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Causes of Water Supply Problems in Urbanised Regions in Developing Countries

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Abstract An analysis was made of the underlying factors leading to water supply problems in urbanized regions in developing countries. Three interrelated factors were identified and described: (1) a high rate of population growth, (2) lack of investments in water supply infrastructure, and (3) the upper limit imposed by the availability of water sources. This background allows understanding failures in water supply systems in large cities in developing countries. Each of these factors may individually compromise water supply, but in many cases the context is a complex interplay of these factors, often fed by political or military instability and poverty. Sanitation is often closely related to water supply systems, although the situation is generally worse. Based on this analysis, an evaluation was made of water supply in Kinshasa, D.R. Congo, in comparison with the historical case of London, UK, and the development of Los Angeles, CA, USA. In addition, reference is made to the case of Tokyo, Japan. From this comparison, opportunities and threads for Kinshasa can be shown.

Keywords Water supply · Developing countries · Urbanization · Population growth · Infrastructure · Resource depletion

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1 Introduction

Water is essential for life on Earth, but it is also important for social and economic development. Natural water resources are becoming more and more scarce, and global water use is increasing, which means that a global water crisis is a realistic threat. Looking at the 'Water Conflict Chronology' published by Gleick (2009), one can assume that the trend will continue and that scarcity of water resources will lead to more disputes. In the same publication, the concept of 'peak water' is described, in comparison with 'peak oil'. Indeed, valuable non-renewable freshwater resources are rapidly depleted, and although the parallel with oil is not always applicable, the recognition of the value of water can help drive towards an important and needed shift in the way water is managed and priced (Gleick 2009).

A known challenge for water management is the uneven distribution in time and space of water resources. Precipitation is very variable from decade to decade, from year to year and from season to season. During the wet season, typically 3–4 months, 60–80% of the yearly runoff is obtained. The dry season yields less than 10% of the yearly runoff (Shiklomanov 1999). The availability of water, measured as annual discharge flowing mainly through the rivers from continents to the sea, was reported to be 45,500 km^3 (Oki and Kanae 2006). UNEP (2008) reports a somewhat different value, as the difference between total precipitation (119,000 km^3) and evaporation on the land (74,200 km^3), which equals 44,800 km^3. A more detailed review of water availability is given by Shiklomanov and Rodda (2003). However, much of the water available can in fact not be used. To overcome this, reservoirs are constructed on small or large scale. Small scale reservoirs can be found in Sub-Saharan Africa and Asia (Van der Zaag and Gupta 2008), but their use is usually limited to non-urban regions. In terms of water availability, small-scale dams allow overcoming the dry season, and may manage to ensure water supply throughout the year. This is of high importance for e.g., irrigation; however, if the water is used for human consumption, care should be taken about the water quality in terms of e.g., eutrophication and the occurrence of blooms of toxic cyanobacteria (Dejenie et al. 2008). This may have an adverse influence on public health due to direct effects of water quality and indirect effects related to breeding spots for malaria vectors (Yohannes et al. 2005; Amacher et al. 2004), although positive effects on reducing malaria transmission were also reported (Sharma et al. 2008). The positive effects were ascribed to the alteration of the water flow above and below the dam, thereby making it unfavourable for the breeding of the anthropophagic vector *Anopheles fluviatilis*, which affected malaria transmission.

To serve a large population, large dams are constructed to solve problems of water supply. A classical example is the Aswan Dam in Egypt, with Nasser Lake being used as a large-scale reservoir for water supply (Okbazghi 2008). New constructions are undertaken for combined water storage and hydroelectricity production, in spite of the potential adverse effects, and will play an important role in urban water supply in the future (Gleick 2009). Examples include the Gilgel Gibe Dam in Ethiopia (Yewhalaw et al. 2009) and the Three Gorges Dam in China (Gleick 2009). For large-scale dams, long-term effects on water quality may be suspected, but more direct problems are on a different level: environmental (e.g., siltening of the Nile delta), ecological (drastic changes in habitats for fish, birds and insects), cultural (inundation of villages, cities and historical monuments) and even seismographic (reported risk for the Three Gorges Dam). These dams, however, will not solve the problems of water management in urban areas, although it is evident that they may contribute to the availability of water.

