Science of the Total Environment 408 (2010) 447–455

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Review

Eutrophication and nutrient release in urban areas of sub-Saharan Africa — A review

P.M. Nyenje [a,b,*], J.W. Foppen [a], S. Uhlenbrook [a,c], R. Kulabako [b], A. Muwanga [b]

[a] UNESCO-IHE Institute for Water Education, Delft, The Netherlands
[b] Makerere University, Kampala, Uganda
[c] Delft University of Technology, Department of Water Resources, Delft, The Netherlands

ARTICLE INFO

Article history:
Received 21 July 2009
Received in revised form 7 October 2009
Accepted 8 October 2009
Available online 3 November 2009

Keywords:
Sanitation
Nutrients
Eutrophication
Hydrology
Slums
Sub-Saharan Africa

ABSTRACT

Eutrophication is an increasing problem in sub-Saharan Africa (SSA), and, as a result, the ecological integrity of surface waters becomes compromised, fish populations become extinct, toxic cyanobacteria blooms are abundant, and oxygen levels reduce. In this review we establish the relationship between eutrophication of fresh inland surface waters in SSA and the release of nutrients in their mega-cities. Monitoring reports indicate that the population of mega-cities in SSA is rapidly increasing, and so is the total amount of wastewater produced. Of the total amounts produced, at present, less than 30% is treated in sewage treatment plants, while the remainder is disposed of via onsite sanitation systems, eventually discharging their wastewater into groundwater. When related to the urban water balance of a number of SSA cities, the total amount of wastewater produced may be as high as 10–50% of the total precipitation entering these urban areas, which is considerable, especially since in most cases, precipitation is the most important, if not only the 'wastewater diluting agent' present. The most important knowledge gaps include: (1) the fate and transport mechanisms of nutrients (N and P) in soils and aquifers, or, conversely, the soil aquifer treatment characteristics of the regoliths, which cover a large part of SSA, (2) the effect of the episodic and largely uncontrolled removal of nutrients stored at urban surfaces by runoff from precipitation on nutrient budgets in adjacent lakes and rivers draining the urban areas, and (3) the hydrology and hydrogeology within the urban area, including surface water and groundwater flow patterns, transport velocities, dynamics of nutrient transport, and the presence of recharge and discharge areas. In order to make a start with managing this urban population-related eutrophication, many actions are required. As a first step, we suggest to start systematically researching the key areas identified above.

Contents

1. Introduction

Eutrophication is one of the most prevalent global problems of our era. It is a process by which lakes, rivers, and coastal waters become increasingly rich in plant biomass as a result of the enhanced input of plant nutrients mainly nitrogen (N) and phosphorus (P) (Golterman and De Oude, 1991). A recent issue of The Water Wheel (Water Research Commission, South Africa; issue September/October 2008) reports that 54% of the lakes/reservoirs in Asia are impaired by eutrophication, in Europe this is 53%, in North America 48%, in South America 41%, and in Africa 28%. In inland sub-Saharan Africa (SSA), there are many documented cases of eutrophication of fresh water

---

* Corresponding author. UNESCO-IHE Institute for Water Education, Delft, The Netherlands. Tel.: +31 015 2151 1748.
E-mail address: p.nyenje@unesco-ihe.org (P.M. Nyenje).

0048-9697/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.scitotenv.2009.10.020

resources. Examples include Lake Victoria, which is shared between Uganda, Tanzania, and Kenya (e.g. Robarts and Southall, 1977; Hecky and Bugenyi, 1992; Muggide, 1993; Hecky et al., 1994; Kansiime and Nalubega, 1999; Scheren et al., 2000; Verschuren et al., 2002; Cózar et al., 2007; Oguttu et al., 2008; Witte et al., 2008), Lake Chivero in Zimbabwe (Munro, 1966; Jarvis et al., 1982; Moyo and Worster, 1997; Magadza, 2003; Nhapi and Tirivarombo, 2004; Nhapi et al., 2006; Nhapi, 2008), Lake Albert on the boundary between Uganda and Congo (Tallings, 1963; Talling and Talling, 1965; Campbell et al., 2005), various fresh water resources in South Africa, like the Zeekoevlei (Das et al., 2008, 2009), Rietvlei (Oberholster et al., 2008), and Lake Krugersdrift (Oberholster et al., 2009), rift lakes in Ethiopia (Talling and Talling, 1965; Zinabu and Taylor, 1989; Talling, 1992; Zinabu et al., 2002; Devi et al., 2008; Beyene et al., 2009), or inland delta lakes and fresh water resources in western SSA, like in Cameroon and Nigeria (Kemka et al., 2006; Arimoro et al., 2007).

Most of the nutrients causing eutrophication originate from agricultural and urban areas (Thornton et al., 1999; Jarvie et al., 2006). In developing countries, like those in SSA, wastewaters from sewage and industries in urban areas, which are often discharged untreated in the environment, are increasingly becoming a major source of nutrients, causing eutrophication of surface water bodies (e.g. Thornton and Ashton, 1989; Dillion, 1997; Kulabako et al., 2004, 2007, 2008; Nhapi and Tirivarombo, 2004; Mladenov et al., 2005; Tournoud et al., 2005; Vos and Roos, 2005; Kemka et al., 2006; Nhapi et al., 2006; Bere, 2007; Nhapi, 2008; Beyene et al., 2009). This paper therefore reviews the state of knowledge with regard to N and P transport from urban settlements into the environment. More specifically, this review tries to establish the loads of these nutrients, their transport routes, and the dominant hydrochemical processes along those routes, including the adverse side effects. We shall limit ourselves to inland sub-Saharan Africa, since the rate of development of mega-cities in this region has been alarmingly high over the last decade (WWAP, 2009). Attention is also given to urban slums, because they are a major characteristic of many African mega-cities (UN-Habitat, 2003; Kulabako et al., 2004).

2. Effects of eutrophication

Before detailing the relationship between urban areas and eutrophication, it is important to first describe the effects of eutrophication in SSA, in order to highlight the importance of the adverse effects of excess nutrients in fresh water resources. The most prominent example is Lake Victoria. This lake has in recent decades undergone a series of profound ecological changes, including strong increases in phytoplankton primary production (Hecky and Bugenyi, 1992; Muggide, 1993), replacement of diatoms by cyanobacteria as the dominant group of planktonic algae (Kling et al., 2001), large scale blooms of the water-hyacinth, and most importantly, the eradication of several species of endemic cichlid fishes. The elimination of cichlid species has been predominantly associated with a Nile perch population explosion, an introduced pescovore (Barel et al., 1985). However, according to Verschuren et al. (2002) and based on evidence from paleolimnological records of lake bottom sediments (Hecky et al., 1994), eutrophication-induced loss of deep water oxygen started in the early 1960s. This may have contributed to the 1980s collapse of indigenous fish stocks starting with the elimination of suitable habitat for certain deep-water cichlids.

A second adverse effect of eutrophication is the rapid growth of phytoplankton species and aquatic macrophytes. In extreme cases, this leads to the development of mono-specific blooms of cyanobacteria (Oberholster et al., 2005, 2009). Harmful cyanobacterial blooms are typically characterized by heavy biomass accumulations that often consist of a single or a few species, usually members of the genera *Microcystis* and *Anabaena* (Oberholster et al., 2009). Blooms of cyanobacteria in rivers, lakes, and reservoirs disrupt the normal patterns of phytoplankton succession, decrease phytoplankton diversity, and alter virtually all of the interactions between organisms within the aquatic community — from viruses through zooplankton to fish (Figueredo and Giani, 2001). One of the most serious effects of cyanobacterial blooms is the production of harmful secondary metabolites that have serious adverse effects on the health and vitality of humans and animals (Wiegand and Pflugmacher, 2005).

A third effect is the alteration of the ecological integrity of fresh water resources. This may lead to a decline in macroinvertebrate abundance and composition and species richness (Oberholster et al., 2008; Beyene et al., 2009), including fish species (Campbell et al., 2005) and *Diptera* larvae (Arimoro et al., 2007) or to remarkable physiological adaptations of phytoplankton communities to nutrient variations (Kemka et al., 2009).

