Water Quality Assessment and Pesticide Fate Modeling in the Lake Naivasha area, Kenya

By

Tang Zhen Xu

April 1999

Water Quality Assessment and Pesticide Fate Modeling in the Lake Naivasha Area, Kenya

By

Tang Zhen Xu

Thesis submitted to the International Institute for Aerospace Survey and Earth Sciences (ITC), Enschede, The Netherlands, in partial fulfillment of the requirements for the degree of Master of Science in Water Resources Survey with specialization in Watershed Management.

Degree Assessment Board:

Prof. Dr. A.M.J. Meijerink (Chairman of the Examination Board)
Prof. Dr. Ir. P.M. Driessen (External Examiner)
Dr. C.M. Mannaerts (Main Supervisor)
Dr. W. Siderius (2nd Supervisor)

ITC

APRIL, 1999

INTERNATIONAL INSTITUTE FOR AEROSPACE SURVEY AND EARTH SCIENCES
ENSCHEDE, THE NETHERLANDS

Dedicated To

My parents Mr. Tang Zhi Chen and Mrs. Li Wen Dong

&

My dearest Tianbo and Pang pang

ACKNOWLEDGEMENT

I wish to express my thanks to the government of the Netherlands for sponsoring my study through the Netherlands Fellowship Program (NFP).

I am deeply grateful to my supervisor and Director of studies, Dr. Ir. C. M. M. Mannaerts. His guidance, advice, and valuable comments have greatly contributed to the success of this study.

Special thanks to my second supervisor, Dr. W. Siderius for his guidance and encouragement during both fieldwork and thesis preparatory period. Thanks also to Mr. B. de Smeth not only for his assistance in the experimental work but also for his care during my stay in Delft.

I am indebted to Mr. Ir. Van Lieshout, who was my Director of Studies in the diploma course, for his “Caspar” and the usual remark “You are the excellent group I have ever seen”. I admit I used to feel content at it.

I would like to convey my heart felt appreciation to Mr. Mekonnen. His invaluable help never stopped during all my study. His encouragement assisted me getting over many situations, which I felt I couldn’t go through.

I would like to express my special thanks to all my classmates Mr.Duah (Ghana), Ahmad (Egypt), Ashfaque (Bangladesh), Behar (Ethiopia), Fathi (Egypt), Jorge (Bolivia), Julian (Indonesia), Mekonnen(Ethiopia), Mmbui (Kenya), Robert (Cuba), and Tonny (Cape Verde), whom we have worked and complained together in Ms.c room, in Spain, and in Kenya. You left me sweet memories of the past two years.

I am deeply grateful to Ms. Dai Feng with whom I shared the happiness and sometimes bitterness of two years of my life in the Netherlands.

No words can fulfill my gratefulness to my husband Mr. Tianbo and my son Pang pang who were always the source of my strength. Finally, thanks to my parents, my sisters and brothers for their continuous supports in spite of the distance apart.

Zhenxu

April 1999, Enscede

TABLE OF CONTENTS

TABLE OF CONTENTS

List of Tables

List of Figures

List of Maps

List of Appendices

CHAPTER 1

INTRODUCTION

This chapter gives a general introduction about research objectives and methodology, along with a description of the study area.

1.1 Introduction

Water pollution is one of the critical issues in environmental conservation. Agriculture, as the single largest user of freshwater on a global basis and as a major cause of degradation of surface and groundwater resources, has cause to be concerned about the implications of water quality. The agrochemical pollutants are mainly from pesticides, fertilizers, and animal manure. Many of these pollutants cause the deterioration of surface and ground water quality through erosion, chemical runoff, and percolation. The pollution from these sources is classified as “non-point” sources pollution. Agriculture is considered as the largest contributor to the non-point source pollution in a global scale (Ongley, 1996).

The sources of water pollution are distinguished as point and non-point sources based on the way that pollutants join receiving water bodies. Non-point water pollution, once known as “diffuse” source pollution, arises from a broad group of human activities for which the pollutants have no obvious point of entry into receiving watercourses. In contrast, point source pollution represents those activities where wastewater is routed directly into receiving water bodies by where they can easily be measured and controlled (Ongley, 1996). Therefore, identification, measurement and control of non-point source pollution are much more difficult than those of point source pollution.

Various numerical models have been developed and applied for the prediction and quantification of agricultural non-point source pollution. GIS is usually incorporated with models as a very effective tool to acquire input data and presents simulation results.

This study will assess water quality of the lake and model the pollution risk caused by the application of pesticides in the riparian zone of Lake Naivasha.

1.2 Problem formulation

Lake Naivasha, a shallow freshwater lake, is located in the center of the Rift Valley in Kenya. It is not only an important ecological site due to its biodiversity, but also a main economic resource of Kenya for its horticultural production and tourism development.

With the rapid expansion of cultivation around the lake, considerable quantities of pesticides and fertilizers are applied in the riparian zone of the lake which posed a potential threat to the lake water quality. Therefore, a study of the pollutants originating from the agricultural sector is very necessary as a part of an integrated management plan.

1.3 Previous relevant studies

Extensive research has been carried out to study lake water chemistry since 1932. Gaudet and Melack (1981) did a systematic survey of the various Naivasha water bodies for the period of one year. They quantified the ion concentration and conclude that the lake water is alkaline bicarbonate type with sodium and calcium as the major cations. Harper (1985) measured some nutrient variables and found the nutrient content to be very low.

Limited studies have dealt with agrochemicals. Some pesticide analysis were carried out in KARI/ODA crop protection project in 1993. Aldrin and DDT were detected for ppm or ppb levels in water samples from the lake, although they haven’t been used any more for a very long time.

However, there hasn’t been any study focusing on agrochemical pollution of the lake water. Analysis of the content of heavy metals, which is one of the components of fertilizers, has never been documented. Fewer studies were conducted after vast expansion of flower production which resulted in more agrochemical inputs in the past five years. This study will try to fill the research space about agrochemical pollution.

1.4 Objectives

- Identify and evaluate potential pollution sources around the lake, focusing on agrochemicals and Southeast lakeside;
- Survey and assess water quality of the lake;
- Predict and quantify pollutants from different pathways: volatilization, surface runoff, erosion and leaching;
- Predict the vulnerability of the soil type to leaching of different types of pesticides and mapping potential leaching risk.

1.5 Methodology

This study mainly contains two sections: i) pollution sources and lake water quality assessment; ii) modeling the fate and mapping pollution risk of pesticides. The description of research methodology is based on different methods employed to handle these two parts. Figure 1-1 presents the flow chart of research methodology.

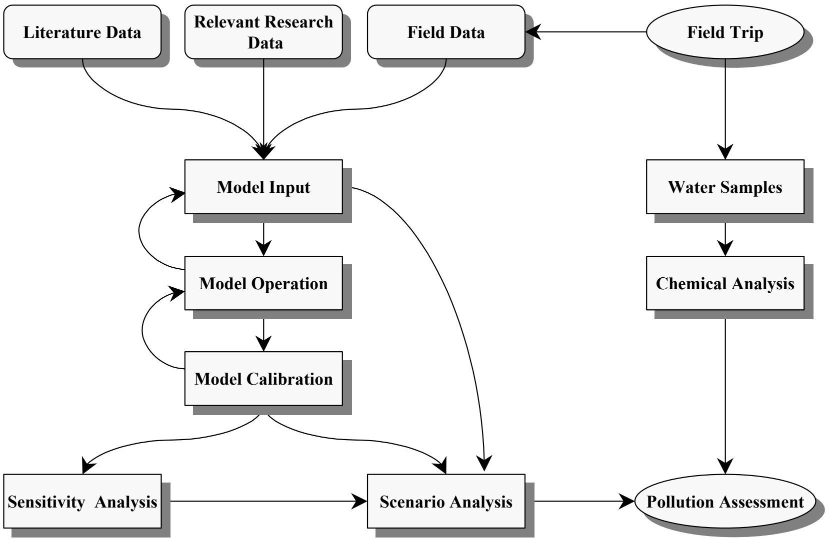


Figure 1-1 Research methodology flow chart

1.5.1 Pollution sources and lake water assessment

Field data collection

District agricultural organizations and riparian farms have been visited to acquire fertilizer and pesticide data. Twenty-two water samples were collected from the lake, farms and sewage outlet.

Data analysis and assessment

Fertilizer and pesticide inventories were compiled from the field data. Nutrients were quantified for fertilizers. Toxicity and persistency assessments were conducted for pesticides.

Six category parameters were measured in situ and laboratory. They are general water quality variables, organic matter, nutrients, pesticides, heavy metals, and major ions. The assessments were conducted in three aspects: direct comparison with guidelines, lake water quality classification using water quality index (SAR), and trophic status survey of the lake water.

1.5.2 Mapping pollution risk of agrochemicals

The SESOIL model version 3.0 with RISKPRO (GSC, 1998) was used to predict the fate of pesticides and conduct the assessment of the risk to groundwater.

Input data acquirement

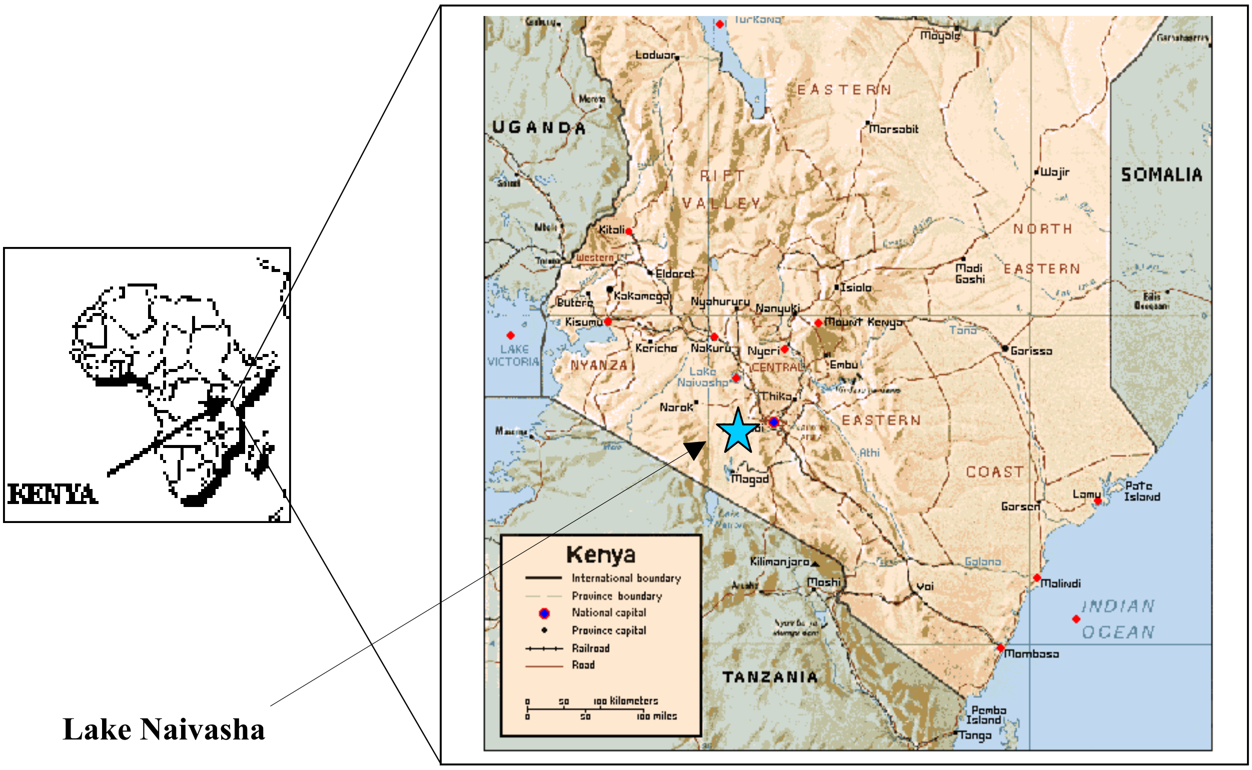
The input parameters are drawn from diverse sources. Soil property data (i.e. soil texture, hydraulic conductivity, organic carbon content, and bulk density), geomorphology, and landuse data are collected from relevant research and fieldwork. Some of them are presented in GIS map formats. Most chemical data are acquired from literature and pesticide databases.

Model calibration and application

Site-specific data soil moisture, surface runoff are used to calibrate the model. Scenario analysis was performed to predict and quantify pollution from pesticides of different categories in varied soil types. Pollutant leaching fraction maps were built up to present the pollution risk to groundwater.

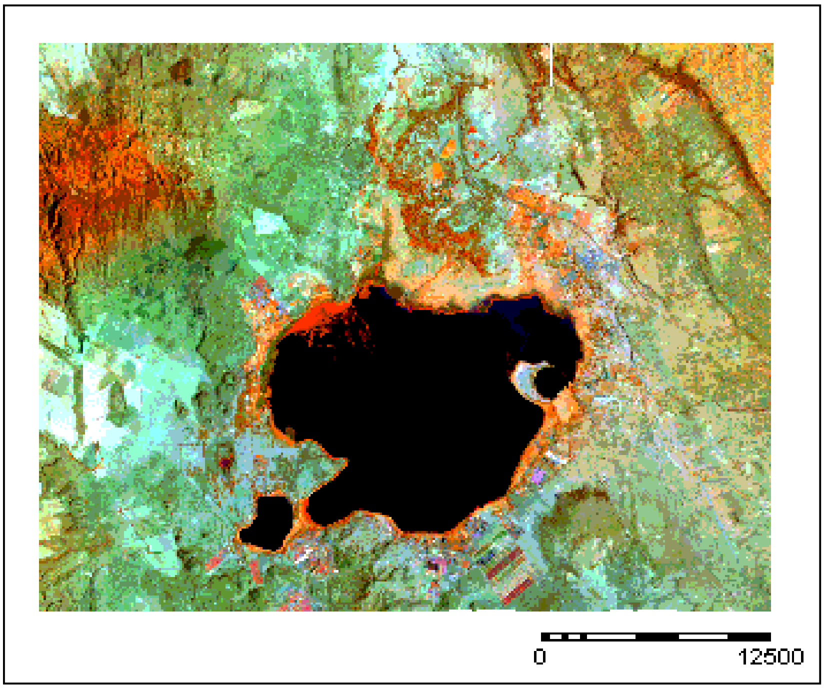
1.6 Description of the study area

The study area covers lake Naivasha and its southeastern lake shore area. Lake Naivasha is the only lake with fresh water in the Eastern Rift Valley of Kenya. It is in a closed drainage basin and has no visible surface outlet. The lake surface area is about 120km^2 when the lake water level is 1885m. There are many horticulture and dairy farms around the lake. Intensive agricultural practices occur in the riparian zone of the southeastern part of the lake. The riparian area (southeast side) selected in this study is about 80km^2. The natural properties of the study area will be given in the following sections except soil and landuse, which will be descried in detail in Chapter 3.



Lake Naivasha

Map1-1 Location map of the study area



Map1-2 False color composite (FCC) image of Lake Naivasha area (bank 4 5 3)

1.6.1 Location

Lake Naivasha is located 100 km North-west of Nairobi in the Naivasha Division of Nakuru District, Kenya (Map1-1). The center of the lake is at latitude $00^0$46'S and longitude $36^0$22'E. It is within the UTM zone 37. Its boundary coordinates are X_{min} 190000, Y_{min} 9907000; X_{max} 221000, Y_{max} 9934000. Altitude is around 1900m.

The lake shore area selected in this study located at southeastern part of the lake, within boundary coordinate ranging from X_{min} 196000, Y_{min} 9905000 to X_{max} 219100 Y_{max} 9920000.

1.6.2 Climate

The lake Naivasha area has a local semi-arid type of climate (East African Meteorological Dept., 1964). Mean monthly temperatures vary from 15.9 to 17.8^0C. Mean monthly maximum temperature ranges from 24.6 to 28.3^0C, with highest temperatures in January and February. Mean minimum temperatures range from 6.8 to 8.0^0C with coldest months in July and August (Jaetzold, 1983).

The direction of wind is mainly from the southeast or northeast depending on the season. In contrast to the calm conditions or slight winds in the morning over the lake, the typical wind speed is 11-15 km/h in the afternoon. It causes mixing of the lake water down the complete water column, and cause well-oxygenated water from top to bottom (LNROA, 1993). This situation helps to increase the concentration of dissolved oxygen of the lake water and improve the lake water quality.

1.6.3 Geology

Lake Naivasha is situated in the eastern branch of the African Rift Valley - a complex graben that runs from Ethiopia to Tanzania. The Rift valley was formed through many episodes of faulting and volcanism some 30 million years ago. The geology of the area is characterized by volcanic rocks and Quaternary lacustrine deposits from large ancient lakes, which were formed during pluvial periods, becoming shallow or drying completely during Inter-pluvials (Cole, 1950).

There are two lithologic units in the lake shore area, lacustrine and volcanic origin. The prevailing quaternary deposit is of lacustrine origin which largely comprises of fine volcanic ashes besides clay and silt. In addition, due to the soil erosion and deposition resulting from the lake levels fluctuations, there appeared also some coarse loamy with occasional fine gravel deposits.

1.6.4 Geomorphology

Three types of landscapes can be identified in the Naivasha catchment: the Kinangop plateau, the Mau escarpment, and the Rift valley floor (Thompson, 1958). The study area is within the Rift Valley floor. It contains two major units lacustrian plain and volcanic plain as identified by Kwacha (1998).

The topography near the lake is flat and is part of the recent lacustrine plain. The dominant slopes are within the range 0-2%, in parts 2-5%. Away from the lake the land rises gradually and slopes between 2 to5% are common.

1.7 Water balance of the lake

There are several contributors to the water balance of the lake. The inputs to the lake consist of rainfall, surrounding surface run-off, river flows, and seepage inflow from catchment. The outputs include evaporation from the lake and swamp area, water abstraction, and seepage outflow from the lake. The approximate annual water budget was calculated by LNROA (LNROA, 1996) (Table 1-1). The evapotransporation amount from swamp has been modified since the values given by LNROA are not certified.

Table 1-1 Approximate annual lake water budget (unit: $10^6 m^3$)

Inputs	Wet condition	Mean condition	Dry condition
Rainfall	140.8	72.9	45.0
Malewa River	378	153	53
Gilgil river	74	24	3.2
Karati	6.5	2.1	0.28
Unguaged area	117.8	77.9	34.2
Seepage	54	54	32
Sum (∑)	771.1	383.9	167.7

Outputs	Wet condition	Mean condition	Dry condition
Evaporation	229	183.5	177.8
Evapotransporation	27.5	18.3	15.6
Seepage	54	54	32
Abstraction	33.8	44.6	53.2
Sum(∑)	344.3	300.4	278.6

Source: LNROA, 1996

1.7.1 Inflow to the lake

Rainfall

Long term rainfall for the period 1966-1993 is calculated and presented in Figure 1-2. This rainfall data series are from meteorological station W.D.D (Water Development Department) with coordinates are x: 216173, y: 9918872. There are two rainy seasons, March/April/May and October/November. The rainfall varies from 432-

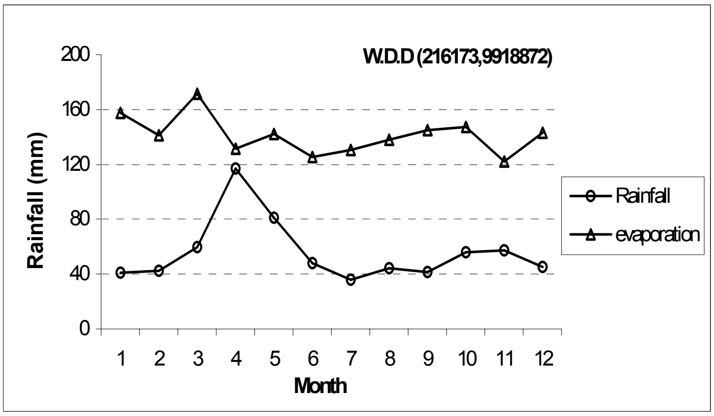


Figure 1-2: Average long-term precipitation (1966-1993) and potential evaporation (1968-1997)

961mm/year. Average rainfall is 669mm/year. The maximum monthly rainfall (117mm) appears in April. It contributes to17% of total rainfall per annum. A second peak rainfall (57mm) occurs in November.

LNROA (1996) classified rainfall years with three conditions: wet, mean and dry. The corresponding representative annual rainfall are 939mm, 608mm and 442mm per annum. Direct rainfall on the lake surface contributes about 20% of the total lake water inputs in wet and mean condition, and about 26% in the dry condition.

River flows

The lake receives drainage water mainly from two perennial rivers Malewa and Gilgil that account for 90% of the river inflows to the lake. Their drainage areas are 1730 and 420 km^2 respectively. River Karati also contribute considerable amount of water. Several ephemeral streams flow into the lake in the southern part. Their contributions are insignificant. The inflow rivers of the lake are shown in map 1-3.

Subsurface flow

Many studies since 1922 demonstrate Lake Naivasha catchment has an internal underground drainage system, draining in and out. Most of the water leaving the lake goes out between Olkaria and Longonot, whilst a small portion goes north between Eburru and Gilgil. The outflow from the lake has been traced up to 30 km south (Darling et al., 1990). The inflow was assumed equal to the outflow in the lake water budget (LNROA, 1996).

1.7.2 Outflow from the lake

Evaporation

Lake evaporation is the principal source of the lake water loss. It accounts for more than 60% of total water losses. The average Pan evaporation from 1968 to 1987 at meteorological station W.D.D is calculated and presented in Figure 1-2. Pan factor used for free lake water is taken as 0.95 (personal communication with Ashfaque). The highest evaporation 181mm occurs in March, while the lowest evaporation 128mm occurs in November. As shown in Figure1-2 evaporation has a decisive influence upon lake water budget.

Evapotransporation

Evapotransporation from the swamps in Table 1-1 are refined data from LNROA. The evapotransporation and lake evaporation rate given by LNROA are 2141 mm and 1529 mm respectively. According to Bastiaanssen's field observation (personal communication), evapotransporation from the swamps should not exceed lake evaporation. Since we don't have exactly data, the evapotransporation rates are assumed equal to the lake water evaporation rate in Table 1-1.

