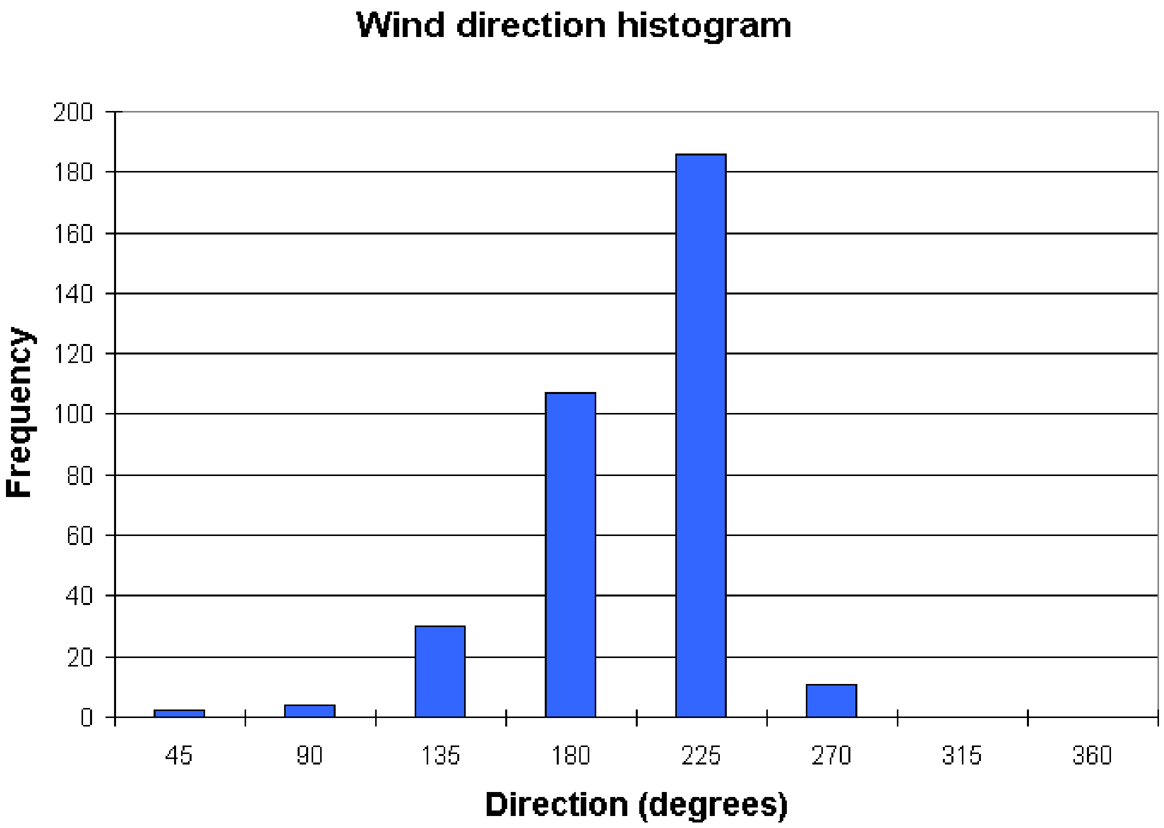
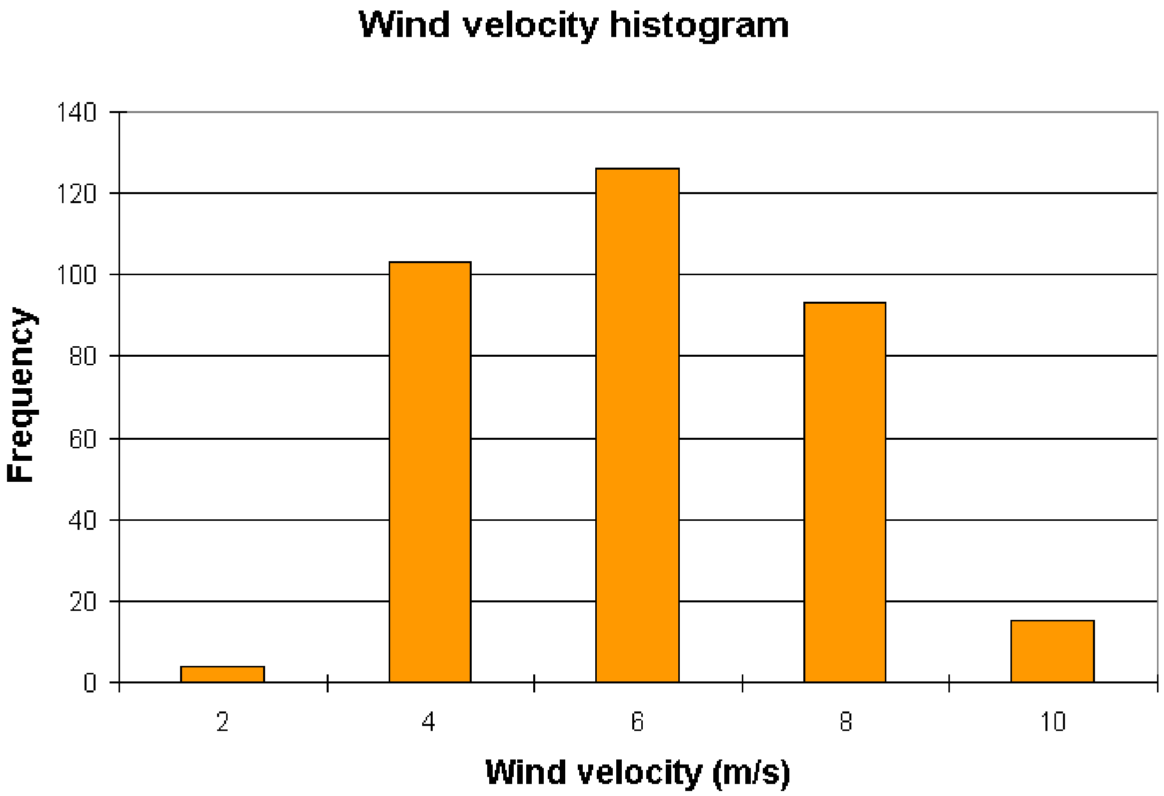


Figure 6. Wind velocity histogram from Sulmac farm data



The precipitation data was collected at Oserian and Sulmac but the values from the last one are quite low compared to the historical data, therefore are not included in the analysis. The data corresponds to the 1997-2000 period and the summary is presented in the Figure 7 and 8, the averages correspond to the total monthly average.

Figure 7. Precipitation average 1997-2000 from Oserian farm data

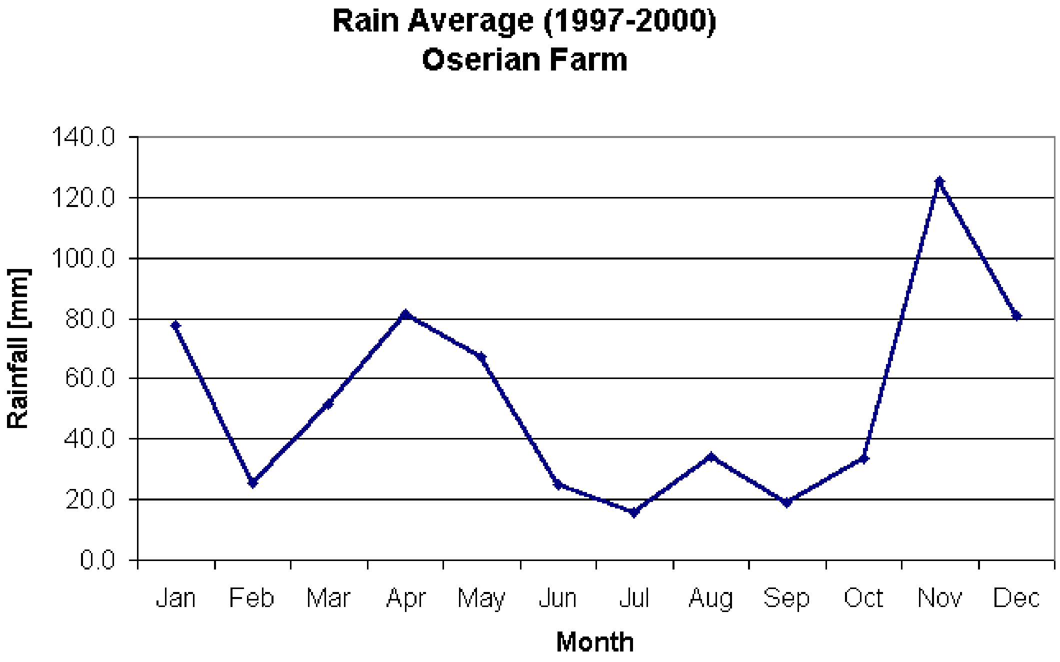
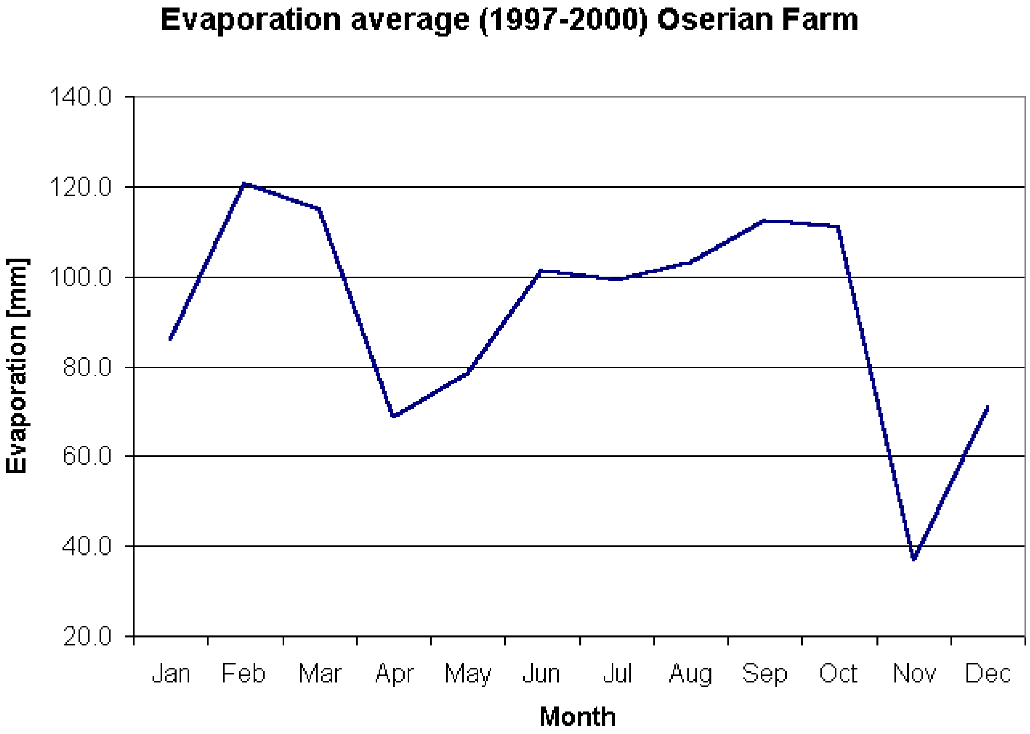


Figure 8. Evaporation average 1997-2000 from Oserian farm data



In order to analyze the different pollution sources it is suitable to include the hippo population as a non-point pollution source of nitrogen compounds, the table 8 shows the census of the last years.

Table 8. Hippo population around the lake 1997-2000

Date	Number of Hippos
March 1997	176
October 1997	213
March 1998	148
October 1998	109
April 1999	180
October 1999	186
April 2000	133

Provided by the chairman of the Nakuru wildlife forum Mr. Chris Campbell-Clause the data excludes the Malewa River (He reckons some hippo maybe missed during aerial counts. E.g. submerged).