Finally, a fourth effect is the total depletion of oxygen. This is associated with the accumulation and decomposition of dead organic matter which consumes oxygen and generates harmful gases such as methane and hydrogen sulphide. When this occurs, many macroinvertebrates and fish species suffocate, while immobile bottom dwelling species can die off completely. In extreme cases, anaerobic conditions ensue, promoting growth of bacteria such as *Clostridium botulinum* that produces toxins deadly to birds, animals and humans. These toxins are also believed to causes of gastro-enteritis amongst children (Zilberg, 1966).

3. Evidence of the urban areas causing eutrophication

In an important report on the ecology of inland African lakes, Viner et al. (1981) already indicated that by far the most important problems concerning nutrients in Africa are related to urbanization. Their remark concerned deep lakes, like Lake Victoria, Lake Edward, and Lake Turkana (Coulter and Jackson, 1981), shallow lakes, like Lake Bloemhof, Lake Chad, Lake Chilwa, Lake George, Lake Kioga, Lake Naivasha, Lake Ngami, Lake Ogavango, Lake Opi, Lesotho Mountain Lakes, and Lake Wuras (Howard-Williams and Ganf, 1981), man-made lakes, like Lake Kariba, Volta Lake, Lake McIlwaine, presently known as Lake Chivero, including various man-made lakes in South Africa (Adeniji et al., 1981), and the rivers contributing to the inflow of these lakes. Although for Lake Victoria, Scheren et al. (2000) reported that atmospheric deposition contributes the largest input of nutrients together accounting for approximately 90% of phosphorus and 94% of nitrogen, comparative studies done by Cózar et al. (2007) between inshore and offshore lake waters indicate stronger eutrophication effects in the inshore areas of Lake Victoria, where nutrient and chlorophyll-a concentrations are markedly higher (Hecky, 1993; Muggide, 1993). In addition, a recent study carried out by the Ministry of Water and Environment of Uganda reported that large urban centres contribute 72% of the pollution loading into Lake Victoria shores compared to 13% by industries and 15% by fishing villages (MWE, 2007). Kansiime et al. (2007) also showed that Lake Victoria's Murchison bay, due to the inflow of wastewater from Kampala (Uganda), has deteriorated in the past decades, as evidenced by an increased loading of nutrients, presently estimated to be 28 mg/l NH_4–N from the initial 5.6 mg/l NH_4–N in 1999.

In western SSA, Kemka et al. (2006) showed that Yaounde Municipality Lake in Cameroon is experiencing hypertrophic eutrophication as a result of the inflow of increasing quantities of domestic wastewater from Yaounde city. Already more than 30 years, Marshall and Falconer (1973), Robarts and Southall (1977) and Thornton and Nduku (1982) showed that serious eutrophication in Lake McIlwaine (Zimbabwe; now known as Lake Chivero) was a result of increased sewage effluent. Nhapi and Tirivarombo (2004) demonstrated the eutrophying influence of the Marimba River, discharging into Lake Chivero (Zimbabwe). This river receives treated wastewater from the Crowborough Sewage Treatment Works in Harare. Bere (2007) reported high nutrient concentrations in the Chinyika River, a tributary of the Mazowe River (Zimbabwe), as a result of sewage inflow from the Hatcliffe Sewage Works. The Hartbeespoort Dam, in South Africa, has become a hypertrophic impoundment, predominantly due to the influence of domestic wastewater discharges from the city of Johannesburg and surrounding area (Allanson and Gieskes, 1961; Thornton, 1989; Robarts, 1988; Thornton and Ashton, 1989). De Villiers (2007) reported increased nutrient input due to anthropogenic activities in the Berg River (South Africa). Oberholster et al. (2009) studied the influence of toxic cyanobacterial blooms on algal populations in Lake Krugersdrift (South Africa). One of the major causes of eutrophication here is the nutrient rich inflow of water from the Modder River, which receives treated domestic and industrial effluent from the city of Bloemfontein. Another example in South Africa is the Hennops River (Oberholster et al., 2008), which receives treated effluent from the Hartbeesfontein Sewage Purification Works, and causes eutrophication in the Rietvlei nature reserve wetland area. The Borkena River in Ethiopia is hypertrophic due to inflow of wastewater from the towns of Dessie and Kombolcha (Beyene et al., 2009). These towns do not possess sewer lines, sewage treatment plants, or proper solid waste disposal sites, and the inflow of nutrient masses is relatively uncontrolled.

A similar situation of uncontrolled disposal of wastewater from informal settlements to surface water was reported for the Umtata River in South Africa (Fatoki et al., 2001) and the Orogodo River in Nigeria (Arimoro et al., 2007). The latter receives an uncontrolled inflow of nutrient masses from the towns of Agbor, Owa-Ofie, Ekuma-Abovo and Oyoko, before it ends up in the swamps between Obazagbon-Nugu and the oil rich town of Oben in Edo State, southern Nigeria. Finally, Kulabako et al. (2004, 2007, 2008) reported on the anthropogenic pollution occurring below Bwaise III Parish, a peri-urban slum area in Kampala (Uganda), and its linkage to uncontrolled discharge of nutrients via groundwater into Lubigi swamp, causing eutrophication of the swamp and surface waters downstream of the swamp. Uncontrolled discharge of nutrients via groundwater was also reported by De Villiers and Malan (1985) for a small urban catchment near Durban, South Africa. In their study, they found out that the high nutrients concentrations found during base flow conditions in drainage channels were above background levels and were linked to leakages from waterborne sewerage.

4. Nutrient production and disposal in urban areas

Most of the examples documented in literature above are related to the controlled release of (treated) wastewater into surface water bodies from wastewater treatment plants. Indeed several studies currently indicate that nutrient production in urban areas is more related to wastewater disposal, especially in densely populated areas (Cronin et al., 2003; Wakida and Lerner, 2005; Kemka et al., 2006). This immediately poses a number of important questions: How much wastewater is produced in the larger cities in SSA, which percentage of the wastewater produced is treated, and what are the predominant treatments and (un)controlled disposal mechanisms?

Table 1 gives key figures on the water and sanitation coverage in selected mega-cities in Africa. Coverage in this case refers to the number of people with access to safe and adequate drinking water and improved means of sanitation. On average, water supply and sanitation coverage is over 70% across sub-Saharan Africa. However, sewerage coverage is generally below 30%. Sewage treatment plants collect and purify these wastewaters, and dispose the purified product in surface waters. Apparently, in many cases the purification is insufficient, giving rise to eutrophication across SSA, as discussed in the previous section of this paper. From Table 1, it is clear that the non-sewered part of the total urban population is more than 70%, while 63% (the difference between the percentage 'having access to sanitation' and the percentage 'connected to a sewer') relies on on-site sanitation systems. Therefore, around 63% of the total urban population (minimum of 17% in Windhoek and a maximum of 93% in Dar es Salaam) of the mega-cities mentioned in Table 1 rely on either septic tanks or traditional/improved pit latrines, eventually discharging their wastewater into aquifers underlying these urban areas. Based on data in Table 1, the potential wastewater flows can be obtained by multiplying the population with the consumption rates factored by the unaccounted for water percentages (Table 2). With the exception of a few cities in Southern Africa, such as Windhoek, there is a very high proportion of untreated wastewater across all major cities in Africa compared to the total wastewater production. On average, over 80% of the wastewaters produced in large cities in sub-Saharan Africa are untreated and are either discharged in the

Table 1
Water and sanitation coverage in selected mega-cities in sub-Saharan Africa in 1999.
Source: JMP (1999) and WHO (2000).

City (country)	Pop.	Population served		Water production	Unaccounted for water	Water connections	Sewer connections
		Water	Sanitation				
	(1000 s)	(%)	(%)	(l/c/d)	(%)	(%)	(%)
East Africa							
Addis Ababa (Eth)	2444	98	NMV	40	40	4	NMV
Nairobi (Ken)	2086	100	99	189	40	78	30
Kigali (Rwa)	445	NMV	NMV	118	–	NMV	NMV
Dar-es-Salaam (Tan)	3000	61	98	150	60	7.3	5
Kampala (Uga)	1200	72[*]	78[*]	110	32[*]	71[*]	7[*]
Southern Africa							
Maputo (Moz)	967	99	96	133	34	22	25
Windhoek (Nam)	271	100	100	214	11	83	83
Harare (Zim)	2380	NMV	NMV	156	30	NMV	NMV
Lusaka (Zam)	1212	81	NMV	225	56	26	NMV
Mbabane (Swa)	94	75	97	100	32	38	47
Luanda (Ang)	4000	50	62	30	60	18	17
West Africa							
Lome (Tog)	806	67	80	66	28	55	1.02
Cotonou (Ben)	667	81	83	62	41	81	0.2
Dakar (Sen)	1925	78	78	128	26	63	26

NMV = No meaningful value.