During the last century, the world population has grown rapidly, and further growth is projected for the next decades. This phenomenon is mainly related to urbanized regions in developing countries, with explosively growing local centres. Population growth translates to an increase in food production, and more industrial activities. Agriculture and industry are two large water consumers, and even when these activities take place elsewhere, the water required for these activities remains the same on a global scale. This corresponds to the concept of virtual water, as described by Hoekstra and Chapagain (2008).

In addition, urban water should be available for daily household use. In principle, the high population density in cities should make water supply and wastewater discharge more easy, but in practice, several problems arise that may be technical or management-related. In developing countries, urbanization typically occurs in a fuzzy way, without any plan. This is a challenge for water supply systems, but not impossible, as shown through the Japanese example (He et al. 2009). Large cities in Japan also developed in a non-organized way, leaving paddy fields as an integral part of the city; however, Japan is well organized with respect to water supply.

Water abstraction in 1995 was in total 3,906 km^3, which is expected to increase to over 5,000 km^3 in 2025, with a dramatic increase in Africa and South America, and a slow increase in North America and Europe (Shiklomanov and Rodda 2003). These volumes are much less than the 44,800 km^3 available for exploitation. However, it is estimated that only between 12,500 and 14,000 km^3 each year (corresponding to 28–31% of the total volume) is in fact available for human consumption (UNEP 2008), due to losses in the rainy season, flooding, and geographical reasons (some water bodies are too remote for abstraction). This is in principle enough to cover the growing water consumption in the next decades. Thus, it can be concluded that the challenge of global water supply is more complex than numbers would suggest.

This paper analyzes the complexity of water management challenges in developing countries, from the point of view of urbanized regions with a strong population growth. Together with lack of (investments in) infrastructure and depletion of natural resources, this determines the extent to which a water crisis is expected to develop in urbanized regions. Furthermore, the interconnection of the three factors will be discussed through a comparative study of London, Los Angeles and Kinshasa.

2 Demographic Pressure on Water Management

As already stated, overall numbers for water availability may lead to wrong conclusions. Table 1 summarizes the total water availability for different continents (Shiklomanov 1999), and the specific water availability per capita. The numbers are calculated as the difference between precipitation and evaporation, not taking into account the losses as mentioned above. Table 1 suggests an abundance of water in Oceania, North and South America, in contrast with a water stress situation in Europe, Africa and Asia. However, reality is much more complex and largely influenced by local factors. Urbanization may be one of the most important factors, since it leads to a high local population density and in many cases, a low specific water

Table 1 Water availability and specific water availability per continent (Shiklomanov 1999)

Continent	Area (million km^2)	Population (millions)	Average water resources (km^3/year)	Water availability per capita (1,000 m^3/year)
Asia	43.5	3,445	13,510	3.92
Africa	30.1	708	4,050	5.72
Europe	10.46	685	2,900	4.23
North America	24.3	453	7,890	17.4
South America	17.9	315	12,030	38.2
Oceania	8.95	28.7	2,404	83.7
World	135	5,633	42,785	7.60

availability per capita. This is not always the case: Kinshasa is a typical example of a large city with sufficient water resources, yet failing in supplying urban water to its residents. The complex interplay between various factors will be discussed later.

Population growth mainly has an influence on water supply through growth rates. These are particularly high in urban regions in developing countries. Rapid urbanization is a relatively recent phenomenon: the global urban population increased from 3% in 1800 to 14% in 1900 and 30% in 1950 (Biswas 2006). Since then, many regions reached 50% very rapidly, but it was only until 2008 that the global urban population exceeded the rural population (UN-ESA 2008). Less developed regions will reach this point by 2019, and it is expected that in 2050 all developing countries will have a mainly urban population. In this year, it is presumed that the urban population will have doubled compared to 2007, with a projected global population of 9.2 billion, of which 6.4 billion will live in cities. The rural population will have a maximum in 2018–2019, upon which a yearly decrease by 1.67% in developed regions and 0.75% in less developed regions will occur. At present, the urban population in developing countries increases by five million per month (UN Habitat 2008). The growth will be caused mainly by cities currently below one million inhabitants, and new inhabitants will be mainly in the category low to middle class income. Figure 1 shows the history of urban and rural population growth since 1950, and the projected numbers for the coming four decades (UN Population Division 2007). It can be seen that the intercept of both curves is approximately in 2008.

