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Estimation of water pollution sources in Lake Victoria, East Africa: Application and elaboration of the rapid assessment methodology

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Pollution resulting from increased human activities is threatening Lake Victoria, its effects being characterised by eutrophication and the occurrence of dramatically low dissolved oxygen levels. This study applies a system of pollution inventory methods to estimate waste loads from pollution sources on the basis of functional variables and pollution intensities. Penetration factors are used to incorporate the effects of treatment facilities and of natural 'purification' in rivers and wetlands. The application of a basic error analysis provides insight into the reliability of results. A one-dimensional model is applied to assess the overall nutrient balance.

Results show that biological oxygen demand (BOD) load is highest on the Kenyan side. Domestic BOD loads exceed industrial loads in all regions, and management policies should therefore be directed primarily towards a reduction of domestic pollution. It was concluded that through effective operation of existing treatment facilities alone BOD loads on the Kenyan side could be reduced by 50%.

Nutrient input appears to originate mainly from atmospheric deposition and land runoff, together accounting for approximately 90% of phosphorous and 94% of nitrogen input into the lake. The increase in eutrophication is most probably due to an increase in nutrient input from these sources, as a result of increased human activities in the lake surroundings, such as land exploitation for agriculture and forest burning. Policies for sustainable development in the region, including restoration and preservation of the lake's ecosystem, should therefore be directed towards improved land-use practices and a control over land clearing and forest burning.

Keywords: water pollution, environmental assessment, error analysis, nutrient loading, Lake Victoria.

Introduction

With a surface area of 68 800 km^2 and an average depth of 40 m, Lake Victoria is the second largest water body in the world and of crucial socio-economic importance to its riparian population. The three surrounding countries Tanzania, Uganda and Kenya control 49, 45 and 6%, respectively, of the area of the lake and make use of its resources for fishery, freshwater and avenues of transportation. The lake's 1 94 000 km^2 catchment area stretches further across Rwanda and Burundi (Figure 1). The lake's water balance is dominated by evaporation and precipitation, its single outlet being the Victoria Nile at Jinja, Uganda.

In the last few decades, the lake has undergone large changes in chemistry and biology as a result of growing human interference. Threats to the lake's ecosystem include overfishing, the introduction of exotic fish species such as the notorious Nile perch (*Lates Niloticus*) accompanied by a drastic reduction in endemic species (Goldsmith *et al*., 1993; Gophen *et al*., 1993; Kaufman, 1992; Witte *et al*., 1992a,b), and the large scale infiltration of the water-hyacinth (*Eichhornia crassipes*). Pollution from domestic, industrial and agricultural activities have lead to a deterioration of water quality, characterised by algal blooms, even offshore (Ochumba & Kibaara, 1989), and periodic massive fish kills caused by oxygen

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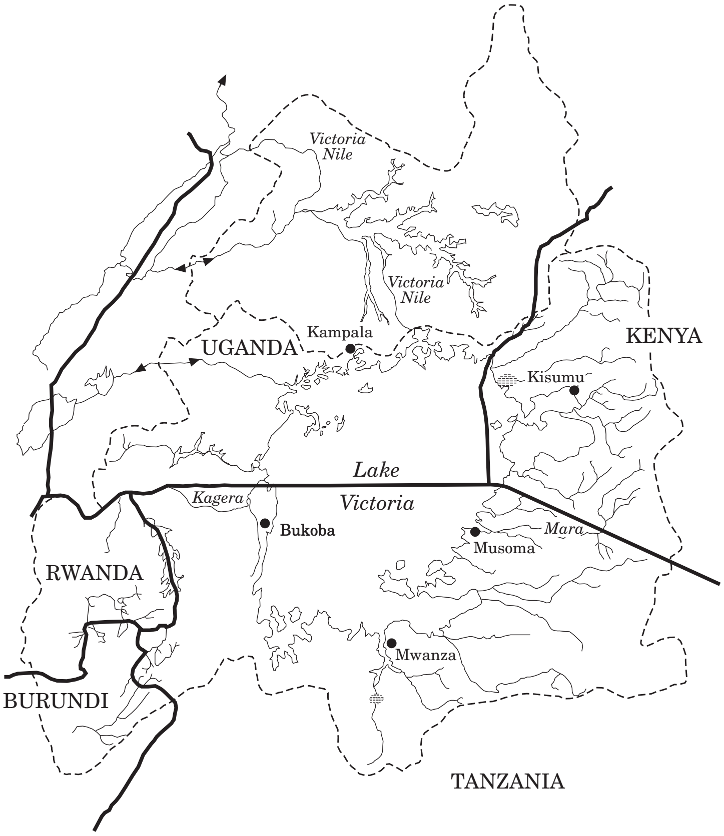

Figure 1. The Lake Victoria catchment area.

depletion (Ochumba, 1988; Hecky *et al.*, 1994). Widespread water-borne diseases and reduced benefits to riparian people result.