[*] 2007 estimates from Water and Sanitation sector performance report 2007, Uganda.

Table 2
Estimated wastewater volumes in a number of mega-cities in sub-Saharan Africa.
Source: JMP (1999) and WHO (2000).

City (country)	Wastewater production ($10^6 m^3/y$)	Treated ($10^6 m^3/y$)	Not treated ($10^6 m^3/y$)
East Africa			
Addis Ababa (Eth)	21.4	?	?
Nairobi (Ken)	86.3	25.9	60.4
Kigali	?	?	?
Dar-es-salaam (Tan)	65.7	3.3	62.4
Kampala (Uga)	32.8	2.3	30.5
South Africa			
Maputo (Moz)	31.0	7.7	23.2
Windhoek (Nam)	18.8	15.6	3.2
Harare (Zim)	94.9	?	?
Lusaka (Zam)	43.8	?	?
Mbabane (Swa)	2.3	1.1	1.2
Luanda (Ang)	17.5	3.0	14.5
West Africa			
Lome (Tog)	14.0	0.1	13.8
Cotonou (Ben)	8.9	0.0	8.9
Dakar (Sen)	66.6	17.3	49.2

soil via on-site sanitation systems or directly discharged into rivers and lakes. Depending on the population size of the city, these untreated wastewater volumes can range from approximately 20 to 60 million m^3/y. When multiplied with the composition of medium strength wastewater (Table 3), then an approximate annual average of 1×10^6 kg N and 0.1×10^6 kg P is produced by the mega-cities shown in Tables 1 and 2.

Of course, the distribution of nutrient load across the urban area differs tremendously. In sewered parts of a town, untreated wastewater recharge rates from leaking sewers to the underlying aquifers are estimated to be relatively low (generally less than 50–100 mm/y; Wolf et al., 2006), while wastewater concentrations are likely to be of low-medium strength. In areas where on-site sanitation systems are used, which is true for the vast majority of the urban population in SSA (63% of the total population, as was calculated above), low wastewater volumes with high concentrations are produced (Table 4). In informal settlements, population densities are high, sewerage is lacking, and, if present, sanitation facilities are almost exclusively on-site (mainly pit latrines, VIPs, elevated pit latrines, etc.; Zingoni et al., 2005; Kulabako et al., 2007). The nutrient load produced in these areas is extremely high: the proportion of the urban population residing in slums in SSA is estimated to be 4–80% with an average of around 50% (Fig. 1B). Given the increasing urbanisation trends in the future (Fig. 1A), the number of people living in urban slums in SSA is expected to rise continuously. This is expected to give rise to increased concentration and nutrient fluxes from these areas.

Table 3
Characteristics of low, medium and high strength wastewater.
Source: Feigin et al. (1991).

Parameter	Low	Medium	High
BOD (mg/l)	100	200	350
pH	7	7.2	8
Cl (mg/l)	10	150	650
Ammonia, NH_4–N (mg/l)	10	25	50
Nitrate, NO_3–N (mg/l)	0	0.2	1.5
t-PO_4 (mg/l)	4	10	36
Alkalinity (mg/l $CaCO_3$)	50	200	400
Na (mg/l)	10	120	460
Ca and Mg (combined) (mg/l)	5	10	25
Boron (mg/l)	<0.123–2.0		

Table 4
Faecal sludge characteristics in on-site sanitation systems in Kampala.
Source: NWSC (2008).

Parameters	VIP latrine	Septic tank
Total solid, TS (mg/l)	30,000	22,000
Total volatile solids (% TS)	65	45
COD (mg/l)	30,000	10,000
BOD (mg/l)	5500	1400
Total Kjedhal nitrogen, TKN (mg N/l)	3400	1000
Ammonia, NH_4 (mg/l)	2000	400
Nitrates, NO_3 (mg N/l)	–	–
Total phosphorus, TP (mg P/l)	450	150
Feacal coliforms (cfu/100 ml)	1×10^5	1×10^5

5. The urban water balance

How important are these loads in the entire water balance of the city and what is the role of the hydrological processes in the transport of nutrients to surface water bodies? Ideally, a hypothetical water balance of the upper part of the soil (say from the surface to 2–4 m below the surface) of an urban area consists of (Fig. 2): precipitation, evapotranspiration, water imported/exported, outflow/inflow to/from groundwater, stormwater runoff, and sewer outflow and changes in storages. All these variables indicate flow across the boundary of the urban area (Marsalek et al., 2008). Within the urban area the following terms can be discerned: impervious surfaces, soil, household and sewerage (wastewater, storm water, or combined). As an example, the water balance of Kampala, Uganda (Fig. 2) is given. The following dominant fluxes of water (or hydrological pathways) can be identified:

- Most of the precipitation (1450 mm/y) is evaporated (1151 mm/y), while the rest (330 mm/y) flows into Lake Victoria via open and closed drains present in Kampala city.
- Around 170 mm of water is imported (from Lake Victoria) and used indoor. Although there are some leakages (17 mm/y) and outdoor usages (5 mm/y), most of this water (148 mm/y) is converted into wastewater, of which 138 mm/y is disposed of via on-site treatment facilities (pit latrines, septic tanks, etc.), while 10 mm/y is transported to Lake Victoria.
- A part of the wastewater disposed of on-site is mixed and diluted with precipitation. Of the total amount of water reaching the soil (1245 mm/y), finally around 120 mm/y recharges groundwater, of which 10 mm/y reappears as springs. Most of the remainder (1100 mm/y) evaporates, while some water (24 mm/y) is stored. Of course, the long term storage component should be zero, indicating a situation of steady state. However, in this case, Kampala itself is not in a situation of steady state: urbanisation is taking place, and, as one of the consequences, water is stored in the subsurface, and the groundwater table is — on average — on the rise.

Table 5 provides an overview of the urban water balance for selected cities in sub-Saharan Africa, including the example of Kampala (Uganda). Based on the table, the amount of wastewater that is disposed of via on-site sanitation facilities or via drainage channels without being treated, ranges from 10% (Keren) to 50% (Khartoum) of the total precipitation entering the urban areas. This is a large percentage of untreated wastewater especially considering the fact that in most cases, precipitation is the most important, if not the only 'wastewater diluting agent' present. It should be mentioned here, that probably most of the wastewater generated is disposed of via on-site sanitation facilities. In recent years, it has even become apparent that the common way of handling wastewater in developing countries through on-site sanitation systems generates rather high rates of infiltration, often referred to as 'modern recharge' in developed countries (Morris et al., 2006; Wolf et al., 2006). Within and outside sub-Saharan Africa, there are many examples testifying of an increased recharge of wastewater (Morris et al., 2003), thereby sometimes even causing

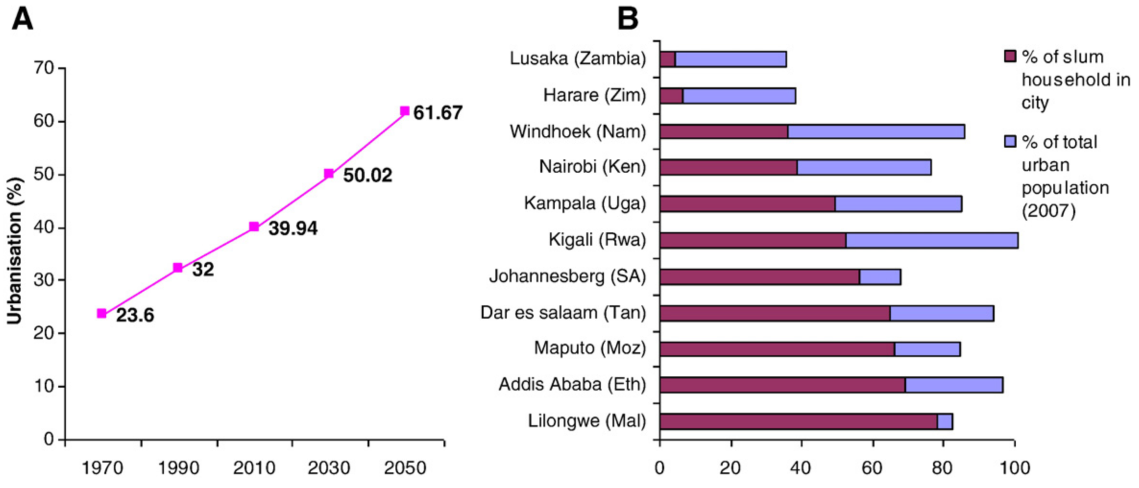

Fig. 1. Urbanisation trends and slum proportions in Africa: (A) Urbanisation trends (%) 1970–2050 and (B) Slum proportions (%) in selected cities. (Source: UN-Habitat, 2008).