Water abstraction

The abstraction loss of the lake water are mainly used for agriculture and geothermal power generating. The abstraction amounts listed in Table 1-1 were estimated based on electric power consumption amounts used by water pumping.

1.7.3 Lake water budget

Based on the data shown in Table 1-1, the lake water balance has been calculated and shown in Figure 1-3. The figure shows that in wet and mean conditions, inputs exceed outputs by about $430*10^6$ and $85*10^6$ m^3/year respectively. While during the dry condition, outputs exceed inputs by about $100*10^6$ m^3/year.

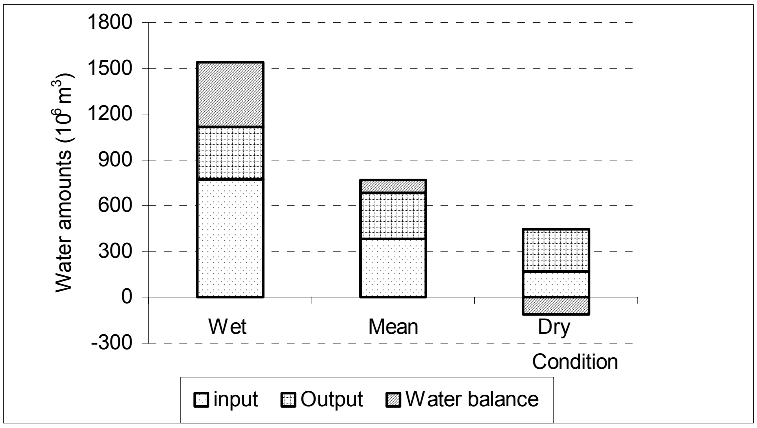
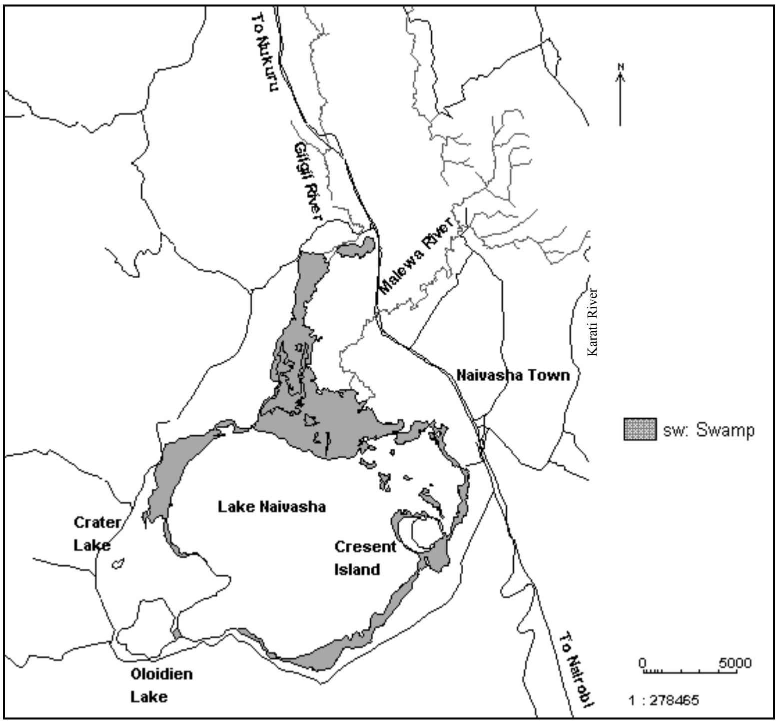


Figure 1-3 Lake water budget



Map1-3 Lake Naivasha and its inflow rivers

CHAPTER 2

POLLUTION SOURCES AND WATER QUALITY ASSESSMENT

This chapter includes three parts: pollution sources focusing on agricultural sector, lake water quality, and farm effluent survey and assessment.

2.1 Lake ecological function and water use

Considerations of water quality are inseparable from water use. Therefore, a description of specific water uses of the lake is given first.

Lake Naivasha has high ecological and economic value because of its fresh water, in contrast to most of the eastern Rift valley lakes, which are saline. It has always been an important ecological site to kenya due to the diversity of flora and fauna in the range of vegetation-zones associated with the lake and its hinterland (Lincer et al., 1981).

There is multiple competing lake water use (Table 2-1). The major use is for irrigation. It is about $100*10^6$ m^3 (Ahmad, 1999 personal communication) per annum, accounting for 84 % of the total lake water abstraction.

Table 2-1 Lake water abstraction for different sectors

Category	Detailed use	Percentage of water consumption*
Agriculture	Irrigation; domestic farm supply; cattle watering	84
Municipal use	Drinking water supply; domestic uses; recreation	8
Industry	Power generation and others	6
Others	Wild life and others	2

*Huaccho, 1998

2.2 Pollution sources identification and assessment

The pollution sources to the lake water can be distinguished: agrochemical diffusion, sewage discharge, and other source effluents. They are discussed in the following parts.

2.2.1 Agro-chemicals diffusion

Intensive agricultural practice in the riparian zone of the lake is the predominant potential pollution source of the lake water. The rapid expansion of horticultural farms around the lake in last ten years, with an increase of the irrigated area from 981.8 ha in 1988 (LNRON, 1993) to 7353 ha in 1998 (Huaccho, 1998), resulted in a rapid increase of agrochemical inputs.

2.2.1.1 Water quality impacts of ago-chemicals

Fertilizers. Fertilizers involve mineral fertilizers (N, P, K) and organic fertilizers (manure). The application of manure in the study area is only restricted to vegetable farms with negligible amount due to the relatively high cost. Therefore, only mineral fertilizers are addressed here.

Mineral fertilizers, as water pollutants, deteriorate water quality mainly in three ways:

- Nutrient loads through runoff and erosion result in eutrophication of surface water;
- Fertilizers leaching leads to nitrate pollution of groundwater;
- Trace elements can cause heavy metal contamination of surface water and ground water.

Pesticides. Pesticides" is a composite term that includes herbicides, insecticides, fungicides, nematocides and rodenticides. The intentional release of pesticides from agricultural use can have serious environmental consequence and pose potential threat to human health. The ecological impact of pesticides in water are determined by the following factors:

Toxicity: toxicity refers to concentration of the pesticide that will kill fifty percent of a set of organisms over a specified test period, usually expressed as lethal dose LD 50.

Persistence: persistence is the time required for the ambient concentration to decrease by 50%, measured as half-life.

Degradates: degradates are formed by a degradational process which may have greater, equal or lesser toxicity than the parent compound.

Fate: fate is the behavior of a pesticide in the environment, affected by the natural affinity of the chemical for one of four environmental compartments. Detailed explanation will be given in Chapter 4.

2.2.1.2 Fertilizer & pesticide survey and assessment

Data collection and analysis

District agricultural organizations and riparian zone farms were investigated during fieldwork in order to collect fertilizer and pesticide data. Nine representative farms were selected from about 150 farms around the lake. They were Aberdare Estate, Kijabe, Lake Naivasha vineyard, Sher agency, Sulmac, Oserian, Brixia, Three point, and Nini. There were two reasons for choosing them:

- Big farm size with high socio-economic impact can be expected to produce higher inputs of fertilizers and pesticides, from quantity to category.
- Crops in these farms represent all the cropping systems around the lake.

Riparian agricultural crops involve various flowers and vegetables. The dominant types are rose and French bean. Based on field data, fertilizer and pesticide inventories have been compiled (Table 2-2, 2-3).

Most of fertilizers are applied by dilution in the irrigation water. Fertilizer type and application amount change in different farms due to soil conditions and specific farm management. For the common used fertilizers, average application amounts are used in Table 2-2. Otherwise, the values provided by single farm are used.

Pesticides are assessed in two aspects: toxicity and persistency. The toxicity assessment is based on WHO toxicity classification (Kidd, 1991). The persistency assessment is based on EPA (USA) persistence classification (ETA, 1993). The persistence of pesticides is expressed by half-life. The toxicity and half-life of the pesticides in the inventory are derived from literature (Kidd, 1991) (Crowe, 1992) (Internet).

Results and discussion

Fertilizers. Ten major kinds of fertilizers are currently being used.

Based on the average composition of fertilizer materials (FAO, 1985) and application amounts provided in Table 2-2, the total nutrient quantity from fertilizer application are calculated for French bean and rose fields. The results are presented in Table 2-4.

Table 2-4 Average annual nutrient quantity of the fertilizer application dose in the study area (unit: kg/ha/year)

Crop type	Total N	Available P_2O_5	Water soluble Potash K_2O
French bean	250	140	140

Rose	370	170	630

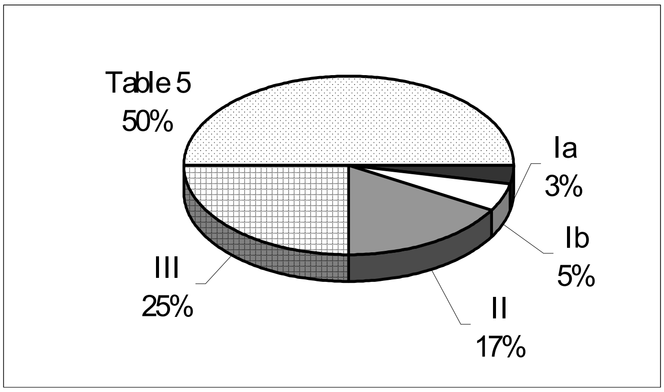
Pesticides. Sixty kinds of pesticides are applied in the rose and vegetable fields.

The toxicity and persistency classifications are illustrated in Figure 2-1 and Figure 2-2. Half-life values for some pesticide are lacking in the literature. “Unknown” class was set for these pesticides.

As depicted in the Figure 2-1, about half of the pesticides is not hazardous. However, still two kinds of “extremely hazardous” pesticide are being used. They are fenamiphos and aldicarb. The trade names are Nemacur and Temik respectively. The half-life of fenamiphos is 120 days. It belongs to “high persistent” class of ago-chemicals according to the EPA classification. Hence, it is recommended to stop using them at once.

Figure 2-2 showed, regardless of “high persistent” pesticides may appear in the “unknown” class, 10% “high persistence” pesticides are being applied. How the persistency of pesticide affects the fate of pesticides and impacts the environment quality will be dealt in detail in Chapter 5.

Figure 2-1 Pesticide toxicity classification



WHO toxicity classification:
Ia: extremely hazardous
Ib: highly hazardous
II: moderately hazardous
III: slightly hazardous
Table5: product unlikely to Present acute hazard in normal use.

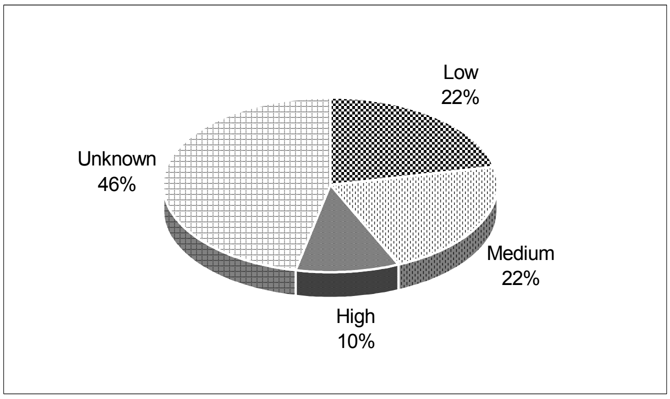


Figure 2-2 Pesticide persistence classification

EPA(USA) persistence classification (ETN, 1993)

Low: 0-30 days
Medium: 30-60 days
High: >100 days

Table 2-2 Fertilizer inventory in the riparian agricultural area

Fertilizer type	Chemical formula	Total nitrogen (N) %*	Available phosphoric acid (P_2O_5) %*	Water soluble potash (K_2O) %*	Application amount (kg/ha/year)	
					French bean	Rose
Diammonium phosphate	$(NH_4)_2HPO_4$	17	47		240	
Urea	$CO(NH_2)$	45			160	120
Calcium ammonium nitrate	$Ca(NO_3)_2.NH_4NO_3$	17			400	385
N-P-K(20:10:10)		20	10	10	280	600
Potassium nitrate	KNO_3	13		44	120	600
Potassium sulphate	K_2SO_4			51	120	600
Magnesium sulphate	$MgSO_4$				80	200
Magnesium nitrate	$Mg(NO_3)_2$	19				270
Phosphoric acid	H_3PO_4		53			200
Foliarphosphate	Mixed				120	
Micro mutrients	Mixed					

* FAO, 1985

Table 2-3 Pesticide inventory in the riparian agricultural area

Number	**Common name**	**Trade name**	**Toxicity**		**Persistence**
			WHO	EPA	Half lIfe
1	Acrinathrin	Rufast	III	IV	52
2	Acephate	Orthene	III	III	7-10 days
3	Aldicarb	Temik	Ia	I	10 weeks
4	Alfa-cypermethrin	Fastac	II	II	13 weeks
5	Amitraz	Mitac	III	III	<1
6	Azocyclotin	Peropal	Ib	II	3 weeks
7	Bacillus thuringiensisi	Dipel	III	III	
8	Benomyl	Benlate	Table5	IV	6-12 months
9	Bifenthrin	Brigade	II	II	62
10	Bitertanol	Bayor	Table5	IV	
11	Bupirimate	Nimrod	Table5	III	6-7 weeks
12	Cadusafos	Rugby	III	III	45 days
13	Captan	Captan	Table5	IV	
14	Carbosulfan	Marshal	II	I or II	2-3 days
15	Carboxin	Vitavax	Table5	III	24 hours
16	Chloropyrifos	Pyrinex	II	II	30-60 days
17	Chlorothalonil	Bravo	Table5	IV	1.5-3 months

18	Clofentezine	Apollo	Table5	III	28-56 days
19	Copper oxychloride		III	III	
20	Cymoxanil	Milraz	III	III	<2 weeks
21	Cypermethrin	Ripcord	II	II	16 week
22	CyproConazole	Alto	Table5	IV	3 months
23	Cyromazine		Table5	III	
24	Dichlofluanid	Euparen	Table5	IV	
25	Dicofol	Kelthane	III	II	
26	Dienochlor	Pentac	III	III	
27	Diflubenzuron	Dimili	Table5	III	<7 days
28	Dimethoate		II	II	7-120 days
29	Dodemorph	Meltatox	Table5	IV	
30	Endosulfan	Thiodan	II	I	plant 3-7 days
31	Fenamiphos	Nemacur	Ia	I	4 months
32	Fenaznquin	Pride	III	III	
33	Fenbutatin	Oxide	Table5	III	
34	Flusilazole	Nustar		III	
35	Fosetyl	Alliette	Table5	III	
36	Hexaconazole	Anvil	Table5	IV	
37	Imidacloprid	Gaucho	Table5	IV	
38	Iprodione	Rovral	Table5	IV	20-160 days
39	Lambda-cyhalothrine	Icon			4-12 weeks
40	Mancozeb	Dithane M-45	Table5	IV	
41	Metaxyl	Ridomil	III	III	70-90 days
42	Methiocard	Mesurol	II	II	
43	Methomyl	Lannate	Ib	I, IV	
44	Metiram	Polyram-combi	Table5	IV	
45	Oxamyl	Vydate	Ib	I	7 days
46	Oxycarboxin	Plantvax	Table5	III	
47	Pirimiphos-methyl	Actellic	III	III	<30 days
48	Polyoxins	Polyoxin		IV	
49	Procymidone	Sumilex	Table5		4-12 weeks
50	Propancarb	Previcur N	Table5	IV	3-4 weeks
51	Propargite	Omite	III	III	2-4 weeks
52	Propineb	Antracol	Table5	IV	
53	Pyrethrins	Py-mark	II	II	
54	Quintozene	Brassicol	Table5		4-10 months
55	Sulphur		Table5	IV	
56	Tetradifon	Tedion	Table5	III	
57	Thiocyclam	Evisect	II	II	1
58	Thiophanate-methyl	Cercobin	Table5	IV	
59	Thiram	Thiram	III	III	
60	Triforine	Saprol	Table5	IV	3 weeks

2.2.2 Sewage discharge

Sewage discharge is another pollution source of the lake water. Sewage effluents usually contain high levels of fecal material and organic matter which not only represent a major source of biodegradable organic material but also of nutrient phosphorus and nitrogen. Normally, they are considered as the major potential pollution source for eutrophication of a waterbody.

Among the approximate 250000 people living round the lake, urban population in Navaisha town is 69000 (LNROA, 1996). Water consumption is classified as four classes in the Kenya human water consumption classification (Table 2-5).

Table 2-5 Kenya human water consumption classification

Class	Water consumption per capita per day* (l)
Rural	50
Low	75
Median	150
High	250

* From Kenya design manual for water supply

Sewage effluents can be estimated from water consumption amounts. It is normally considered 80% of the water consumption. Sewage effluents in Navaisha town are routed into the lake by a sewage network, which represents point source pollution. On the contrary, sewage from rural populations has no obvious point of entry into the lake, which is categorized as non-point source pollution.

Quantification of sewage effluents

Urban water consumption: in Naivasha town, 30% population belongs to “low”class, and the rest belongs to “median” class of water consumption (Kenya design manual for water supply). Based on Table 2-5, among 69000 inhabitants, the water consumption is 75 l/d per capita for 20700 people. While for the rest, it is 150 l/d per capita. The total amount for “low” class and “median” class are 1552500 and 7245000 liter per day respectively.

Rural water consumption: rural inhabitants are 181000 among the total population 250000 around the lake. The water consumption is 50 l/d per capita. The total amounts are 9050000 liter per day accordingly.

The sewage discharge is taken 80% of the water consumption. The total annual amount from urban and rural are calculated and presented in Table 2-6.

Table 2-6 Annual sewage discharge

Pollution source	Population	Sewage amount (ton/y)	Category

Urban	69000	2.56E+06	Point
Rural	181000	2.64E+06	Non-point

Sewage pollutant amount: the main pollutants in the sewage effluent were quantified based on inhabitant equivalent (I.E.) value (Verstraete, 1984) and shown in Table 2-7.

Table 2-7 Annual pollutant discharge from sewage of Naivasha town

Chemical pollutant	COD	BOD_5	Total N	Total P
Discharge amount (ton/y)	9.12E+3	4.93E+3	9.12E+2	1.37E+2

Discussion

As clearly shown in Table 2-6, about 50% of the sewage is from Naivasha town, whose population is only 27% of total population around the lake. In addition, the growth rate of Naivasha town is 8% per year, one of the highest growth rate districts in Kenya. Therefore, the efficient treatment of wastewater and effective management of sewage network plays a significant role in an effort towards controlling sewage pollution of the lake water. Unfortunately, sewage treatment works in Navaisha town established in 1984 has not been working any more since 1992. The sewage water discharges into the lake directly through a ditch nearly without any treatment.

2.2.3 Other pollution sources

Industrial effluent: it is a significant pollution source as the consequence of industrial development. Samir (1998) gives the inventory of industrial pollution sources. However, the wastewater discharge of the pollution sources needs to be collected and the main pollutants contained need to be identified.

Livestock farms: the pollution due to cattle excreta from livestock farms in the north of the lake should be given consideration. It is one of the important potential nutrient contributors.

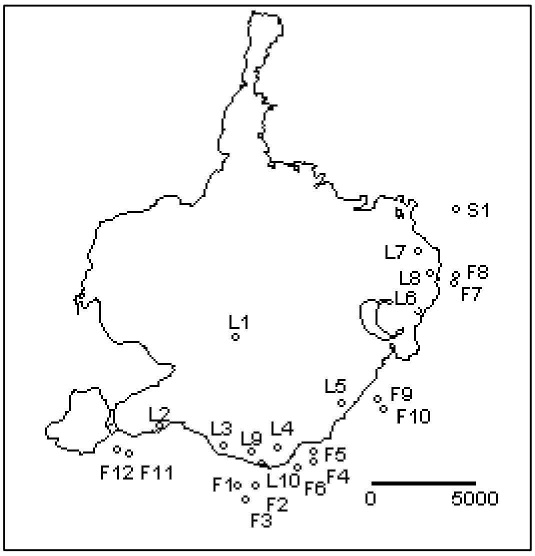
Recreation & tourism: with the development of recreation and tourism in the lake area, the pollution from this sector will increase correspondingly.

Since the assessment of these pollution sources is beyond the scope of this study, they are not treated here.

2.3 Lake water quality survey and assessment

2.3.1 Water samples collection

In order to assess the pollution caused by riparian agricultural activities and lake water quality, twelve water samples from different vegetable and flower farms, ten water samples from southeastern part of the lake and one sewage water sample have been collected during fieldwork. The location of sampling sites is shown in Map 2-1, and detailed sample descriptions see Appendix 1.



Note: Lake water samples — L1-L10
Farm water samples — F1-F12
Sewage water sample — S1

Map 2-1 The location of the water sampling sites

2.3.2 Water quality indicator selection

Generally the most important contaminants in the aquatic environment are organic matter, synthetic organic compounds (pesticides), microbial organisms, nutrients, oil, litter,heavy metals, and radionuclides. The particular pollutants for a waterbody depend on specific pollution sources.

Two aspects were taken into account to select chemical and physical indicators: water use and pollution sources. As stated before, the major use of the lake water is irrigation among a multiple competing use. Other uses involve drinking water supply and fisheries. Agricultural sector is considered the potential pollution source for the lake water quality. Thus, six category indicators were selected (Table 2-8) for the water samples based on the following criteria:

- WHO, UNESO, UNEP suggested water quality variables appropriate to irrigation and drinking water supply and in relation to pollution sources of agriculture (Chapman, 1992).

- Hydrochemical variables measured in the last year (Morgan, 1998) are not included, such as chloride, sulphate, hardness, and fluoride.