Chapter 4

Building the Physical System

The physical system is a network where water flow and quality are estimated based on the one-dimensional partial differential equation that describes non-stationary flow in open channels and the one dimensional transport equation to describe the concentration of a constituent in one dimensional system as function of time and place. [Delft University of Technology, 1989, Delft University of Technology, 1992, Delft University of Technology, 1995, STOWA, 2000, STOWA, 1999, STOWA/EDS, 1998]

Flow

Equation 1

$$\frac{\partial B}{\partial t}+\frac{\partial Q}{\partial x}=0 \tag{1}$$

and,

Equation 2

$$\frac{\partial Q}{\partial t}+gA\frac{\partial H}{\partial x}+\frac{\partial(\alpha Qv)}{\partial x}+\frac{g|Q|Q}{C^2AR}=a\gamma w^2\cos(\Phi-\phi) \tag{2}$$

Equation 3

$$Q = v * A \tag{3}$$

where,

t	time
x	distance as measured along the channel axis [m]
H(x, t)	water level with respect to reference level [m]
v(x, t)	mean velocity (averaged over the cross-sectional area) [m/s]
Q(x, t)	discharge at location x and time t [m^3/s]
R(x, H)	hydraulic radius of cross-section [m]
a(x, H)	cross-sectional flow width [m]
A(x, H)	cross sectional flow area [m^2]
b(x, H)	cross-sectional storage width [m]
B(x, H)	cross-sectional storage area [m^2]
g	acceleration due to gravity [m/s^2]

C(x, H)	coefficient De Chézy [m^2/s]
w(t)	wind velocity [m/s]
Φ(t)	wind direction [degrees]
ϕ(x)	direction of channel axis measured clockwise from the north [degrees]
γ(x)	wind conversion coefficient [ ]
α	correction factor for non-uniformity of the velocity distribution in the advection term, defined as:

Equation 4

$$\alpha = \frac{A}{Q^2} \int v(y,z)^2 \, dydz \qquad (4)$$

Where the integral is taken over the cross section A [m^2]

Quality

Equation 5

$$\frac{\partial (BC)}{\partial t} = -\frac{\partial (QC)}{\partial x} + \frac{\partial}{\partial x}\left(AD \frac{\partial C}{\partial x} \right) + P \qquad (5)$$

where,

C	constituent concentration [g/m^3]
Q	flow [m^3/s]
A	cross-sectional flow area [m^2]
D	dispersion coefficient [m^2/s]
B	cross-sectional storage area [m^2]
x	x-coordinate [m]
t	time [s]
P	production or withdrawal of the constituent per unit length of the section [g/m.s]

4. The network

The first step to build the physical system is to establish a geo-referenced map in order to get results on a real geographic basis. The selected map contains the Lake's boundaries in Arcview shape file format easily imported into DMS and serving like a background layer including real UTM coordinates. The conceptual model is based on a simple network which subdivides the lake in straight wide channels where the laws of conservation of mass and of momentum can be applied based on the one-dimensional partial differential equation that describes non-stationary flow in open channels [Abbot, 1979] [Dronkers, 1964]. The simple grid-type network with 20 nodes and 31 sections was designed trying to cover the lake area but the limitations are evident because of the irregular natural shape of the lake compared with the rectangular shape of the proposed network. For the purpose of this thesis these limitations are accepted. The representation of a shallow lake by DMS used here was similar to the system used for water quality modeling of the "Noordeinderplas" lake te Niuewkoop.[STOWA, 1999].

4.1 Nodes

The nodes are points from which one or more sections arise or end, these sections represent the flow direction and include the cross section scheme establishing its shape, water depth and all the hydraulic elements which define the water flow along the mentioned section. The nodes are distributed in a regular fashion over the lake based on a 2500 * 2500 m grid built on ILWIS and imported as a shape file similar to the background layer of the lake.

4.2 Sections

The nodes are connected through sections that form a rectangular pattern (Figure 12). The length of each section is 2500 m, the flow direction was initially based on the flow patterns observed by Hubble [Hubble, 2000]. The Manning coefficient corresponds to a "channel clean, winding, some pools and shoals n = 0.040 "[Dingman, 1993].

4.3 Cross Sections

The selected cross section is the line type represented by a rectangle that changes its height based on the elevation taken from the DEM (Digital Elevation Model) of the corresponding starting and ending point of the section (Node). The cross sections were built up in such a way that the width times the length of all sections corresponds to the lake surface for a water level of 1887 m.a.s.l, approximately 145 km^2 [Gitonga, 1999]. And the total length times the width times the depth of all sections is approximately equal to the volume of the lake for those conditions (lake water level 1887 m.a.s.l, then volume 580.000.000 m^3). The dimensions of the cross section are 1870 m. wide, height variable depending on the location of the section and the lake water level, and length of the section is 2500 m.

4.4 Boundary conditions

Once the network is constructed and the steady state condition of the lake established through the channel representation, the inputs and outputs to the system are included as boundary conditions (discharge points). They are time series of data with positive or negative sign for input or output respectively. The input boundary conditions are the precipitation over the lake (estimated over the average of the exposed water area), the discharge of the rivers contributing to the lake water volume, the runoff from the Naivasha town and three representative farms around the lake calculated with the RAM (Runoff Precipitation Module) included in the DMS. The output boundary conditions are the evaporation (estimated from the exposed water area of the lake), the water abstraction (by the farms, industries and settlements) and the estimated groundwater outflow [Gitonga, 1999]. Other important parameters are the wind direction and velocity, the precipitation and evaporation for calculation of the RAM areas and the boundary conditions.

4.4.1 Time series

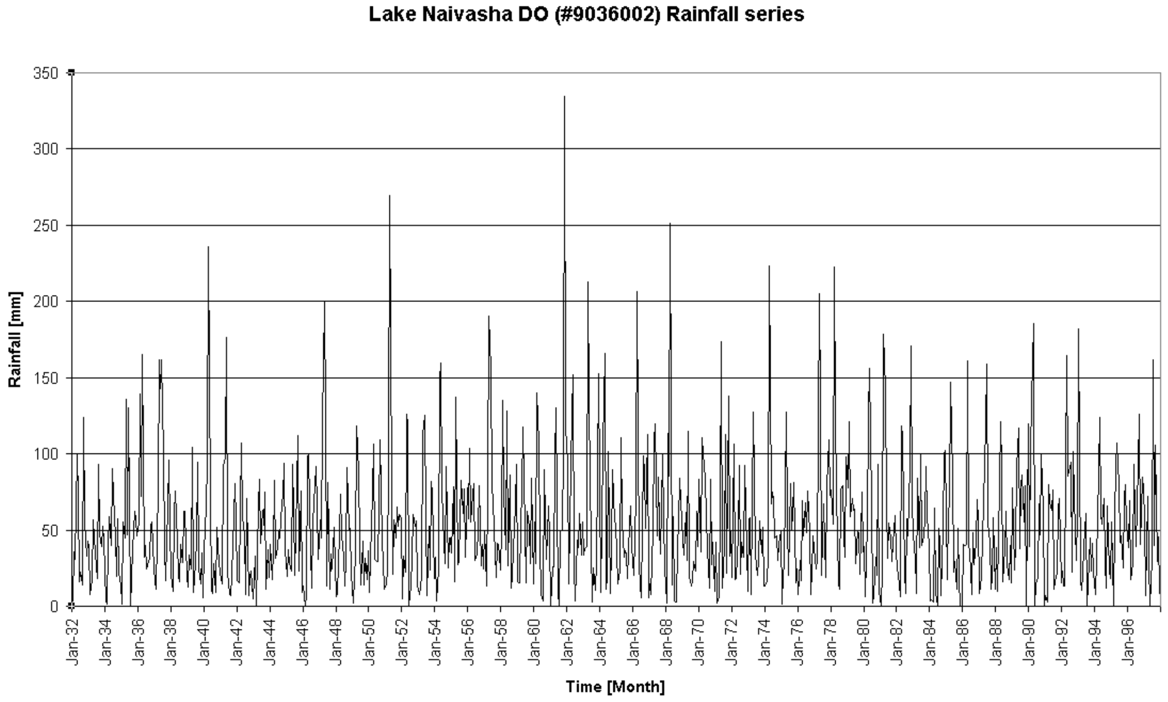
The first objective was to obtain a complete set of time series for all the inputs to the model, but in some cases like wind data the information available corresponds to a short 10 months period, although the readings were taken every 10 minutes. In others cases like the evaporation, the daily data was complete and consistent for the period between 1968 and 1990 [Gitonga, 1999]. This drove the decision to apply the model also on a long-term scenario for the period 1968-1990.

4.4.2 Precipitation

In general terms the rainfall is well distributed throughout the year with a discernible peak in April. Naivasha experiences an average rainfall of 610 mm/year and the evaporation is some 1360 mm/year, so the runoff from the non-immediate catchment would seem to be broadly sufficient to maintain lake level. [Stuttard, 1995]

The Naivasha district officer rainfall station (#9036002) is selected for the necessary rainfall data, some of the gaps in the series were infilled using a neighboring station from the Kenya Meteorological Department (#9036179) located at Korongo Farm on the western shore of the lake. The process was carried out considering the good correlation between them. [Gitonga, 1999]. Nevertheless the information was included as available and could contents some outliers and other inconsistencies.

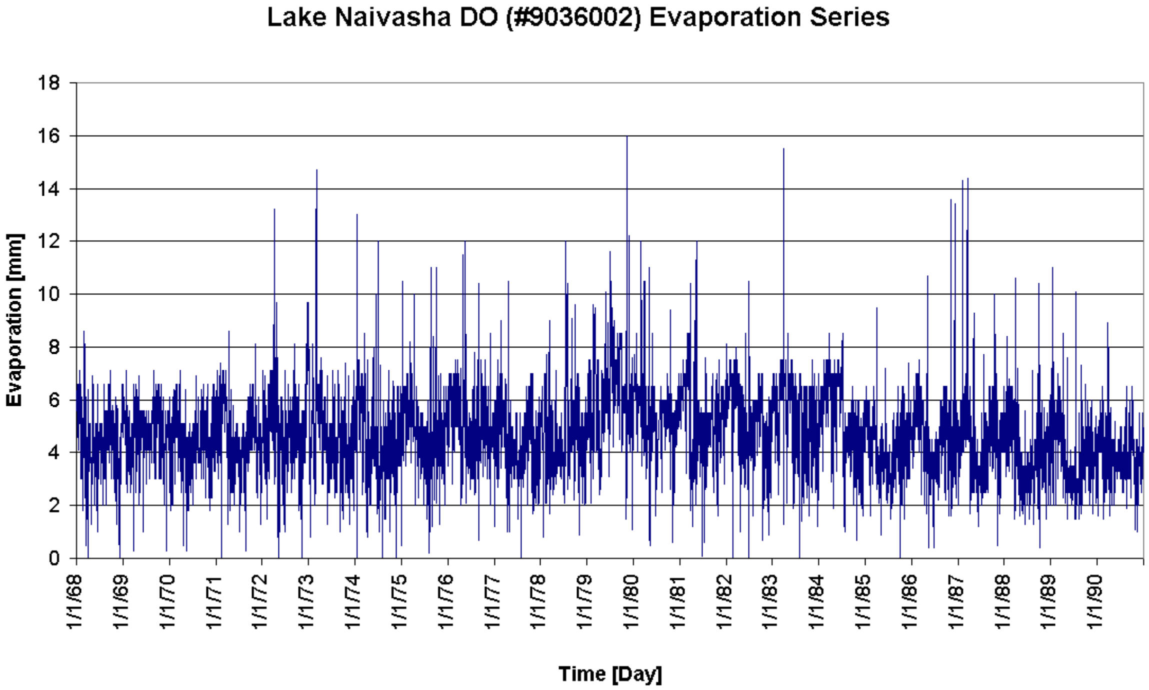
Figure 9. Naivasha DO station monthly rainfall series 1932-1997. (Adapted from Gitonga)



4.4.3 Evaporation

For the pan class A evaporation, the same station (Naivasha DO #9036002) is used, the figure 10 shows the registered values. Some of the data gaps (For the years 1958, 1972 and 1978) were filled using linear regression [Gitonga, 1999] and data from same periods over different years. As stated before the information was not processed but used as available and can contents some outliers and inconsistencies.

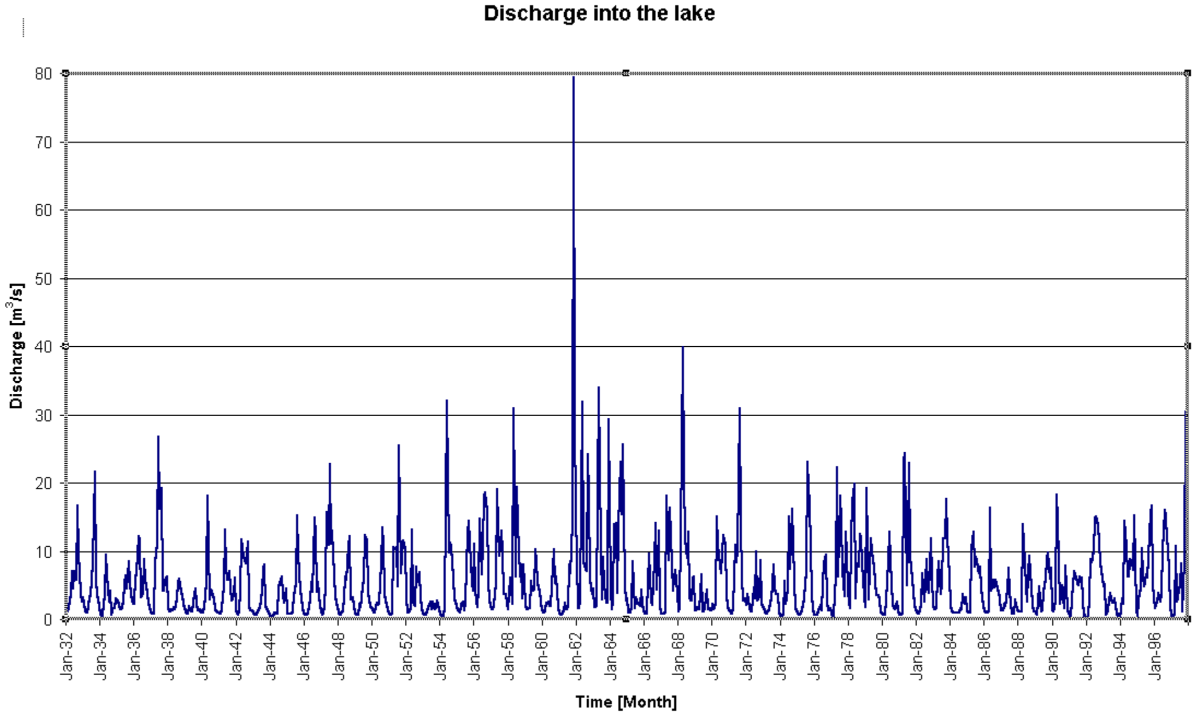
Figure 10. Naivasha DO station daily pan evaporation series 1968-1990



4.4.4 Discharge of the rivers to the lake

The Malewa River contributes with the 80-90 % of the inflow to the lake; the other two contributing rivers are the Turasha (seasonal) and the Gilgil that discharges over the lake through a long swamp. Gitonga [Gitonga, 1999] worked on the discharge series and using interpolation, simple and multilinear regression with neighboring stations to get the discharge series presented in Figure 11. The big discharge of 1961 was confirmed by Gitonga and like in the other cases (precipitation and evaporation) was included as supplied.