From these data, it can be derived that development of water supply will have to be concentrated on those parts of the cities which have the least financial opportunities. Moreover, it can be stated that among the cities, the main challenge will be in the

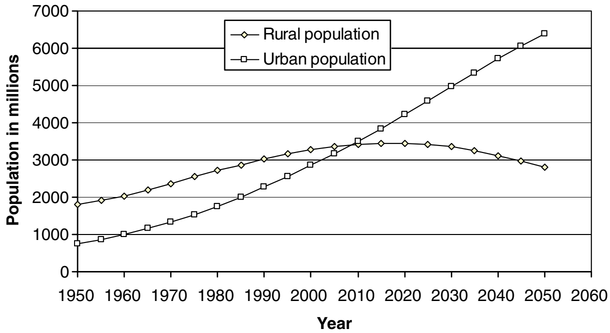

Fig. 1 Rural and urban population since 1950, with projected numbers until 2050 (UN Population Division 2007)

water supply in (poor parts of) mega-cities in developing countries. Water supply in slums is particularly difficult to organize, whereas urban population growth is mainly related to expansion urban areas in less developed countries (Thomas 2009), which often appear as slums and similar areas. Mega-cities were once defined as cities with over eight million inhabitants. According to this definition, New York was the only mega-city in the world. Later on, the threshold was increased to ten million; at the beginning of the twenty-first century, 16 mega-cities were counted. It is predicted that five more mega-cities will develop by 2025, all of which will be situated in developing countries (Biswas 2006). The number of cities with over one million inhabitants will increase dramatically as well (Cohen 2006).

Nevertheless, population growth in smaller cities should not be overlooked. Mega-cities were housing 3.7% of the world population in 2000; this will probably increase to 4.7% in 2015, but smaller cities (<500,000 inhabitants) accounted for 24.8% of the world population (numbers for 2000), with a projected increase to 27% in 2015 (Biswas 2006).

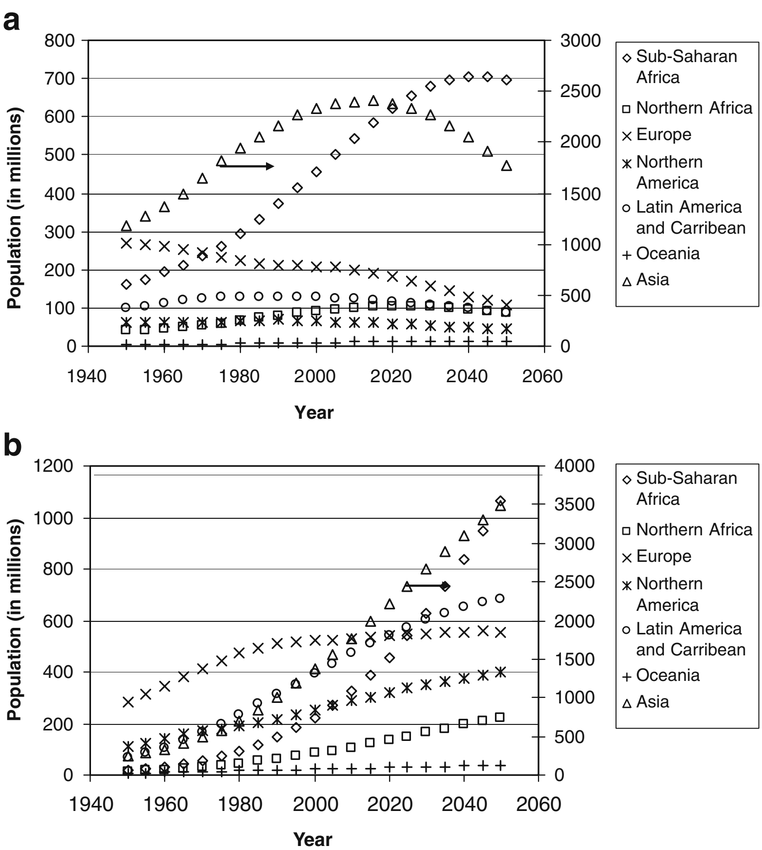

Fig. 2 **a** Rural population per (sub)continent (Asia on *right axis*, all other on *left axis*) from 1950 to 2050 (in millions). **b** Urban population per (sub)continent (Asia on *right axis*, all other on *left axis*) from 1950 to 2050 (in millions; calculated using UN Population Division 2007)