Table 2-8 Water quality indicators selected in this study

Category	**Indicator**
General water quality variables	pH, conductivity, turbidity, dissolved oxygen
Organic matter	Chemical oxygen demand
Nutrients	Nitrate-nitrogen, total nitrogen, total phosphorus; ortho-phosphate, phosphate-phosphorus
Pesticides	Various chemical family indicators
Heavy metals	Copper, iron, cadmium
Major ions	Sodium, potassium, calcium, magnesium

2.3.3 Experimental instrument and measurement

Three instruments were mainly used for the measurements. Some variables were measured in the field. Others were determined in the laboratory. The specific treatments such as filtration, acidulation and storage for all variables of water samples were carried out preceding analysis.

Water quality checker (U-10)

The instrument is for simultaneous multiparameter measurement of water quality. It is used for the on-spot field measurement of general water quality parameters, including temperature (^{0}C), pH, conductivity (mS/cm), turbidity (NTU), and dissolved oxygen (mg/l).

MP-Photometer (AL 25)

It is used for the spectrometric measurement of NO_3^--N, COD, PO_4^{3-}, phosphate-P in the laboratory. The inorganic constituents of sample water are made to react with specific aqualytic reagents. The intensity of the colour produced form the chemical reaction is proportional to the concentration of the inorganic ion, which is analyzed. The concentration is achieved by this relation.

Atomic absorption spectrometry (VDB 1275)

Atomic absorption spectrometry (AAS) is a well-established technique for metal determination. The line spectrum of atoms is used for quantitative analysis. Analyte atoms absorb light from a special light beam at their characteristic wavelengths and remit in random direction. The concentration obtained is based on the measurement of absorbance (the degree of attenuation at that wavelength)(Rowland, 1996). It is distinguished as flame AAS and furnace AAS methods based on the type of sample containers. Graphite furnace AAS is used for very low concentration. The lowest detection limit with a factor 20-1000 compared to the flame AAS methods. Flame emission spectrometry (FES) has similar principle with AAS, based on the emission of the light of excited atoms returning to the groundstate.

The equipment what we used can be operated in AAS and FES two ways. AAS is much more sensitive and less susceptible to interference. We used it for the measurements of heavy metal Cu, Cd, Fe and major ion Ca, Mg; among them, Cu, Fe, Ca, and Mg were measured by flame AAS, while Cd was measured by graphite furnace AAS. FES is more appropriate for atoms that are easily excited, so it is used for the measurements of major cations Na and K.

The standard curves and peak height of absorbance or emission for determined the concentrations of all measured elements are illustrate in Appendix 3.

Result

The experiment results for all water samples are presented in Appendix 2. The assessment of the result will be given in the following section.

2.3.4 Water quality assessment

Water quality assessment can be divided into two categories, use-orientated and impact-orientated. Use orientated assessment test whether water quality is satisfactory for specific purposes, such as drinking water supply, irrigation, and industrial use. Impact oriented assessment examines the effects of specific activities on water quality, it is undertaken in relation to effluent discharges, urban or land run-off (Chapman, 1992).

In this study, we apply use-orientated assessment for water quality of the lake, while impact oriented assessment for water quality of the farm effluents.

2.3.4.1 Lake water assessment

The simplified aim of the lake water assessment is to test the fitness for use. As mentioned before, the lake water has multi-purpose uses. It is used for irrigation, drinking water supply and fishery. The assessment, therefore, will focus on these uses. Three methods were employed to carry out this assessment.

1. Direct comparison with guidelines

The experiment results for the lake water samples are summarized in Table 2-9. The ratios between water quality variables and the corresponding guideline were calculated in order to observe the difference between them easily. A ratio chart was constructed as well (Figure 2-3). The values of water quality variables used are maximum values of all samples. Therefore, the ratio demonstrate the maximum difference between the lake water quality variables and the guidelines, in other word, it shows the worst lake water condition.

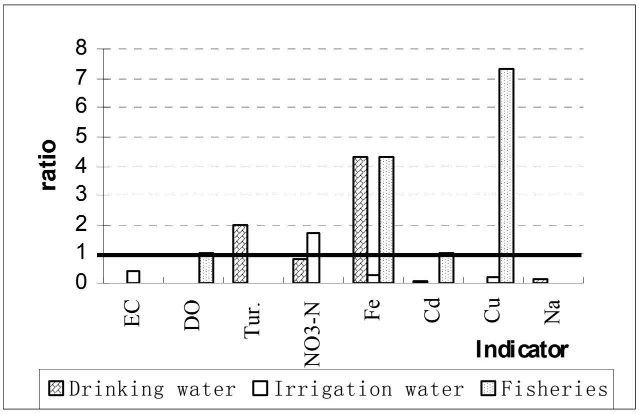


Figure 2-3 Ratio of maximum concentrations measured to the guideline values as a function of the water quality indicators

Note: i) Ratio>1 indicates the water quality indicators exceeding the guidelines.

ii) Tur.: turbidity

Result and discussion

As shown in Table 2-9, guideline values are only available for some water quality indicators. The following discussion, therefore, will limit to these indicators based on water use.

— For irrigation purpose: all indicators are much lower than the guideline value except NO^-_3-N. Its maximum concentration measured exceeded *irrigation water* guideline value 0.7 times. It is classified as “slight to moderate” in the “Degree of restriction on use” for irrigation. However, as noted in the guideline, “restriction on use” does not indicate that the water is unsuitable for use. It indicates that there may be a limitation in choice of crop, or special management may be needed to maintain full production capability.

— For drinking water purpose: turbidity is twice of the *drinking water* guideline, while Fe concentration is 4.3 times of the *drinking water* guideline. Fe concentrations measured range from 0.8 to 1.3 mg/l. The median Fe concentration in rivers has been reported to be 0.7 mg/l (WHO, 1996). Hence, the Fe content of the lake is relatively high. Total Fe iso-concentration map for groundwater (Morgan, 1998) showed Fe concentration in groundwater ranges from 0.2 to 0.6 mg/l in the east of the lakeshore where is near to the sampling sites in this study. The maximum Fe concentration in groundwater is 3 times of the guideline value 0.3 mg/l. However, the higher concentration in groundwater is not necessary contribute to the higher concentration of the lake since the Fe^{2+} will be oxidize to Fe^{3+}in the aerated water and precipitate as insoluble iron (III) hydroxide. Therefore, Inflow rivers and application of fertilizers around the lake are the potential contributors to the higher Fe content in the lake.

As stated in the section 2.2.1.1, one of the major ways that mineral fertilizers impair water quality is through trace elements to cause heavy mental contamination of surface water and groundwater. Fertilizer application in the riparian agricultural area, hence, should be partly responsible for Fe pollution of the lake.

- For fishery purpose: DO and Cd concentrations are equal to the *fisheries* guidelines. Fe and Cu concentrations are above *fisheries* guidelines 3.3, 6.3 times respectively.

- COD and phosphate-P are 2.3, 10.5 times higher comparing with indicative values for unpolluted water (WHO, 1993). They are not presented in the Figure 2-3 since the standard is not a guideline.

It is difficult to trace the exactly direct reasons that result in those indicators exceeding the guidelines. Because there are no routine monitoring data for the lake and its inflow rivers (i.e. Malewa, Gilgil and Karati) and the sampling sites are very limited in this study.

2. Water quality index of the lake water

Although the number of the lake water samples is very limited for water quality classification purpose, we still can get some indication from it. An irrigation water quality index like the sodium adsorption ratio (SAR) was exploited to assess the suitability of water for irrigation purposes. SAR indicates the effect of relative cation concentration on sodium accumulation in the soil. The potential for a sodium hazard increases in waters with higher SAR values. SAR is defined as followings:

$$SAR = \frac{[Na^+]}{\sqrt{\frac{[Ca^{2+}] + [Mg^{2+}]}{2}}}$$

Where $[Na^+]$, $[Ca^{2+}]$ and $[Mg^{2+}]$ are ionic concentrations in milliequivalents per liter (meq/L).

Average concentrations of Na^+, Mg^{2+}, Ca^{2+} were used to calculate SAR. The result is 2.46. Average conductivity is 288mS/cm, according to the diagram of U.S. Salinity Laboratory classifications (Mannaerts, 1998), lake water fall in section C2-S1, which represents medium-salinity and low-sodium water. C2 can be used if a moderate amount of leaching occurs, S1 can be used for irrigation on almost all soils with little danger of developing harmful levels of sodium.

However, the content of bicarbonate of the lake water is relatively high, an adjust SAR could be better used to evaluate the sodium hazard of the water.

Table 2-9 Water quality of Lake Naivasha in relation to the guideline values (unit: mg/l except pH, turbidity NTU, and EC mS/cm)

Indicators	Sample numbers	Range	Average	Drinking water		Irrigation water		Fisheries and aquatic life	
				Guideline value^1	Ratio	Guideline value^2	ratio	Guideline value^3	Ratio
pH	7	6.67-6.95	NA	6.5-8.5		6.5-8.4		6.5-9.0	
EC(23.2^{0}C)	7	0.282-0.298	0.288			0.7	0.4		
Turbidity	7	10-10	10	5	2				
DO	7	7.93-9.3	8.59	10*	0.93			5.0-9.5	1
COD	10	21-63	43	20*	3.3				
NO_3-N	9	1.5-8.4	3.6	10	0.84	5	1.7		
NH_4^+	1	0.5	0.5						
PO_4^{3-}	7	0.2-0.3	0.2						
Phosphate-P	10	0.09-0.23	0.18	0.005*-0.02*	11.5				
Fe	10	0.8-1.3	1.0	0.3	4.3	5.0	0.3	0.3	4.3
Cd	10	1e-4-2e-4	1e-4	3e-3	0.1	0.01	0.02	2e-4-1.8e-3	1
Cu	10	1.05e-2-2.9e-2	1.75e-2	1	0.03	0.2	0.1	2e-3-4e-3	7.3
Na	10	20.2-22	21.1	200	0.11				
K	10	9.2-10.1	9.7	12					
Ca	10	5.8-9.5	6.6						
Mg	10	4.9-5.2	5						

1. WHO, 1993
2. FAO, 1985 (Ayers et al., 1985)
3. Canada, 1993 (Chapman, 1992)
4. Maximum value measured to guideline value
5. * Indicative values for unpolluted water (Chapman, 1992)

3. Trophic status of the lake water

The trophic status of lake is a central concept in lake management. It describes the relationship between nutrient status of a lake and the growth of algae in the lake. Eutrophication is the process of change from one trophic state to a higher trophic state by enrichment of surface water with nutrients. Agriculture is a major factor in eutrophication of surface water (Ongley, 1996). Both nitrogen and phosphorus contribute to eutrophication, the historical monitoring data for the lake water are presented in Table 2-10.

Table 2-10 Trends in N and P contents of the lake water

Year	Soluble N (mg/l)	Soluble P (mg/l)	Data source
1984	0.045	0.005	Harper, 1990
1988	0.125	0.012	Harper, 1990
1997	0.452*		Morgan, 1997
1998	3.6*	0.18	Tang, 1998

* NO^-_3-N concentration

Soluble N is the sum of NO^-_3-N, NO^-_2-N, and NH^+_4-N. NO^-_3-N was used in place of soluble N in 1997 and 1998, since latter data was not available. Thus, the soluble N concentration for this two years should be higher than the values listed in Table 2-10. The actual increase rate from 1984 to 1997 should be higher correspondingly.

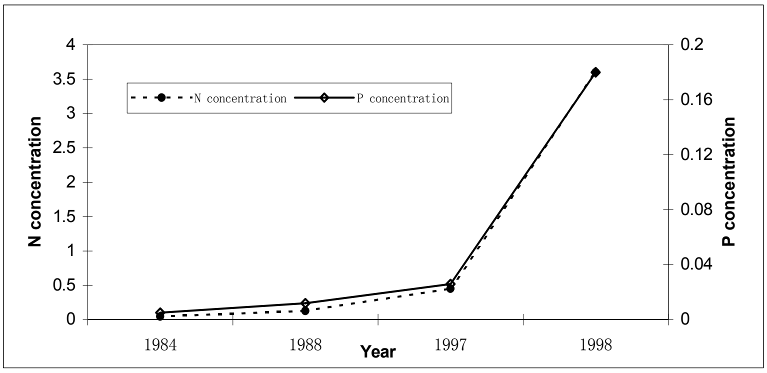


Figure 2-4 N and P concentration of the lake water showing the increasing trend

Result and discussion

Figure 2-4 shows obvious increasing trend from 1984-1998, and the increasing rates are almost the same for both N and P respectively.

A significant increasing rate appeared from 1997 to 1998, It could be attributed to the vast expansion of the lake area in 1998. There appears to be a pattern of high and low water levels every seven years, according to the record of the lake water level (LNROA, 1993). Because of the almost flat slopes of the riparian area, a

change of 0.5m in the lake level can causes an change of several square kilometers in flooded area, particularly along the Northeast shores that are gently sloping. High rainfall in 1998 resulted in a 10 feet rise of the lake water level as compared to 1997, indicating the lake water flooded a vast of land area. Certain agricultural fields were inundated; a large amount of nutrient loads unavoidably entered the lake, caused a big increment of N and P concentration in the lake water.
Although we can't get quantitative eutrophication status of the lake as all eutrophication classification schemes need annual indicator data, the worrying increase of nutrient level in the lake can be a definite evidence of degraded lake water quality.

2.3.4.2 Farm effluent assessment

The analysis results of the farm water samples and comparison with the Kenya effluent guidelines are summarized in Table 2-11. Two guidelines are used in this assessment. They are "Guideline for discharge into public watercourse" and "Guideline for discharge into public sewers" (Appendix 4). The latter is only used when the water quality indicators in the former are not available. The ratios in Table 2-11 are between the maximum values and guideline values, indicating the extent that indicator value exceed the guideline. It is illustrated in Figure 2-5.

Discussion

All the farm water samples were collected in the drainage ditch or water recycling ponds of the farms. The collection conditions varied from no rain to very heavy rain in which the pollutants are highly diluted. Thus, the concentrations of different samples also vary a lot. However, the maximum values of all variables are very high. As shown in Figure 2-5, all maximum water quality indicators except Cd are higher than the guideline values. The maximum level to exceeded guideline is 16.9 times of the guideline value for NO^-_3-N, while the minimum is 1.7 times of the guideline value for COD.

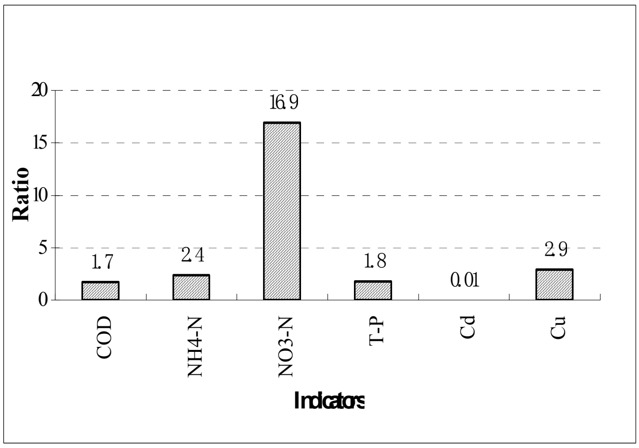
The pollutants can cause the lake water quality deterioration either through surface runoff or through leaching to groundwater. Since the very permeable soil and very gentle slopes in the study area, surface runoff is insignificant. However, when the storm intensity is very high (i.e. the extreme event), the pollutants will have chance to flow into the lake through this pathway. Pollutants may also enter the lake when riparian cultivated land is flooded due to the increase of the lake water level. The same soil properties give more chance for the leaching of pollutants to the groundwater than entering the lake through surface runoff.

NO_3^- is considered to have a very high leaching potential because of its low adsorption to the clay. Thus, the high concentration of NO^-_3-N can cause the potential risk to the groundwater quality. Actually, the higher NO_3^- content of the groundwater has been found in the cultivated area than in other areas (Morgan, 1998).

Recommendation

Irrigation water recycling systems in one of the farms is worthy to be recommended to in the study area. There are eight water ponds in this farm, four of them operate everyday, and others are prepared for extra use. The double functions of water ponds are providing irrigation water and receiving drain water from fields, all the drains are connected to the ponds. Thus, no wastewater discharges into lake through surface runoff directly. Water level of ponds is always kept lower than lake, which means water flow through seepage is only one direction from lake to pond, no pollutants are introduced into the lake by interflow. Therefore, on the one hand, this irrigation water recycling system alleviated pollution impact from farm to lake, on the other hand, it reduced water consumption and saved water resource.

Indicators	Sample numbers	Value range (mg/l)	Guideline values (mg/l)	Ratio*
COD	12	28-83	50	1.7
NO_3^--N	12	1.0-76	4.5**	16.9
NH_4^+	10	<0.05-60.6	25.7	2.4
PO_4^{3-}	12	0.2-8.6		
Phosphate-P	10	0.07-17.4		
T-P	10	0.1-53.8	30**	1.8
Fe	9	0-47.0		
Cd	9	1e-4-7e-4	0.05	0.01
Cu	9	2.18e-2-1.44e-1	0.05	2.9
Na	9	11.0-55.8		
K	9	5.7-23.2		
Ca	9	<0.5-38.6		
Mg	9	0.3-15.2		



Note: Ratio>1 indicates the water quality indicators exceeding the guidelines

* maximum value measured to guideline value

** guideline for discharge into public sewers

Table 2-11 Water quality of the farm effluents in relation to the guideline values

Figure 2-5 Ratio of maximum concentrations measured to the guideline values as a function of

Sewage water sample

One sewage water sample was collected. High analysis results but common for sewage occurred in the sewage water sample. COD, EC, NO^-_3-N, and PO_4^{3-} are 520 mg/l, 2880ms/cm, 160mg/l, and 570mg/l respectively. Compared with guideline for discharge in Kenya (Appendix 4), COD and NO^-_3-N exceeded guideline values by about 10 and 40 times. As concluded in the part of pollution sources assessment, Naivasha town is the main contributor for the sewage discharge. Hence, the effective treatment of sewage water is highly needed.

CHAPTER 3

GIS DATA DEVELOPMENT

This chapter gives the spatial description about the study area in thematic maps. Groundwater and soil maps were also created as base maps for constructing the pesticide leaching fraction maps.

3.1 Introduction

Geographic Information System (GIS) is a georeferenced database management system for spatially distributed data. It is designed to store, manipulate and display geographic information. GIS technology is the leading technology that is interfaced interactively to mathematical environmental modeling for input-output, processing, and visualization of simulation. ILWIS (Integrated Land and Water Information System) GIS software was used in this study.

Thematic maps DEM, slope percentage, soil texture, landuse, groundwater depth are created. These maps have two functions: i) providing spatially referenced information about the study area. Some input data such as slope steepness for specific area can be obtained from slope map. ii) Processing the visualization of the model simulations.

3.2 DEM and slope map

Digital Elevation Model (DEM) (Map 3-1) for the South and East of the lake riparian zone was created from the digitized contour lines using contour interpolation operation (ILWIS, 1997). The contour lines are digitized manually from 1:50000 topographic map Naivasha. The intensive cultivation areas occur below 1950 meter elevation.

A Slope map (%) (Map 3-2) was calculated in X and Y direction using DEM, gradient filters (Dfdx and Dfdy) and a map calculation formula (ILWIS, 1997). The lakeshore area is quite flat. The predominant slope percentage is 1.12 calculated from map histogram. The dominant slope percentages for the agriculture area range from 0.7 to 1.6.

3.3 Soil maps

Map 3-3 was derived from a geopedological soil map by Kwacha (1998). The landscape was classified as 8 units as shown in the map. Units PL444 and PL223 in Kwacha's map were excluded, since PL444 represents mainly the riparian area with papyrus vegetation and the area of unit PL223 is negligible. Soil properties were determined for these soil units, including soil texture, hydraulic conductivity, bulk density, and organic carbon (OC) content. These data will be used as the model input parameters. Map 3-3 will be used to present OC content of these soil units and to calculate the pesticide leaching maps as one of the base maps in Chapter 5.

The determination of the soil grain size distribution was done for the depths 20 cm, 50 cm and 120 cm by Kwacha (1998). The results showed mainly two types of the soil texture, which are sandy loam and clay loam soils (Map 3-4). The boundary of these two soils was set by Siderius (personal communication, 1999). All input parameters about soil properties in the SESOIL model are differentiated related to the two soil textures. The detailed explanation will be given in Chapter 4. Map 3-4 will be used as one of the base maps to create the pesticide leaching maps in Chapter 5.

3.4 Landuse map

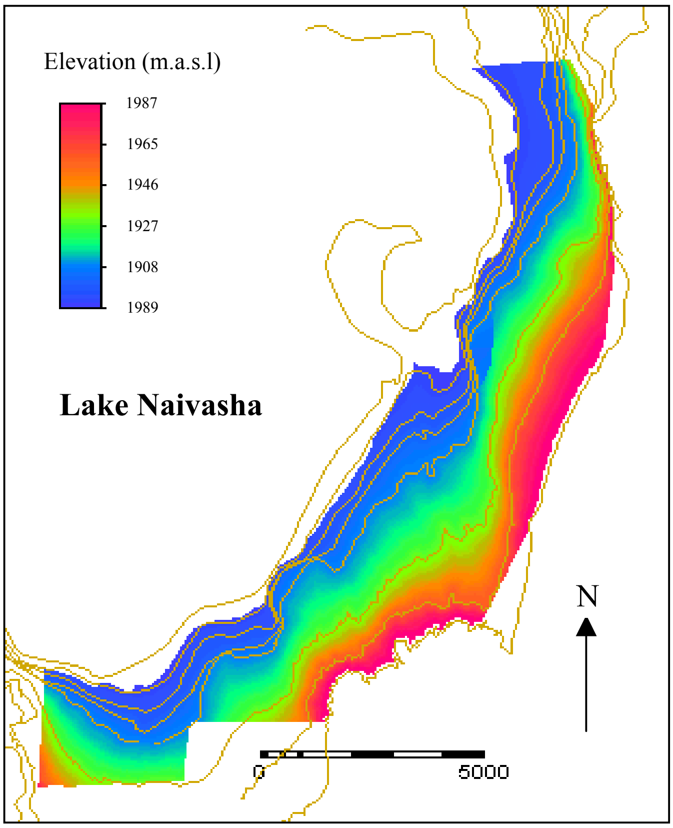
A landuse map was prepared in the following way:

1. Photo interpretation before fieldwork, using aerial b/w photos. Scale 1:12500 (1984).
2. Double check the interpretation with Landsat FCC (false color composite) image (Map 1-2) (January 21, 1996).
3. Check representative units during fieldwork.
4. Modify pre-interpretation after fieldwork.
5. Digitize the interpretation and create landuse map following the procedure in ILWIS.