This study presents an assessment of pollution sources and their contribution to the changes taking place in Lake Victoria. The assessment makes use of the scattered amount of data already available, applying a set of methodologies for translation of this data into conclusions that could contribute to the design of effective pollution control approaches. Data was gathered both through literature survey and field surveys in the period 1993–1996, building upon earlier work, though less extensive, of others (Calamari *et al.*, 1993; Scheren *et al.*, 1994, 1995; Kirugara & Nevejan, 1996).

The study is also thought to contribute to the development of effective methods for pollution assessment in data and resource poor situations. The methodology followed has proven to be effective for pollution assessment in situations where extensive monitoring programs can not be executed, such as often the case in developing countries. In view of the catchment area's characteristics, with organic pollution from industries, farming and basic consumption patterns prevailing, the results presented here are limited to three major organic pollution parameters: The 5 day biological oxygen demand (BOD) load, as an indicator for the pollution load of industries and domestic effluents to bays and near-shore waters (often associated with water born diseases), and nitrogen (N) and phosphorus (P) as nutrients associated with the eutrophication of the lake.

Methodology

The method described below consists of four main components: (1) a *pollution sources assessment*, based on what is often referred to as 'rapid assessment' method (World Health Organization, 1982; Economopoulos, 1993; Scheren *et al.*, 1994, 1995); (2) *penetration factors*, to incorporate the effects of 'natural purification' by rivers and wetlands, and the 'enforced purification' of treatment facilities; (3) an *error analysis* to evaluate the margins

Table 1. Functional variables and pollution intensities for the principle pollution sources

Pollution source	Functional variable	Pollution intensity
Industries	Annual production	Waste production per unit product
Households	Population number	Annual waste production per person
Agriculture	Area of (non)-cultivated land	Annual export coefficients of nutrients
Atmospheric deposition	Surface area	Annual deposition per unit of surface area

of reliability of conclusions; and (4) an evaluation of the relative contribution of pollution sources to the lake's *nutrient balance*.

Pollution sources assessment

The procedure used to estimate pollution from the various land-based pollution sources is based on the following general formula:

$$\text{waste load} = \text{functional variable} * \text{pollution intensity}$$

In which the pollution intensity represents the characteristic amount of waste produced per unit of a certain functional variable. A suitable selection of parameters allows estimation of waste loads on the basis of more easily measurable data, such as population, production and land-use figures. Table 1 presents functional variables and pollution intensities as proposed in this study.

Table 1 categorises atmospheric deposition, in cases an important factor in the nutrient balance of lakes (Bootsma *et al.*, 1996), as a source of pollutants. Human activities in a wide area around the water body, such as biomass burning and land cultivation resulting in erosion, are known to be of potentially large influence to nutrient flow via this avenue (Crutzen and Andreae, 1990; Galloway *et al.*, 1982; Goldman *et al.*, 1990; Lewis, 1981).

The actual assessment first demands the collection of baseline data on the functional variables chosen. Data may be collected through field surveys, but also often extracted from available statistical reports, data from local, national and regional governmental and non-governmental institutions, scientific literature, and other written and non-written resources.

In using the above procedure, the choice of characteristic pollution intensities becomes very delicate, since factors like export coefficients and waste per unit product or person vary widely across cases. As a result, attention should due be given to the selection of these parameters, demanding a review of literature data from cases as similar as possible to the one surveyed. A range of possible values for each parameter may be defined.

Penetration factors

The actual pollutant load to a given water body may not be equal to what leaves the source at its origin. Wastewater treatment facilities and self-purification in rivers and wetlands may reduce the actual load. An elaboration of the standard formula allows for such effects to be incorporated in the assessment:

$$\text{waste load} = \text{functional variable} * \text{pollution intensity} * \text{penetration factor(s)}$$

where the value of the penetration factor may vary between 0 and 1.

The most common penetration factors are efficiency factors for domestic and industrial wastewater treatment facilities. Typical performances of normally operating plants are described by Economopoulos (1993), although bad operation may require estimations of treatment efficiencies to be made on the basis of site visits and effluent analysis data.

Furthermore, natural purification effects of rivers and streams reduce BOD from a distant source. The breakdown of BOD in rivers can be described as a first-order decay process:

$$\frac{L}{L_0} = \exp\left(\frac{-K \times D}{86{\cdot}4 \times v}\right) \tag{1}$$

In which L represents downstream BOD, L_0 represents BOD at the point of discharge, K is the decay rate (day^{-1}), D is the distance between discharge point and lakeshore (km), and v is the flow velocity (ms^{-1}). L/L_0 thus provides a value for the penetration factor at distance D from the lakeshore. It should be noted that the decay factor K depends on many different river characteristics such as bacterial composition, water temperature, water turbulence and stream velocity, and will be different for individual (parts of) rivers. Values reported range from 0·2 to 0·8 day^{-1}, but are most often found to be in the order of 0·3 day^{-1} (Thomann and Mueller, 1987; Metcalf and Eddy Inc., 1991; Zanting, 1996).