Figure 11. Monthly discharge time series of the Malewa river 1932-1997 [Gitonga, 1999]



4.4.5 Outflow from the lake

The lake does not have any surface outlet therefore the groundwater outflow was considered as constant over the time with a value of 1.2 m^3/s, based on the results of Gitonga and lately adjusted with the results from the model.

4.4.6 Wind

The wind velocity and direction data were obtained during the fieldwork for the period 1999-2000 (10 months) in 10 minutes intervals, from the automatic weather station installed on October 1999 at Sulmac farm offices. The data were converted in a Fourier series in order to cover the modeled period as one of the input options offered by DMS. [STOWA, 2000].

4.4.7 Discharges from the town and farms

As mentioned before, the runoff discharge from the Naivasha town and three representative farms around the lake is considered in the model using the RAM (Runoff precipitation module). The farms were selected because of the availability of the basic information and their close relation with the lake. Because of the RAM module works separately from the Duflow network and only contributes as a discharge time series, its parameters will be presented following the network description. The information associated corresponds to the samples collected during the fieldwork and analyzed in the Netherlands for Kjekdahl Nitrogen and total Phosphorus. (Table 4).

4.4.8 External variables

The external variables are associated with the water quality model used. The main variable calculated for all the scenarios is the dispersion coefficient applied in the one dimensional transport equation, this partial equation describes the concentration of a constituent in a one dimensional system as function of time and place. The calculation, according with Fischer and McQuivey and Keefer [Thomann and Mueller, 1987], of the longitudinal dispersion coefficient for rivers and streams is mainly based on the shape of the cross section, the slope and the velocity of the flow. The results of applying these equations was absurd (7500 m^2/s) because of the known limitations of the segmentation of a lake in channel sections that can not be treated as river sections. The Handbook of Hydrology [Maidment, 1993] states the clear difference between the dispersion coefficient applied to oceans and large lakes but once more the approach of the model is not suitable for the application of this calculation method. Finally the DMS user's manual [STOWA/EDS, 1998] suggests the following equation based on Fischer et. al.:

Equation 6

$$D = C_e n u R^{5/6} \sqrt{g} \qquad (6)$$

D = dispersion coefficient [m^2/s]
C_e = proportionality constant [$m^{1/6}$]
g = gravity acceleration [m/s^2]
n = Manning constant [$s/m^{1/3}$]
u = velocity on the river [m/s]
R = hydraulic radius [m]

The obtained value based on a typical section and applied for the rest is $D = 20.1\ m^2/s$. Because of a quite low L/W (length/width) ratio of the sections (2500/1870= 1.3), use of empirical equations from literature for estimating the longitudinal dispersion coefficient not always gave satisfactory results, generating instability in the water quality calculation. Many warning messages about instability in that process were received when the first calculations were performed, this instability can generate negative concentrations in the results or even worse, no results at all. Usually this instability is caused by a too large value of the Peclet number (Pe>2). If a chart is drawn where the concentration of a substance is shown against its position (in the network) it results most of the times in a heavily toothed chart, where for each calculation point alternating a minimum and a maximum is show.
The Peclet value is defined by: [STOWA/EDS, 1998]

Equation 7

$$Pe = \frac{v * \Delta x}{D} \qquad (7)$$

where:

Pe = Peclet value [ ]
v = Mean flow velocity (averaged over the cross sectional area) [m/s]
Δx = Section length (distance between two calculation points)
D = Dispersion coefficient [m^2/s]

To keep the stability of the calculation, the dispersion coefficient was increased to 150 m^2/s that is a reasonable value compared with some channels and rivers around the world. [STOWA, 1999]

In very wide shallow channel sections, with low flow velocities ($v<<0.1$ m/s), we can expect dispersion to be largely governed by wind forces acting upon the water. Therefore, velocity-based methods for estimating dispersion values may not be fully adequate. Also lateral dispersion (perpendicular to the flow direction), can be expected to be significant due to variable wind directions and forces. In this system, another method for estimating dispersion values could be recommended.

4.4.9 RAM rainfall-runoff modeling design

The RAM module included in the DMS program works as a tool to estimate the rainfall-runoff response from adjacent areas to a water body based on the mass balances of the different processes considered in the hydrologic cycle. The point of departure in the development of the precipitation runoff model is a model for operational use (simple set-up with a limited number of input parameters). This model corresponds to the soil moisture reservoir taken up in the Wageningen model. In this conceptual model the nature of the various processes is described ('soil moisture' reservoir for the storage in the unsaturated zone, convection-difussion equation and model Krayenhoff van de Leur for the quick respective slow ground water runoff). The parameters in the model do not have a direct (measurable) physical meaning, but should be determined by calibration. It is important to distinguish between the various runoff processes (surface runoff, interflow, drainage and slow ground water discharge) for a correct description of the water quality. The module presents three types of surfaces with subdivisions as follows. [STOWA/EDS, 1998]

- Water surface

- Paved surface

    - ☐ Paved surface in a rural area
    - ☐ Urban area
    - ☐ Greenhouse area

- Unpaved surface

    - ☐ Infiltration into the soil moisture (unsaturated zone)
    - ☐ Percolation into the ground water (saturated zone)
    - ☐ Ground water discharge into the drainage system

A general insight into the hydrologic cycle of a catchment area is obtained by setting up a water balance with the following form:

Equation 8

$$P + Qi + K = Qu + E + W + \Delta S \qquad (8)$$

In which

P	: precipitation in mm
Qi	: incoming flows in mm (originating from adjoining catchment areas)
Qu	: outgoing flows in mm
K	: seepage in mm
E	: evapotranspiration in mm
W	: downward seepage in mm
ΔS	: change in storage in the catchment basin for the reflected time interval in mm

The soil type around the lake is highly permeable and the observed surface runoff during the fieldwork time from the agricultural fields around the lake was not considerable. But considering that everything can change during the rainy season, is useful to run the model using the results from the surface runoff samples from Sulmac farm, Naivasha town and the Karagita informal settlement and apply them on the others farms on the basis of the irrigated area and crops developed to evaluate in some extent the capability of DMS to model the water quality of the lake.

4.5 RAM input generation

4.5.1 Area

One of the main characteristics of the RAM module is the possibility of performing a detailed partitioning of the contributing areas to the surface runoff. The following table shows the used percentages based on the combination of field measurements and digital image interpretation of the areas around the lake [Sayeed, 2001] and Naivasha town [Mbathi, 2001].

Table 9. Estimated surface areas for the RAM discharge calculation

Name of RAM farm/area	Total Area [Ha]	% Open water	% Greenhouses	% Sewer	% Other paved	% Unpaved
Three points	252.3	0	0	0	0	100
Naivasha	982.9	1	4	17	1	77
Aberdares	25.3	0	0	0	0	100
Oserian	738.2	0.1	21	1.5	0.4	77

4.5.2 Q open water surface

In practice, no open water surfaces were present in the RAM areas (town and farms) so, hardly any slowing down of the discharge through open water will occur. In this case a value of 0 can be taken as time constant reservoir. The crop factor for open water is equal to E_0/E_R in which E_0 is the open water evaporation according to Penmann. The factor varies somewhat but may approximately be equated to 1.25. [STOWA/EDS, 1998] The table 10 shows the values entered for the calculation.

Table 10. Input values used in the discharge from open water surface calculation

Name of RAM farm/area	Time constant reservoir [day]	Crop factor Makkink [ ]
Three points	0	1.25
Naivasha	0	1.25
Aberdares	0	1.25
Oserian	0	1.25

4.5.3 Paved surface

The paved surfaces are considerable only in Naivasha town and Oserian farm, the storage of water corresponds to a reasonable guess and information from the infiltration tests conducted during the fieldwork [Dao, 2001]. The order in the values corresponds to the sequence Sewer/Greenhouse/Other paved surfaces as established in the entry format to RAM calculation. Where one only value is supplied, it means the same for all categories was assumed. The table 11 shows the input values considered for the paved surface areas by farm.

Table 11. Input values used in the discharge from paved surface calculation

Name of RAM farm/area	Time constant reservoir [day]	Maximum storage in depressions [mm]	Storage in Reservoirs [mm]	% Open Surface	Pump over capacity [mm/day]	Infiltration capacity [mm/day]
Three points	0.0001	0/0/1	1/0/-	0/-/0	0/0/-	2880
Naivasha	0.0001	2/2/1	0.8/0.6/-	5/-/60	0/0/-	1872
Aberdares	0.0001	0/0/0	2/0/0	15/-/2	0/0/-	2570
Oserian	0.0001	3/0/0	1/0/0	4/-/0	0/0/-	1728

4.5.4 Unpaved surface settings

The values included in the Table 12 are indicative and were the best available averages from the existing soil and landuse of the area.

Table 12. Unpaved surface settings for the RAM calculation process

General attributes	Three points	Naivasha Town	Aberdares	Oserian
Infiltration capacity [mm/day]	288	187	187	172
Crop factor Makkink [ ]	1.25	1.25	1.25	1.25
Moisture storage at pF=0 [mm]	1040	1008	1008	1158
Moisture storage at pF=2 [mm]	770	821	821	1035
Moisture storage at pF=4.2 [mm]	391	335	335	445
Initial moisture storage [mm]	770	821	821	1035
Initial depth of the unsaturated zone [mm]	2000	2000	2000	2000
Pore content [ ]	0.520	0.504	0.504	0.639
Storage value in linear reservoir at which capillary rise is activated [mm]	2000	2000	2000	2000
Percolation to saturated zone between pF=0 and pF=2 (maximum) [mm/day]	288	187	288	172
Maximum capillary rise [mm/day]	0.0001	0.0001	0.0001	0.0001
Time constant reservoir unpaved surface [day]	0.0014	0.002	0.0014	0.0014
Time constant fast groundwater discharge [day]	0.0014	0.005	0.0014	0.0014
Time constant slow groundwater discharge [day]	0.0014	0.005	0.0014	0.0014
Distribution formula for fast and slow groundwater discharge [ ]	0	0	0	0
2 Nash cascades No. reservoirs Slow / Quick	1/1	1/1	1/1	1/1
Nash cascade/ Krayenhoff van de Leur No. reservoirs Slow (N) / Quick (K)				

The moisture storage is determined as the product of the length of the unsaturated zone and the volume fraction. (i.e. Aberdares moisture storage at pF(2) = 2000 mm*0.416 = 821 mm), the moisture content values were calculated on samples taken by Jolicoeur.[Jolicoeur, 2000]

4.5.5 Discharge or flow from seepage (Q seepage)

These values are derived from the properties of the soil analyzed before but must be tested in the field for proper calibration of the model.

Table 13. Discharge from seepage input values

Name of RAM farm/area	Vertical hydraulic resistance of covering layer [day]	Hydraulic head difference covering layer and water transporting package [m]
Three points	10	2
Naivasha	10	2
Aberdares	10	2
Oserian	10	2

4.5.6 Ammonium, Nitrate and Phosphorus

The collected samples were analyzed for Total Nitrogen Kjeldahl and Total Phosphorus. Based on comparisons with samples and analysis collected for other studies the following ratio was established and compared with the target values supplied in the RAM Reference Manual. It is recommendable to collect samples during the rainy season and run the required analysis in order to fulfill the water quality model parameters.