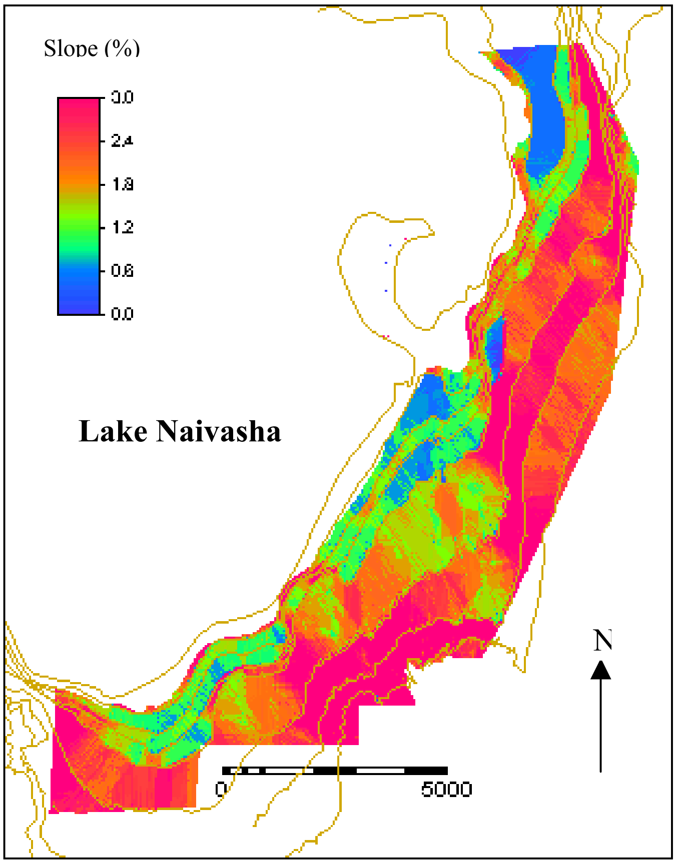
Map3-5 shows there are mainly seven landuse units. The dominant landuse is natural vegetation “bushes”. It accounts for about 45% of the total areas. The cultivation area is about 2083 hectares and accounts for 45% of the total area as well. The prevailing crops are flowers and vegetables. The most representative crop types are rose and French bean. Other crops include flowers Carnation, Limonium and vegetables French bean, cabbage, tomato, potato, baby corn and etc. Map 3-5 will be used to build up the pesticide leaching maps in Chapter 5.

3.5 Groundwater depth map

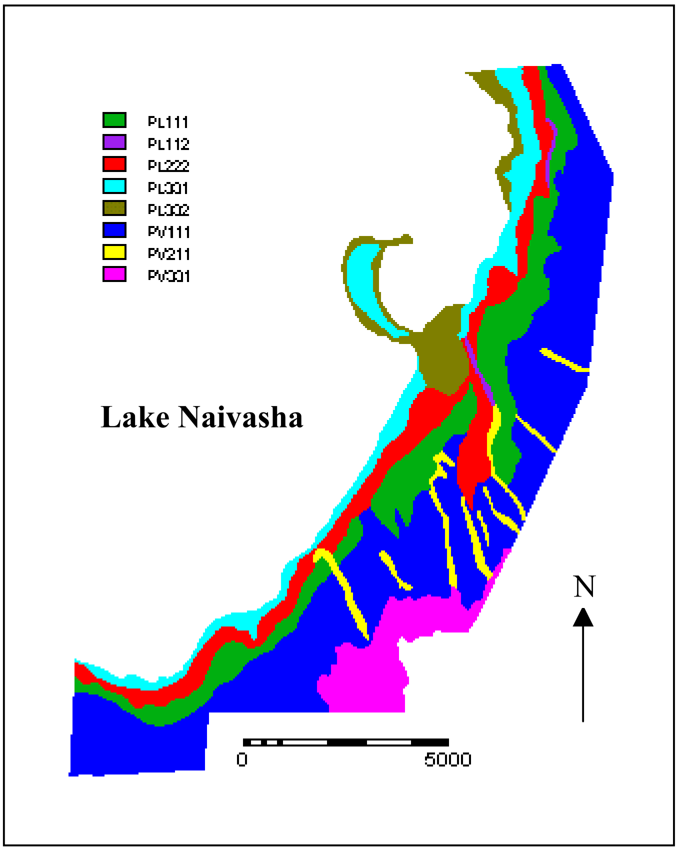
The groundwater depth map was needed to study potential pesticide leaching risk to groundwater. The spatial and temporal variation of the ground water table brought difficulties for building this map. A manual interpolation method was used to get the contours of the groundwater depth (personal communication with Dr. Gieske). Some groundwater depths were derived from 10 boreholes scattered in the study area. The contour lines are almost evenly distributed in this area. It is assumed, therefore, the linear relationship between the distance from the certain point to the lake boundary and the ground water depth in the same point. Historical groundwater depth records of the boreholes were used. The lake level was taken 1886 meters above sea level which is the long-term average value from 1940-1970 (Mmbui, 1999). The manual interpolation was used to follow the trend of the contour lines. Based on the manual interpolated contours of the groundwater depth, the final groundwater depth map (Map 3-6) was created by interpolation process in ILWIS (ILWIS, 1997). It is also one of the base maps for constructing the pesticide leaching maps in Chapter 5.



Map 3-1 Digital elevation model (DEM) of the study area

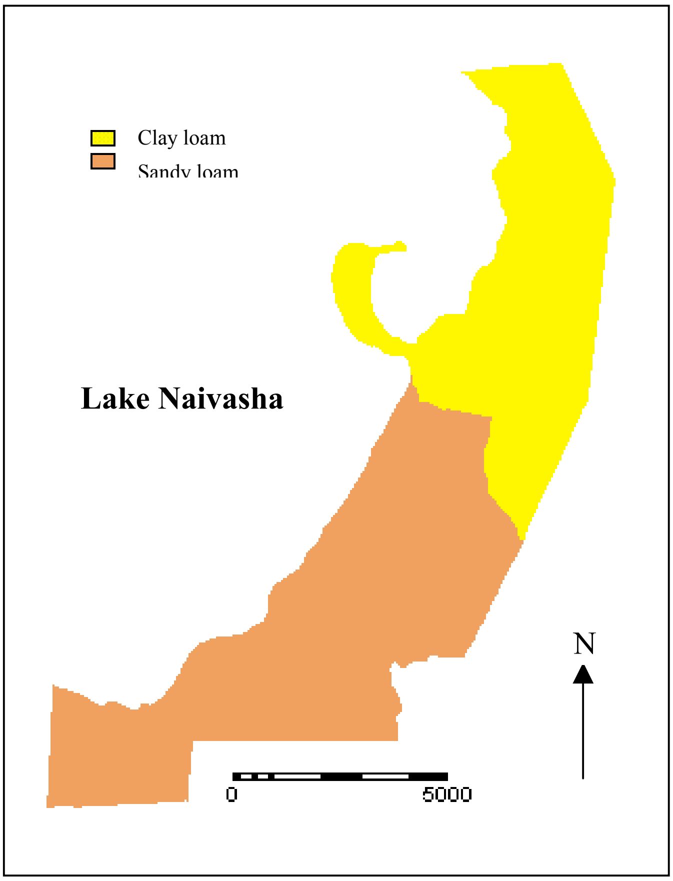


Map 3-2 Slope percentage map of the study area

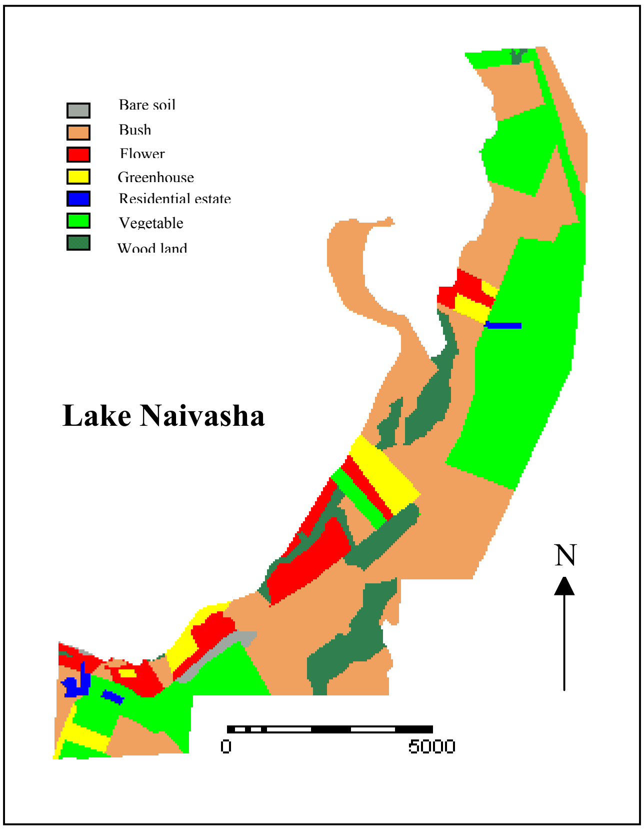


PV units - volcanic plain
PL units - Lacustrine plain
Detailed descriptions of the units see Kwacha (1998)

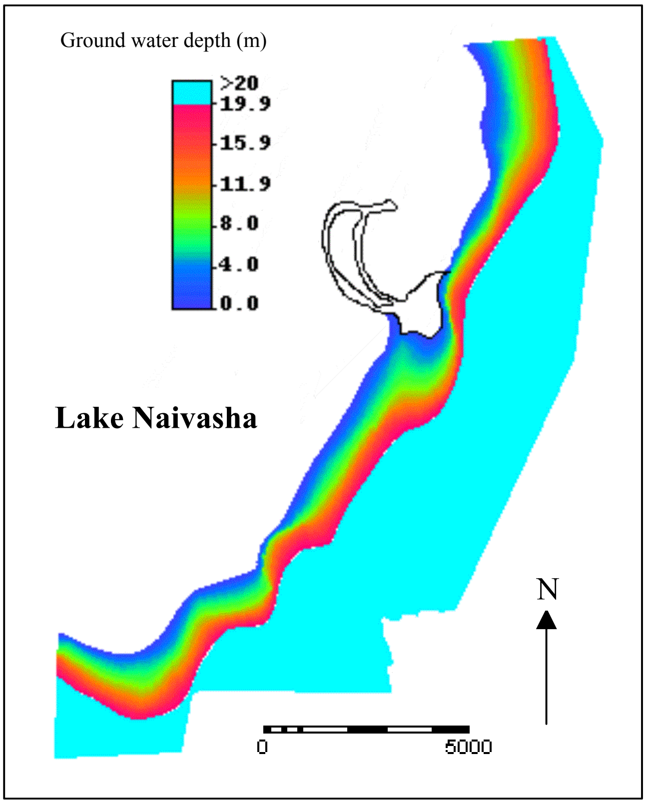
Map 3-3 Geopedological soil map of the study area



Map 3-4 soil texture map of the study area



Map 3-5 Generalized Landuse map of the study



Map 3-6 Groundwater depth map of the study

CHAPTER 4

MODEL THEORY AND FIELD CALIBRATION

This chapter describes the model input data and field calibration. Brief introductions about the fate of pesticides and model theory are given as well.

4.1 Fate of pesticides

4.1.1 Transport of the pesticide in the environment

Fate and transports of pesticides in the environment are very complex. The environment can be thought of as a series of homogeneous compartments such as air, water, soil, sediment, and biological material (Hounslow, 1995). Actually, the deterioration of environment resulting from pesticides is the impacts to these compartments. The fate of a pesticide can be visualized as in Figure 4-1.

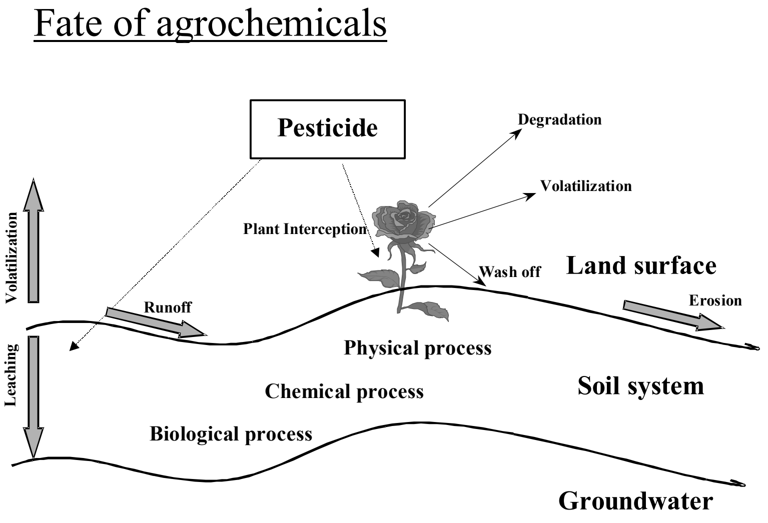


Figure 4-1 Fate of pesticides

There are mainly two ways to apply pesticides, spraying to the plants or applying to the soils. Following release into the environment, pesticides may go many directions. Pesticides sprayed are partly intercepted by the plants, and partly reach soils. The part intercepted by plants will end up in the air through photodegradation, volatilization or reaching the soils through washing off. The part reaching soils has the same fate with pesticides applied directly to the soils. They may follow four directions once they reach the soil.

- They can be washed off into nearby bodies of surface water either associated with the soil particles or dissolved in the runoff. Soil erosion and surface runoff are main pathways for pesticides impacting surface water;

- They may percolate through the soil to lower soil layers or be adsorbed to the soil particles;
- They can also dilute in the soil moisture and leach toward groundwater;
- They may volatilize to the air as well.

The movement of pesticide in the soil compartment is much more complex than in other media. The chemical, physical and biological properties of a substance, in conjunction with the environmental characteristics of an area, result in physical, chemical, and biological processes associated with the transport and transformation of the substance in the soil compartment. These processes then govern fate — the ultimate and long-term distribution of that substance in the environment (i.e., air, soil, water, biota) (Bonazountas et. al., 1997).

4.1.2 Fate processes in soil compartment

Almost all pesticides are synthetic organic compounds. Major physical transport processes for organic dissolved contaminants are advection, dispersion, diffusion, volatilization, sorption, and ion-cation exchange. Chemical transformation processes are mainly ionization, solubility and hydrolysis, oxidation/reduction, and complexation. Biological processes involve bioaccumulation and biodegradation. Some of these processes governing pesticide migration and related to this study are briefly explained below. (Bonazountas et. al., 1997).

Advection: Pollutant mass movement by the medium carrying it.

Diffusion: Movement or spread of the pollutant, relative to the mass of the medium, as driven by molecular or micro turbulence-scale dynamics. In solution this process results in an overall net flux of solutes from a zone of high concentration to a zone of lower concentration.

Volatilization: Volatilization refers to the process of pollutant transfer from soil to air phase and is also a form of diffusion, the movement of molecules or ions from a region of high concentration to a region of low concentration.

Sorption: Sorption refers to adsorption and desorption of a chemical onto soil particles. Adsorption is the adhesion of pollution ions or molecules to the surface of soil solids, causing an increase in the pollutant concentrations on the soil surface over the concentration present in the soil moisture. Desorption is reversible process of adsorption. Adsorption and desorption have a large effect on transport of pollutants in soils.

Transformation: Production or consumption of the pollutant, usually driven by the chemical reactions in the medium.

Dissolution in water: Solubility is a factor usually inversely related to the soil adsorption. It has a reverse effect for the migration of chemicals with adsorption. A pesticide with high solubility results in quick distribution in the soil moisture and relatively low soil adsorption. Such pesticides can decay readily.

Hydrolysis: Hydrolysis is a chemical transformation process in which an organic compounds reacts with water, dissociating and forming a new molecule. It occurs normally with organic compounds.

Biodegradation. Biodegradation refers to the process of transformation of a chemical by biological agents, usually microorganisms (i.e., bacteria, fungi).

Many numerical estimation models have been developed to simulate these transport and transformation processes with specific focuses. The same process can be represented by different mathematical functions in various models in order to coincide with the actual situation.

4.2 SESOIL model description

SESOIL, Seasonal Soil compartment model, was developed for the EPA Office of water and the Office of Toxic Substances (OTS) in 1981. The SESOIL Version 3.0 for windows (May 1998 & updated February 1999) with the RISKPRO system is used in this study (GSC, 1998).

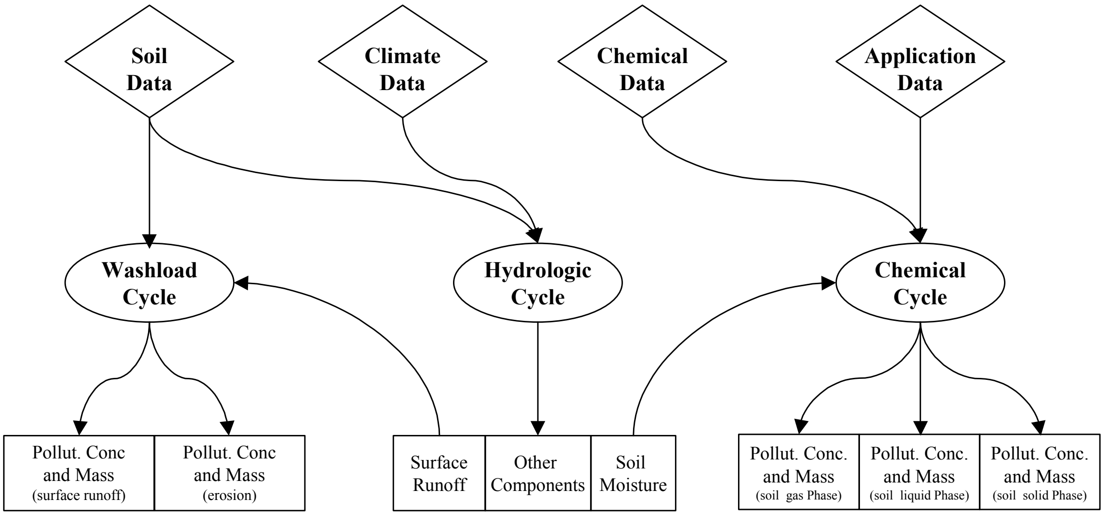


Figure 4-2 SESOIL model description

SESOIL is designed to describe long-term pollutant environmental fate with respect to the parameters: *water transport; sediment transport; chemical migration to groundwater, and soil quality.* Three cycles defined by this model handle the conditions that decide the fate of pollutant. The hydrologic cycle models the soil moisture movement or flow through the compartment. The sediment washload cycle deal with runoff conditions from soil surface. The pollutant fate cycle accounts for the various chemical transport and transformation processes occurring in the soil.

SESOIL operates based on soil column which is a user-defined compartment extending from the surface through the unsaturated zone to the groundwater table. The model structure is depicted by Figure 4-2.

4.2.1 Hydrologic cycle

Hydrologic cycle simulates the expected site-specific hydrologic condition. The hydrologic cycle is one-dimensional and considers only vertical movement. The model uses the water balance dynamics theory of Eagleson (Eagleson, 1978). This model utilizes long-term average water balance equations stated in Eq.(4-1).

$$\begin{aligned} &P - E - MR = S + G = Y \\ &I = P - S \end{aligned} \qquad \text{[cm]} \quad (4\text{-}1)$$

where: P— Precipitation; E — Evapotranspiration; MR —Moisture retention; S — Surface runoff; I — Infiltration; Y — Yield; G — Groundwater runoff or recharge (includes term or capillary rise)

Infiltration is described by the Philip equation (Philip, 1969). Percolation to the groundwater is assumed to be steady throughout each time step of simulation, at a rate determined by the long-term average soil moisture content. Capillary rise from the water table is assumed to be steady throughout the time period and to take place to a dry surface.

In the hydrologic cycle the entire unsaturated zone is conceptualized as a single layer and the prediction for soil water is considered as an average value for the entire unsaturated zone.

4.2.2 Sediment washload cycle

Chemical sorption on eroded sediments is quantified in the sediment washload cycle. It accounts for surface runoff conditions that can be computed in the hydrologic cycle. The model employs EROS (Foster et al., 1980) sediment yield model which consider soil detachment and sediment transport processes separately.

Soil detachment process employs Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978). Sediment transport process is accomplished by the Yalin transport equation (Yalin, 1963).

4.2.3 Pollutant fate cycle

Pollutant fate cycle models the migration of chemicals through the soil column. It focuses on the various chemical transport and transformation processes that control the ultimate fate and distribution of the pollutants interrelated by a mass balance equation. The model outputs are annual or monthly pollutant mass and concentration in the soil water (µg/ml), soil air (µg/ml), and absorbed in solid phase (µg/g) up to four major soil layers.

Foundation of the cycle

Mass balance equation

The pollutant fate cycle is based on a mass balance equation (Eq. 3-6) that tracks the pollutant as it moves with the soil moisture between subcompartments.

$O(t-1) + I(t) = T(t) + R(t) + M(t)$ [ug/cm^2] (4-2)

Where:
O (t-1) — the amount of pollutant originally in the soil compartment at time t-1;
I (t) — the amount of pollutant entering the soil compartment during time step;
T (t) — the amount of pollutant transferred within soil compartment at time step;
R (t) — the amount of pollutant remaining in the soil compartment at time t;
M (t) — the amount of pollutant migrating out of the soil compartment during the time step.