If the population growth divided as rural/urban is compared between different continents (Fig. 2), remarkable differences can be observed. The rural population is predicted to decrease in all parts of the world by 2050, although the start of the decline differs from region to region. Europe and Northern America were already in decline in 1950, in contrast to any other region. At present, Latin America and the Caribbean have joined in this trend. Asia follows in 2015, then Northern Africa (2025), Oceania (2035) and finally, Africa (2045). This might be considered a delayed trend.

The urban population shows a remarkably different evolution. Here an overall increase can be observed, but the rate of increase is very different from region to region. Europe is expected to have a slight decrease in the urban population by 2050. All other regions increase steadily. If the urban population is compared between 2050 and 1950, the increase factors are comparable for Europe (2.0), Northern America (3.7) and Oceania (4.7), somewhat higher for Latin America (9.8), quite high for Asia (14.7) and Northern Africa (16.9), but incredibly high for Sub-Saharan Africa at 53.4! This means that for every urban citizen in Sub-Saharan Africa in 1950, 53 have to be accommodated in 2050, and, in particular, supplied with water.

3 Lack of (Investments in) Infrastructure

Water supply and sanitation are the basis of a society's development. They are directly linked, due to their mutual influence, but the availability and utilization of sanitation facilities is generally worse than water supply systems. In the context of this paper, it must be understood that large cities such as London, Now York and Paris were once a hotbed of infectious diseases; with the layout of sanitation infrastructure, life expectancy in the UK increased with 15 years in a period of 40 years (UNDP 2006). Therefore, it is not surprising that the Millennium Development Goals (MDG), set for 2015, include Target 10 of Goal 7, which aims to 'halve, by 2015, the proportion of people without sustainable access to safe drinking water and basic sanitation' (WHO/UNICEF 2006). The MDG refers to 'improved water sources' and 'improved sanitation facilities'. Table 2 gives an overview of which installations are considered (un)improved drinking water sources and (un)improved sanitation facilities (WHO/UNICEF 2006). At present, 1.1 billion people have no access to improved water sources, whereas 2.6 billion people have no access to improved sanitation. Every year 1.6 million children below five die from the use of polluted water in combination with the lack of sanitation (WHO/UNICEF 2006). The MDG for water and sanitation is relatively well on schedule, except for Sub-Saharan Africa (Gleick 2009). However, when the number of people without improved water sources or sanitation facilities is considered, the total number hardly decreases. This is due to the fact that the MDG refer to proportions, whereas the world population in absolute numbers keeps increasing at rapid speed. In addition, there are also large regional differences. Figure 3 shows the percentage of households without tap water, flush toilet and electricity as a function of the size of the urban area and the (sub)continent (Cohen 2006; National Research Council 2003). These numbers tend to decrease with the size of the urban area, and are the highest for cities with less than 100,000 inhabitants. It is thought that cities below 100,000 inhabitants and in the range of 100,000 to one million inhabitants are the most

Table 2 Overview improved and unimproved drinking water sources and sanitation facilities (WHO/UNICEF 2006)

Improved drinking water sources	Unimproved drinking water sources	Improved sanitation facilities[a]	Unimproved sanitation facilities
Piped water into dwelling, plot or yard	Unprotected dug well	Flush or pour-flush to piped sewer system, septic tank or pit latrine	Flush or pour-flush to elsewhere[b]
Public tap/standpipe	Unprotected spring	Ventilated improved pit latrine	Pit latrine without slab or open pit
Tubewell/borehole	Cart with small tank/drum	Pit latrine with slab	Bucket
Protected dug well	Bottled water[c]	Composting toilet	Hanging toilet or hanging latrine
Protected spring	Tanker-truck		No facilities or bush or field
Rainwater collection	Surface water (river, dam, lake, pond, stream, canal, irrigation channels)		