Nutrient and oxygen demanding waste concentrations in rivers and sewage outlets may also be drastically reduced when draining through swamp areas. The purification capacity of wetlands is related to various aspects of wetland hydrology such as water depth, retention time and degree of channelisation. Appropriate wetland penetration factors should therefore be assessed for each individual case.

Error analysis

Errors in the calculation of waste loads may be caused by either variability or bias (Reckhow and Simpson, 1980). In our case, variability may result from fluctuations inherent in a characteristic of the pollution source, represented by the 'functional variable'. Bias may result from the fact that the estimate may not fully represent the characteristic that it was selected to estimate. Uncertainty in this regard is for example introduced when values for 'pollution intensities' generated from other cases (e.g. watersheds in temperate climates) are applied to the Lake Victoria basin.

Here, the danger of bias errors originating from the selection of pollution intensities is much larger than that caused by variability, since the latter refers to primary data collected and verified in the field. To account for bias in the assessment parameters, a range, represented by 'high', 'most likely', and 'low' values may be selected by the analyst. For pollution intensities, these values may be based on reported ranges in literature. The width of the selected high-low interval expresses the confidence of the analyst in the most likely value. The procedure applied here is based on first-order analysis (Benjamin and Cornell, 1970). A modification of the Chebyshev inequality results in confidence limits for the estimated total waste load W, as follows:

$$P[(W_{(\mathrm{ml})}-h\times s^{-})\leq W\leq (W_{(\mathrm{ml})}+h\times s^{+})] \geq 1-\frac{1}{2{\cdot}25\times h^{2}} \tag{2}$$

$$s^{+}=\frac{W_{(\mathrm{high})}-W_{(\mathrm{ml})}}{2} \tag{3}$$

$$s^{-}=\frac{W_{(\mathrm{ml})}-W_{(\mathrm{low})}}{2} \tag{4}$$

Equation (2) states that the probability (P) that the true waste load (W) lies within certain bounds around the most likely value (W_{ml}), defined by a multiple (h) of the estimation error (s), is greater than or equal to $1–1/2{\cdot}25h^2$. For a theoretical elaboration on the procedure we refer to Reckhow and Simpson, 1980. It is important to state, that with this procedure it is not required that the error term be normally distributed, which contrary to many other methods implies that low and high intervals need not necessarily be symmetric.

Nutrient balance assessment

To assess the overall nutrient budget of a lake, a one-dimensional input-output model is proposed. Although such a model averages concentrations over the lake, and is therewith not suitable to predict local deviations and fluctuations, it is a useful tool to assess the overall nutrient balance. Under steady-state conditions (when nutrients concentrations are relatively constant), and assuming that lake volume and outflow are constant and that all processes involving nutrients (e.g. sedimentation) are linearly related to the nutrient concentration, Equation (5) describes the lake's nutrient balance:

$$W_{\mathrm{A}}=C_{\mathrm{A}}\times\left(Q_{\mathrm{E}}+V\frac{v_{\mathrm{S}}^{\mathrm{A}}}{H}\right) \tag{5}$$

in which W_{A} represents input of nutrient A (g yr^{-1}), C_{A} is the concentration of nutrient A (g m^{-3}), Q_{E} is the river outflow ($\text{m}^3\ \text{yr}^{-1}$), V is the lake volume [m^3], $v_{\mathrm{S}}^{\mathrm{A}}$ is the sedimentation velocity for nutrient A (m yr^{-1}), and H is the average lake depth [m]. Since the assumptions made are generally valid approximations for a large water body such as Lake Victoria, Scheren (1995) elaborates on this), Equation (5) thus provides an estimation of the total nutrient load W_A.

Results

The following results of the assessment are reported in a systematic order, starting with an assessment of relevant lake basin characteristics, followed by a definition of pollution indices and penetration factors, and concluded with the actual results on BOD and nutrient loading and an assessment of the nutrient balance.

Lake basin characteristics

Industrial pollution—Most industry is located in the larger towns bordering the lake; Kampala and Jinja in Uganda, Mwanza and Musoma in Tanzania, and Kisumu in Kenya. Exceptions are the large sugar factories in Kenya located at some distance from the lake. Table 2 presents an overview of the industrial production characteristics of the region. Although in Tanzania and Uganda industrial wastewater treatment facilities are generally absent, a majority of the Kenyan factories does operate a treatment plant. A minority of industries is furthermore connected to an urban sewage system. Although treatment efficiencies are generally low, their effect should not be neglected. Much of Ugandan industrial effluents furthermore drain through wetlands before reaching the lake surface water.