Partitioning equations

Pesticides are not randomly distributed in the environmental compartments. The concentrations of pesticide in air, soil and water are interrelated by specific distribution coefficients. This chemical partitioning theory is used to solve the mass balance equation. The three phases (soil air, soil moisture, and soil solids) are assumed to be in equilibrium with each other at all times. The concentrations of pollutants in three phases are interrelated through partition coefficients and rate constants. The relationship is defined by equation 4-3 to 4-5.

$$C_{sa} = C * H \big/ R * (T + 273) \qquad [\mu g/ml] \quad (4\text{-}3)$$

Where:
C_{sa} — pollutant concentration in soil air [µg/ml]
C — pollutant concentration in soil water [µg/ml]
H — henry's law constant [m^{3}atm/mol]
R — gas constant 8.2*10^{-5} [m^{3}atm/(mol*K)]
T — soil temperature [^0C]

$$S = K_d * C^{1/n} \qquad [\mu g/g] \quad (4\text{-}4)$$

Where:
S — pollutant concentration adsorbed on soil [µg/g]
K_d — pollutant partitioning coefficient [(µg/g)/(ug/ml)]
C — pollutant concentration in soil water [µg/ml]
N — Freundlich exponent

$$C_0 = f_a * C_{sa} + \theta * C + \rho_b * S \qquad [\mu g/cm^3] \quad (4\text{-}5)$$

Where:
Co — overall pollutant concentration [µg/cm^3]
f_a — (f-θ) the air-filled porosity [ml/ml]
f — soil porosity [ml/ml]
θ — soil water content [ml/ml]
ρ_b — soil bulk density [g/cm^3]

Algorithms of fate processes

Pollutant fate cycle accounts for the following transport and transformation processes: advection, diffusion/volatilization, adsorption/desorption, chemical degradation, biological transformation, and other processes. The algorithms of these processes are presented by Equation 4-6 to 4-9.

Advection

Advection in SESOIL accounts for retardation due to vapor phase partitioning and the adsorption of the pollutant on the soil particles. The depth of soil moisture movement is calculated as shown in Eq. 4-6.

$$D = \frac{J_w t_c}{\theta + \rho_b K_d + \frac{f_a H}{R(T + 273)}} \qquad \text{[cm]} \quad (4\text{-}6)$$

Where:

D — depth [cm]

Jw — water velocity [cm/s]

T_c — advection time [Sec]

θ — soil water content [cm^3/cm^3]

Volatilization/Diffusion

In SESOIL, volatilization/diffusion includes movement of the pollutant from the soil surface to the atmosphere and from lower soil layers to upper ones. The volatilization/diffusion model uses the same equation to define the volatilization and diffusion process. The vapor phase diffusion flux through soil is described as equation 4-7.

$$J_a = -D_a \frac{f_a^{10/3}}{f^2} \frac{dC_{sa}}{dz} \qquad [\mu\text{g/cm}^2\text{s}] \quad (4\text{-}7)$$

Where:

D_a — the vapor diffusion coefficient of the compound in air [cm^2/s]

Z — depth between two major layers [cm]

Adsorption/desorption

SESOIL employs the general Freundlich equation (Equation 4-4) to model soil sorption processes. For most organic chemicals, adsorption occurs mainly on the organic particles within the soil (Hounslow, 1995). The relation between the organic partitioning coefficient K_{oc} and partitioning coefficient K_d is presented by equation 4-8.

$$Koc = Kd * \frac{100}{\%oc} \qquad \text{[ml/g]} \quad (4\text{-}8)$$

oc: organic carbon

Biodegradation

Biodegradation in SESOIL is estimated using the chemical’s rate of first order decay in both the dissolved and adsorbed phases according the first-order rate equation 4-9.

$$P_d = (C * \theta * K_{dl} + S * \rho_b * K_{ds}) * A * d_s * \Delta t \qquad [\mu g] \quad (4\text{-}9)$$

Where:
P_d — decayed pollutant mass during time step t (μg).
K_{dl} — biodegradation rate of the compound in the liquid phase (/d)
K_{ds} — biodegradation rate of the compound in the solid phase (/d)
A — area of pollutant application (cm^2)
D_s — depth of the soil sublayers (cm)
Δt — time step (d)

4.3 Model input data acquisition

As shown in Figure 4-2, SESOIL mainly includes four kinds of input parameters. The basic rule to decide input parameters in this study is to make the widest possible uses of site-specific data if available. Otherwise, use literature data or default values recommended by the model.

4.3.1 Climate data

Input climate data are shown in Table 4-1.

Table 4-1 climate input data

Month	Temp. (degree)	Evapo (cm/d)	Precip. (cm)	Storm duration (day)		Storm number		Length (day)
				Sandy	Clay loam	Sandy loam	Clay loam	
Oct.	17.25	0.34	17.9	0.1145	0.61	9.15	10	30.4
Nov.	16.9	0.33	18	0.11	0.67	9	9	30.4
Dec.	17.15	0.31	18	0.4	1.3	8.17	9	30.4
Jan.	17.8	0.33	18	0.5	1.3	5.62	9	30.4
Feb.	18.15	0.32	18	0.58	1.3	5.38	9	30.4
Mar.	18.45	0.35	18	0.1	0.55	9.14	10	30.4
April	18.25	0.28	19	0.0515	0.31	10.6	10	30.4
May	17.45	0.23	18	0.074	0.47	9.5	9	30.4
Jun.	16.4	0.24	18	0.54	1.1	8.23	7.8	30.4
July	15.85	0.23	18	0.64	1.5	5.31	8.5	30.4
Aug	16.05	0.24	18	0.43	1.5	6.85	8.5	30.4
Sep.	16.6	0.37	18	0.64	1.5	5.77	8.5	30.4

Evapotransporation and precipitation are major components of input climate data. The riparian agriculture strongly depends on the irrigation instead of rainfall. In this case, actual evapotransporation (EP_A) from cultivation area is assumed to be equal to the potential evapotransporation (EP_0). The potential evapotransporation for a hypothetical grass having a uniform height of 12 cm has been calculated by Mekonnen (1999) for a period from January 1998 to December 1998 on a daily basis. Although EP_A is crop-dependent, the EP_A values for the different crops under study don’t vary much (in personal communication with Mekonnen). Thus, monthly average EP_A for grass is used as input evapotransporation.

The average monthly precipitation in the model input are almost the same since they represent the sum of irrigation water consumption and rainfall. According to the field investigation, the average irrigation water consumption is about 6-8 mm/day, varying with rainfall conditions. How to decide the input precipitation? In other words how to decide the amount of irrigation water? Average crop water requirement was calculated as about 3 mm/day. If 6mm/day were used, the project efficiency of irrigation should be 50%. If 8 mm/day were used, the project efficiency of irrigation should be 38%. Since both drip and sprinkler irrigation utilized in the study area have high efficiency irrigation, a value of 6mm/day seems reasonable and has been used as input precipitation.

Following the irrigation situation, the numbers of storm and average storm duration are adjusted based on the calibration of surface runoff. They don't represent the actual rainfall situation. Surface runoff condition will be explained in the calibration part.

4.3.2 Soil data

The soil file presents the physical property of the subsurface soil. The file requires the following parameters: soil bulk density, intrinsic permeability, soil disconnectedness index, effective soil porosity, organic carbon content, Freundlich exponent, and cation exchange capacity.

Soil input file is presented in Table 4-2. They are basically distinguished as sandy loam and clay loam which are the dominant soil textures in the study area. Both are subdivided as four types based on the major soil units PL111, PL222, and PL331, PL332. Soil bulk density, organic carbon content, and hydraulic conductivity have been measured for these soil units classified on the geopedological map 3-3 (Kwacha, 1998). The intrinsic permeability was calculated from hydraulic conductivity using the following formula (Fetter, 1994):

$$K_i = K * \mu / g\rho \qquad [\mathrm{cm}^2] \quad (4\text{-}10)$$

Where:
K_i — intrinsic permeability [cm^2]
K — hydraulic conductivity [cm/s]
μ — dynamic viscosity of water [g/s.cm]
ρ — density of water [g/cm^3]
g — acceleration of gravity [cm/s^2]

Average bulk density and intrinsic permeability for different units are used as model inputs. Organic carbon content is distinguished as four major soil units since it is a sensitive parameter in the partitioning theory. The default values were used for the Freundlich exponent and cation exchange capacity because of no measuring method for the former and the latter is mostly used for simulating metal chemicals. The disconnectedness index and effective porosity were used to calibrate the site-specific soil moisture contents.

Table 4-2 Soil input data

Parameter	Clay loam	Sandy loam	Data source
Bulk density (g/cm3)	1.2	1.4	Field
Intrinsic permeability (cm^2)	2.8E-9	1.60E-08	Field
Disconnectedness index	12	11	Calibrated
Effective porosity	0.475	0.45	Calibrated

Organic carbon content of top layers (%)	Table 4-5	Table 4-5	Field
Cation exchange capacity	0	0	Default
Freundlich exponent	1	1	Default

4.3.3 Chemical data

Two types of data are required in this file. Chemical-specific data include the solubility in water, air diffusion coefficient, Henry law constant, molecular weight, and organic carbon partition coefficient. They were obtained from extensive literature (Kidd, 1991) (Crowe, 1992) (Young, 1995). Site-specific chemical data include biodegradation rate in the liquid and solid phase, hydrolysis rate constants (neutral, basic, and acidic). Biodegradation was derived by the half-life. Several half-life values are found on the literature. The value related to the soil condition was chosen if available. Otherwise, the maximum value was chosen for conservation reasons. The hydrolysis process is a negligible process for the investigated organic chemicals, and also the hydrolysis rate constants can vary for magnitudes. So hydrolysis process is not considered.

Fenamiphos was chosen to do model calibration. It is an active ingredient of nematicide "Nemacur". Fenamiphos is of high persistence in the soil environment and not strongly adsorbed to soils. The input chemical data is shown in Table 4-3.

Table 4-3 Chemical input parameters

Parameter	Value
Chemical name	Fenamiphos
Solubility (mg/l)	700
Air Diffusion coefficient (cm^2/s)	0.036
Adsorption coefficient of organic carbon (g/ml)	169.82
Henry's law constent (m^3.atm/mole)	5.87E-10
Molecular weight (g/mol)	303.4
Degradation rate in Moisture (1/day)	0.005775
Degradation rate in soil (1/day)	0.005775

4.3.4 Washload data

The washload files includes washload area, percent of silt, sand, and clay, slope length, average land slope, soil erodibility factor, soil loss ratio, contouring factor, and Manning coefficient. The percent of silt, sand, and clay are measured in the field. The representative slope length was set 100m. As derived from slope map (map3-2), the dominant slope percentages for the agriculture area range from 0.7 to 1.6. A representative value of 1.6 was used. The soil erodibility factor is taken from Hamududu's study (Hamududu, 1998). For the determination of soil loss ration factor (C), as described by Nill (1996), it can be derived from available experimental data or calculated by using subfactors. The crop types in representative area are beans and chill. From the table (Appendix 6) summarized from the experiment data, the average value for this two crops are 0.3. The C factor can be calculated from subfactors by:

$$C = C_1 * C_2 * C_3 \tag{4-11}$$

Where: $C1$ influence of canopy cover
$C2$ influence of mulch cover

C3 residual influence of former vegetation

C1 was derived from Figure (appendix 5) (Nill, 1996) and equal to 0.25. C2 was derived from Figure (Appendix 5) and equal 1. Since there are no former vegetation, C3 is assumed equal to 1. The average value from these two methods is used in the washload file. For the specific land surface condition, a Manning's coefficient of 0.1 was obtained from Table (Dingma, 1993). The washload data are shown in Table 4-4.

Table 4-4 Washload input parameters

Parameter	Value
Washload area (cm^2)	8E+7
The fractions of silt, sand, and clay	0.30; 0.28;0.42
Slope length (cm)	100
Average slope (cm/cm)	0.016
Soil erodibility (tons/acre)	0.21
Loss ratio	0.28
Contouring factor	1
Manning's coefficient	0.1

4.3.5 Application data

Application input file describes the following information.

- Soil compartment specifications with parameters: number of soil layers and sublayers for each layer, layer thickness, application area of compartment.
- Characteristics of the pollutant loading expressed by monthly loading rates, initial pollutant concentration for any sublayer.
- Layer dependent soil properties: permeability, pH, and organic carbon content. (These parameters are optional)

The soil schematic soil profiles for sandy loam and clay loam areas are shown in Figure 4-3 based on soil augering. The soil texture was identified by Sediris (personal commuincation). No auger hole reached a depth of more than 7 meters. Since there is no important deviation for the permeability suggested by the model for the soil texture in the upper 7 meters, it was assumed that subsoil from 4.8 meters depth till the ground water table as one layer.

Organic carbon content was measured at 20cm, 50cm and 120cm soil depth. It is a layer-dependent parameter. The average carbon content at 20cm and 50cm depth are used for layer 1. The carbon content at 120cm depth is used for layer 2. It is known that the organic carbon is mainly concentrated within the rooting depth of the soil. The rooting depth of plants in study area is about 100cm. The layer 3 begin with depth 160 cm, hence, the carbon content is set as zero in layer 3 and layer 4. It indicates no pollutant is absorbed on the soil after 160cm depth. Organic carbon content for different layer in all soil units are shown in Table 4-5.

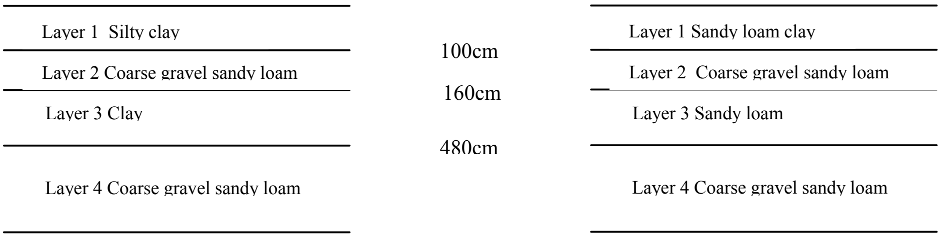


Figure 4-3 Schematic soil and vadose zone depth profiles

Table 4-5 Organic carbon content in soil layers of different soil units (unit: %)

Soil Unit	PL111	PL222	PL331	PL332
			Groundwater table	
Layer 1	1.57	1.32	0.70	2
Layer 2	0.74	0.45	0.27	0.45
Layer 3	0	0	0	0
Layer 4	0	0	0	0

4.4 Model calibration

The underlying principle behind model calibration is that the transport of the pollutants in the model should represent the reality as well as possible. A selected input parameter adjusting process, therefore, is required in order to get reliable results. This adjusting process is realized by model calibration. The SESOIL model in this study was calibrated using measurements of soil moisture content and evidences of surface runoff.

Many application of the SESOIL model used soil moisture for calibration (Pandey et. al, 1997) (Hetrick et. al, 1986). Soil moisture is the dominant parameter in the model since all the hydrology processes in Eq. 4-1 are written in terms of soil moisture. Unfortunately, soil moisture is one of the parameters which are difficult to obtain in practice. This problem becomes more serious especially when analysis are carried out with a spatial dimension. To alleviate this problem, either sufficient point measurements or passive microwave data must be available. But in a situation when both are lacking, like the current case, how can be spatially representative soil moisture data available? Since the study area is under irrigation, not too much spatial deviation is expected. Thus, estimation was made. Soil moisture data from limited number of measurements were accepted to perform calibration. It is recommended that adequate emphasis should be given on sufficient soil moisture data in the future.

The model calibration using measured soil moisture was undertaken in both sandy loam and clay loam soils. Soil moisture profile measurements, from 5 cm to 140 cm soil depths, were carried out by Mekonnen (1999). The volumetric soil moisture contents didn't vary with plant types significantly. The results mainly range from 24% to 40% in sandy loam area and 30% to 48% in clay loam area. In the Sesoil model, the entire unsaturated soil zone is conceptualized as a single layer and the prediction for soil water content is an average value for the entire unsaturated zone. The ground water depth in most cultivation areas ranges from 3m to more than 20m as observed from landuse map (map 3-5) and groundwater depth map (map 3-6). How to decide one single value for soil moisture content for the entire vadose zone instead of a value range? The predictions of watershed hydrologic components using the Sesoil model have been compared to empirical measurements in a grass watershed (Hetrick.,1986).The predictions are considered to be in good agreement with empirical measurement by the model developers, although soil moisture predicted are about 7% lower than the observed values in depth of 0-150 cm. The underpredictions are explained, because SESOIL estimates only one value for soil water content for the entire soil column extending from surface to groundwater for 500 cm depth. The lower values are expected and reasonable. Based on this idea, estimation was made to set the soil moisture value. The mean soil moisture values are about 32% in sandy loam soil and 39% in clay loam soil. The 7% soil moisture was subtracted from the mean values. Therefore, soil moisture values around 25% for sandy loam and 32% for clay loam were chosen for the calibration.

The disconnectedness index(c) and soil porosity parameters were adjusted to get desired soil moisture content (Bonazountas et. al, 1997). The disconnectedness index, which is related to the soil type, is defined as the exponent relating the "wetting" or "drying" time-dependent permeability of a soil to its saturated permeability (Eagleson, 1978). The model suggests appropriate default values for c and porosity. These values were varied to optimize agreement between the prediction of soil moisture contents and field data. The optimum values for sandy loam, clay loam ,and desired volumetric soil moisture contents are presented in Table 4-6.

Table 4-6 Calibration results for selected input parameters and output of soil moisture

Soil type	Soil disconnectedness index	Soil effective porosity	Soil moisture contents (%)
Sandy loam	11	0.45	25
Clay loam	12	0.475	32

Surface runoff is used for quantifying chemical transport with eroded sediments. No significant surface channel drainage was observed in the study area. Based on field investigation and information provided by farmers, even sheet flow is not pronounced. This situation is attributed to the very gentle slopes (map 3-2) in the most cultivation area and high permeable soils. Therefore, surface runoff is calibrated as zero in the dry seasons. In the wet seasons, it is estimated using the rational formula. Runoff coefficient is considered 0.25. The calibration of surface runoff is done by adjusting the number of storm and storm duration parameters. The optimum values for these two parameters are provided in Table 4-1.

4.5 Sensitivity analysis

The purpose of a sensitivity analysis is to show the influence of specific model input parameters on model output. Sensitivity analysis was undertaken for the parameters used for calibration: effective porosity (η) and disconnectedness index (C); the parameters defining pesticide characteristics: sorption coefficient of organic carbon (K_{oc}), biodegradation rate constant (K_b), and organic carbon content (oc%). The sensitivities of these parameters were represented by the breakthrough concentration profile of Fenamiphos at 500 cm depth. All these parameters were reduced 25% and 50% based on the optimum values. The results are presented in Figure 4-4 to Figure 4-7 and their effect for the maximum breakthrough concentration are summarized in Table 4-7.

Table 4-7 sensitivity analysis results

parameter variation (%)	Maximum breakthrough concentration changed (%)				
	η	C	K_{oc}	K_b	OC%
-25	+58	+17	+58	+97	+58
-50	+148	+79	+124	+297	+124

A closer inspection of Table 4-7 and model output lead to the following conclusion:

- All selected model input parameters have a significant impact on the maximum breakthrough concentration, but a slight impact on the time to breakthrough. Generally, the decrease of these parameters gives accelerated breakthrough of pesticide, higher maximum concentration.
- Certain pesticide properties are more sensitive than soil properties. For instance the biodegradation rate constant K_b.
- The effective porosity is more sensitive than the disconnectedness index. The calibration processes also showed this.
- Persistence of pesticide is more sensitive than sorption constant.

However the above conclusion should be seen within the context of the parameter variation (i.e. 25% to 50% reduction) listed in the above table.

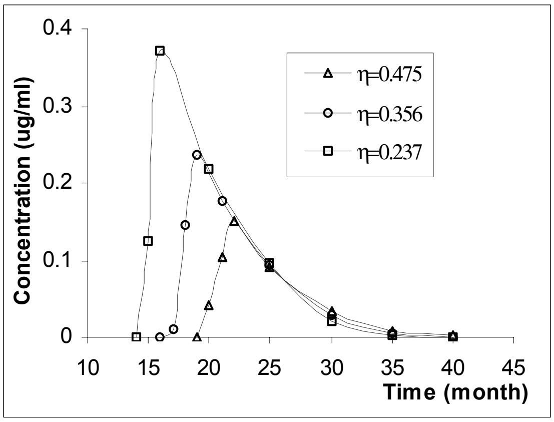


Figure 4-4 Breakthrough concentrations for Fenamiphos at 500 cm groundwater depth showing the sensitivity of effective porosity.

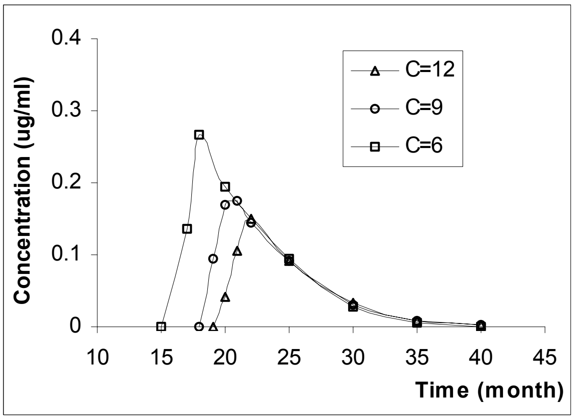


Figure 4-5 Breakthrough concentrations for Fenamiphos at 500 cm groundwater depth showing the sensitivity of Disconnectedness index.

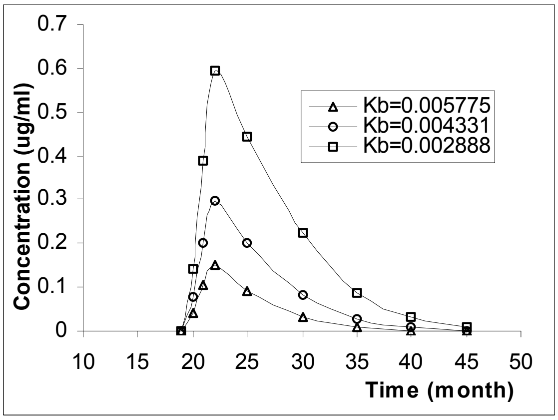


Figure 4-6 Breakthrough concentrations for Fenamiphos at 500 cm groundwater depth showing the sensitivity of biodegradation rate constant.