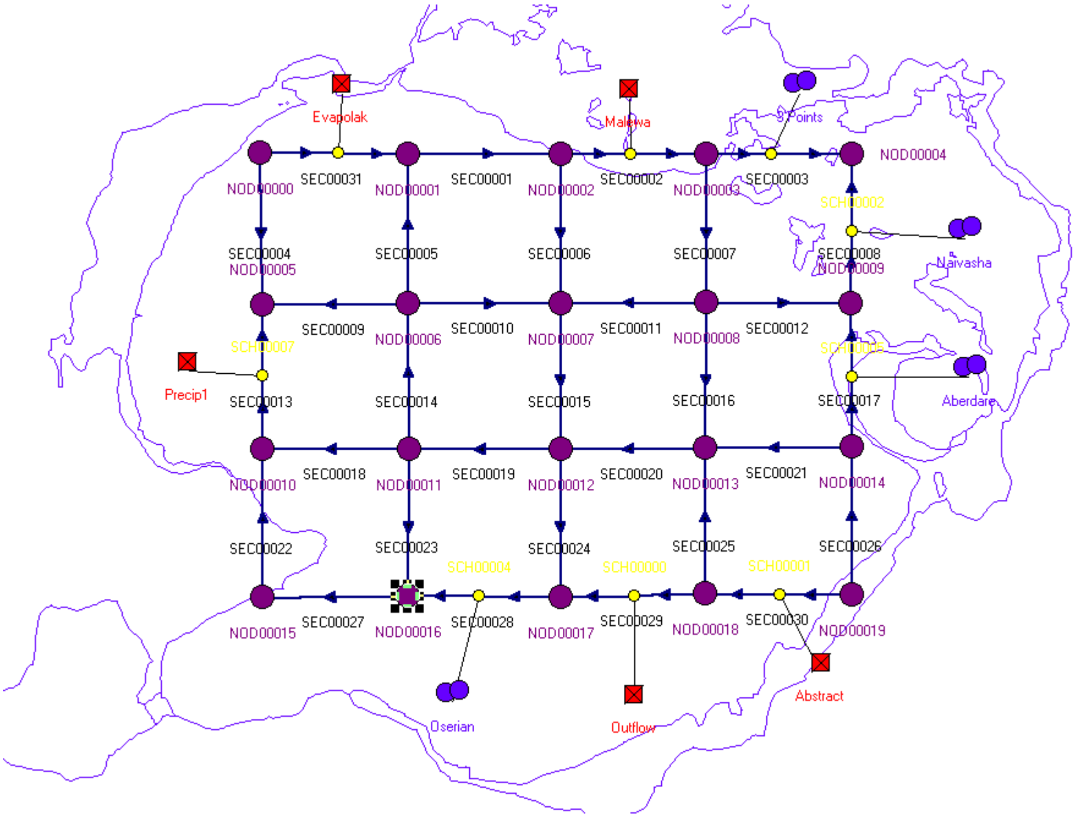
Total nitrogen Kjeldahl = 78 % (Ammonium) + 20% (Nitrates) + 2% (Nitrites)

Considering the selected farms grow similar type of vegetables and flowers the same concentrations in terms of ammonia and phosphorus were applied in all of them. In the case of Naivasha town the same ratio was used but calculated over the results obtained from the sample taken in one of the rain water channels.

4.5.7 The final physical modeling system (network)

Finally the Figure 12 shows the network where the jointed round points represent the RAM areas and the boxes with internal crosses the flow and quality boundary conditions (rainfall and evaporation over the lake) as discharge points, the Malewa river discharge, the water abstraction and the groundwater outflow.

Figure 12. DMS network representing Lake Naivasha



4.5.8 Modeling Scenarios

All the scenarios were run with the same physical network setup with some changes in the initial and boundary conditions and eventually in the quality model. The modeled periods are changed to check time variations and accuracy using different data sets.

4.5.9 Scenario 1: Longterm flow scenario, lake level simulation

In order to get a system capable of predicting in some extent the possible reactions of the lake in terms of quality and quantity, the first necessary step is to calibrate that one to follow the historical behavior of the lake. This scenario called long-term flow scenario simulates dynamically the water balance of the lake based on the long time series prepared by Gitonga.

- Modeled time period

The modeled period extents from January 1968 to December 1990 on a daily basis, although some information is on a monthly basis (i.e. the precipitation and Malewa river data), trying to keep the collected information as original as possible and also test indirectly its accuracy and trustiness.

- Calculation settings

✓ Calculation type:	Flow
✓ Resistance Formula:	Manning
✓ Time step size :	1 day

- Initial conditions

The initial conditions for this scenario correspond to the lake water level for January 1968, 1887.87 m.a.s.l. This defines the water depth for the cross sections at each node as was explained in 4.3 Cross sections.

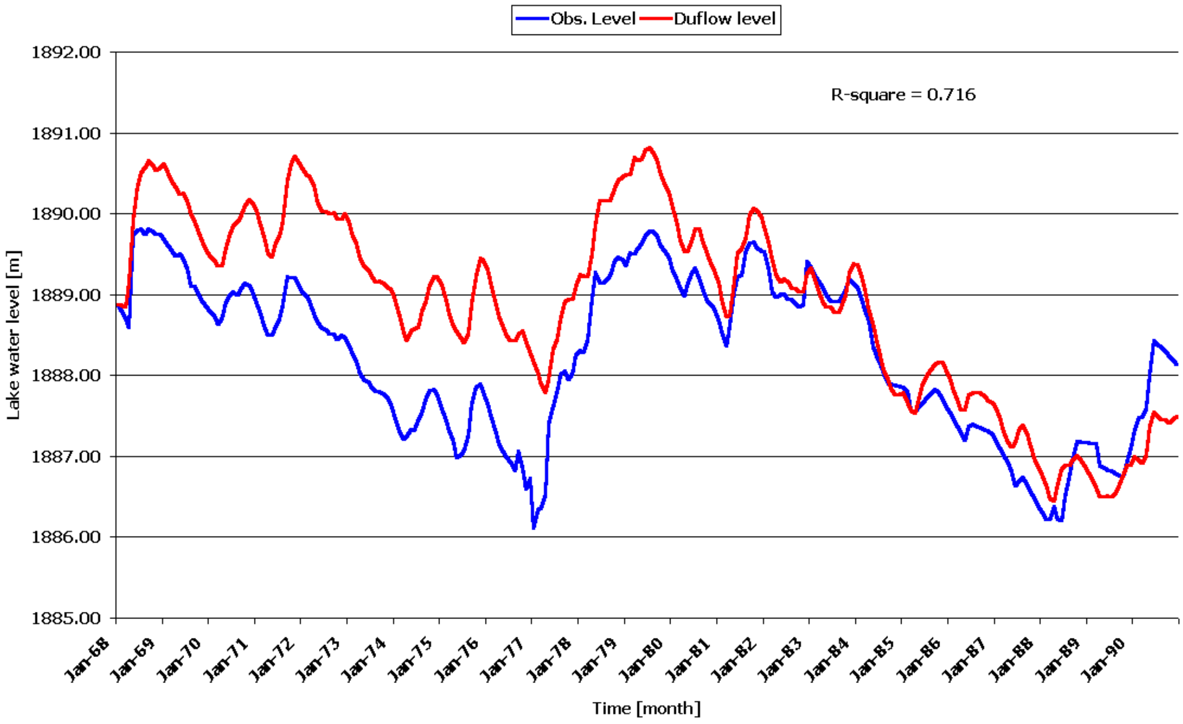
- Boundary conditions

The evaporation, precipitation and input from the Malewa river added to the RAM areas (Three points farm, Naivasha town, Aberdares farm and Oserian farm) in time series schemes are the inputs to the system. The only output of the system is the groundwater discharge located in the southern part of the lake with a constant value of 1.2 m^3/s (estimated from the long-term water balance [Gitonga, 1999]and calibrated for the model). The initial conditions are the water level of the lake in January 1968, used also as datum for the calculation of the height of the flow in the cross section scheme and the flow directions based on the DEM information.

- Results

No warnings or error messages were generated by the DMS in this simulation run set up. The figure 13 illustrates a comparison between simulated and measured lake levels for the 1968 – 1990 period.
The regression analysis shows that the model explains about the 72 % of the measured lake levels, although the value is satisfactory could be improved by creating a discharge-area scheme for the calculation of the precipitation and evaporation over the lake. These values were calculated for the average of the lake area, which induces some errors, but for the purpose of this thesis comply with the formulated objectives, demonstrating the capability of the system of modeling the lake water level.

Figure 13. Comparison between the historical and simulated lake levels at the section number 15 (center of the lake) for the 1968-1990 period.



An additional adjust was necessary to fit the initial observed lake level because of the differences between this one and the level (bottom lake level at the starting node + length of the water column at the same node) calculated from the DEM and used in the simulation. Considering that the wind velocity and direction corresponds to data in Fourier series form, it is still possible to get better accuracy and finer calibration by obtaining a time series, preferably on a daily basis, and running again the model. It is also possible to correct the RAM areas contributing to the lake in terms of discharge (runoff) considering they are taken from satellite imagery and fieldwork survey developed in 2000 and the modeled period corresponds to 1968 – 1990. Is possible some changes in the surfaces characteristics considered in the model could have changed in that period (i.e. new greenhouses, more paved roads, etc). It is also necessary to calculate all the farms' surface runoff because here only 4 big areas were included in the calculation process. Additionally some considerable error is introduced keeping the groundwater outflow constant over the time considering that it could be variable according with the different levels of the lake (Pressure head differences).

4.5.10 Scenario 2: Short term flow and lake level scenario

A short time scenario was built in order to evaluate the sensitivity of the system to changes for a number of boundary conditions (i.e. wind, precipitation, and evaporation) on a short time basis. The scenario was planned according to the wind data available and the information collected during the fieldwork survey.

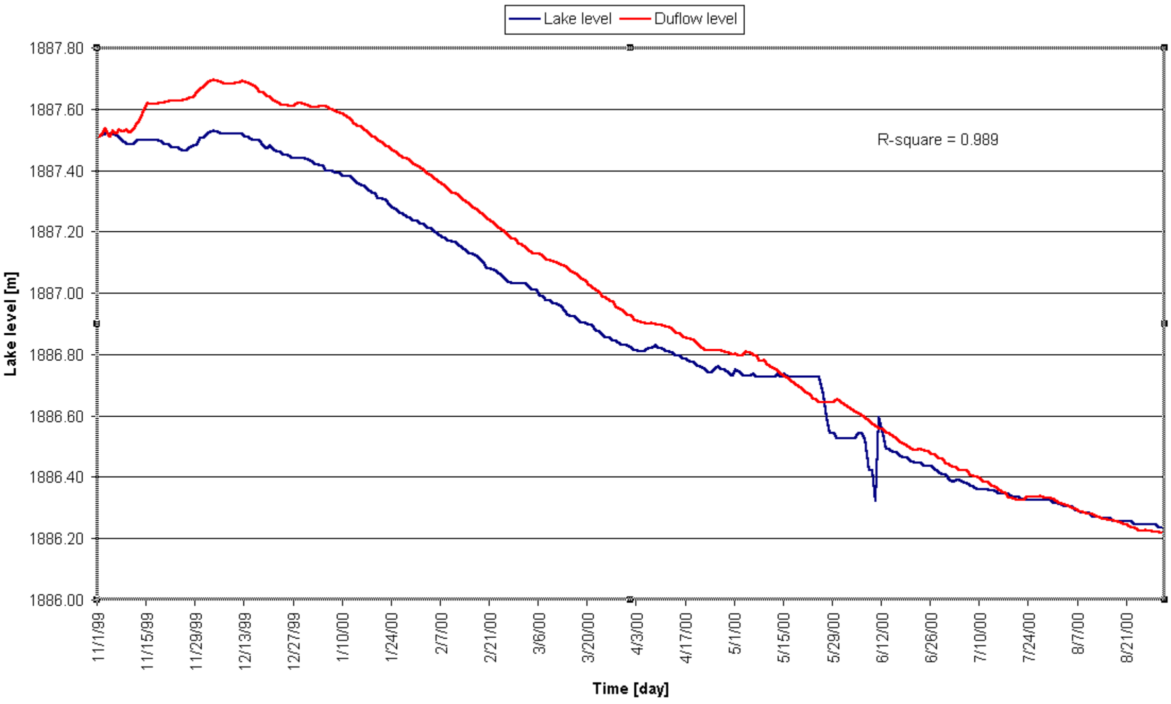
- Modeled time period

The chosen time-period corresponds to the available wind data (November 1999 – August 2000) in order to evaluate its real daily effect instead of the Fourier series used in the first scenario.

- Boundary conditions

The precipitation and evaporation data correspond to the information collected at Oserian farm during the period. These data sets also change the precipitation and evaporation values applied to the lake water surface. In this scenario some changes over the network were made, the estimated water abstraction for the town, industries and farms are included with a constant value of 1.5 m^3/s. This information was not included previously in scenario 1 because of the abstraction was considered to be minimal before 1985.

Figure 14. Comparison between the historical and simulated lake levels for Scenario 2 at the section number 15 (1999-2000)



- Results

The simulation seems more accurate, possibly because of the main data like precipitation, evaporation and inflow from the Malewa river were all entered on a daily basis making easier the fine tuning. Additionally the model is run for a ten-month period and following a constant trend in the "target" lake levels. The Figure 14 shows an unusual behavior in the observed lake level apparently due to the absence of data from the normal source (Yacht club from May 1999 – June 1999). The data for this period was taken from the Loldia Farm and seems to have a strange change for the cited days.

a) Wind effect on water flow velocity and directions on the lake

To evaluate the effect of the wind over the lake water level two simulations runs were made i.e. with and without included in the calculation process. The comparison with the normal situation is evaluated using the flow velocity in the channel section number 15 for the normal conditions in the Figure 15 and excluding the wind factor the in Figure 16. The effect is considerable comparing 12 cm/s for the first case and 0 cm/s for the second one. This could confirm the "completely mixing" assumption cited by some authors [Hubble, 2000], [Gaudet and Melack, 1981] and confirmed also through the temperature and dissolved oxygen measurements developed in the lake during the fieldwork survey [McLean, 2001].