Domestic pollution—With an approximate population of 30 million, the Lake Victoria catchment area is one of the most densely populated parts of Africa. Annual population growth is 2–4% in most parts of the lake basin but urban population growth is over 5–10% per year in most of the larger towns. Table 3 summarises population statistics for the lake basin.

Land runoff—There are many densely cultivated areas in the Lake Victoria basin, especially in Kenya, Rwanda and Burundi. Important staple crops are maize and bananas. The main cash crops are sugarcane, coffee and tea. Land-use characteristics are summarised in Table 4. Most values are extrapolations from recent surveys, assuming a 1% annual growth rate for the area of cultivated land (Ministry of Water Development, 1992).

Atmospheric deposition—Average rainfall over Lake Victoria is 1450 mm yr^{-1}(±10%), equivalent to approximately 100 $\mathrm{km}^3\mathrm{yr}^{-1}$. Regional rainfall varies between 895 mm yr^{-1} in Musoma (Tanzania) and 2216 mm yr^{-1} in

Table 2. Estimated 1995 production of major industries in the catchment area of Lake Victoria by country and industrial (sub)sector

ISIC	Industry	Shared production of major factories [t yr^{-1}] (number of major factories)		
		Kenya	Uganda	Tanzania
3111	Slaughter houses	3000 (1)	14 000 (3)	—
3112	Dairy factories	—	25 000 (1)	—
3114	Fish factories	18 000 (6)	12 000 (4)	6630 (2)
3115	Vegetable oil refineries	—	3300 (2)	31 400 (4)
3118	Sugar factories	640 000 (6)	—	3500 (1)
3131	Distilleries	18 000 (1)	460 (1)	—
3133	Breweries	60 000 (1)	17 000 (1)	—
3134	Bottleries	41 000 (1)	40 000 (2)	11 100 (2)
3211	Cotton mills	1500 (1)	—	1320 (2)
3231	Leather tanneries	270 (1)	60 (1)	220 (1)
3411	Paper mills	94 000 (2)	—	—
3523	Soap factories	—	40 000 (2)	15 000 (1)

Sources: Kenya: Calamari, 1994; Kirugara and Nevejan, 1996; Ministry of Planning and National Development, 1994; Oerlemans, 1985; selected industrial site visits. Uganda: Droruga, 1990; Ministry of Natural Resources, 1995; Ministry of Finance and Economic Planning, 1993; selected site visits. Tanzania: Höjlund and Marwa, 1993a,b; Regional Trade Office Mwanza, 1991; Scheren *et al*., 1995a.

Table 3. Domestic characteristics of the Lake Victoria catchment area, 1995

	Total population [1000 people]	Urban population [1000 people]		
		Sewered	Unsewered	Number of towns
Kenya	10 200	390	630	18
Uganda	5600	210	870	9
Tanzania	5200	27	340	4
Rwanda	5900	—	400	5
Burundi	2800	—	140	4
Total	29 700	627	2380	40

Sources: Kenya: Ministry of Water Development, 1992; Uganda: Ministry of Finance and Economic Planning, 1992; National Water and Sewerage Corporation, 1995; Ministry of Natural Resources, 1993. Tanzania: (Matowo, 1992; Scheren *et al*., 1995a). Rwanda and Burundi (Verlinden, P., 1996).

Table 4. Aricultural characteristics of the Lake Victoria catchment area, 1995

	Catchment land area (1000 ha)		
	Cultivated	Non-cultivated	Total
Kenya	1470	3400	4870
Uganda	1400	2100	3500
Tanzania	1500	5540	7040
Rwanda	930	1130	2060
Burundi	670	640	1310
Total	5970	12 810	18 780

Sources: Kenya: Lake Basin Development Authority, 1987; Ministry of Water Development, 1992; Kirugara and Nevejan, 1996; Kenya Grain Growers Cooperative Union, 1991. Uganda (Ministry of Natural Resources, 1996; Ministry of Agriculture, 1992, 1995; World Bank, 1993; Bank of Uganda, 1995). Tanzania (KILIMO/FAO Fertilizer Programme, 1988, 1989; Ministry of Agriculture and Livestock Development, 1988; Scheren *et al*., 1995a). Rwanda and Burundi Bullock *et al*., 1995; United Nations, 1995.

Kalangala (Uganda) (Crul, 1993; Piper *et al*., 1986).

Wetlands—The largest wetland area in the Lake Victoria basin is in western Uganda. The entire drainage of the Katonga and Ruizi-Kibali river basins is through river channels that used to be more rapidly flowing in history but which are now sluggish, choked with swamps and in places flooded out to form small swampy lakes (Beadle and Lind, 1960). Other important wetlands in Uganda are the small swamps on the lakeshore receiving the domestic and industrial wastewater from Kampala and Jinja (Ogaram and Kalema, 1995). Furthermore, the Kagera river basin, draining through Rwanda, Burundi, Tanzania and Uganda, is covered with large areas of wetlands. Important swamps on the Kenyan side are at the mouths of the rivers Yala and Nyando.