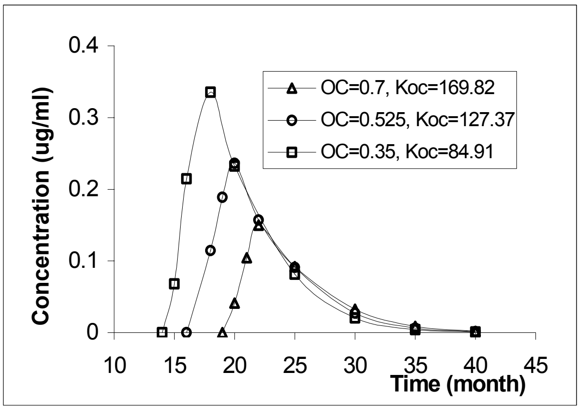


Figure 4-7 Breakthrough concentrations for Fenamiphos at 500 cm groundwater depth showing the sensitivity of organic carbon content and adsorption coefficient.

CHAPTER 5

MODELING THE FATE AND MAPPING POTENTIAL LEACHING RISK OF PESTICIDES

This chapter discusses the factors that affect the fate of pesticides, with emphasis on pesticide leaching. The susceptibility of the soil type to leaching of different pesticides is predicted and potential leaching maps are presented.

5.1 Scenario analysis

The objectives of scenario analysis in this study are:

1. To simulate the fate of pesticides with different chemical properties in different soil types.
2. To predict the vulnerability of the soils for potential pesticide leaching.
3. To map potential pesticide leaching in the study area.

The SESOIL model has been calibrated in Chapter 4 using site-specific soil moisture data for a sandy loam and a clay loam soil. Sensitivity analysis showed pesticide chemical properties (sorption, persistence) and soil characteristics (effective porosity, organic carbon content) play a significant role in leaching of pesticides. These parameters were taken into account in the scenario analysis.

5.2 Pesticide indicator selection

As described in the current U.S. EPA (1989) and CAL-EPA (1990) guidance, the purpose of selecting indicator chemicals is to focus the investigation on those chemicals that can reasonably be expected to pose a significant risk to human health (Sullivan et. al, 1997). Thus, the basic rule for selecting indicator in this study is that the pesticide should pose a potentially high toxicity. Specific criteria chosen were as follows:

1. The pesticide should be classified as I or II class by WHO toxicity classification;
2. The persistence of selected pesticides should vary from low to high based on the EPA (USA) classification;
3. The migration potential of the selected pesticides should vary from low to high based on literature values for solubility and sorption coefficient.

Besides the above criteria, only pesticides applied directly to the soil were selected for simplicity. Chemical families to which the pesticides belong to were taken into account as well.

Based on these standards, the indicator pesticides for scenario analyses were selected from the pesticides inventory in the study area and shown in Table 5-1.

Table 5-1 Indicator pesticide characteristics

Common name	Trade name	Chemical family	Pesticide type	Organic carbon partition coefficient (µg/ml)	Half life (day)	Toxicity
Bifenthrin	Talstar, brigade	Pyrethroid trifluoromethyl	Insecticide acaricide	24000	50	Π
Chlorpyrifos	Pyrinex, Dursban	Organophosphate; pyridine	Insecticide	6026	30	Π
Dimethoate	cygon, logon, rogor	Organophosphate	Insecticide acaricide	20	20	Π
Oxamyl	Vydate	Carbamate	Insecticide nematicide	25	6	Ib
Fenamiphos	Nemacur	Organophosphorus	Nematicide	170	120	Ia

5.3 Modeling the fate of pesticides

As described in Chapter 4, pesticides may follow four pathways after application: i) washed off into nearby water bodies either associated with soil particles or diluted in the surface runoff. ii) percolate through the soil to lower soil layers and adsorbed to the soil particles. iii) leach to ground water. iv) volatilize to the air. The SESOIL model is capable of simulating all these directions.

5.3.1 Pesticide in washload

The washload cycle simulates the removal of sorbed chemicals on eroded sediments by surface runoff. An estimation of erosion and sediment yield is needed. The model employs the USLE equation to handle the detachment process of soil erosion. the sediment transport is estimated using the Yalin equation (Yalin, 1963).

USLE soil erosion is insignificant in the study area according to the field investigation. No signs were observed to represent the sheet and rill erosion. There is even no drain to discharge water in some farms since no surface runoff occurs base on information provided by farmers. This situation can be attributed to the following factors, which help infiltration of rainwater and prevent the occurrence of erosion effectively.

- *Gentle slopes.* The prevailing land slopes are 1%-2%. They are classified as "flat to gentle undulating" (0-5%) according to FAO Guideline for soil description (1990).
- *Dense surface covers.* Landuse are mainly crops and natural vegetation for grazing. Little bare soil exists.
- *High permeable soils.* The dominant soil types are clay loam and sandy loam. The mean values of hydraulic conductivity are 0.97cm/hr and 6.17cm/hr, respectively. The permeability of clay loam and sandy loam soils are classified as "moderately high" and "high" (Renard et. al., 1997).

Hamududu (1998) employed three erosion models to quantify soil erosion in Lake Naivasha catchment. The result gave very little amount of washload in the riparian zone of the lake. Thus, both field observation and theory calculation clarified the soil erosion is quite small. Consequently, the amount of chemicals entering the lake through surface runoff and soil erosion is negligible.

In order to verify the above result, we did simulation using SESOIL in two scenarios. In the SESOIL model, the washload cycle is optional. The model suggests if the pollutant surface runoff is considered negligible, the washload cycle can be neglected. Washload was taken into account in scenario 1. The washload cycle was turned off in scenario 2. A representative farm Lake Naivasha Vineyard was chosen to show the effect of washload on the pollutant distribution. Application area is 0.8 ha. Fenamiphos in soil unit PL222 sandy loam was chosen for the simulation while the ground water depth is set at 5m. The climate, soil, chemical and application files are the same for two scenarios (Table 4-1 to 4-3 and Table 4-6). The washload file is shown in Table 4-4.

Result and analysis

The model output for annual washload is 4193 kg/km^2 (0.493 ton/ha) in scenario 1. According to the soil erosion susceptibility classification (Bergsma, 1986), it belongs to "very low" class (0-5 ton/ha). The mass balance for Fenamiphos in the first year was calculated and presented in Table 5-2.

Table 5-2 Mass balance for Fenamiphos in the 1st year after application showing the washload condition in the riparian zone of the lake

Distribution	Mass (mg/year)		Percentage (%)
	Scenario 1	Scenario 2	
In washload	2.84E+01	0.00E+00	<0.001
Degraded	2.05E+07	2.05E+07	57.9
Adsorbed on soil	1.36E+07	1.36E+07	38.5
In soil moisture	1.29E+06	1.29E+06	3.6
In groundwater runoff	0.00E+00	0.00E+00	0
Volatilized	1.81E-01	1.81E-01	<0.001
In soil air	2.41E-02	2.41E-02	<0.001
Total output	3.53E+7	3.53E+7	100
Total input	3.53E+07		

As clearly shown in the table, mass of Fenamiphos in washload is 28.4 mg/year for 0.8 ha, accounting for total input less than 0.001%. Mass distributions of Fenamiphos are the same for all components except washload in two scenarios. It indicates even the accuracy of the model is incapable of differentiating so minor amounts. The pollutant amount in washload, therefore, is negligible. In other words, the amount of pollutant washed off into the lake either associated with soil particles or diluted in the surface runoff is equal to zero. In the following simulation, the washload cycle will be neglected for simplicity.

The SESOIL simulates pollutant distribution on a monthly basis. It doesn't have storm resolution. The washload output has limitations therefore when the intensity of storm is very high, i.e., the extreme storm event.

5.3.2 The fate of indicator pesticides

The fate of pesticide can be analyzed actually by viewing the mass distribution in all fate processes. Mass balances were undertaken for the four indicator pesticides (except Dimethoat) in order to quantify the distribution of pesticides with varied chemical property in all SESOIL processes. Since Dimethoat has similar chemical property with Oxamyl. It was excluded in the simulation. Environmental partitioning of pesticides includes the following compartment: dissolved in soil moisture, adsorbed on soil, in soil air, the total mass lost to volatilization and in groundwater runoff. Soil unit PL-222 (sandy loam), in which most cultivation occurs, was chosen as representative soil unit. Groundwater depth varied from 300 cm to 1000 cm in this soil unit. The depth of 500 cm was used in the simulation. The simulation area is $8*10^7 cm^2$ (0.8 ha). Input climate and soil files are shown in Table 4-1 and 4-2. The chemical input data and application amount are presented in Table 5-3.

Table 5-3 Chemical and application input data

parameters	Bifenthrin	Chlorpyrifos	Dimethoat	Oxamyl	Fenamiphos
Solubility (mg/l)	0.1	2	25000	280000	700
Air Diffusion coefficient (cm^2/s)	0.026	0.031	0.0476	0.0497	0.036
Molecular weight (g/mol)	422.9	350.6	229.3	219.4	303.4
Adsorption coefficient of organic carbon (g/ml)	24000	6026	19.95	25.12	169.82
Henry's law constant (m^3.atm/mole)	1E-6	4.45E-6	1.12E-9	2.45E-10	5.87E-10
Degradation rate in Moisture and in soil (1/day)	0.01386	0.0231	0.03465	0.01155	0.005775
Application amount (kg/ha/month)	0.312	0.322	1.51	3.49	3.68

The pesticides are applied in each month and assumed to be applied for one year. Although pesticides are normally applied when needed, an average monthly application dose and interval is common in the study area. The model output provides the mass distribution in three soil phases and mass lost due to volatilization and leaching for each month. The mass balances were calculated for the 1st, 2nd, 3rd, 4th, and 5th year after application. Since the specific mass value is area dependent, they can't represent the general situation. Thus, the mass percentages, which equal to the mass in each component account for the total mass input, were calculated. The result of mass balance for Fenamiphos is shown in Table 5-4 as one example. For the rest of pesticides, only the results of mass percentage are shown in Table 5-5. Because of negligible mass in soil air and lost to volatilization, these two components are not included in the Table 5-5. The percentage distributions for the 1stafter application are depicted in Figure 5-1.

Table 5-4 Environmental partitioning of Fenamiphos as a function of time after application

Compartment	Year 1 (mg)	Percentage account for the total input	Year2 (mg)	Percentage account for the total input	Year 3 (mg)	Percentage account for the total input	Year 4 (mg)	Percentage account for the total input	Year 5 (mg)	Percentage account for the total input
Ad.on soil	1.36E+07	3.8E+01	1.58E+06	4.5E+0	1.08E+05	3.1E-01	7.15E+03	2.0E-02	4.68E+02	1.3E-03
In soil moisture	1.29E+06	3.6E+00	2.88E+05	8.2E-01	9.64E+04	2.7E-01	8.26E+03	2.3E-02	6.02E+02	1.7E-03
soil air	2.41E-02	6.8E-08	5.37E-03	1.5E-8	1.80E-03	5.1E-9	1.54E-04	4.4E-10	1.12E-01	3.2E-11
Volatilized	1.81E-01	5.1E-07	1.15E-01	3.3E-07	1.55E-04	4.4E-10	1.02E-05	2.9E-11	6.63E-01	1.9E-12
Degraded	2.05E+07	5.8E+01	3.35E+07	9.5E+01	3.51E+07	9.9E+01	3.52E+07	1.0E+02	3.52E+07	1.0E+02
Gr. Runoff	0.00E+00	0.0E+00		0.0E+00	4.38E+04	1.2E-01	7.84E+04	2.2E-01	8.14E+04	2.3E-01
Total output	3.53E+7	1.0E+02	3.53E+07	1.0E+02	3.53E+07	1.0E+02	3.53E+07	1.0E+02	3.53E+07	1.0E+02
Total input	3.53E+7		0		0		0		0	

Table 5-5 Environmental partitioning in percentage (as fraction of the total input) for the indicator pesticides as a function of time after application (unit: %)

Compartment	Year 1				Year 2				Year 3
	Bifenthrin	Chlorpyifos	Oxamyl	Fenamiphos	Bifenthrin	Chlorpyifos	Oxamyl	Fenamiphos	Fenamiphos
Ab.on soil	19.89	11.99	1.42	38.41	0.00	0.00	0.00	4.48	0.31
In Soil mois.	0.01	0.03	0.98	3.65	0.00	0.00	0.00	0.82	0.27
Degraded	80.10	87.98	97.60	57.94	100.00	100.00	100.00	94.79	99.40
Gr. Runoff	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02

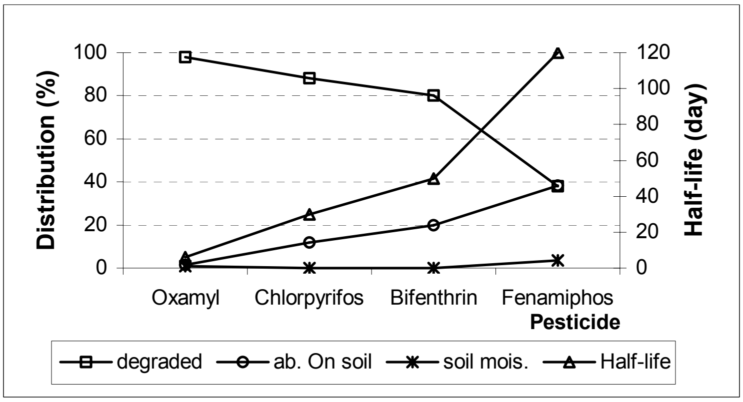


Figure 5-1 Environmental partitioning of the pesticides in relation to their persistence (half-life)

1. As observed from Table 5-4, the mass percentages in soil air and lost to volatilization in each year range from 10^{-7} to 10^{-9}. These minimal amounts are expected since the Henry's law constant, which governs the chemical partitioning in soil air and volatilization for unvolatilized organic substance, is very small for these chemicals. Thus, the contribution of volatilization to the loss of the pesticide is negligible. It can therefore be concluded that the environmental pathways of the pesticides to soil air and lost by volatilization to the atmosphere are equal to 0.

2. The dominant pathway in the environmental partitioning is the fraction degraded. In the 1st year after application, the mass degraded account for the total input from 57.94% for high persistent pesticide Fenamiphos to 97.6% for low persistent pesticide Oxamyl. In the 2nd year after application, all chemicals are degraded completely except Fenamiphos.

3. The second dominant pathway is the fraction adsorbed on soil for all pesticides in the first year. The highest value occurred to the medium sorption pesticide Fenamiphos. The lowest value happened to the low sorption pesticide Oxamyl.

4. Breakthrough to the groundwater (500 cm) only happened with the high persistence pesticide Fenamiphos in the 3rd year after application.

5. In the sensitivity analysis, biodegradation rate constant was concluded as a very sensitive parameter. The mass balance results endorses this conclusion again.

Figure 5-1 presented the relations between half- life and mass distributions in soil moisture, adsorbed on soil, and degraded in the 1st year after application for the different pesticides. As depicted in the Figure, higher half-life, in another words, lower biodegradation rate resulted in higher percentage distribution of the mass in soil moisture and adsorbed on soil generally. Although the sorption coefficient Koc of Bifenthrin and Chlorpyrifos are 140 and 34 times higher than Fenamiphos (Table 5-1), the percentage of mass adsorbed on soil for Bifenthrin and Chlorpyrifos are 0.9 and 2.2 times lower than Fenamiphos, respectively. The same situation happened to the mass in soil moisture. The solubility of Oxamyl is about 400 times higher than Fenamiphos, but the percentage of mass dissolved in soil moisture is about 3 times lower than Fenamiphos. Hence, the biodegradation rate constant is a decisive factor for environmental partitioning of pesticides. The fate of a pesticide is mainly governed by its persistence.

5.3.3 The fate of pesticide in different soil texture

The aim of this scenario is to compare the fate of pesticides between a sandy loam and a clay loam soil, which are the dominant soil textures in the study area (Map 3-4). As stated in Chapter 4, the soil moisture content is an important parameter in the SESOIL hydrology cycle. It is higher in the clay loam soil than in the sandy loam soil due to relatively lower permeability of clay loam soil. The model had been already calibrated for sandy loam and clay loam area with soil moisture contents. Fenamiphos was selected to perform this simulation. The input climate and soil files are different for sandy loam and clay loam soils (Table 4-1 and 4-2). The chemical file and application amount are the same (Table 5-2).

The fate difference of pesticide between sandy loam and clay loam soil is represented by the difference of mass distribution. The simulation results are summarized in Table 5-6. The mass distribution in soil air and lost to volatilization were excluded because of their negligible amounts. The mass difference in percentage for all distribution components was calculated for the five years using Eq.5-1 and depicted in Figure 5-2.

$$D = (A - B) / A * 100 \qquad (5\text{-}1)$$

where:
D: mass difference in percentage
A: mass in the distribution compartment in sandy loam (μg)
B: mass in the distribution compartment in clay loam (μg)

Table 5-6 Environmental partitioning of Fenamiphos in sandy loam and clay loam soil as a function of time after application (unit: mg)

Compartment	Year 1		Year2		Year 3		Year 4		Year 5	
	Sandy loam	Clay loam	Sandy loam	Clay loam	Sandy loam	Clay loam	Sandy loam	Clay loam	Sandy loam	Clay loam
Ad.on soil	1.36E+07	1.32E+07	1.58E+09	1.59E+06	1.08E+05	1.12E+05	7.15E+03	7.55E+03	4.68E+02	5.05E+02
soil moisture	1.29E+06	1.61E+06	2.88E+05	2.75E+05	9.64E+04	1.20E+05	8.26E+03	1.14E+04	6.02E+02	9.10E+02
soil air	2.41E-02	1.77E-02	5.37E-03	3.02E-03	1.80E-03	1.31E-03	1.54E-04	1.25E-04	1.12E-05	9.99E-06
Volatilized	1.81E-01	8.27E-03	1.15E-01	8.50E-04	1.55E-04	5.66E-05	1.02E-05	3.77E-06	6.63E-07	2.51E-07
Degraded	2.05E+07	2.05E+07	3.35E+07	3.35E+07	3.51E+07	3.51E+07	3.52E+07	3.53E+07	3.52E+07	3.53E+07
Gr. Runoff	0.00E+00				6.84E+03	3.82E+03	6.68E+02	7.21E+02	5.09E+03	6.15E+01

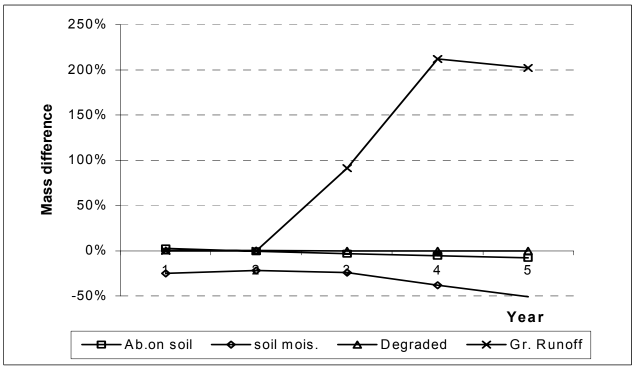


Figure 5-2 Mass distribution difference of Fenamiphos in percentage in sandy loam and clay loam soils as a function of time after application

As observed in Figure 5-2, the mass differences vary for the distribution compartment. The following points can be observed:

1. The total mass degraded in sandy loam is equal to that in clay loam. Decayed pollutant mass is related to the soil property parameter soil moisture content and soil bulk density. However, the difference of these two parameters in the sandy loam and the clay loam is not large enough to cause the mass difference of decayed in these soil units.

2. The mass adsorbed on soil in the sandy loam is almost the same as in the clay loam. The difference after 5 years is only 8%.

3. The mass in soil moisture in the sandy loam is lower than in the clay loam by about 23% to 51%. This is attributed to the higher effective porosity and lower hydraulic conductivity in clay loam. More water is available, more chemicals will dissolve in it.

4. The significant differences appear for the mass lost to groundwater. The mass of pesticide entering the groundwater in sandy loam is higher than in clay loam more than 200%. This situation will be dealt in detail in the leaching part.

5.4 Mapping the potential leaching risk of pesticides

As discussed before, the pollution to the lake from riparian agricultural area through surface runoff and washload is assumed insignificant with the exception for extreme events which were not simulated by the model. The main pathway for agrochemicals to deteriorate the lake water is through leaching to groundwater. Thus, the pesticide leaching has been studied in detail.

The pollution from leaching is the downward movement of soluble substance through the soil profile with percolating water. Agrochemicals can enter groundwater through leaching and cause the degradation of groundwater. This low-level nonpoint-source leaching of agrochemicals is usually of great concern, because i) it can be widespread. ii) it is difficult to control since neither the sources nor the leaching behavior of the agrochemicals are well understood.

In the study area, the groundwater supplies drinking water and contributes substantially to the lake water. It also interacts with river and streams such as Malewa. (Behar, 1999 personal communication). Consequently, groundwater is an important resource that must be protected from the entry of potentially harmful agrochemicals. Pesticide leaching poses a significant risk to the groundwater quality.

Pesticides leaching depend on many factors. Basically, these factors include *pesticide properties, soil properties, site and vadose zone conditions, and application conditions*. The following discussion will show how these factors affect pesticides leaching behavior. All these factors are taken into account to simulate leaching of pesticides. GIS, as a useful tool, is used to mapping potential risk of pesticide leaching to ground water.

5.4.1 Pesticide properties

Physical and chemical characteristics of pesticides such as solubility, adsorption, volatility, and the persistency are the main factors for governing the leaching of pesticide. The simulation is undertaken for the five pesticides shown in Table 5-1 in two scenarios. Scenario 1 considers biodegradation. The simulations have been already undertaken in session 5.3.2. Scenario 2 is without biodegradation. Why was the scenario 2 selected? As discussed before, the biodegradation is a very sensitive parameter in the SESOIL model. If the persistence of pesticide is low, the potential leaching will be also low regardless of sorption and solubility characteristics. In fact, the biodegradation is a very site-dependent factor. The half-life of a pesticide may vary from a few days to a few months. In order to exclude this uncertainty and check the affect of sorption and solubility as well, scenario 2 was chosen. The percentage leached of pesticides account for total application amounts were calculated in Table 5-7.