local wastewater flooding problems, including associated health problems, road damage, and odour nuisance. The increased recharge due to urbanization is somewhat contradictory, since urbanization implicates the construction of roofs, and paved surfaces, which reduce recharge. Those impervious surfaces do indeed reduce recharge from precipitation, and on many occasions, cause fast surface runoff responses leading to flooding of lower lying parts of the city. Good examples for the latter are the Bwaise III slum area in Kampala (Kulabako et al., 2004, 2007, 2008), which is frequently flooded by stormwater from the upland urban catchment area, and various other slum areas in Nairobi (Kenya), Kampala (Uganda), Lagos (Nigeria), Accra (Ghana), Free Town (Sierra Leone) and Maputo (Mozambique) (Douglas et al., 2008). In contrast, Kelbe et al. (1991) reported a reduction of the peak discharge from catchments inhabited with informal settlements as compared to similar pristine catchments.

6. Processes related to the nutrients N and P in SSA

In SSA, research related to processes on N and P has been mainly focused on the natural retention and carrying capacity of the environment. Bere (2007) for example found out that nutrient loads in the Chinyika River (Zimbabwe) were retained over a distance of 4 km from the wastewater treatment discharge point into the river due to a high natural retention capacity of the river. Bere (2007) concluded that the natural retention capacity was most likely the result of the presence of swamps and wetlands near the banks of the river. Wetlands are able to retain nutrients (N and P) through retention by sediments and uptake by plants or by sedimentation of nutrient-rich particulate matter (Kansiime et al., 2005, 2007; Kelderman et al., 2007; Mugisha et al., 2007; van Dam et al., 2007). They act as buffers to eutrophication and constitute an important role in maintaining

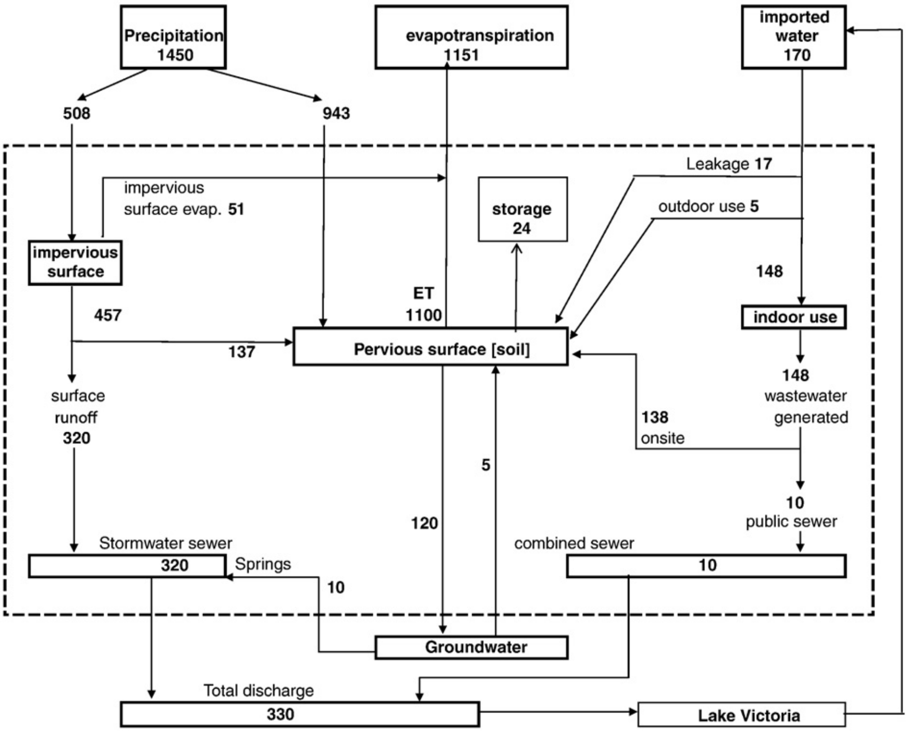

Fig. 2. Estimated water balance (mm/y) for the upper soil compartment of Kampala city, Uganda (within the dashed line; data from KDMP, 2002 and Kaggwa, 2009).

Table 5
Estimates of water balances (in mm/y) of the upper part of the subsurface in selected cities in (sub-Saharan) Africa.
Sources: Kampala: Kaggwa (2009) and KDMP (2002); Sunninghill: Stephenson (1991). Other cities: estimates provided by expert judgements of relevant ministerial employees.

Component of urban water cycle	Khartoum	Keren	Sunninghill	Yaounde	Kampala
	(Sudan)	(Eritrea)	(South Africa)	(Cameroon)	(Uganda)
Inflow					
Precipitation	140	400	724	1302	1450
Imported water	–	8	114	288	170
River inflow	491	–			
Groundwater inflow (springs)	65	–	–	–	10
Capillary rise	–	–	–	–	5
Outflow					
Evapotranspiration	140	207	457	275	1151
Wastewater flow (sewered)	4	1	95	–	10
Wastewater infiltration	78	5	–	128	120
Recharge to groundwater	390	227	179	–	–
Surface runoff in stormwater	–	2	107	1187	330
River outflow	113	–	–	–	–
Change in storage					
Soil storage (vadose zone)	−29	−34	–	–	24

lake and river ecosystems. Van Dam et al. (2007) constructed a dynamic model for nitrogen cycling to understand the processes contributing to nitrogen retention in a wetland and to evaluate the effects of papyrus harvesting on their nitrogen absorption capacity. The model used data from Kirinya wetland in Jinja (Uganda), which receives effluent from a municipal wastewater treatment plant. Kelderman et al. (2007) showed that Kirinya wetland on the Uganda coast of Lake Victoria can retain nutrients from secondary treated wastewater up to 40% to 60%. A wetland model was also constructed by Mwanuzi et al. (2003) to simulate the buffering processes of nutrients and organic matter based on results of wetlands in the Tanzanian part of Lake Victoria. The model established that there was a net export of nitrates and organic matter produced in wetlands while most inorganic P (60% to 90%) was retained in wetlands. Kansiime et al. (2005, 2007) showed that papyrus vegetation exhibited a higher wastewater treatment potential than the agricultural crop cocoyam. Mugisha et al. (2007) concluded that wetland plant species with high phytomass productivity and well developed root systems and ability to withstand flooding are best suited for nutrient removal. Encroachment on wetlands and increased wastewater production in urban areas, however, have increased nutrient loading beyond the buffering capacity of wetlands, thus impacting on lake ecosystems. Kansiime et al. (2007) for example found that there was 7 times more nutrient loading in wetlands located in urban areas in Uganda than those in rural areas. This was attributed to urban wastewater discharges with nutrient concentrations reaching as high as 4–7 mg/l of total-P and 15–17 mg/l of total-N. The Nakivubo channel in Kampala Uganda for example currently carries approximately 90% of N and 85% of P, discharged every day into the Inner Murchison Bay of Lake Victoria via Nakivubo wetland (NWSC, 2008).