Table 5. Pollution Intensities for industrial BOD_5 load, classified according to the International Standard Industrial Classification (ISIC)

ISIC	Industry	BOD_5 [kg t^{-1}]
3111	Slaughter houses	6
3112	Dairy factories	3·21
3114	Fish factories	7·9
3115	Vegetable oil refineries	12·9
3118	Sugar factories	2·9
3131	Distilleries	220
3133	Breweries	18·8
3134	Bottleries	2·1
3211	Cotton mills	155
3221	Coffee factories	—
3231	Leather tanneries	89
3411	Paper mills	8
3521	Paint factories	—
3523	Soap factories	6

Sources: WHO, 1982; Economopoulos, 1993.

Definition of pollution intensities

Industrial Pollution—World Health Organization (1982) and Economopoulos (1993) present pollution intensities for industrial waste loads, averaged from data all over the world. Table 5 presents values for estimation of BOD loads from industries typical to the region. Although the individual values may be biased, the overall waste load estimation for a large batch of sources may be expected reasonably accurate (Economopoulos, 1993). An error analysis would therefore not be required.

Domestic Pollution—Table 6 presents ranges and most likely values for waste generated by both sewered and unsewered urban domestic population, based on reviews by World Health Organization (1982), Economopoulos (1993), Iwugo (1990),

Table 6. Selected pollution intensities for urban domestic liquid waste generation

Sanitation	Interval	BOD$_5$ [kg pers^{-1} yr^{-1}]	N [kg pers^{-1} yr^{-1}]	P [kg pers^{-1} yr^{-1}]
Sewered	Low	8	2·2	0·2
	Most likely	16	3·3	0·4
	High	20	4·4	1·6
Unsewered	Low	7	2·2	0·2
	Most likely	8	3·3	0·4
	High	11	4·4	1·6

Jørgensen (1980), and Vighi and Chiaudani (1987). Unlike the population in cities and towns, often located directly on the lake shores or its adjacent bays and streams, rural households are scattered (in the case of lake Victoria over an area up to 250 km from the lake) and their waste streams for the major part not directly linked to watercourses. Their contribution to the overall inputs would be accounted for within the overall land-runoff stream.

Land runoff—The method applied for the estimation of nutrient land runoff employs the export coefficient approach of Jørgensen (1980), a procedure widely used in many studies (e.g. Scheren, 1995; Mattikalli and Richards, 1996). The loss of nitrogen and phosphorus to watercourses is estimated as a function of area and export coefficients, where export coefficients may vary for different categories of land use. Many characteristics control nutrient export, including precipitation runoff, soil texture, slope, type of crop cultivated and fertiliser application. The selection of suitable and universal export coefficients therefore introduces major uncertainty. The range of values reported in various extensive reviews of nutrient-export relations (Beaulac and Reckhow, 1982; Ritter, 1988; Thomann and Mueller, 1987), as summarised in Table 7, expresses this uncertainty.

Unfortunately, data on nutrient export in the vicinities of Lake Victoria, and in fact for the African continent as a whole, is very rare, and where available represents loss of nutrients from plots of agricultural land, rather than the actual amount eventually ending up in watercourses (Aroya & Juo, 1982; Omoti *et al*., 1983; Walters and Malzer, 1990). Smaling *et al*. (1993) and Lijklema (1995) report values for Kisii in Western Kenya and Rwanda respectively, where nutrient loss through leaching and erosion from arable land range from 4, 5 to 10 kg ha^{-1}y^{-1} for phosphorus and 40 to 45 kg ha^{-1}y^{-1} for nitrogen.

Table 7. Selected nutrient export coefficients

Interval	Unit	Cultivated land N	Cultivated land P	Non-cultivated land N	Non-cultivated land P
Low	kg ha^{-1} yr^{-1}	0·5	0·1	1	0·1
Most likely	kg ha^{-1} yr^{-1}	1·4	0·3	1·4	0·3
High	kg ha^{-1} yr^{-1}	12	1·4	7	0·9

That the actual amount ending up in Lake Victoria would be substantially smaller may be shown by comparing data for Lake Malawi, which catchment area has similar soil texture and precipitation characteristics as Lake Victoria. Bootsma *et al*. (1996) report values for nutrient input via rivers flowing through the catchment area, which translated into actual input per area of land lead to export factors of 1·4 kg ha^{-1}y^{-1} for nitrogen and 0·3 kg ha^{-1}y^{-1} for phosphorus. Although land-use practices vary between the two catchment areas, Table 7 indicates that the difference in export coefficient for different types of land use would probably not be of dramatic influence to a rough calculation. In the absence of more reliable data, therefore, export coefficients calculated for Lake Malawi are applied as a first estimate. However, keeping in mind the higher population density and more intensive land-use around Lake Victoria, these values should be considered within the lower range for Lake Victoria.