Table 5-7 Leaching percentages (as fraction of the total input) of indicator pesticides as a function of time after application (%)

	2nd year		3rd year		4th year		5th year	
	Scenario 1	Scenario 2	Scenario 1	Scenario 2	Scenario 1	Scenario 2	Scenario 1	Scenario 2
Chlorpyrifos	0	0	0	0	0	0	0	0
Oxamyl	0	55	0	33	0	9	0	2
Dimethoate	0.02	58	0	31	0	8	0	1.8
Fenamiphos	0	0	0.12	13	0.22	35	0.23	23

1. As concluded in the section (5.3.2). The persistency is a decisive factor for controlling the fate of pesticide. The persistence of these pesticides varied from low to high. In Scenario 1, the maximum percentage leached appeared for the pesticide Fenamiphos that has the highest half-life. However, when the solubility is very high, leaching can also occur for a low persistence pesticide, for instance, as the case for Dimethoate in scenario 1.

2. For the high sorptive pesticide, the leaching potential is zero in spite of its low persistency. The leaching of Chlorpyrifos has clarified it. Chlorpyrifos is highly adsorbed on organic matter. Even without considering biodegradation, there is still no potential leaching.

3. The higher solubility may not necessary result in higher leaching. In scenario 2, the solubility of Oxamyl is 10 times higher than Dimethoate, on the contrary, the leaching percentage for Oxamyl is lower than Dimethoat by about 3% in the 1st year after application. The total leaching amount is almost the same for five years after application.

4. On the whole, the leaching process of the pesticide is controlled by the interaction of the factor solubility, adsorption, and persistency. The susceptible pesticides to the leaching are those have high solubility, low adsorption, and high persistence.

5.4.2 Soil properties

In order to identify the relative vulnerability of the soil to leaching, the simulations were undertaken for the three soil units PL331, PL222, PL111 in sandy loam and clay loam area, in which most cultivation occur (map 3-3). These three soil units represent different organic carbon contents (OC). The two soil textures represent the varied permeability of soils. Fenamiphos was chosen to do simulation, because it is the most leachable chemical among indicator chemicals in Table 5-1. The simulations were conducted for groundwater depths from 3 to10 meters.

The mass percentages leached to groundwater were calculated from model outputs. Figure 5-3 and Figure 5-4 present the leaching percentage of pesticide in varied groundwater depths in three soil units in sandy loam soil and clay loam soil respectively.

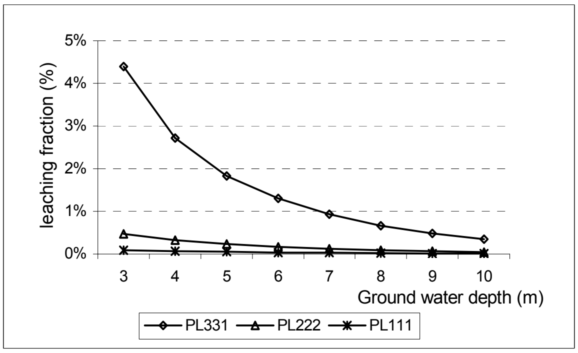


Figure 5-3 Leaching fraction of Fenamiphos in sandy loam soil units as a function of ground water depth

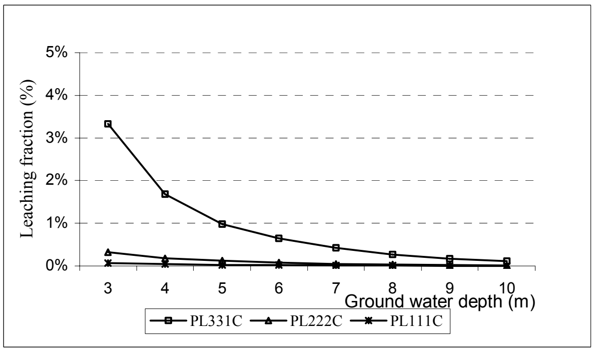


Figure 5-4 Leaching fraction of Fenamiphos in clay loam soil units as a function of ground water depth

1. As shown in Figure 5-3 and 5-4, the % of pesticide leached per soil unit is PL331>PL222>PL111 in both sandy loam and clay loam. Since the OC is PL331<PL222<PL111, higher OC results in more pesticide adsorbed on soil and thus, less pesticide is available for leaching.

2. The percentage of pesticide leached in the sandy loam for the same OC soil unit is higher than in the clay loam as observed in Figure 5-3 and 5-4. This is attributed to the difference in permeability of these soil textures. The permeability of sandy loam soil is 10 times higher than of clay loam soil. The movement of percolating

water in sandy loam, consequently, is faster than in clay loam. The pollutant depth curves in two soil type are shown in Figure 5-5. The effect of permeability for the soil units with higher adsorption potential is more than the soil units with lower adsorption potential.

3. The pollutant depth curves shows pollutant move faster in the sandy loam soil than in the clay loam soil. For 500 cm ground water depth, the time taken by the pollutant to breakthrough is 30 months in sandy loam soil and 36 months in clay loam soil after the first application.

   As depicted in Figure 5-5, the movement rate of pollutant increased abruptly after reaching 160 cm depth in these two soil units. It can be explained by the fact that the reduce of OC content after this depth caused the decrease of adsorption. The adsorption is a factor, which retarded the movement of pollutant.

4. The vulnerable soil type to pesticide leaching has a relatively coarser soil texture, higher permeability and lower OC. PL331 soil unit in sandy loam area was identified as the most susceptible soil for pesticide leaching.

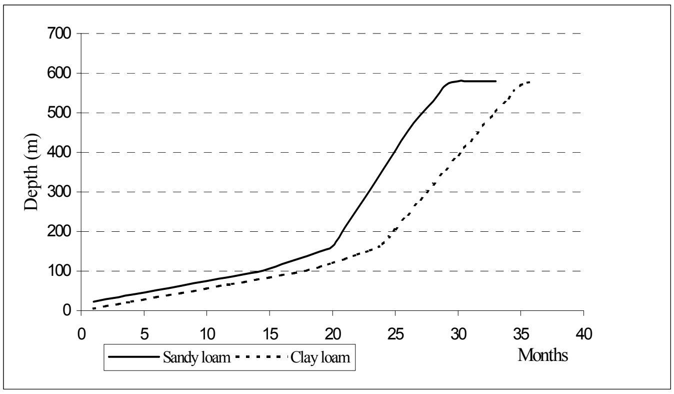


Figure 5-5 Leaching depth of Fenamiphos in sandy loam & clay loam as a function of time after application

5.4.3 Site condition

Site conditions include the depth to groundwater, the geological conditions of vadose zone, and the climate. The geological condition of vadose zone which affect leaching is typically represented by the heterogeneity of the soil property in different soil depths. As described in Chapter 4, there is no important deviation for the permeability value suggested by the model for the soil texture in the upper 7 meter of ground water depth. The effect of the climate condition is insignificant, because the long term average rainfall is quite low (669mm/year). The cultivation around the lake mainly depends on irrigation. The irrigation amount is 6-8 mm/day. The efficiency of irrigation will influence the leaching of pesticides. If the percentage of leached pesticides less than 0.001% is considered as negligible, the negligible amount appears in the groundwater depth of about 11 meter. Therefore the simulation are undertaken for every one meter from groundwater depth 3 to 11 meter. The results are depicted in Figure 5-6 to 5-8 for the three soil units of the sandy loam and clay loam area.

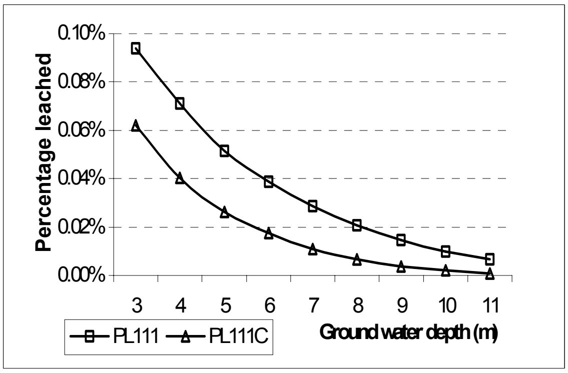


Figure 5-6 Leaching fraction of Fenamiphos in a sandy loam and a clay loam soil PL111 as a function of ground water depth

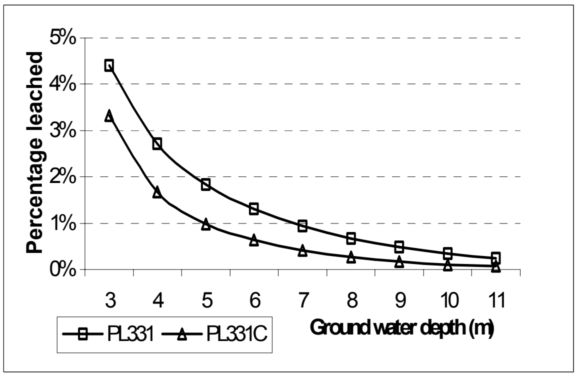


Figure 5-7 Leaching fraction of Fenamiphos in a sandy loam and a clay loam soil PL331 as a function of ground water depth

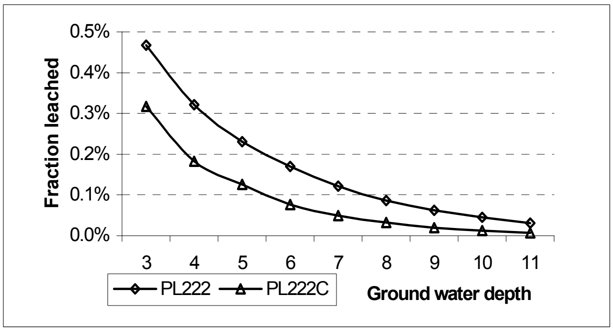


Figure 5-8 Leaching fraction of Fenamiphos in a sandy loam and a clay loam soil PL222 as a function of ground water depth

With the increase of the groundwater depth, the percentage of pesticide leached reduces exponentially. It occurred for all soil units of the sandy loam and clay loam area as shown in Figure 5-6 to 5-8. The percentage leached for groundwater depth at 3 meter is higher than for groundwater depth at 11 meter by a factor of 15 and 57 averaged for the three soil units in the sandy loam area and in clay loam area respectively. The deeper the depth to groundwater, the more soil there is to act as a filter. There are also fewer opportunities for degradation or adsorption of pesticides.

5.4.4 Potential pesticide leaching map

Spatial modeling of pesticide leaching

The simulation scenarios took into account pesticide properties, soil properties, site conditions, and application conditions which affect the pesticide leaching dosage. The model simulated four types of pesticide. They are high sorption and medium persistence pesticide Bifenthrin; high sorption and low persistence pesticide Chlorpyrifos; low persistence and low sorption pesticide Dimethoat and Oxamyl; high persistence and medium sorption pesticide Fenamiphos. The soils are classified as eight units: four different OC soil PL331, PL222, PL111, PL332 in the sandy loam and clay loam. The groundwater depth varied from 3 meter to 17meter. The pesticides were assumed to be applied for one year and the simulation for five years after the first application.

The model results showed the breakthrough to groundwater only happened to Fenaminphos and Dimethoate. The leaching percentage for Fenamiphos ranges from 0 to 4.4%. Fenamiphos was chosen to perform mapping the potential leaching risk.

GIS input

ILWIS was used to carry out the cartographic modeling work. Geopedological soil map which represents different OC in this study (Map 3-3), soil texture map (Map3-4), groundwater depth map (Map 3-6), and landuse map (Map 3-5) were used as the input maps. The resultant maps were calculated using script operation (Appendix 7). Ground water depths were classified by 1-meter interval. Leaching fraction for 1-meter interval used the model result in its mean ground water depth, i.e., from groundwater 2.5 meter to 3.5 meter, we used the leaching fraction for 3 meter. Two maps are presented: soil vulnerability map to potential pesticide leaching (Map 5-1) and actual leaching map for the flower and vegetable fields (Map 5-2).

The maps are classified as five classes based on the percentages leached to groundwater: <0.001%, 0.001-0.01%, 0.01-0.1%, 0.1-1%, >1%. As observed in map 5-2, the area that the leaching fraction more than 1% mainly occurs in soil unit PL331. This resulted from two aspects: i) as verified before, the most vulnerable soil unit is PL331. ii) the groundwater is relatively shallow in PL331.

5.4.5 Special case: greenhouse

With the expansion of the horticulture in the riparian zone of the lake, the greenhouse area showed a large increase in the past 5 years, and this trend is continuing. Based on the landuse map (Map 3-5), greenhouses occupy 224 hectares, about 11% of the total agricultural area. Due to the difference in evapotransporation and irrigation application, the greenhouse situation is discussed below as a special case.

The evapotransporation inside greenhouse was calculated by Mekonnen (1999). It is 36% lower than the evapotransporation outside due to low solar radiation. Because of different farm management, there are two situations for the irrigation application. i) In some farms, the irrigation water consumption inside greenhouse is 3-4 mm/day. It is 50% lower than in the open field. ii) In other farms, application is 10 mm/day. It is 40% higher than in the open field. In order to observe the leaching differences of pesticides in the open field and in the greenhouse, two simulation scenarios were chosen.

Scenario 1: the irrigation application was considered as 6 mm/day. It is the same as in the open field.

Scenario 2: the irrigation application was considered as 3 mm/day.

Scenario 1 shows the situation with only reduced evapotransporation. Scenario 2 shows what the outcome is when evapotransporation and irrigation application decrease simultaneously.

Fenamiphos in soil unit PL222 (sandy loam) was used for the simulation. The groundwater depth was set to 5 meter. For the input files, the evapotransporation for the greenhouse used 36% lower than for open field; the precipitation is 6mm/day for scenario 1 and 3 mm/day for scenario 2. Other input parameters are the same with the open field. The results were depicted in Figure 5-9 and 5-10.

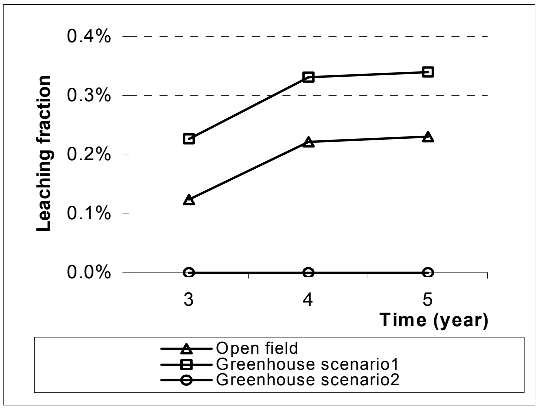


Figure 5-9 Comparison of leaching of Fenamiphos (sandy loam soil) between greenhouse and open field

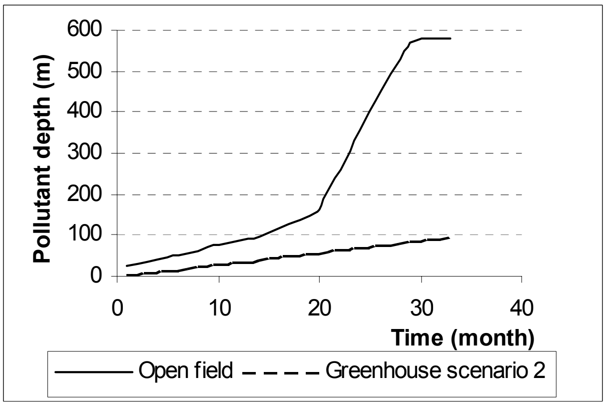


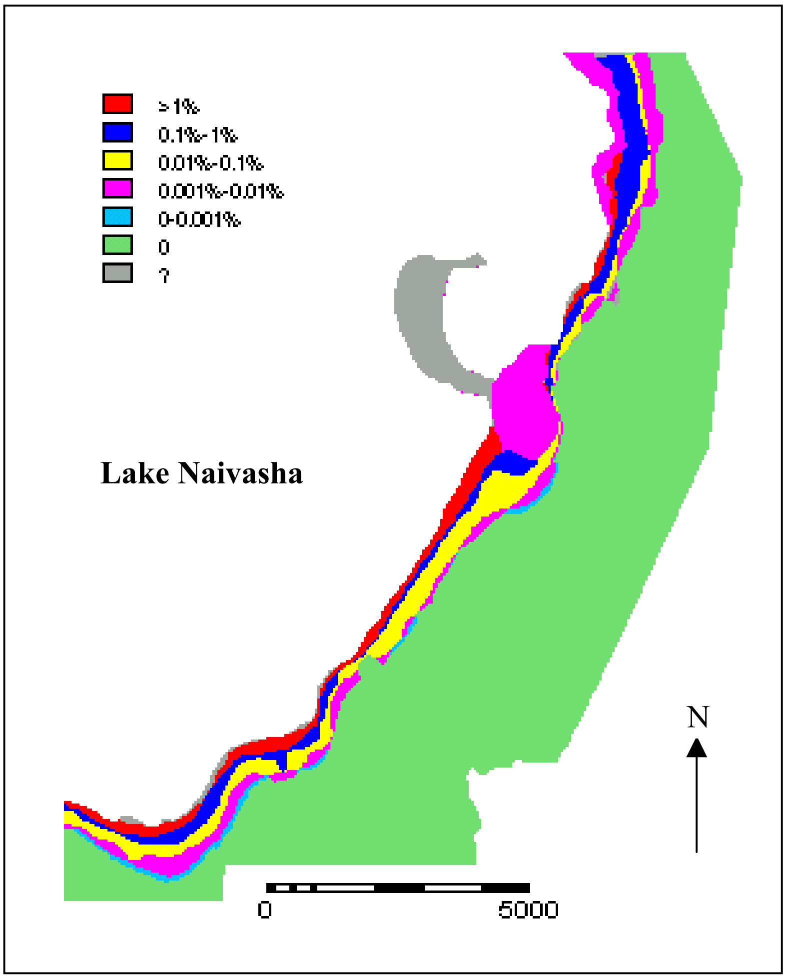
Figure 5-10 Comparison of leaching depths of Fenamiphos (sandy loam soil) between greenhouse and open field

1. As shown in Figure 5-9, during the 5 years simulation after application, there is no breakthrough to groundwater for the scenario 2. Breakthrough to groundwater happened in the 3rd years after application in the open field and inside the greenhouse in scenario 1. The leaching fraction difference is 0.1%. The leaching percentage in scenario 1 is higher than in the open field by a factor 80% in the 3rd year and 50% in the 4th and 5th year.

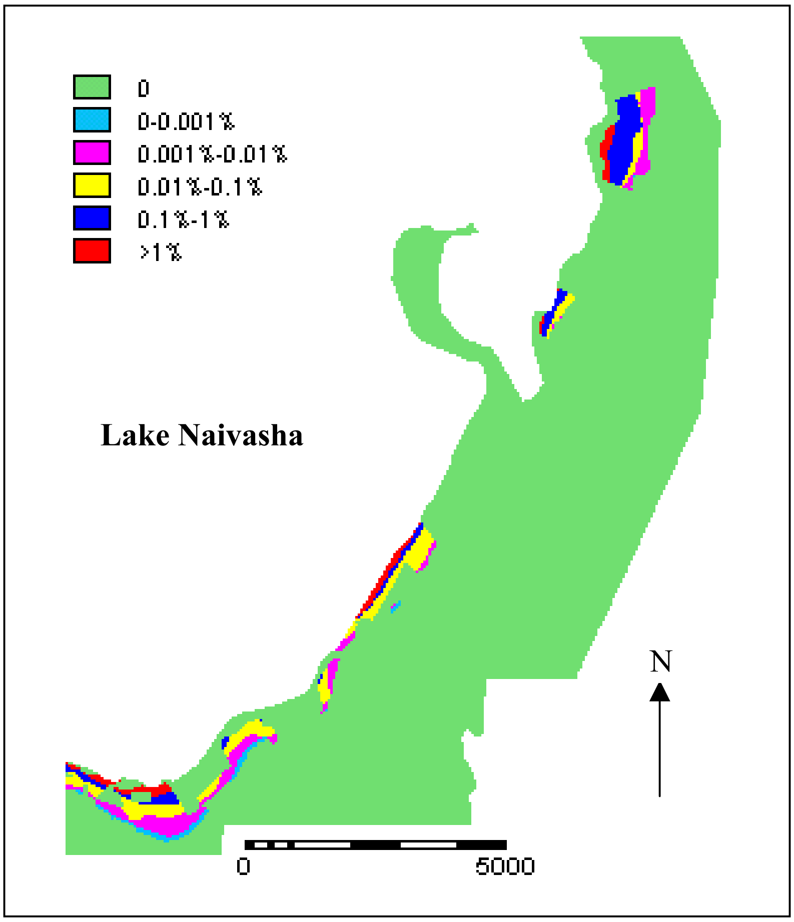
2. The input difference between scenario 1 in the greenhouse and in the open field is only evapotransporation. It is 36% lower in scenario 1 than in the open field. This difference resulted in more groundwater recharge in scenario 1. The leaching dosage increased accordingly.

3. In scenario 2, the 50% decrease in irrigation application caused zero leaching, although the evapotransporation reduce 36% simultaneously. As shown in Figure 5-10, the speed of the pollutant advection for scenario 2 is much lower than in the open field. Before the pollutant reached the ground water table, it has already been degraded completely.

4. The 10 mm/day water application for irrigation surveyed in some farms is too much. It causes much higher leaching in the greenhouses than in the open field.



Map 5-1 Vulnerability of the soils to potential leaching for a pesticide Fenamiphos after five years of application.



Map 5-2 The leaching map for cultivation area for a pesticide Fenamiphos after five years of application.

Note: for both maps, the legend presents the leaching fraction (%) of total applied doses.

5.5 Limitation

The discussion for all scenario analysis results in this chapter should taken into account the following limitations, which originate from the model and study itself:

- SESOIL is a one-dimensional vertical transport model. It doesn't consider the lateral flow of soil moisture. Hence, the pollutant lateral transport to the lake is not considered. Mass of pollutant in soil moisture and lost to the ground water are overestimated.