Although more than 60% of the wastewater in mega-cities is disposed of via the sub-surface, research aimed at identifying the fate and transport mechanisms of both N and P in soils and aquifers is almost completely absent in SSA. An exception is Kulabako et al. (2007) who looked at the fate of P in the Bwaise III slum area in Kampala. They found out that P transport mechanisms are a combination of adsorption, precipitation, leaching from the soil media and by colloids, with the latter two playing a far more important role. These findings concur with previous studies which showed the potential for remobilisation of P accumulated in soils caused by reductive dissolution of P, rainfall recharge, changes in pH and decreases in redox potential (Zurawsky et al., 2004, Datry et al., 2004; Golterman and De Oude, 1991). In addition, the Langmuir and Temkin isotherm equations could be used to describe the P adsorption phenomena of the soils in Bwaise. From sequential and parallel extraction techniques for P present in the soils, residual P consisting mainly of organic phosphorus compounds was the dominant fraction in all soil layers, followed by Ca-bound P, and, finally, Fe and/or Al-bound P. From this, we conclude that these soils, which consist mostly of debris deposited by slum dwellers, possess a natural retention capacity. This capacity is however limited, since P concentrations in shallow groundwater in the area may be as high as 13 mg/l total-P (Kulabako et al., 2004). The capacity to remove nitrogen in these soils seemed to be limited: maximum concentrations up to 779 mg/l NO_3 were measured with average concentrations of several 10 s of mg/l. In general, all samples taken from the shallow groundwater of the Bwaise III area pointed towards oxic conditions.

The presence of nitrate and therefore the oxic state of groundwater is reported for various locations in the region (e.g. Faillat, 1990; Uma, 1993; Gelinas et al., 1996; Barrett et al., 1999; Nevondo and Cloete, 1999; Ikem et al., 2002; Edet and Okereke, 2005; Efe, 2005; Zingoni et al., 2005; Alagbe, 2006; Dzwairo et al., 2006; Arimoro et al., 2007; Cronin et al., 2007; Yidana et al., 2008). Several researchers in SSA also report on the oxic state of unpolluted groundwater without nitrate (e.g. Kortatsi, 2006; Pritchard et al., 2007; Diop and Tijani, 2008; Mkandawire, 2008; Pritchard et al., 2008). To our knowledge, there are very few reports testifying of deeply anaerobic conditions of urban groundwater, whereby sulphides are produced or methane is formed. Exceptions are discussed in Kortatsi (2007) and Kortatsi et al. (2008), who have reported on the reductive dissolution of iron oxides and the presence of Fe^{2+} in the regolith of Ghana at depths varying between 90 and 120 m. Vis-a-vis the 'redox'-model, which was formulated by Lawrence et al. (2000), a supposed lack of (deeply) anaerobic groundwater is somewhat remarkable. Based on their findings in Hat Yai, a town in Thailand, these authors have stated that dissolved organic carbon (DOC) can be considered the primary driver of chemical processes in aquifers contaminated with wastewater. Decomposition of DOC by bacteria depletes oxygen and causes suboxic and anoxic groundwater. If the decomposition of DOC can continue, then nitrate reduction may take place, followed by the release of Mn and Fe (II), the production of sulphides and, finally, methane. It should be noted that the reductive dissolution of Fe oxyhydroxides can result in mobilisation of various sorbed harmful components, like phosphates, arsenic, selenium, and a multitude of polar organic contaminants. It is also worth noting that these components and most especially the exchangeable ions Ca^{2+} and Mg^{2+} can also be released into water through cation exchange processes with ammonium (NH_4^+) in wastewater (Foppen et al., 2008; Navarro and Carbonell, 2007). In the Hat Yai case, all zones described above were observed. In all reported cases for urban areas in SSA, not even the first zone (nitrate reducing zone) was reported. This might be due to:

- If anaerobic groundwaters exist, then the procedures for anaerobic sample taking were not followed properly.
- Oxygen entry into the unsaturated zone for accepting the electrons required to fulfil the redox reaction is almost unlimited. This might be due to variations in seasonal recharge and the thickness of the unsaturated zone, which may cause seasonal replenishment of oxygen supply in the unsaturated zone.
- There is not enough reactive DOC in wastewaters present in SSA to complete all redox reactions.

- The model suggested by Lawrence et al. (2000) might require reactive sedimentary organic material, which might have been present in the organic rich Hat Yai aquifers, but is most likely almost absent in the weathered regoliths of large parts of SSA.

7. Knowledge gaps

In sub-Saharan Africa, eutrophication of fresh water resources, like lakes and rivers, is currently on the rise and most lakes and fresh water sources located near urban areas are deteriorating at an alarming rate. A large part of the problem is caused by rapid increase in population and urbanisation, especially in informal settlements where there is uncontrolled disposal of wastewater. With over 80% of the wastewater generated remaining untreated, and disposed of in the soil via on-site sanitation systems or directly discharged into rivers, one of the most important questions is "where do the nutrients in wastewater end up?" This question can be sub-divided in a number of more specific research topics:

1. Although most of the on-site facilities dispose off their wastewater in the subsurface, the fate and transport of N and P originating from this infiltrating wastewater is unknown. There is evidence that in wetlands and surface waters denitrification is occurring, resulting in a net loss of nitrogen, which, in turn, could give rise to N being the limiting factor for primary production and eutrophication. The rate of denitrification in aquifers, however, is unknown. The reports on chemical groundwater quality in urban areas in the region suggest that denitrification in aquifers is relatively limited, and that transformation of nitrogen species (e.g. nitrate) is not a dominant process.
2. Phosphorus transport, including sorption, dissolution and precipitation of iron- and manganese-oxyhydroxides and iron phosphate minerals to either lake bottom sediment, riverine sediments or to aquifer materials, and their dynamics as a result of input variations and temperature changes, has not been studied in great detail.
3. The effect of episodic removal of nutrients stored at the urban surface and near surface erosion by runoff from precipitation on nutrient budgets in adjacent lakes and rivers draining the urban areas is unknown. How is this temporary storage of nutrients related to eutrophication in downstream surface waters, and is the temporary influx of nutrients in any way related to the cyanobacteria blooms, which occur frequently in the region?
4. There is no insight in the hydrochemical state of both surface and subsurface contaminated water. Most reports check for WHO guidelines, and/or check for the presence of nutrients/microbiological parameters, but research identifying hydrochemical processes is lacking: what are the dominant redox processes, which dissolution and precipitation reactions take place, is cation exchange an important mechanism, and how important is sorption of contaminants? The processes are widely unknown in most catchments in SSA mega-cities.
5. There is very little insight in the hydrological cycle within the urban area, including surface water and groundwater flow patterns and interactions, associated transport velocities, dynamics of nutrient transport, and the presence of recharge and discharge areas in the urban area and their space and time variability in different seasons.
6. Although not specifically addressed in this review paper, there is no insight in the presence and spreading of organic micro-pollutants in mega-city catchments in SSA. Prominent examples of emerging contaminants are pharmaceuticals, estrogens, ingredients of personal care products, biocides, flame retardants, benzothiazoles, benzotriazoles or perfluorinated compounds (PFC). Adverse effects by individual emerging contaminants can occur with concentrations even as low as a few nanograms per litre, as reported for 17α-ethinylestradiol and tributyltin. Besides endocrine disrupters also pharmaceuticals (e.g. carbamazepine, diclofenac, fluoxetine, and propranolol) have been shown to cause effects at environmentally relevant concentrations. Contaminations of groundwater and drinking water by emerging contaminants are well reported. Since current treatment processes of municipal wastewater and drinking water treatment plants (e.g. nitrification/denitrification, flocculation and filtration) are not able to remove the majority of these emerging contaminants and advanced treatment techniques (e.g. ozonation, PAC addition and membrane treatment) may either be too costly or do not guarantee complete removal of these compounds, the question that arises is: which are the most hazardous or "unwanted" emerging contaminants? Criteria for answering this question might be the ecotoxicological (aquatic and terrestric) and toxicological relevance, the potential to bioaccumulate as well as the potential to contaminate groundwater and drinking water. In the SSA region, research on the presence and dynamics of these pollutants in the urban environment, both in groundwater and in surface waters and their linkage to eutrophication is absent.