Atmospheric deposition—As a consequence of both natural and human factors, atmospheric nutrient loading varies widely between cases. As reviewed by Bootsma *et al*. (1996) and Lewis (1981), for remote non-marine tropical watersheds, values reported in literature range from 0·3 to 1·7 kg ha^{-1}y^{-1}

for phosphorus and 7·5 to 19 kg $ha^{-1}y^{-1}$ for nitrogen. Rare data on nutrients in atmospheric deposition in the region is given by Bootsma *et al*. (1996), who report values measured in non-populated areas of Lake Malawi to be 0·53 kg $ha^{-1}y^{-1}$ for phosphorus and 12·43 kg $ha^{-1}y^{-1}$ for nitrogen. In the absence of more reliable data than that of Bootsma *et al*. (1996), their data are used as most likely values, with the full literature range of values (Bootsma *et al*., 1996, Lewis, 1981) as upper and lower limits.

It should be noted that Bootsma & Hecky (1993), Scheren (1995), Visser (1961) and ICRAF (1995) report data on rainwater analysis for samples taken on the shores of Lake Victoria. Values range from 0·58 to 0·92 mg/l−1 for nitrogen and from 0·07 to 0·11 mg/l^{-1} for phosphorus, which is substantially higher than values reported for other remote tropical data sets (Galloway *et al*., 1982), and does suggest large interference with the effects of human activities on the lake shores. Although most probably therefore not representative for the open lake, discussion exists as to whether these high nutrient concentrations might be caused by the extensive forest burning in the adjacent Rwanda and Burundi highlands (Bootsma & Hecky, 1993; Scheren, 1995), a phenomenon also described by Crutzen and Andreae (1990) and Goldman *et al*. (1990).

Determination of penetration factors

The treatment efficiencies of individual industrial wastewater treatment facilities were estimated, where available on the basis of effluent analysis data, and otherwise upon judgement of the auditor, using as a starting point the efficiencies for optimum operation as reported by Economopoulus (1993). Penetration factors were rated between 0·3 and 0·7 (corresponding to 30 and 70% efficiency). The factory-by-factory results of this data intensive exercise have been reported elsewhere (Scheren, 1995; Scheren *et al*., 1994; 1995; Zanting, 1996). Central treatment facilities for the treatment of domestic effluents were rated similarly, with penetration factors estimated from 0·3 at reasonably effective operation for example in Jinja and Kampala, up to 0·9 for some of the Kenyan plants. 50% reliability intervals were adopted because of the uncertainty imposed by the judgements.

For those industries and towns not located on the lakeshores, distance penetration factors were defined according to Equation (1). In accordance with literature, a most likely value of 0·3 day^{-1} was adopted for the decay factor K, with as boundaries 0·2 to 0·8 day^{-1}. River flows were determined using an empirical relation described by Burke (1983) through which velocity is related to characteristics such as river volume flow, slope, drainage area and length. The characteristics of several Kenyan rivers (Ministry of Water Development, 1992) were used to determine the velocity v, which was estimated to vary between 0·3 and 1·0 ms^{-1} for rivers around Lake Victoria. Calibration of Equation (1) with these ranges for K and v and for several values of the distance D results in BOD penetration factors as presented in Table 8.

Wetland penetration factors were applied for domestic and industrial sources draining through wetlands. BOD penetration factors as reported by Richardson and Nichols (1985), ranging from 0·30–0·05, with 0·20 as most common value, were adopted. Richardson and Nichols (1985) furthermore present relations between phosphorus and nitrogen removal rates and loading, based on studies on several (North American) wetlands. The results of applying these relations to the wetlands around Lake Victoria are presented in Table 9. 50% uncertainty intervals were adopted.

Table 8. Selected distance penetration factors for BOD_5

Distance (km)	Low	Most likely	High
0–10	0·90	1·00	1·00
10–50	0·50	0·90	0·95
50–100	0·15	0·75	0·85
100–150	0·05	0·60	0·70
150–250	0·00	0·45	0·65

Table 9. Nutrient penetration factors through wetlands (selected most likely values)

Loading [g(N/P) m^{-2} yr^{-1}]	N	P
2		0·4
10	0·3	0·6
50	0·7	0·75
500	0·9	0·8

BOD loading estimates

Organic waste loads, represented by a BOD load, were assessed for domestic and industrial (point) sources. As the study focuses on the pollution of the lake, the estimated generated BOD loads were corrected for purification in treatment plants, rivers and wetlands. Table 10 shows the results.