Figure 15. Water flow velocity in section number 15 for realistic weather conditions (wind direction and velocity also included in the calculation)

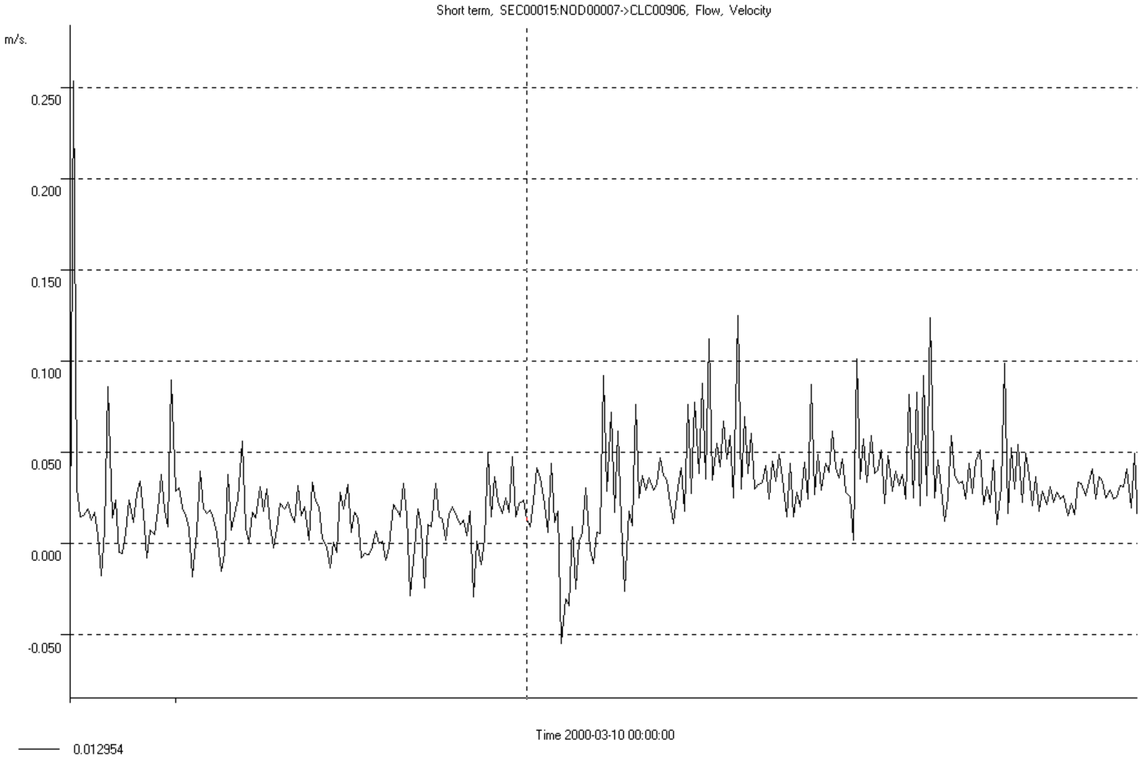
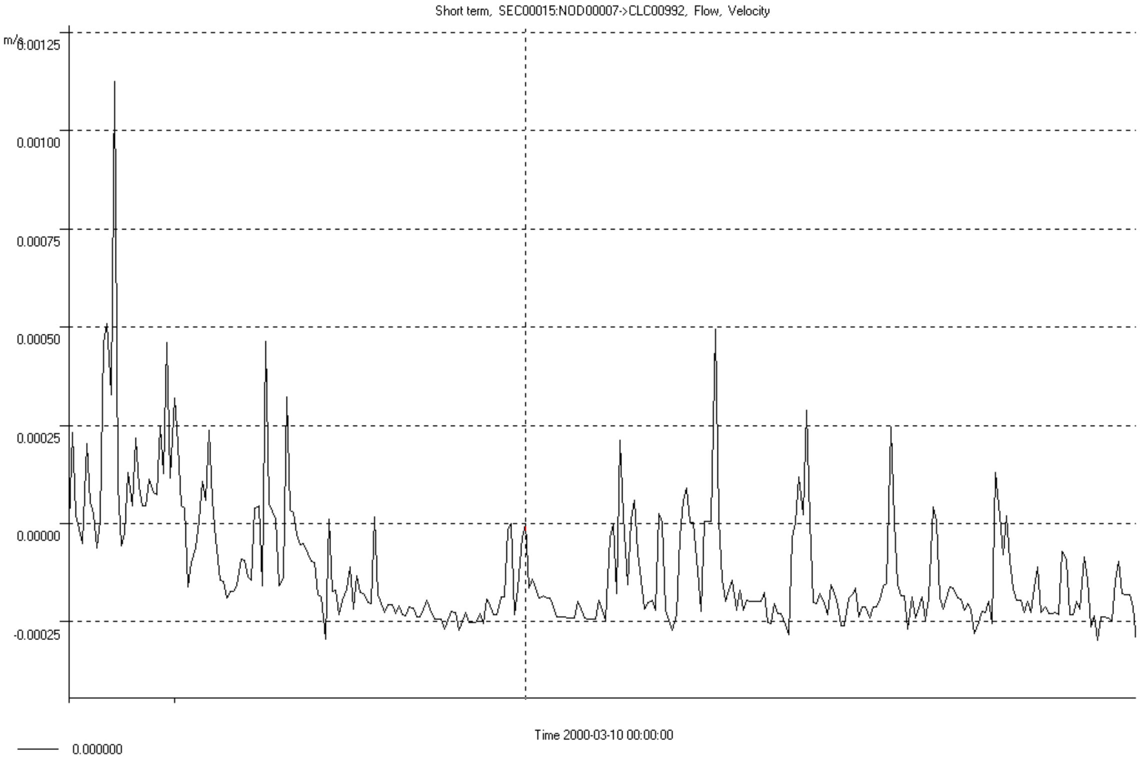


Figure 16. Effect of the wind in the flow calculation. Flow velocity in section number 15 under "no-wind" conditions (wind direction and velocity are excluded from the calculation)



The wind effect was also evaluated in terms of discharge at the end of the same section and the results demonstrate the importance of the wind in the model used by DMS for the flow calculation as Figures 17 and 18 show it.

Figure 17. Effect of the wind in the flow calculation. Water discharge for the section number 15 in normal conditions (wind direction and velocity are included)

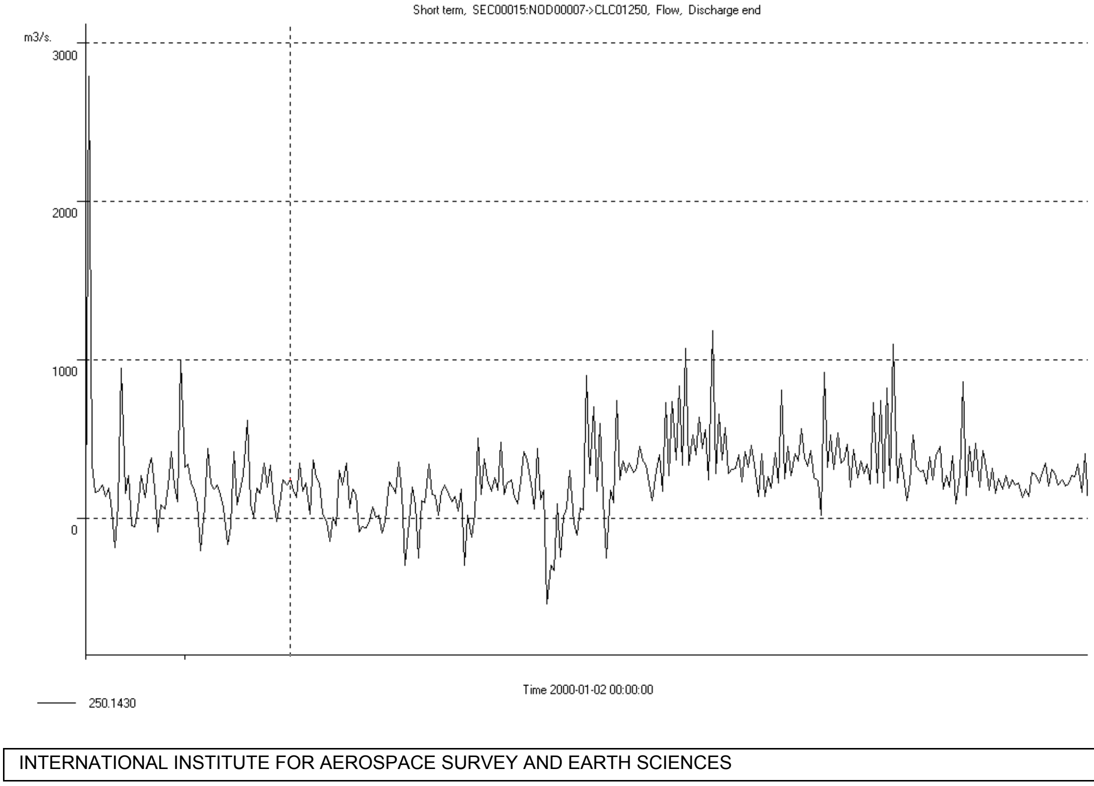
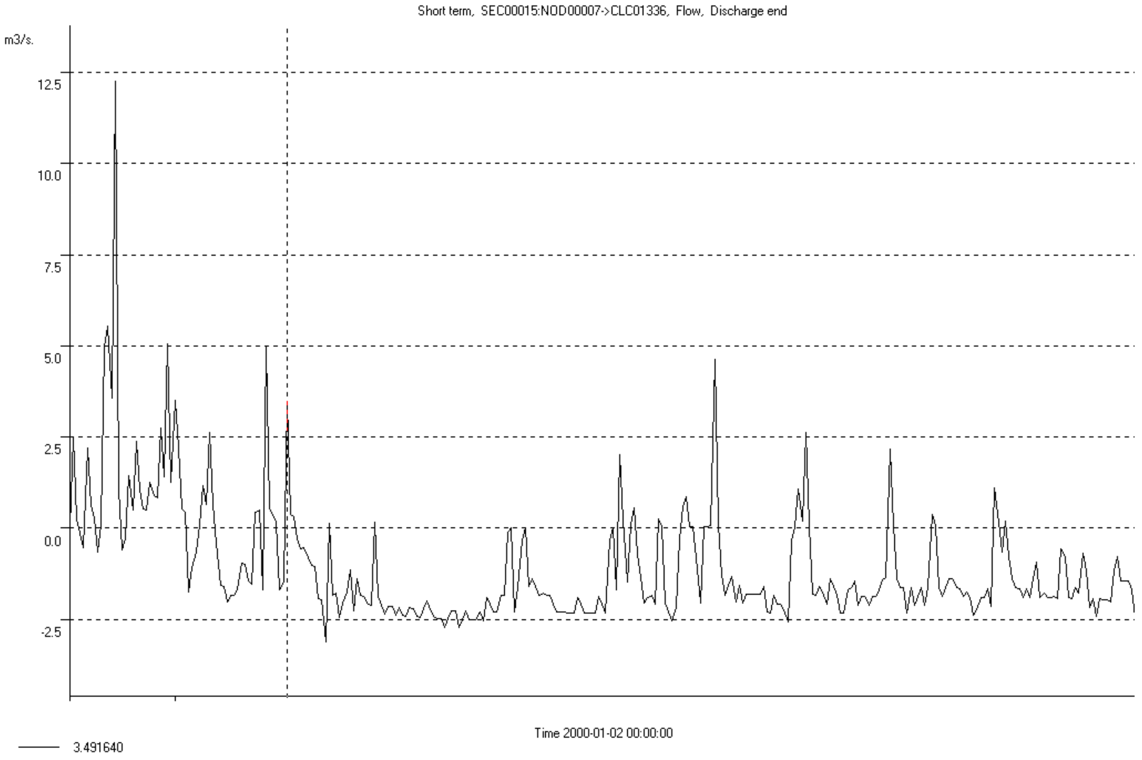


Figure 18. Effect of the wind in the flow calculation. Water discharge for the section number 15 in abnormal conditions (wind direction and velocity are excluded)



The effect of the wind was used to set up the proper direction of the flow in all the sections evaluating the velocity and assuming that the positive velocity corresponds to the correct direction of the flow in the section.

b) Wind effect over the flow direction in the section

The flow velocity in some sections demonstrated that maybe the first flow direction assumed according to the bathymetry of the lake [Donia, 1998] and the flow patterns described by Hubble, were not correct and the influence of the wind on the water column is larger than the assumed one; considering also that the shallowness of the lake increases this effect. The following figures present the flow velocity in one section based on the first guess and the corrected one after run the model.