- When the fraction of organic carbon input to SESOIL is greater than 0, the model ignores sorption onto inorganic mineral matter (Wu et. al., 1997). The model output will give a higher estimation for the mass of pollutant in soil moisture and lost to ground water.

- SESOIL is a long-term monthly or annual simulation model compared to the storm based models. It doesn't have storm resolution. The pollutant in washload, therefore, is underestimated for the extreme storm event.

- The study didn't go further for the degradates, which are products of the pesticides biodegradation. Although, the ultimate products for most pesticides are CO_2 and H_20, the intermediate products for some pesticide may appear more toxic than the parent compound.

- Hard soil layers, concrete and hardpans due to natural cementation (silica, diatoms, iron oxides) and/or cultivation (ploughing) may exist in the study area. They will prevent or modify leaching of pesticides greatly. The simulation didn't consider the effect of the hardpans, since the spatial distribution and detailed information about hardpans is still unclear.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

This chapter gives the conclusions drawn from the study achievement, as well as the recommendations for future study and farm management.

6.1 Conclusions

This study aimed at surveying and evaluating the chemical pollution of the lake water, with emphasis on the pollution from the agricultural sector. Traditional experimental analysis method conducted the general assessment of the lake water quality. Identification and assessment of the pollution sources showed the application of agrochemicals around the lake posed a potential risk to the lake water quality. A model method was used to predict the fate of the pesticides and assess the factors governing the fate processes. Based on the modeling results and specific site conditions of the study area, the model went further to quantify the potential leaching risk of the pesticides. The vulnerability of the soils was evaluated as well. GIS, as an effective tool, is used to map the potential leaching risk of pesticide to ground water. The following conclusions were drawn from the achievement of this study.

Pollution sources survey and assessment

- More than ten major kinds of fertilizers and sixty kinds of pesticides are currently being used in the riparian lake area. The toxicity classification of the pesticides showed about half of the pesticides is hazardous. Two of them belong to “extremely hazardous” group classified by WHO. The persistency classification revealed above 10% of the pesticides being “high persistence”.

- Sewage assessment indicated Naivasha town is the main contributor to the total sewage discharge. The efficient treatment of wastewater and effective management of sewage network play a significant role in preventing nutrient enrichment and organic pollution of the lake water.

Water quality survey and assessment

- *Lake water quality assessment*. The assessment was carried out based on the lake water use. The following conclusions were derived from the limited water sample measurement.

  Generally speaking, the water quality of Lake Naivasha is in a good condition for its irrigation purpose. Comparing with irrigation guideline, only NO^-_3-N slightly exceeded the guideline value.

  Heavy metal pollution should be given essential concern. Total iron content of the lake significantly exceeded the drinking water guideline value. The lake water is not suitable for the drinking water purpose without treatment. Fertilizer application in the riparian agricultural area should be partly responsible for Fe pollution of the lake.

The nutrient contents of the lake water showed the worrying increased trend in the last decade. Riparian agriculture development can be one of the reasons.

- *Farm effluent assessment*. all water quality indicators measured except Cd exceeded discharge guideline values. The concentration of NO^-_3 is much higher than the guideline value. Degradation of the groundwater due to NO^-_3 pollution is already detected in certain area.

Modeling the fate of pesticides

The following conclusions were derived from modeling results for indicator pesticides in spite of model limitations.

- The average pesticide amounts washed off into the lake either associated with soil particles or diluted in the surface runoff is very small. This outcome resulted from gentle slopes, dense surface covers, high permeable soils in the study area.

- The pesticides distributions both in soil air and lost to volatilization are negligible due to their low Henry's law constant. In other words, the risk to the air pollution from pesticide is minimal.

- All pesticides are degraded after 2 years of application except high persistent pesticides, such as Fenamiphos.

- The fate of a pesticide is mainly governed by its persistence. The biodegradation rate constant is a decisive factor for the environmental partitioning of pesticides.

The leaching risk of pesticides

- The pesticides susceptible to leaching all have a relatively high solubility, low adsorption, and high persistence.

- The vulnerable soil type to pesticide leaching has a relatively coarse soil texture, high permeability, and low organic carbon content. The movement of pollutant is faster in the sandy loam soil than in the clay loam soil. PL331 soil unit in sandy loam area was identified as the most susceptible soil to pesticide leaching.

- The PL331 soil unit in combination with a shallow ground water depth (dominate depth range 2-6 meters) were determined being vulnerable areas for groundwater contamination.

- The leaching of the pesticides is lower than 0.1% in most of the study area due to deep groundwater table.

6.2 Recommendations

Future study

In order to give a comprehensive assessment for the lake water quality and effectively control pollution sources. The following studies are suggested to carried out in the future:

- Sufficient spatial and temporal water quality data should be acquired.
- Quantifying wastewater discharge and pollutant content from the industry pollution sources.
- Monitoring the water quality variables of the inflow rivers of the lake, i.e. Malewa, Gilgil, Karati.
- A non-point pollution model with storm resolution can better quantify the pollution from washload and surface runoff in the riparian zone of the lake.
- Ample spatial soil moisture data are needed to increase the accuracy of the simulation results.
- The spatial distribution and detailed information about subsoil concrete, hard layers, hardpans should be studied since they are important site-condition properties for preventing the leaching of the pesticides.
- The importance of temporary perched water tables and horizontal contamination transport in the vadose zone near to the lake should be investigated further to clarify the importance of this pathway.
- Most models (such as SESOIL) analyze chemical transport through the soil primary matrix porosity. Dual porosity effects of preferential pathways should also be studied further.
- A verification process for the model output is very necessary. The pesticide measurements in different environment components are needed.

Farm management

- It is recommended to use "no hazardous" and low persistence pesticides. The application of the "extremely hazardous" and "highly hazardous" pesticides should be stopped, especially for the high persistence pesticides.
- Developing irrigation water recycling system to prevent pollution from surface runoff and save water resources.
- Reducing the application amount of the irrigation water. The current application amount of irrigation is almost twice of the crop requirements. The decrease of the irrigation water can alleviate the risk of pesticide leaching to ground water greatly.
- The cultivation should be away from the lake as far as possible, since the vulnerable soil type for the pesticide leaching occurred near to the lake, as well as the relatively shallow ground water table nearby.

Appendix 1 Location and description of the water samples

Sample number	Coordinate		Description
	X	Y	
F1	204461	9907143	Farm Sulmac (rose green house)
F2	204831	9907397	Farm Sulmac (French bean field)
F3	204478	9906723	Farm Sulmac (French bean field)
F4	207157	9908732	Farm Sher (rose field, rain before the day we took sample)
F5	207630	9908875	Farm Sher (pond 1, just after a very heavy rain)
F6	207034	9908438	Farm Sher (pond 2, just after a very heavy rain)
F7	214507	9917237	Farm Aberdare (vegetable field, after a little rain)
F8	214583	9917396	Farm Aberdare (vegetable field applied manual recently, after a very heavy rain.)
F9	210887	9911200	Farm Vineyard (vegetable field, after a very heavy rain)
F10	211148	9911023	Farm Vineyard (vegetable field, after a very heavy rain)
F11	1998853	9908951	Farm Oserian (flower field, before treatment)
F12	198577	9909136	Farm Oserian (flower field, after treatment)
L1	204015	9910300	Central of the lake
L2	200590	9910101	Around borehole 9, about 10m from the lake shore
L3	203378	9908982	About 15m from fish eagle harbor, tourism area
L4	206015	9909071	About 10m from papyrus, 100m from land, near to Sher agency.
L5	209136	9911223	Western part of the island
L6	212774	9915644	Near to the farm, between island and town
L7	212812	9918480	Near to Naivasha town
L8	213350	9917426	The water abstraction point of Farm Aberdare
L9	204830	9908590	The water abstraction point of Farm Sulmac
L10	205410	9908520	Besides the water recycling pond of Farm Sher agency
S1	214690	9920409	Sewage water at sewage discharge point of Naivash town

Appendix 2 Analysis results of the lake and sewage water samples

Sample number	**General water quality parameter**				**Organic parameter**	**Nutrient parameter**				**Heavy metal**			**Major ion**			
	pH	EC (21.3^0)	Tur	DO	COD	NO_3^--N	NH_4^+	PO_4^{3-}	Phosphate-P	total Fe	total Cd	total Cu	Na^+	K^+	Ca^{2+}	Mg^{2+}
L1	6.92	0.286	10	8.55	21			0.2	0.18	1.2	1 E-4	1.14 E-2	20.2	9.3	6.0	4.9
L2	6.81	0.284	10	8.1	63	1.5		0.3	0.16	1.3	1 E-4	1.65 E-2	21.0	9.6	5.9	4.9
L3	6.83	0.285	10	8.6	36	3.4		0.2	0.09	1.3	1 E-4	2.90 E-2	20.2	9.2	5.8	4.9
L4	6.87	0.285	10	8.7	43	2.0		0.2	0.20	0.9	1 E-4	1.05 E-2	20.8	9.6	5.9	4.9
L5	6.95	0.282	10	8.97	42	3.0	0.5	0.3	0.20	1.2	1 E-4	1.32 E-2	20.8	9.5	6.3	4.9
L6	6.95	0.298	10	9.3	44	2.6		0.2	0.19	0.8	1 E-4	1.24 E-2	21.2	9.8	6.6	5.1
L7	6.67	0.297	10	7.93	50	2.1			0.23	0.9	2 E-4	1.84 E-2	22.0	10.0	6.6	5.2
L8	6.80	0.295	10	7.97	46	5.9			0.22	0.9	2 E-4	2.10 E-2	22.0	10.1	6.8	5.2
L9	6.84	0.283	10	8.65	44	3.8		0.2	0.17	1.1	1 E-4	2.09 E-2	21.5	9.8	6.2	5.0
L10	6.85	0.284	10	8.6	41	8.4			0.18	0.9	1 E-4	2.15 E-2	21.2	9.7	9.5	5.0
S11		2880	10		520	160		570	25.1							

Note: except pH , turbidity (NTU), and EC (mS/cm), the unit of other paramenters is mg/l.

Appendix 2 Analysis results of the water samples from the farms

Sample number	**Organic parameter**	**Nutrient parameter**					**Heavy metal**			**Major ion**			
	COD	NO_3^--N	Total p	NH_4^+	PO_4^{3-}	Phosphate-P	total Fe	total Cd	total Cu	Na^+	K^+	Ca^{2+}	Mg^{2+}
F1	54	68	53.8	<0.05	8.6	17.4							
F2	50	6	2.5	<0.05	2.7	1.13							
F3	54	3			3.3	1.6	1.5	4E-4	2.08E-2	23.2	10.6	5.4	5.6
F4	40	5.3	4.2	0.6	4.4	0.07	2.2	3E-4	1.44E-1	45.0	19.1	3.8	1.9
F5	44	4.2	0.2	0.1	0.4	1.0	0.0	7E-4	5.91E-2	42.4	18.1	2.1	4.0
F6	51	1.8	0.1	<0.05	0.2	1.23	0.1	2E-4	7.3E-2	49.0	20.5	5.8	8.1
F7	83	8.8	2.1	0.7	5.3	2.68	47.0	7E-4	9.1E-2	55.8	23.2	<0.5	0.3
F8	74	1.0	4.2	0.7	6.6	Over							
F9	46	2.0	5.1	1.1	4.6	2.72	2.4	1E-4	1.02E-1	13.9	6.8	<0.5	0.6
F10	28	4.0	6.0	0.5	5.7	2.98	2.2	1E-4	7.26E-2	11.0	5.7	<0.5	0.6
F11	34	24			7.6	9	0.0	2E-4	9.02E-2	27.5	12.5	36.6	15.2
F12	33	76	16.7	60.6	6.0		0.0	2E-4	4.51E-2	28.6	12.6	38.6	15.2

Note: except pH , turbidity (NTU), and EC (mS/cm), the unit of other paramenters is mg/l.

Appendix 6 Determination of C- factors (Nill, 1996)

Appendix 7 Script

```
N0=iff((texture="sandy loam")and(s_wdepth>=2.5)and(s_wdepth<3.5)and(soil="PL222"),4.7e-3,0)
n1=iff((texture="sandy loam")and(s_wdepth>=3.5)and(s_wdepth<4.5)and(soil="PL222"),3.2e-3,N0)
n2=iff((texture="sandy loam")and(s_wdepth>=4.5)and(s_wdepth<5.5)and(soil="PL222"),2.3e-3,n1)
n3=iff((texture="sandy loam")and(s_wdepth>=5.5)and(s_wdepth<6.5)and(soil="PL222"),1.7e-3,n2)
n4=iff((texture="sandy loam")and(s_wdepth>=6.5)and(s_wdepth<7.5)and(soil="PL222"),1.2e-3,n3)
n5=iff((texture="sandy loam")and(s_wdepth>=7.5)and(s_wdepth<8.5)and(soil="PL222"),8.7e-4,n4)
n6=iff((texture="sandy loam")and(s_wdepth>=8.5)and(s_wdepth<9.5)and(soil="PL222"),6.3e-4,n5)
n7=iff((texture="sandy loam")and(s_wdepth>=9.5)and(s_wdepth<10.5)and(soil="PL222"),4.5e-4,n6)
n8=iff((texture="sandy loam")and(s_wdepth>=10.5)and(s_wdepth<11.5)and(soil="PL222"),3.2e-4,n7)
n9=iff((texture="sandy loam")and(s_wdepth>=11.5)and(s_wdepth<12.5)and(soil="PL222"),2.1e-4,n8)
n10=iff((texture="sandy loam")and(s_wdepth>=12.5)and(s_wdepth<13.5)and(soil="PL222"),1.4e-4,n9)
n11=iff((texture="sandy loam")and(s_wdepth>=13.5)and(s_wdepth<14.5)and(soil="PL222"),9.4e-5,n10)
n12=iff((texture="sandy loam")and(s_wdepth>=14.5)and(s_wdepth<15.5)and(soil="PL222"),6.2e-5,n11)
n13=iff((texture="sandy loam")and(s_wdepth>=15.5)and(s_wdepth<16.5)and(soil="PL222"),3.8e-5,n12)
n14=iff((texture="sandy loam")and(s_wdepth>=16.5)and(s_wdepth<17.5)and(soil="PL222"),2.2e-5,n13)
C0=iff((texture="clay loam")and(s_wdepth>=2.5)and(s_wdepth<3.5)and(soil="PL331"),3.3e-2,n13)
C1=iff((texture="clay loam")and(s_wdepth>=3.5)and(s_wdepth<4.5)and(soil="PL331"),1.7e-2,C0)
C2=iff((texture="clay loam")and(s_wdepth>=4.5)and(s_wdepth<5.5)and(soil="PL331"),9.8e-3,c1)
C3=iff((texture="clay loam")and(s_wdepth>=5.5)and(s_wdepth<6.5)and(soil="PL331"),6.4e-3,c2)
C4=iff((texture="clay loam")and(s_wdepth>=6.5)and(s_wdepth<7.5)and(soil="PL331"),4.2e-3,c3)
C5=iff((texture="clay loam")and(s_wdepth>=7.5)and(s_wdepth<8.5)and(soil="PL331"),2.7e-3,c4)
C6=iff((texture="clay loam")and(s_wdepth>=8.5)and(s_wdepth<9.5)and(soil="PL331"),1.7e-3,c5)
C7=iff((texture="clay loam")and(s_wdepth>=9.5)and(s_wdepth<10.5)and(soil="PL331"),1.1e-3,c6)
C8=iff((texture="clay loam")and(s_wdepth>=10.5)and(s_wdepth<11.5)and(soil="PL331"),6.7e-4,c7)
C9=iff((texture="clay loam")and(s_wdepth>=11.5)and(s_wdepth<12.5)and(soil="PL331"),4.3e-4,c8)
C10=iff((texture="clay loam")and(s_wdepth>=12.5)and(s_wdepth<13.5)and(soil="PL331"),2.7e-4,c9)
C11=iff((texture="clay loam")and(s_wdepth>=14.5)and(s_wdepth<15.5)and(soil="PL331"),9e-5,c10)
C12=iff((texture="clay loam")and(s_wdepth>=15.5)and(s_wdepth<16.5)and(soil="PL331"),4.7e-5,c11)
C13=iff((texture="clay loam")and(s_wdepth>=16.5)and(s_wdepth<17.5)and(soil="PL331"),2.4e-5,c12)
CP0=iff((texture="clay loam")and(s_wdepth>=2.5)and(s_wdepth<3.5)and(soil="PL222"),3.2e-3,c13)
CP1=iff((texture="clay loam")and(s_wdepth>=3.5)and(s_wdepth<4.5)and(soil="PL222"),1.8e-3,cp0)
CP2=iff((texture="clay loam")and(s_wdepth>=4.5)and(s_wdepth<5.5)and(soil="PL222"),1.3e-3,cp1)
CP3=iff((texture="clay loam")and(s_wdepth>=5.5)and(s_wdepth<6.5)and(soil="PL222"),7.6e-4,cp2)
CP4=iff((texture="clay loam")and(s_wdepth>=6.5)and(s_wdepth<7.5)and(soil="PL222"),5e-4,cp3)
CP5=iff((texture="clay loam")and(s_wdepth>=7.5)and(s_wdepth<8.5)and(soil="PL222"),3.2e-4,cp4)
CP6=iff((texture="clay loam")and(s_wdepth>=8.5)and(s_wdepth<9.5)and(soil="PL222"),2e-4,cp5)
CP7=iff((texture="clay loam")and(s_wdepth>=9.5)and(s_wdepth<10.5)and(soil="PL222"),1.2e-4,cp6)
CP8=iff((texture="clay loam")and(s_wdepth>=10.5)and(s_wdepth<11.5)and(soil="PL222"),7.2e-5,cp7)
CP9=iff((texture="clay loam")and(s_wdepth>=11.5)and(s_wdepth<12.5)and(soil="PL222"),4e-5,cp8)
CP10=iff((texture="clay loam")and(s_wdepth>=12.5)and(s_wdepth<13.5)and(soil="PL222"),2e-5,cp9)
CP11=iff((texture="clay loam")and(s_wdepth>=13.5)and(s_wdepth<14.5)and(soil="PL222"),7e-6,cp10)
Sp0=iff((texture="sandy loam")and(s_wdepth>=3.5)and(s_wdepth<4.5)and(soil="PL331"),4.4e-2,cp11)
sp1=iff((texture="sandy loam")and(s_wdepth>=3.5)and(s_wdepth<4.5)and(soil="PL331"),2.7e-2,sp0)
sp2=iff((texture="sandy loam")and(s_wdepth>=4.5)and(s_wdepth<5.5)and(soil="PL331"),1.8e-2,sp1)
sp3=iff((texture="sandy loam")and(s_wdepth>=5.5)and(s_wdepth<6.5)and(soil="PL331"),1.3e-2,sp2)
sp4=iff((texture="sandy loam")and(s_wdepth>=6.5)and(s_wdepth<7.5)and(soil="PL331"),9.3e-3,sp3)
sp5=iff((texture="sandy loam")and(s_wdepth>=7.5)and(s_wdepth<8.5)and(soil="PL331"),6.7e-3,sp4)
sp6=iff((texture="sandy loam")and(s_wdepth>=8.5)and(s_wdepth<9.5)and(soil="PL331"),4.8e-3,sp5)
sp7=iff((texture="sandy loam")and(s_wdepth>=9.5)and(s_wdepth<10.5)and(soil="PL331"),3.4e-3,sp6)
sp8=iff((texture="sandy loam")and(s_wdepth>=10.5)and(s_wdepth<11.5)and(soil="PL331"),2.4e-3,sp7)
sp9=iff((texture="sandy loam")and(s_wdepth>=11.5)and(s_wdepth<12.5)and(soil="PL331"),1.6e-3,sp8)
sp10=iff((texture="sandy loam")and(s_wdepth>=12.5)and(s_wdepth<13.5)and(soil="PL331"),1.1e-3,sp9)
sp11=iff((texture="sandy loam")and(s_wdepth>=13.5)and(s_wdepth<14.5)and(soil="PL331"),7.8e-4,sp10)
sp12=iff((texture="sandy loam")and(s_wdepth>=14.5)and(s_wdepth<15.5)and(soil="PL331"),7.8e-4,sp11)
sp13=iff((texture="sandy loam")and(s_wdepth>=15.5)and(s_wdepth<16.5)and(soil="PL331"),7.8e-4,sp12)
sp14=iff((texture="sandy loam")and(s_wdepth>=16.5)and(s_wdepth<17.5)and(soil="PL331"),7.8e-4,sp13)
```

```
sL5=iff((texture="sandy loam")and(s_wdepth>=7.5)and(s_wdepth<8.5)and(soil="PL111"),2.1e-4,sp14)
sL6=iff((texture="sandy loam")and(s_wdepth>=8.5)and(s_wdepth<9.5)and(soil="PL111"),1.5e-4,sL5)
sL7=iff((texture="sandy loam")and(s_wdepth>=9.5)and(s_wdepth<10.5)and(soil="PL111"),9.8e-5,sL6)
sL8=iff((texture="sandy loam")and(s_wdepth>=10.5)and(s_wdepth<11.5)and(soil="PL111"),6.5e-5,sL7)
sL9=iff((texture="sandy loam")and(s_wdepth>=11.5)and(s_wdepth<12.5)and(soil="PL111"),4.1e-5,sL8)
sL10=iff((texture="sandy loam")and(s_wdepth>=12.5)and(s_wdepth<13.5)and(soil="PL111"),2.5e-5,sL9)
sL11=iff((texture="sandy loam")and(s_wdepth>=13.5)and(s_wdepth<14.5)and(soil="PL111"),1.3e-5,sL10)
sM7=iff((texture="clay loam")and(s_wdepth>=9.5)and(s_wdepth<10.5)and(soil="PL111"),2e-5,sL11)
sM8=iff((texture="clay loam")and(s_wdepth>=10.5)and(s_wdepth<11.5)and(soil="PL111"),7.7e-6,sM7)
sM9=iff((texture="clay loam")and(s_wdepth>=11.5)and(s_wdepth<12.5)and(soil="PL111"),1.3e-7,sM8)
```