The probability intervals presented in Table 10 result from the high-low intervals for domestic pollution intensities, distance and wetland penetration factors and wastewater treatment efficiency. High-low intervals for industrial production figures and pollution intensities were not selected, as argued before. However, its contribution to the overall BOD load being relatively small, this has minor influence on the overall result. Breweries, sugar cane factories and soap and oil factories display the largest amount of industrial BOD load.

Most likely BOD loads are presented in Figure 2. The error analysis understates the conclusion that domestic pollution accounts for most of the BOD load. 75% of Uganda's domestic BOD load originates from its capital Kampala, while in Kenya 50% originates from Kisumu. Further calibration of the Kenyan results shows that, in case all the present treatment plants would perform optimally BOD loads could be brought down with 50%.

N and P loading estimates

The results of the assessment of nitrogen and phosphorus loads to Lake Victoria are summarised in Table 11 and Figure 3. Land runoff and atmospheric deposition are the most important sources of both nitrogen and phosphorus, together accounting for approximately 90% of phosphorus and 94% of nitrogen input into the lake. Domestic liquid waste plays only a minor role in nutrient loading. The highest uncertainty is equally in the land runoff and atmospheric nutrient load estimates.

The most likely values for nitrogen and phosphorus loads are presented in Figure 3. The picture shown is that nitrogen originates primarily from atmospheric deposition, while in the case of phosphorus atmospheric deposition and land-runoff are more balanced. Clearly, the uncertainty intervals do

Table 10. Results of the Lake Victoria BOD_5 loading assessment

Unit: t yr^{-1} Source	Kenya most likely	s^-	s^+	Uganda most likely	s^-	s^+	Tanzania most likely	s^-	s^+
Industrial	1810	850	1260	540	50	75	820	90	0
Domestic	5700	2250	2900	4000	760	1500	3100	490	560
Total	7510	2410	3160	4540	760	1500	3920	500	560
$P > 55\%$		5100–10 700			3800–6000			3400–4500	
$P > 90\%$		2700–13 800			3000–7500			2900–5000	

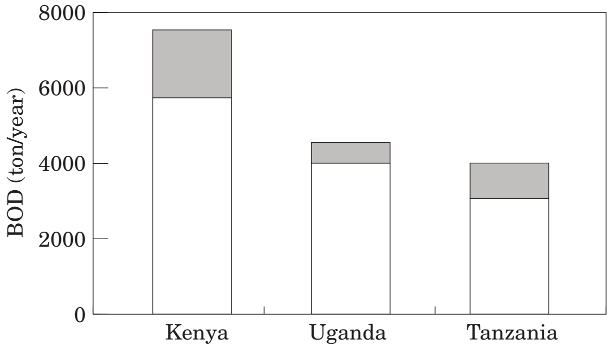

Figure 2. Most-likely BOD loads to Lake Victoria. ▨; Industrial; ☐; Domestic.

Table 11. Results of the Lake Victoria nutrient loading assessment

Unit: t yr^{-1} Source	Total nitrogen most likely	s^-	s^+	Total phosphorus most likely	s^-	s^+
Urban domestic	7600	1800	2100	920	280	1650
Agriculture	2 6292	3756	6 7509	5634	641	4565
Atm. deposition	8 5513	1 6958	2 2599	3647	791	4025
Total	11 9405	17 500	71 200	10 201	1100	6300
$P>55\%$		1 02 000–1 91 000			9100–16 500	
$P>90\%$		84 000–2 62 000			8000–23 000	

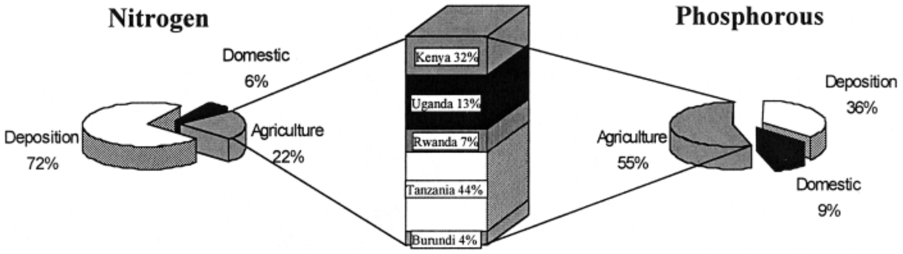

Figure 3. Most-likely nutrient loads by source and agricultural loads by country.

not allow for a definite conclusion on these outcomes, but what is shown is that both sources of nutrients definitely play a significant role in the lake's nutrient balance.