Figure 19. Effect of the wind in the flow calculation. Flow velocity for the section number 21 based on the observed lake flow patterns

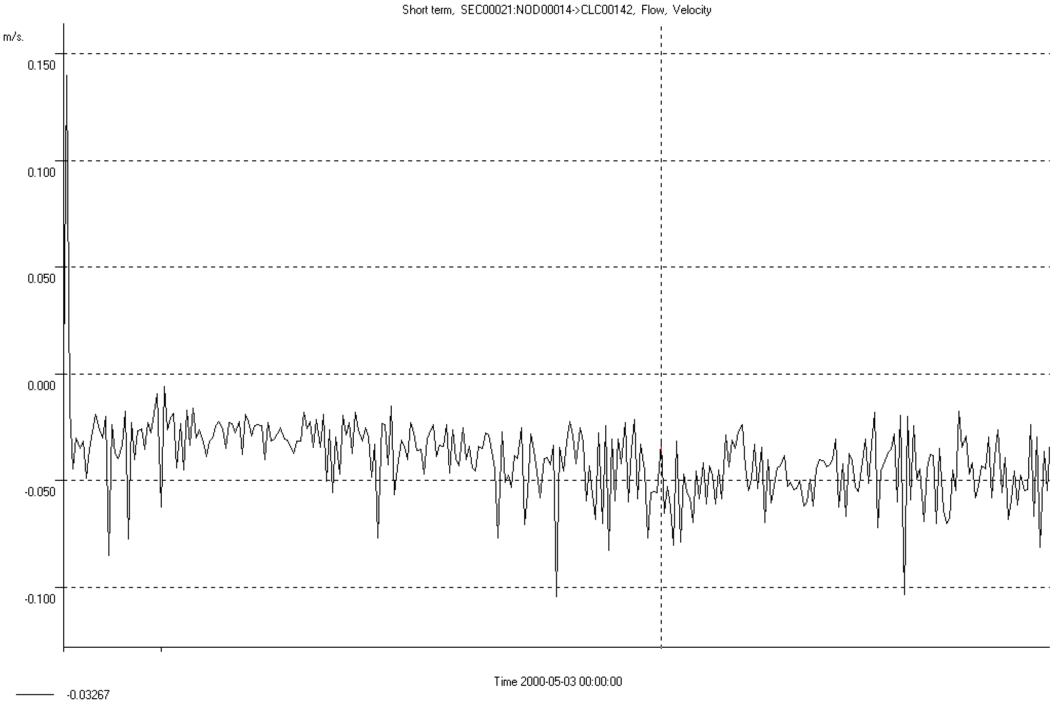
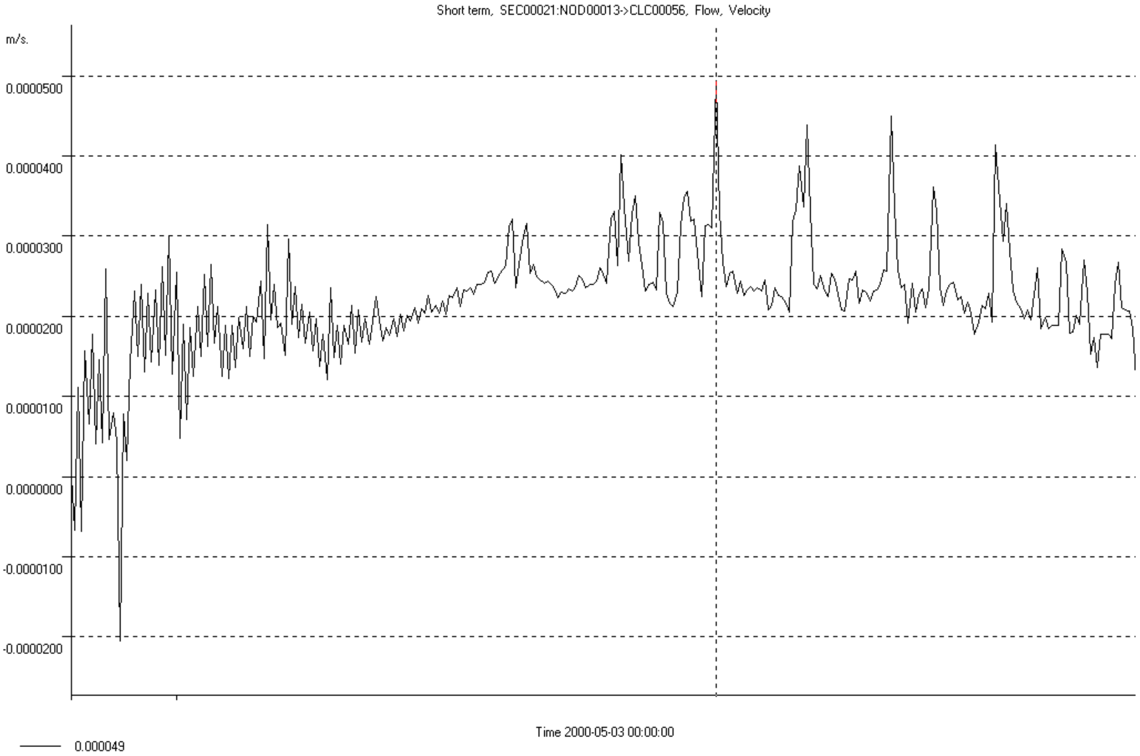


Figure 20. Effect of the wind in the flow calculation. Flow velocity for the section number 21 after changing the initial flow direction the velocity becomes mainly positive



Once the “correct” directions of the flow are established some flow patterns are evident and show the influence of the wind in the movement of the water. When they are compared with the ones observed in a boat by Hubble [Hubble, 2000] the results are similar despite of the prevailing wind directions are slightly different. Figures 21 and 22 show the comparison of flow patterns.

Figure 21. Observed flow patterns and wind direction for Lake Naivasha during November 1997 (Adapted from Hubble, 2000).

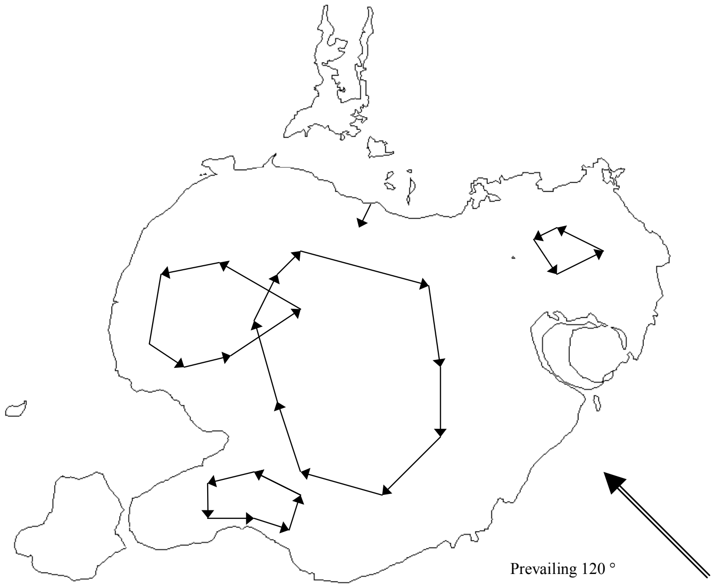
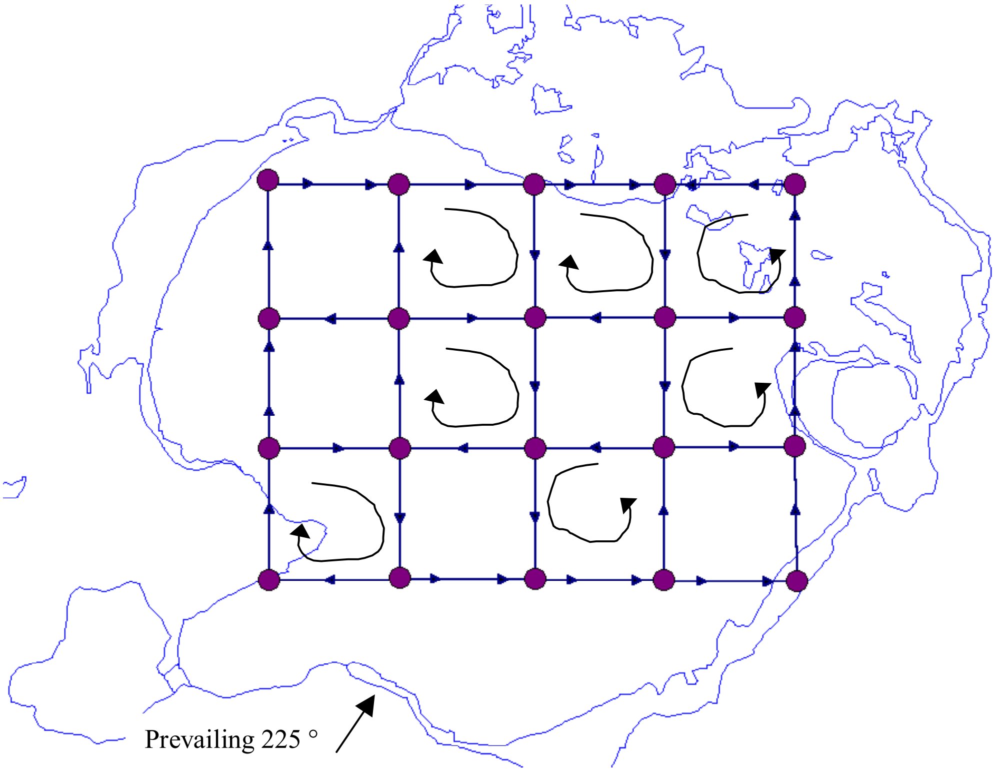


Figure 22. Simulated flow patterns and prevailing wind direction in the DMS network representation of Lake Naivasha



The difference in the prevailing wind directions can be related with the difficulty to get appropriated data for the lake area, one of the main sources of wind data is located at Nakuru (Approximately 80 km from the study area) and conditions can be quite different in such a distance. It is also possible the location of the weather station at Sulmac farm could be influenced by other conditions than those affecting the data source used by Hubble; despite of this the observed patterns in the model follow those registered by himself.

c) Effect of the evaporation and precipitation over the lake water level for Scenario 2

Keeping in mind that for the constructed model the outputs (groundwater outflow and abstraction) are constant in time, and the input from the Malewa river is rather constant, it is interesting to analyze the effect of the precipitation and evaporation over the lake water level. In the following figures the dominance of the evaporation over the precipitation show the inevitable tendency of the lake water level to descend. Added to the increasing abstraction for location of new farms (as it was seen during the fieldwork survey), rings the bell about the sustainability of the exploitation of the resource.

Figure 23. Effect of the evaporation over the lake water level

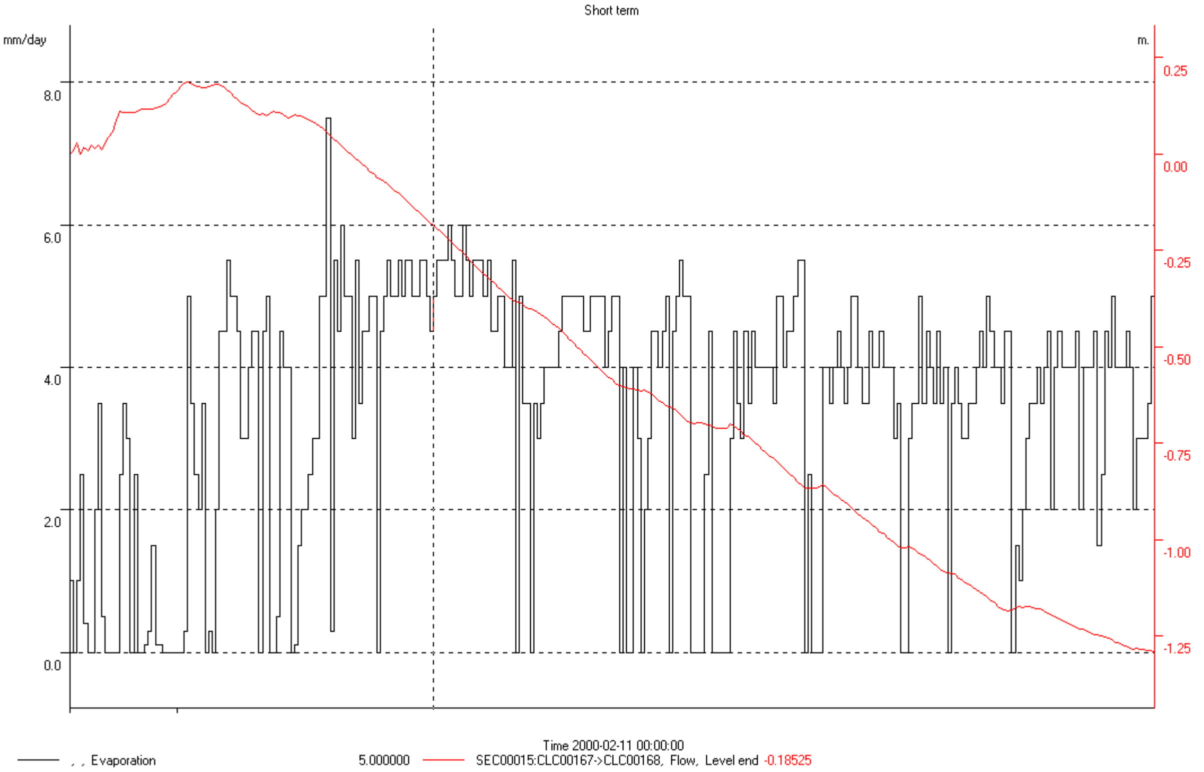
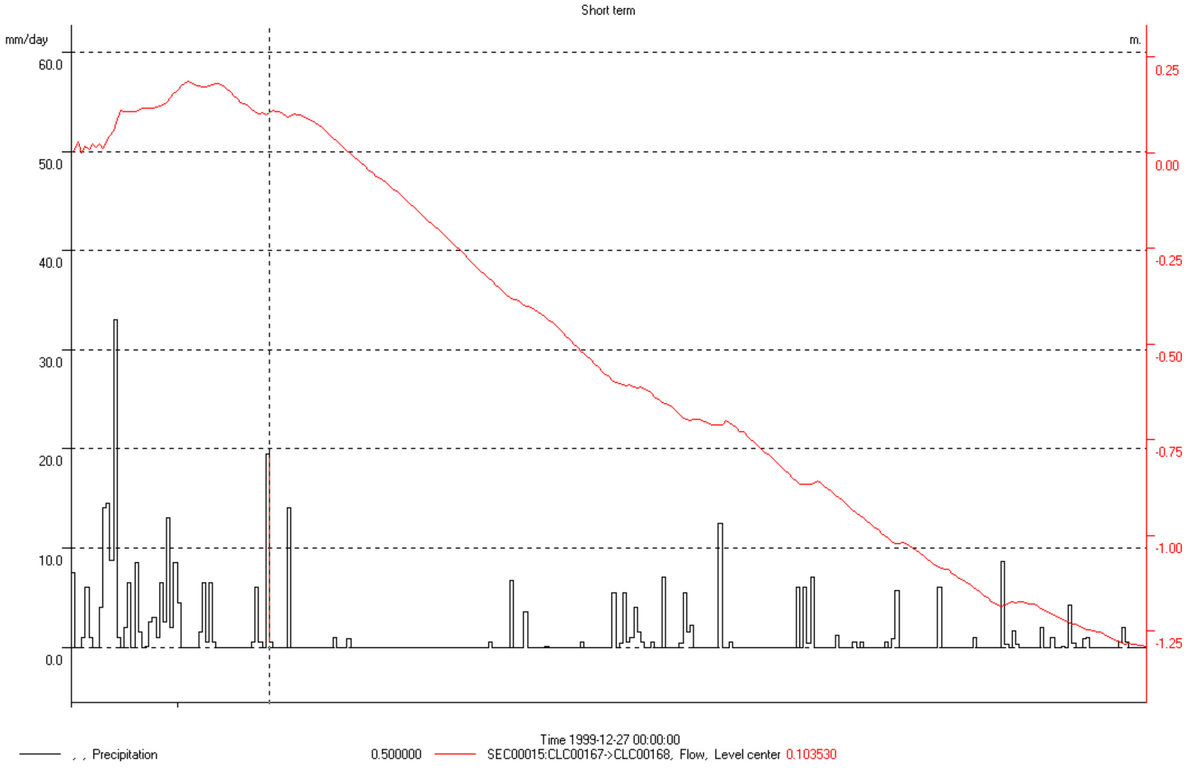