8. Conclusions

The most important conclusions from this review are:

1. Eutrophication is an increasing problem in sub-Saharan Africa (SSA), and, as a result, the ecological integrity of surface waters becomes compromised, entire populations of fish become extinct, toxic cyanobacteria blooms are abundant, and oxygen levels become depleted, thereby promoting the growth of pathogenic bacteria such as *C. botulinum*.
2. In the literature, there are many reports establishing the relation between eutrophication of fresh inland surface waters in SSA and the production of nutrients in the various mega-cities which is fundamentally different from eutrophication mainly caused by agriculture in the so-called North.
3. Monitoring reports indicate that the population of these mega-cities is rapidly increasing, and so is the total amount of wastewater produced. Of those total amounts produced, at present, less than 30% is treated in sewage treatment plants, approximately 60% (on average) is disposed of untreated via on-site treatment systems, discharging their wastewater eventually into groundwater, while the fate of the remaining portion of total wastewater produced is to a large extent unknown.
4. The most important knowledge gaps include: (1) the fate and transport mechanisms of both N and P in soils and aquifers, or, conversely, the soil aquifer treatment characteristics of the regoliths, which cover a large part of SSA, (2) the effect of the episodic and largely uncontrolled removal of nutrients stored at the urban surface due to runoff from precipitation on nutrient budgets in adjacent lakes and rivers draining the urban areas, (3) the hydrology and hydrogeology within the urban area, including surface water and groundwater flow patterns, transport velocities, dynamics of nutrient transport, and the presence of recharge and discharge areas and, (4) the presence and spreading of other compounds present in wastewater, like organic micro-pollutants, trace metals and microbiological pollutants (viruses, bacteria, and protozoa).

In order to make a start with managing this urban population-related eutrophication, many actions are required. As a first step, we suggest to start systematically researching the key areas identified above.

Acknowledgments

The authors are grateful to the Executive Editor John G. Farmer and the two anonymous reviewers whose comments and suggestions resulted in a substantial improvement of this paper. The authors also thank Prof. Piet Lens (UNESCO-IHE, Netherlands) for his constructive comments on an earlier version of the manuscript. The research described here was funded by the Netherlands Ministry of Development Cooperation (DGIS) through the UNESCO-IHE Partnership Research Fund. It was carried out jointly with UNESCO-IHE, Makerere University, and the Kampala City Council in the framework of the Research Project 'Addressing the Sanitation Crisis in Unsewered Slum Areas of African Mega-cities' (SCUSA). It has not been subjected to peer and/or policy review by DGIS, and, therefore, does not necessarily reflect the view of DGIS.

References

Adeniji HA, Denny P, Toerien DF. Man-made lakes. In: Symoens JJ, Burgis M, Gaudet JJ, editors. The Ecology and Utilization of African Inland Waters; 1981. p. 125–34. Chapter 10.

Alagbe SA. Preliminary evaluation of hydrochemistry of the Kalambaina Formation, Sokoto Basin, Nigeria. Environ Geol 2006;5(1):39–45.

Allanson BR, Gieskes JMTM. An introduction to the limnology of Hartbeestpoortdam with special reference to the effect of industrial and domestic pollution. Hydrobiologia 1961;18: 78.

Arimoro FO, Ikomi RB, Iwegbue CMA. Water quality changes in relation to Diptera community patterns and diversity measured at an organic effluent impacted stream in the Niger Delta, Nigeria. Ecol Ind 2007;7(3):541–52.

Barel CDN, Dorit R, Greenwood PH, Fryer G, Hughes N, Jackson PBN, et al. Destruction of fisheries in Africa's lakes. Nature 1985;315(6014):19–20.

Barrett M, Nalubega M, Pedley S. On-site sanitation and urban aquifer systems in Uganda. Waterlines 1999;17(4):10–3.

Bere T. The assessment of nutrient loading and retention in the upper segment of the Chinyika River, Harare: implications for eutrophication control. Water SA 2007;33 (2):279–84.

Beyene A, Legesse W, Triest L, Kloos H. Urban impact on ecological integrity of nearby rivers in developing countries: the Borkena River in highland Ethiopia. Environ Monit Assess 2009;153(1–4):461–76.

Campbell LM, Wandera SB, Thacker RJ, Dixon DG, Hecky RE. Trophic niche segregation in the Nilotic ichthyofauna of Lake Albert (Uganda, Africa). Environ Biol Fish 2005;74 (3–4):247–60.

Coulter GW, Jackson PNB. Deep Lakes. In: Symoens JJ, Burgis M, Gaudet JJ, editors. The ecology and utilization of African inland waters; 1981. p. 114–24. Chapter 9.

Cózar A, Bergamino N, Mazzuoli S, Azza N, Bracchini L, Dattilo AM, et al. Relationships between wetland ecotones and inshore water quality in the Ugandan coast of Lake Victoria. Wetlands Ecol Manage 2007;15(6):499–507.

Cronin AA, Taylor RG, Powell KL, Barrett MH, Trowsdale SA, Lerner DN. Temporal variations in the depth-specific hydrochemistry and sewage-related microbiology of an urban sandstone aquifer, Nottingham, United Kingdom. Hydrogeol J 2003;11(2):205–16.

Cronin AA, Hoadley AW, Gibson J, Breslin N, Komou FK, Haldin L, et al. Urbanisation effects on groundwater chemical quality: findings focusing on the nitrate problem from 2 African cities reliant on on-site sanitation. J Water Health 2007;5(3):441–54.

Das SK, Routh J, Roychoudhury AN, Klump JV. Elemental (C, N, H and P) and stable isotope (δ^{15}N and δ^{13}C) signatures in sediments from Zeekoevlei, South Africa: a record of human intervention in the lake. J Paleolimnol 2008;39(3):349–60.

Das SK, Routh J, Roychoudhury AN, Klump J, Ranjan RK. Phosphorus dynamics in shallow eutrophic lakes: an example from Zeekoevlei, South Africa. Hydrobiologia 2009;619:55–66.

Datry I, Malard F, Gibert J. Dynamics of solutes and dissolved oxygen in shallow urban groundwater below a stormwater infiltration basin. Sci Total Environ 2004;329 (1–3):215–29.

De Villiers DGT, Malan E. The water quality of a small urban catchment near Durban, South Africa. Water SA 1985;11(1):35–40.

De Villiers S. The deteriorating nutrient status of the Berg River, South Africa. Water SA 2007;33(5):659–64.

Devi R, Tesfahune E, Legesse W, Deboch B, Beyene A. Assessment of siltation and nutrient enrichment of Gilgel Gibe dam, Southwest Ethiopia. Bioresour Technol 2008;99(5):975–9.

Dillion P. Groundwater pollution by sanitation on tropical islands. International Hydrological Programme — UNESCO, Adelaide, Australia; 1997. IHP-V Project 6-1.

Diop S, Tijani MN. Assessing the basement aquifers of Eastern Senegal. Hydrogeol J 2008;16:1349–69.

Douglas I, Alam K, Maghenda M, Mcdon-nell Y, Mclean L, Campbell J. Unjust waters: climate change, flooding and the urban poor in Africa. Environ Urban 2008;20 (1):187–205.

Dzwairo B, Hoko Z, Love D, Guzha E. Assessment of the impacts of pit latrines on groundwater quality in rural areas: a case study from Marondera district, Zimbabwe. Phys Chem Earth 2006;31(15–16):779–88.

Edet A, Okereke C. Hydrogeological and hydrochemical character of the regolith aquifer, northern Obudu Plateau, southern Nigeria. Hydrogeol J 2005;13(2):391–415.

Efe SI. Quality of water from hand dug wells in Onitsha Metropolitan areas of Nigeria. Environmentalist 2005;25:5–2.

Faillat JP. Sources of nitrates in fissure groundwater in the humid tropical zone — the example of Ivory Coast. J Hydrol 1990;113(1–4):231–64.

Fatoki OS, Muyima NYO, Lujiza N. Situation analysis of water quality in the Umtata River Catchment. Water SA 2001;27(4):467–74.

Feigin A, Ravina I, Shalhevet J. Irrigation with treated sewage effluent: management for environmental protection. Berlin: Springer3-540-50804-X; 1991.

Figueredo CC, Giani A. Seasonal variation in the diversity and species richness of phytoplankton in a tropical eutrophic reservoir. Hydrobiologia 2001;445(1–3):165–74.

Foppen JWA, van Herwerden M, Kebtie M, Noman A, Schijven JF, Stuyfzand PJ, et al. Transport of *Escherichia coli* and solutes during wastewater infiltration in an urban alluvial aquifer. J Contam Hydrol 2008;95(1–2):1–16.