The nutrient balance of Lake Victoria

Average lake water concentrations of $0{\cdot}640\,\mathrm{mg\,l^{-1}}$ for nitrogen and $0{\cdot}074\,\mathrm{mg\,l^{-1}}$ for phosphorus, where applied, based on reported sampling studies from Gophen *et al*. (1995) and Lehman and Brandstrator (1994). Combined with a lake volume (V) of $2760\,\mathrm{km}^3$, an average depth (H) of 40 m, a river outflow (Q_E) of $23{\cdot}5\,\mathrm{km}^3\ \mathrm{yr}^{-1}$ (Kite, 1981, 1982, 1984; Piper, 1986), the nutrient input (W_A) was calculated. The net settling velocity was calculated by applying: $v_S = r_S * S_A / C_A$, with r_S representing the sedimentation rate (g m^{-2} yr^{-1}) and S_A the concentration of nutrient A in the sediment S_A (mg g^{-1}). Hecky (1993) reports values for r_S and S_A taken from a single sediment core sample of Lake Victoria. The resulting settling velocities are $2{\cdot}3$ m yr^{-1} for both nitrogen and phosphorus.

The resulting W_A are 1 17 000 and 14 000 t yr^{-1} for nitrogen and phosphorus, respectively. In spite of data limitations, specifically with regard to the settling velocity, which is based on a single sediment core sample, the outcome of this simple nutrient balance assessment provides a good idea of the order of magnitude of the total nutrients load to Lake Victoria. Its results are well in correspondence with the results from the pollution sources assessment.

Discussion

This paper presents a methodology for rapid assessments of sources of water pollution, elaborating on generally applied assessment techniques. The methodology has proven to be effective in the case of Lake Victoria, where data and resource scarcity object a more detailed and accurate assessment. The effects of uncertainty in data have been evaluated by using an error analysis as proposed by Reckhow and Simpson (1980). The use of penetration factors furthermore not only refines the method, but also provides insight into the potential reduction of waste loads by artificial and natural treatment processes. Although weakness in data and associated uncertainties in results do not always allow absolute conclusions, the outcome of the assessment form a useful basis for the evaluation of strategic policy options, and for identification of areas requiring further research.

The outcome of the Lake Victoria assessment determines domestic pollution as opposed to industries as the major source of BOD loads, and the Kenyan part of the lake as its largest contributor. Reduction of BOD loads, often associated with the occurrence of water born diseases, should therefore be through better control over domestic sources. It was calculated that, through efficient management of existing treatment facilities only, BOD loads in Kenya could be reduced by 50%. Of the industries, breweries, sugar cane factories and soap and oil factories display the largest load, and would therefore deserve most attention in terms of control measures.

Nutrient loads to the lake are associated mainly with atmospheric deposition and land runoff, together accounting for approximately 90% of phosphorus and 94% of nitrogen input into the lake. Domestic inputs are negligible. In the case of nitrogen, atmospheric deposition is most probably in excess over land runoff, not even mentioning the observed high nitrogen fixation rates (Hecky, 1993). This conclusion, coupled with the suggested nitrogen limitation in lake Victoria (Bootsma and Hecky, 1993; Lehman *et al.*, 1994), corresponds with the observed increase in chlorophyll-a concentration and algal blooms during rainy seasons, which can only partly be linked to nutrient upsurge from sediments (Ochumba and Kibaara, 1989). In the case of phosphorus, runoff and atmospheric deposition are more balanced, although reported high concentration of phosphorus in rainwater on the shores of Lake Victoria (Bootsma and Hecky, 1993; Scheren, 1995; Visser, 1961; ICRAF, 1995), make suspect a larger contribution of atmospheric deposition to the phosphorus balance. Antropogeneous influences in the area, such as forest burning and increased dust due to soil erosion, have been liased to this phenomenon (Bootsma & Hecky, 1993; Scheren, 1995).

In spite of the uncertainties remaining, the assessment allows for certain management options counteracting the apparent increasing nutrient input into Lake Victoria to be defined. In principal the same human activities are at the base of the problem. The increasing population pressure in the region causes a high rate of land clearing for cultivation, and forest burning for this purpose as well as for provision of biomass for household burning. Together with unsustainable land-use practices, the results are increased soil erosion and nutrient land runoff, with forest burning having as a direct effect also its influence on the atmospheric deposition of nutrients. Apart from a control over population growth, often difficult to realise, policies should therefore be directed at an introduction of sustainable land-use practices and a control over forest burning, two aspects which in fact are at the core of any sustainable development program. Improved agricultural practices would not only ensure food supply to the growing population, for now and in the future, but also counteract the soil erosion and land runoff, as well as decrease the need for forest clearing, with its here reported influences on the ecosystem.

For future research, parameters of highest uncertainty remain pollution intensities for land runoff and atmospheric deposition. Further in-depth study on these topics, and in specific also the factors influencing their intensities, would allow for a fine-tuning of management options for preservation and rehabilitation of Lake Victoria's so highly valued but now pressurised ecosystem.

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