Figure 24. Effect of the precipitation over the lake water level



4.5.11 Scenario 3 : Effect of RAM areas on the lake water level

To evaluate the effect of the quantity of water discharged from the non-point pollution sources (rainfall-runoff from adjacent land areas) two different RAM areas were considered in a third scenario. The first one is Oserian farm located on the southern area of the lake with an approximated total area of 740 hectares including 150 hectares of greenhouses, vegetables and open field flowers [Sayeed, 2001] and the Naivasha town with 980 hectares.

- Modeled time period

Based on the previous Scenario 2, the modeled time period is November 1999- August 2000

- Boundary conditions

To keep track of the previous results the boundary and initial conditions were kept, the precipitation and evaporation data sets correspond to the information collected at Oserian farm. The boundary conditions were changed to appreciate the variation. The figure 23 presents the results for the “actual” condition during the modeled period (November 1999- August 2000) and the figure 24 corresponds to a strong rainfall season during 1997-1998 (Dates were changed to facilitate the computing process) for the same modeled period. The scale on the right corresponds to the higher values (water depth in the section considering 1881.5 m.a.s.l. as the bottom level for the end node of that section)

- Results

Because of the runoff discharged volumes are rather small compared to the lake volume, the evaluated section corresponds to the one receiving the correspondent discharge and not to the section 15 used before. The results apparently do not show any difference in the water level of the channel section maybe because of the receiving area of the channel (length=2500, width = 1870). Despite of this the 5-cm of difference between water lake levels indicates the effect caused by the runoff from an almost totally cultivated area during a short rainfall period.

Figure 25. Oserian farm runoff discharge with normal conditions

Figure 26. Oserian farm runoff discharge for a simulated strong rainfall

4.5.12 Scenario 4: Fate of a conservative substance

This scenario applies the advection-dispersion equation in the analysis of the discharge from non-point pollution sources (RAM areas) of total dissolved solids (TDS) as a conservative substance without any biological reaction present during the process. It is assumed there are no biodegradation reactions during the transport process through the channels simulating the lake. The input concentrations are based on a short time series of electrical conductivity taken at the Malewa mouth during 2000. The same time series area was used for all other inputs due to the lack of proper information.

- Modeled time period

The same used for the previous scenarios 1999-2000

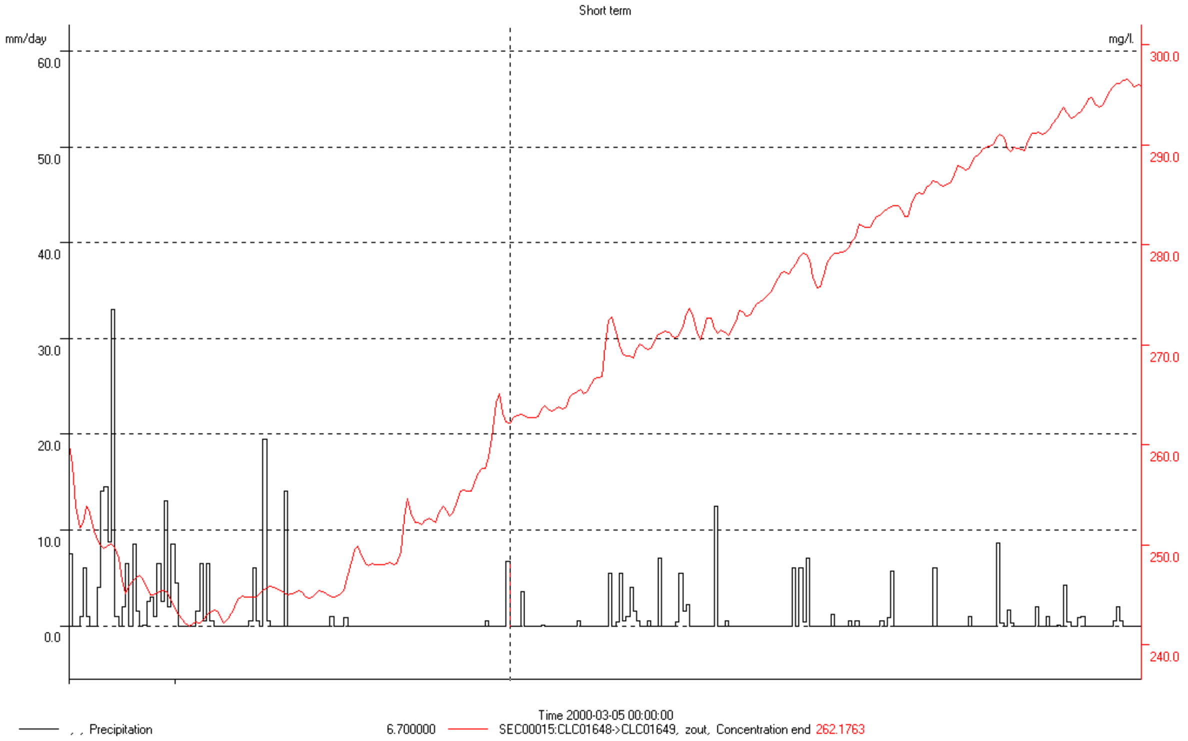
- Boundary conditions

The short time series consists of readings of electrical conductivity (EC [µS/cm]) from an automatic sensor installed in the Malewa River with data. The EC values were converted to TDS [mg/l] via the empirical relation TDS = 0.5 * EC. The average of these three months was used as representative of the ten months modeled period introducing some acceptable error in the results. The same information was linked to the RAM areas as non point pollution sources, the abstraction and groundwater outlets were considered to have a constant value of 260 mg/l [Harper, 1993].

- Results

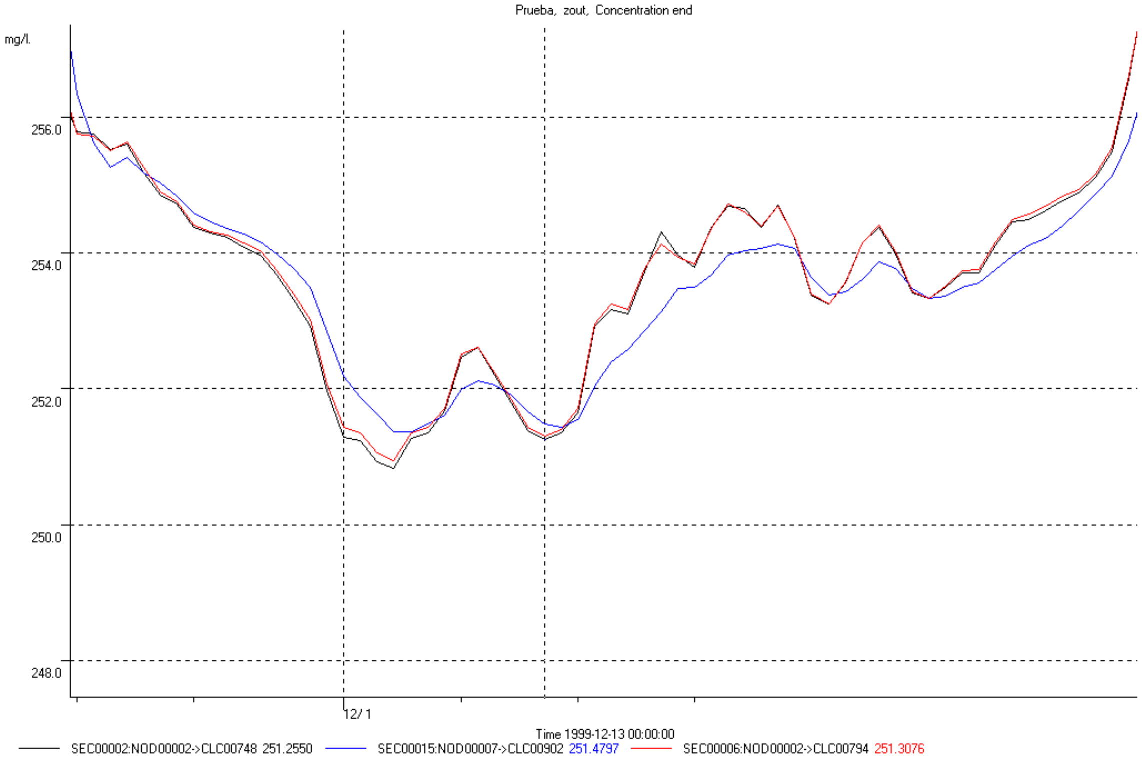
The following figure presents the simulated values of the TDS in the lake and the effect of the precipitation in the concentration, the dilution effect is also associated to the groundwater and abstraction outputs. The increment in the concentration could be related to the discharges from the Malewa river and the RAM areas around the network, but also there could be the explanation for the freshness of the water in a supposed closed lake. The increasing abstraction from the farms could be reducing the residence time of the water in the lake and therefore the amount of evaporated water that easily could raise the concentration of TDS in the lake. On the other hand, that abstraction is reducing the TDS in the lake but increasing them in the soil and (discarding any reaction) polluting it. This is an issue to be analyzed in depth in future research projects.

Figure 27. Total dissolved solids simulated by DMS



The dispersion-advection of the TDS can be evaluated in the following figure. Based on the network route from the Malewa mouth (Section 2) to the center of the lake (Section 15) via the section 6 is evident the difference in the TDS concentrations. The decrease in the concentration is larger in the closest section to the source (Section 2) and viceversa, the increase in the concentration is “firstly felt” at the closest section to the source and lately in the center of the lake.

Figure 28. TDS variation in the channels



4.5.13 Scenario 5: Dissolved oxygen variations in the lake

The scenario is designed to get an understanding of the impact on the dissolved oxygen from the Ammonium discharges coming from the farms.

- Model

The oxygen model used is the following, certain model elements were decoupled from the evaluation (i.e. BOD, SOD, IO) because of the lack of proper information.