Gelinas Y, Randall H, Robidoux L, Schmit JP. Well water survey in two districts of Conakry (Republic of Guinea), and comparison with the piped city water. Water Res 1996;30(9):2017–26.

Golterman HL, De Oude NT. Eutrophication of lakes, rivers and coastal seas. The handbook of environmental chemistry 5 (Part A); 1991. p. 79–124.

Hecky RE. The eutrophication of Lake Victoria. Verh Internat Verein Limnol 1993;25:39–48.

Hecky RE, Bugenyi FWB. Hydrology and chemistry of the African Great Lakes and water issues: problems and solutions. Mitt Int Ver Limnol 1992;23:45–54.

Hecky RE, Bugenyi FWB, Ochumba P, Talling JF, Mugidde R, Gophen M, et al. Deoxygenation of the deep-water of Lake Victoria, East Africa. Limnol Oceanogr 1994;39(6):1476–81.

Howard-Williams C, Ganf GG. Shallow Waters. In: Symoens JJ, Burgis M, Gaudet JJ, editors. The ecology and utilization of African inland waters; 1981. p. 103–13. Chapter 8.

Ikem A, Osibanjo O, Sridhar MKC, Sobande A. Evaluation of groundwater quality characteristics near two waste sites in Ibadan and Lagos, Nigeria. Water Air Soil Pollut 2002;140(1–4):307–33.

Jarvie HP, Neal C, Withers PJA. Sewage-effluent phosphorus: a greater risk ro river eutrophication than agricultural phosphorus? Sci Total Environ 2006;306:243–53.

Jarvis MJF, Mitchell DS, Thornton JA. Lake McIlwaine — the eutrophication and recovery of a tropical man-made lake. Aquatic macrophytes and *Echhornia crassipes*. The Hague, The Netherlands: Dr. W. Junk Publishers; 1982. p. 137–44.

JMP. Joint Monitoring Programme 1999. Website: www.wssinfo.org (accessed June 2009)

Kaggwa R. NWSC Performance Improvement program: Summary of achievements. Website: http://nwsc.co.ug/publications01.php (accessed 20th March 2009).

Kansiime F, Nalubega M. Natural treatment by Uganda's Nakivubo swamp. Water Qual Int 1999:29–31 [MAR./APR].

Kansiime F, Oryem-Origa H, Rukwago S. Comparative assessment of the value of papyrus and cocoyams for the restoration of the Nakivubo wetland in Kampala, Uganda. Phys Chem Earth 2005;30(11–16):698–705.

Kansiime F, Kateyo E, Oryem-Origa H, Mucunguzi P. Nutrient status and retention in pristine and disturbed wetlands in Uganda: management implications. Wetlands Ecol Manage 2007;15(6):453–67.

KDMP. Kampala Drainage Master Plan — Nakivubo Channel Rehabilitation Project. Ministry of Local Government, Kampala City Council, Uganda. July 2002; 2002.

Kelbe BE, Bodenstein B, Mulder GJ. Investigation of the hydrological response to informal settlements on small catchments in South Africa. International Association of Hydrological Sciences IAHS Publication; 1991. p. 219–27.

Kelderman P, Kansiime F, Tola MA, Van Dam A. The role of sediments for phosphorus retention in the Kirinya wetland (Uganda). Wetlands Ecol Manage 2007;15(6): 481–8.

Kemka N, Njiné T, Togouet SHZ, Menbohan SF, Nola M, Monkiedje A, et al. Eutrophication of lakes in urbanized areas: the case of Yaounde Municipal Lake in Cameroon, Central Africa. Lakes Reservoirs Res Manage 2006;11(1):47–55.

Kemka N, Togouet SHZ, Kinfack RPD, Nola M, Menbohan SF, Njine T. Dynamic of phytoplankton size-class and photosynthetic activity in a tropical hypereutrophic lake: the Yaounde municipal lake (Cameroon). Hydrobiologia 2009;625:91–103.

Kling HJ, Mugidde R, Hecky RE. Recent changes in the phytoplankton community of Lake Victoria in response to eutrophication. In: Munawar M, Becky R, editors. The great lakes of the world (GLOW): food-web, health and integrity. Leiden, The Netherlands: Backhuys Publishers; 2001. p. 47–65.

Kortatsi BK. Hydrochemical characterization of groundwater in the Accra plains of Ghana. Environ Geol 2006;50(3):299–311.

Kortatsi BK. Hydrochemical framework of groundwater in the Ankobra Basin, Ghana. Aquat Geochem 2007;13(1):41–74.

Kortatsi BK, Tay CK, Anornu G, Hayford E, Dartey GA. Hydrogeochemical evaluation of groundwater in the lower Offin basin, Ghana. Environ Geol 2008;53(8):1651–62.

Kulabako NR, Nalubega M, Thunvik R. Characterisation of peri-urban anthropogenic pollution in Kampala, Uganda. Proceedings of the 30th WEDC international conference on people centred approaches to water and environmental sanitation, 25–29th October. Vientiane: Lao PDR; 2004. p. 474–82.

Kulabako NR, Nalubega M, Thunvik R. Study of the impact of land use and hydrogeological settings on the shallow groundwater quality in a peri-urban area of Kampala, Uganda. Sci Total Environ 2007;381(1–3):180–99.

Kulabako NR, Nalubega M, Thunvik R. Phosphorus transport in shallow groundwater in peri-urban Kampala, Uganda: results from field and laboratory measurements. Environ Geol 2008;53(7):1535–51.

Lawrence AR, Gooddy DC, Kanatharana P, Meesilp W, Ramnarong V. Groundwater evolution beneath Hat Yai, a rapidly developing city in Thailand. Hydrogeol J 2000;8(5): 564–75.

Magadza CHD. Lake Chivero: a management case study. Lakes Reservoirs Res Manage 2003;8(2):69–81.

Marsalek J, Jimenez-Cisneros B, Malmqvist P, Goldenfum J, Chocat B. Urban water cycle processes and interactions, Urban water series — UNESCO-IHP Volumes. Taylor and Francis, Leiden and UNESCO Publishing, Paris, 2008; ISBN: 978-92-3-104060-3.

Marshall BE, Falconer AC. Eutrophication of a tropical African impoundment (Lake McIlwaine, Rhodesia). Hydrobiologia 1973;43(1–2):109–23.

Mkandawire T. Quality of groundwater from shallow wells of selected villages in Blantyre District, Malawi. Phys Chem Earth 2008;33(8–13):807–11.

Mladenov N, Strzepek K, Serumola OM. Water quality assessment and modeling of an effluent-dominated stream, the Notwane River, Botswana. Environ Monit Assess 2005;109(1–3):97–121.

Morris BL, Lawrence ARL, Chilton PJC, Adams B, Calow RC, Klinck BA. Groundwater and its susceptibility to degradation: a global assessment of the problem and options for management. Early warning and assessment report series, 2003; RS. 03-3. United Nations Environment Programme, Nairobi, Kenya.

Morris BL, Darling WG, Cronin AA, Rueedi J, Whitehead EJ, Gooddy DC. Assessing the impact of modern recharge on a sandstone aquifer beneath a suburb of Doncaster, UK. Hydrogeol J 2006;14(6):979–97.

Moyo NAG, Worster K. The effects of organic pollution on the Mukuvisi River, Harare, Zimbabwe. In: Moyo NAG, editor. Lake Chivero: a polluted lake. Harare, Zimbabwe: University of Zimbabwe Publications; 1997. p. 53–63.

Muggide R. The increase in phytoplankton primary productivity and biomass in Lake Victoria (Uganda). Verh Int Ver Limnol 1993;25:846–9.

Mugisha P, Kansiime F, Mucunguzi P, Kateyo E. Wetland vegetation and nutrient retention in Nakivubo and Kirinya wetlands in the Lake Victoria basin of Uganda. Phys Chem Earth 2007;32(15–18):1359–65.

Munro JL. A limnological survey of Lake McLlwaine, Rhodesia. Hydrobiologia 1966;28 (281–308).

Mwanuzi F, Aalderink H, Mdamo L. Simulation of pollution buffering capacity of wetlands fringing the Lake Victoria. Environ Int 2003;29:95–103.

MWE. Uganda water and sanitation sector performance report. Ministry of Water and Environment (MWE), The Government of Uganda; 2007.