(9)

Equation 9

$$\frac{\partial C_{DO}}{\partial t} = -u\frac{\partial C_{DO}}{\partial x} + D\frac{\partial^2 C_{DO}}{\partial x^2} + \frac{K}{Z}\left(O_S - C_{DO}\right) - K_{BOD} * BOD - A_{ON} * K_{NH4} * NH4 - \frac{SOD}{Z} + \alpha * IO$$

where,

C_{DO} = Dissolved oxygen concentration [mg/l]
t = Time [day]
u = Velocity of the flow [m/day]
x = Distance [m]
K = Mass transfer coefficient oxygen [m/day]
O_S = Oxygen saturation concentration [mg O_2/l]

Z = Water depth [m]
K_{BOD} = Biodegradation rate constant [day^{-1}]
BOD = Biological oxygen demand [mg O_2/l]
A_{ON} = Ratio mg O_2/mg N
K_{NH4} = Rate constant nitrification [day^{-1}]
NH_4 = Ammonium concentration [mg/l]
SOD = Sediment oxygen demand [g/m^2/day]
α = Oxygen production constant (Photosynthesis) [mg O_2/(W/m^2)
IO = Solar Radiation [W/m^2]

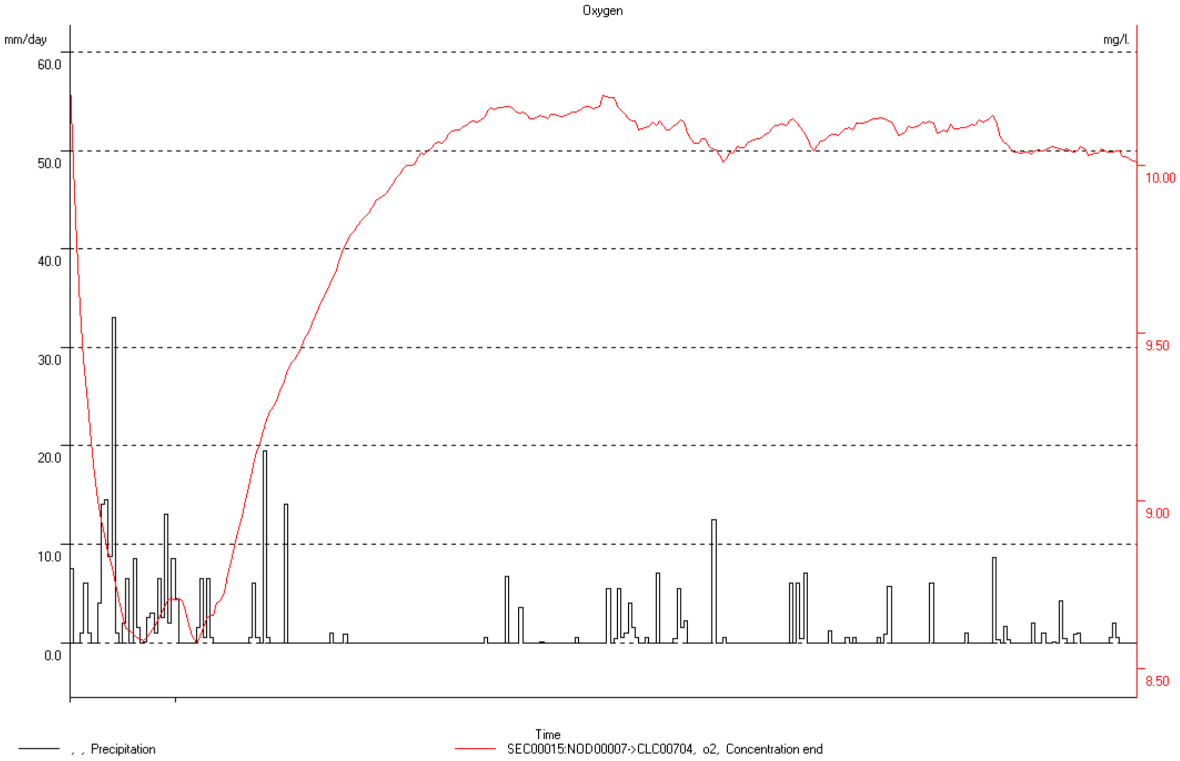
- Initial parameters

K = Mass transfer coefficient oxygen = 0.300 [m/day]
O_S = Oxygen saturation concentration = 10.0 [mg O_2/l]
Z = Water depth [m] = Included in the cross section data
A_{ON} = Ratio mg O_2/mg N = 4.67
K_{NH4} = Rate constant nitrification = 0.100 [day^{-1}]
NH_4 = Ammonium concentration [mg/l] = 0.5 in the lake [Harper, 1993]
NH_4 = [mg/l] =1.3 in the precipitation [STOWA/EDS, 1998]
NH_4 For RAM areas = [mg/l] =Taken from the collected data (Chapter 3)
O_2 in the lake [mg/l] = 10.25 [McLean, 2001]

- Results

The following figure shows the impact of the ammonium (although also all the sources are contributing) in the dissolved oxygen (DO) concentration; as a large concentration was linked to the precipitation, the effect in reducing the available oxygen is evident. The subsequents variations respond almost directly to the precipitation that washes also the farm soils increasing the runoff transporting the ammonium to the lake.

Figure 29. Effect of the ammonium present in the precipitation over the DO in the lake



The figure 30 shows the effect of the ammonium discharge from the Naivasha town (scale on the right hand side) on the concentration of DO on the section receiving that discharge (section 8). The source is not the only cause of the decreasing but it is interesting to analyze how the reduction corresponds to the discharge from the town.

The obtained results are not comparable to any historic data, because of the model is not including all the non point sources and that available information is not related to precipitation or runoff events. But the behavior of the model is quite realistic and finally shows a reasonable value at the end of the modeled period.

Figure 30. Effect of the ammonium discharged from a non point source over the concentration of DO in the lake

Although within the objectives of this thesis the evaluation of the impact of the discharges from the farms is not considered, some of them were included in the model and this scenario shows the effect of the runoff over the water level of the lake.

Chapter 5

Conclusions, discussion and recommendations

5.1 Conclusions and discussion

There are many tools for modeling purposes but the application of them is another way of innovation and seizes the work done expanding its capabilities and usefulness.

DMS is a useful tool to be applied in the analysis of lakes as systems represented by networks of open channels and linked non-point pollutant sources (RAM areas). The representation is somewhat unstable hydraulically speaking but the limitations are handle and the results interesting. The built model was able to follow, with some accuracy, the observed lake water levels for a long run (32 years) with measured data on a monthly basis, and with high precision for a short period (10 months) based on daily information. Obviously the results depend on the information supplied, a good modeling process requires of data carefully analyzed from trustable sources. RAM areas are a feasible way to include the contribution in terms of water quantity and quality to the lake from non-point pollution sources. In this case is also necessary to analyze the real contribution from seepage and other processes related with the groundwater flow patterns. The groundwater over pumping could be changing those flow patterns and the contribution of an area may not be going exactly to the lake. As the model does not include any background information besides of the coordinate system, it is possible to get wrong results assuming incorrect subsurface flow directions.

Of course, we did not attempt an accurate hydraulic analysis of the Naivasha lake system, but were aiming to see if dynamic flow and lake level concentrations could be represented by the DMS modeling system. Therefore we also used Duflow with the larger time steps in order to analyze indeed the historical observed time series of lake levels, inflows and sparse individual data on solute concentration (i.e. electrical conductivity).

DMS has a useful set of graph options to evaluate a large number of relations between analyzed parameters allowing a complete overview of the effect of the different variables considered in the quality model.

The estimated abstraction volume, as part of the outflow discharges has been studied before. The value estimated in this study (1.5 m^3/s) is within the range of the calculated one by the WRAP (Water Resources Assessment Project) study, about 1.55 m^3/s. The fourth scenario (5.6.4 conservative substance) shows the possible relation between the residence time of the water in the lake and the rather constant conductivity levels reported in a previous study (average for seven readings between 1983 and 1991 = 300 μS/cm) [Harper, 1993]. This feature could be analyzed in depth with a time series of the abstraction volumes from the lake and the relation with climatic factors as rainfall, evaporation and even groundwater outflow.

Despite of the absence of historic data for the last two scenarios (Conservative substance and dissolved oxygen variation) in order to evaluate the proper functioning of the model, the obtained results are good estimations of the actual situation based on the rather few input schemes. Particularly in the last scenario, the effect of the estimated concentration of ammonium in the precipitation over the lake (1.3 mg/l), generates an important decrease in the dissolved oxygen concentration that slowly get recovered for the end of the period.

DMS is suitable to understand the relations between some of the variables affecting the water quality of Lake Naivasha, its accuracy depends on the large amount of data that is necessary to collect in the fieldwork and the knowledge of the interactions between those variables.

5.2 Recommendations

- Future water quality analysis of the lake should include an evaluation of all the potential non-point pollution sources with their correspondent runoff analysis in terms of quantity and quality to run a more precise model.
- A database with the fertilizers and pesticides used by farm and crop could help in identifying the relations between applied element, runoff composition and quality of the water in the lake.
- The supplied information about hippos in the lake should be included as contributions of nitrogen and phosphorus compounds in order to assess its impact on the water quality of the lake.
- It is necessary to build a more detailed network following the shape of the lake and reducing the distance between the nodes to improve the accuracy of the results and the stability of the calculation process.
- To get as much wind information as possible in order to expand the short time scenario keeping its high accuracy on a daily basis and carefully analyze the data before running the model.
- Incorporate a time series of the relation of groundwater discharge and lake water levels into the model to evaluate the real groundwater outflow and the mass of contaminants leaving the lake.
- In order to have certainty about the advection-dispersion process in the lake is recommendable to estimate the dispersion coefficient based on experiments applied in the lake.
- In a next step it is recommendable a more detailed hydraulic analysis of the behavior of the water flows in the network in order to verify the realism of the model at same specific points in the network.
- In order to analyze groundwater interactions in the model, the DMS could be linked to Modflow using the Moduflow interface.

References

Abbot, M.B., *Computational hydraulics*. 1979: Pitman.

Ase, L.-E., *A note on the water budget of lake Naivasha, Kenya.* 1987.

Beth Bliss, T.a.L., *Tim and Lara Beth's Kenya*. 1994.

Clarke, M.C.G., Woodhall, D.G.,Allen,D. and Darling, G., *Gological volcanological and hydrogeological controls on the ocurrence of geothermal activity in the area surrounding Lake Naivasha*. 1990: Ministry of Energy, Nairobi, Kenya.

Dao, V.D., *Irrigation efficiency evaluation at farm level using GIS, RS data and SWAP model: Case study at lake Naivasha project - Kenya*. 2001, ITC: Enschede.

Delft University of Technology, I.H.E., *Duflow User's manual version 1.0.* 1989, Delft.

Delft University of Technology, I.H.E., LUT, *Duflow User's manual version 2.0*. 1992, Delft.

Delft University of Technology, I.H.E., Wageningen Agricultural University, STOWA, Informatica Centrum voor Infrastructur en Milieu, Ministerie van Verkeer en Waterstaat Directoraat, *Duflow a micro-computer package for the simulation od unsteady flow and water quality in one-dimensional channel systems*. 2.1 ed. 1995, Leidschendam: EDS.

Dingman, S.L., *Physical hydrology*. 1993: Prentice Hall, New Jersey.

Donia, N.S.M.t., *Integration of GIS and computer modeling to study the water quality of lake Naivasha, central rift valley, Kenya.* 1998, ITC: Enschede.

Dronkers, J.J., *Tidal computations in rivers and coastal waters*. 1964: North Holland.

EPA, U.S.E.P.A., *Nonpoint sources pointers (Fact sheets)*. 1996, EPA.

Gaudet, J.J. and J.M. Melack, *Major ion chemistry in a tropical African Lake basin,*. Freshwater Biology, 1981.

Gitonga, M.S., *A study of long-term water balance of Lake Naivasha, Kenya*. 1999, ITC: Enschede.

Hamadudu, B.H., *Erosion assessment for large basins using remote sensing and GIS, a case study of lake Naivasha basin, Kenya.* 1998, ITC: Enschede.

Harper, D.M., Geoff Phillips, Alison Chilvers, Nzula Kitaka and Kenneth Mavuti, *Eutrophication prognosis for Lake Naivasha, Kenya*. 1993: Stuttgart.

Hubble, D.S., *Controls on primary production in shallow tropical freshwaters*, in *Department of Biology*. 2000, University of Leicester: Leicester.

Jolicoeur, J.L.C., *Groundwater contamination potential of agriculture around Lake Naivasha: comparison of five unsaturated soil zones models*. 2000, ITC: Enschede.

LNROA, L.N.R.O.A., *Lake Naivasha management plan, (Incorporating Amendment List No. 1)*. 1996: Naivasha, Kenya.

Maidment, D.R., *Handbook of hydrology*. Austin, ed. D.R. Maidment. 1993.

Mbathi, M., *Impact of Urban Landuse in Naivasha*. 2001, ITC: Enschede.

McConnell, P., *The Agricultural Notebook*. 1976, London: Newnwes-Butterworths.

McLean, P., *Development of a dynamic model to predict trophic state changes in Lake Naivasha*. 2001, ITC: Enschede.

Morgan, N.E., *Groundwater chemistry and quality assessment of the lake Naivasha area, Kenya*. 1998, ITC: Enschede.

Sayeed, A., *Economy versus environment: how a system with RS/GIS data can assist in decisions for water management, Lake Naivasha case.* 2001, ITC: Enschede.

STOWA, *Duflow for Windows v. 3.3: User's guide. Duflow modeling studio*. 2000, Utecht.

STOWA, *DUFLOW Procesbeschrijvingen*. 1999, Utrecht: STOWA.

STOWA/EDS, *Duflow for Windows, User's guide, Reference Guide Duflow, Reference guide RAM*. 1998, Zoetermeer.

Stuttard, J.H.N., G; Hayball J. B., *Monitoring Lakes in Kenya - Final Report*. 1995: Surrey.

Tang, Z.X., *Water quality assessment and pesticide fate modeling in the Lake Naivasha area, Kenya.* 1999, ITC: Enschede.

Thomann, R.V. and J.A. Mueller, *Principles of surface water quality modeling and control.* 1987, New York.: Harper Collins.