Navarro A, Carbonell M. Evaluation of groundwater contamination beneath an urban environment: The Besos river basin (Barcelona, Spain). J Environ Manage 2007;85 (2):259–69.

Nevondo TS, Cloete TE. Bacterial and chemical quality of water supply in the Dertig village settlement. Water SA 1999;25(2):215–20.

Nhapi I. Inventory of water management practices in Harare, Zimbabwe. Water Environ J 2008;22(1):54–63.

Nhapi I, Tirivarombo S. Sewage discharges and nutrient levels in Marimba River, Zimbabwe. Water SA 2004;30(1):107–13.

Nhapi I, Siebel MA, Gijzen HJ. A proposal for managing wastewater in Harare, Zimbabwe. Water Environ J 2006;20(2):101–8.

NWSC. Kampala Sanitation Program (KSP) — Feasibility study report. National Water and Sewerage cooperation (NWSC), Kampala, Uganda; 2008.

Oberholster PJ, Botha AM, Cloete TE. Biological and chemical evaluation of sewage water pollution in the Rietvlei nature reserve wetland area, South Africa. Environ Pollut 2008;156(1):184–92.

Oberholster PJ, Botha AM, Cloete TE. An overview of toxic freshwater cyanobacteria in South Africa with special reference to risk, impact and detection by molecular marker tools. Biokem 2005;17:57–71.

Oberholster PJ, Botha AM, Ashton PJ. The influence of a toxic cyanobacterial bloom and water hydrology on algal populations and macroinvertebrate abundance in the upper littoral zone of Lake Krugersdrift, South Africa. Ecotoxicology 2009;18 (1):34–46.

Oguttu HW, Bugenyi FWB, Leuenberger H, Wolf M, Bachofen R. Pollution menacing lake victoria: Quantification of point sources around Jinja Town, Uganda. Water SA 2008;34(1):89–98.

Pritchard M, Mkandawire T, O'Neill JG. Biological, chemical and physical drinking water quality from shallow wells in Malawi: Case study of Blantyre, Chiradzulu and Mulanje. Phys Chem Earth 2007;32(15–18):1167–77.

Pritchard M, Mkandawire T, O'Neill JG. Assessment of groundwater quality in shallow wells within the southern districts of Malawi. Phys Chem Earth 2008;33(8–13):812–23.

Robarts RD. Heterotrophic bacterial activity and primary production in a hypertrophic African lake. Hydrobiologia 1988;162:97–107.

Robarts RD, Southall GC. Nutrient limitation of phytoplankton growth in seven tropical man-made lakes, with specific reference to Lake Mcllwaine, Rhodesia. Hydrobiologia 1977;79(1):1–35.

Scheren PAGM, Zanting HA, Lemmens AMC. Estimation of water pollution sources in Lake Victoria, East Africa: application and elaboration of the rapid assessment methodology. J Environ Manage 2000;58(4):235–48.

Stephenson D. Effects of urbanisation on catchment water balance, Water Systems Research Group, University of Witwatersrand, Johannesburg, South Africa; 1991. Report 183/12/93.

Tallings JF. Origin of stratification in an African rift lake. Limnol Oceanogr 1963;8: 68–78.

Talling JF. Environmental regulation in African shallow lakes and wetlands. Rev Hydrobiol Trop 1992;25:87–144.

Talling JF, Talling IB. The photosynthetic activity of phytoplankton in East African lakes. Int Rev Gesamten Hydrobiol 1965;50:1–32.

Thornton JA. Aspects of the phosphorus cycle in Hartbeesport Dam (South Africa). Hydrobiologia 1989;183:87–95.

Thornton JA, Ashton PJ. Aspects of the phosphorus cycle in Hartbeespoort Dam (South Africa). Hydrobiologia 1989;183:73–85.

Thornton JA, Nduku WK. Lake Mcllwaine — the eutrophication and recovery of a tropical man-made lake. Water chemistry and nutrient budgets. The Hague, the Netherlands: Dr. W. Junk Publishers; 1982. 43–59 pp.

Thornton JA, Rast W, Holland MM. Assessment and control of nonpoint source pollution of aquatic ecosystems: a practical approach. Man and the biosphere series v. 23. UNESCO; Parthenon Pub. Group, New York, USA 1999; xi, 466. pp.

Tournoud MG, Perrin JL, Gimbert F, Picot B. Spatial evolution of nitrogen and phosphorus loads along a small Mediterranean river: implication of bed sediments. Hydrol Process 2005;19(18):3581–92.

Uma KO. Nitrates in shallow (regolith) aquifers around Sokoto Town, Nigeria. Environ Geol 1993;21(1–2):70–6.

UN-Habitat (United Nations Human Settlements Program). The challenge of slums — global report on human settlements, 2003. Website: http://www.unhabitat.org/pmss/getPage.asp?page=bookView&book=1156 (Accessed September 2009).

UN-Habitat (United Nations Human Settlements Program). The state of African cities — a framework for addressing urban challenges in Africa, 2008. Website: http://www.unhabitat.org/pmss/getPage.asp?page=bookView&book=2574 (Accessed October 2009).

van Dam AA, Dardona A, Kelderman P, Kansiime F. A simulation model for nitrogen retention in a papyrus wetland near Lake Victoria, Uganda (East Africa). Wetlands Ecol Manage 2007;15:469–80.

Verschuren D, Johnson TC, Kling HJ, Edgington DN, Leavitt PR, Brown ET, et al. History and timing of human impact on Lake Victoria, East Africa. Proc R Soc B Biol Sci 2002;269(1488):289–94.

Viner AB, Breen C, Golterman HL, Thornton JA. Nutrient budgets. In: Symoens JJ, Burgis M, Gaudet JJ, editors. The ecology and utilization of African inland waters; 1981. p. 137–48. Chapter 11.

Vos AT, Roos JC. Causes and consequences of algal blooms in Loch Logan, an urban impoundment. Water SA 2005;31(3):385–92.

Wakida FT, Lerner DN. Non-agricultural sources of groundwater nitrate: a review and case study. Water Res 2005;39(1):3–16.

WHO (World Health Organisation). Water supply and sanitation sector report year 2000 — Africa regional assessment. World Health Organization; 2000.

Wiegand C, Pflugmacher S. Ecotoxicological effects of selected cyanobacterial secondary metabolites a short review. Toxicol Appl Pharmacol 2005;203(3):201–18.

Witte F, Welten M, Heemskerk M, van der Stap I, Ham L, Rutjes H, et al. Major morphological changes in a Lake Victoria cichlid fish within two decades. Biol J Linn Soc 2008;94(1):41–52.

Wolf L, Morris B, Burn S, editors. AISUWRS: urban water resources toolbox-integrating groundwater into urban water management. London, UK: IWA Publishing; 2006. 309 pp.

WWAP (World Water Assessment Programme). Water in a changing world — the 3rd United Nations world water development report 2009. Website: http://www.unesco.org/water/wwap/wwdr/wwdr3/ (Accessed June 2009).

Yidana SM, Ophori D, Banoeng-Yakubo B. Hydrogeological and hydrochemical characterization of the Voltaian Basin: the Afram Plains area, Ghana. Environ Geol 2008;53(6): 1213–23.

Zilberg B. Gastro-enteritis in Salisbury European children: a five-year study. Cent Afr J Med 1966;12(9):164–8.

Zinabu GM, Taylor WD. Seasonal and spatial variation in abundance, biomass and activity of heterotrophic bacterioplankton in relation to some biotic and abiotic variables in an Ethiopian rift-valley lake (Awassa). Freshw Biol 1989;22:355–68.

Zinabu GM, Kebede-Westhead E, Desta Z. Long-term changes in chemical features of waters of seven Ethiopian rift-valley lakes. Hydrobiologia 2002;477(1–3):81–91.

Zingoni E, Love D, Magadza C, Moyce W, Musiwa K. Effects of a semi-formal urban settlement on groundwater quality Epworth (Zimbabwe): case study and groundwater quality zoning. Phys Chem Earth 2005;30(11–16):680–8.

Zurawsky MA, Robertson WD, Ptacek CJ, Schiff SL. Geochemical stability of phosphorus solids below septic system infiltration beds. J Contam Hydrol 2004;73(1–4):129–43.