[a]Only facilities which are not shared or are not public are considered improved

[b]Excreta are flushed to the street, yard or plot, open sewer, a ditch, a drainage way or other location

[c]Bottled water is considered improved only when the household uses water from an improved source for cooking and personal hygiene

vulnerable in terms of water infrastructure, because these are generally expected to be faced with the largest population growth. Nevertheless, it is obvious that the scale of challenges is much larger in megacities. Varis et al. (2006) describe problems with water management in megacities related to continuing urbanization, lack of investment funds for constructing and maintaining water infrastructures, high public debts, inefficient resources allocation processes, inadequate management capacities, poor governance, and inappropriate institutional frameworks. These considerations

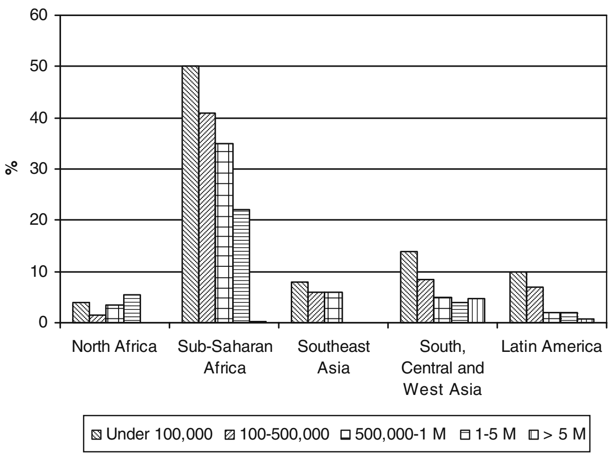

Fig. 3 Percentage of households without tap water, flush toilet and electricity as a function of the size of the urban area and the (sub)continent (adapted from Cohen 2006 and National Research Council 2003)

should be extended to smaller cities developing rapidly, with underdeveloped areas very similar to those encountered in megacities. These 'squatter settlements' may account for 30–60% of the urban population; Mumbai is a well-known example where half of the population lives in such settlements (Biswas 2006). These are usually so overpopulated and so closely built that a systematic layout of water supply and sanitation infrastructure is simply impossible. Poor people from rural areas tend to move in large numbers to cities and end up in these squatter settlements. The use of primitive latrines and the overpopulation have a negative influence of the quality of locally used water sources, because latrines and wells are often too close to one another (Tanawa et al. 2001). National and local governments are usually incapable of responding in an efficient and sustainable way to fast demographic evolutions (Biswas 2006). Furthermore, even when investments are made, corruption and misuse of resources also leads to poor planning and implementation of water supply projects. Corruption plays a double negative role here: not only by making resources 'disappear', but also by scaring off potential future investors, who are afraid of project failures. A bad planning and government result in an increasing backlog in infrastructure; furthermore, maintenance of existing infrastructure is often insufficient. Water supply networks, for instance, are estimated to have an efficiency in urban areas in developing countries, of 40–60%, which means that half of the distributed water is lost through leaks. The local population is not willing to pay for irregular supply of doubtful quality (Khatri and Vairavamoorthy 2007). In India, 85% of the population is connected to tap water, but only 20% meets the WHO quality requirements (Singh 2000). However, lack of infrastructure is the commonly encountered situation. The economic cost of providing the necessary infrastructure is high; in theory, concepts such as integrated water treatment and water recycling could solve many problems of both water supply and sanitation; however, the cost of such projects is too high. Nevertheless, in many cases the alternative is to transport water from far away sources to the cities, which is costly as well.

4 Depletion of Natural Water Resources for Urban Supply

Urbanisation inevitably goes hand in hand with an increase of the population density, which means that more people have to rely on existing water sources. New sources are difficult to find, or expensive in exploitation. The presence of large, renewable sources such as rivers and lakes is therefore of crucial importance. Groundwater sources are increasingly depleted and not renewed. In urban areas, the infiltration capacity is too low due to the presence of roads and buildings, which further decreases the capacity for renewal. Many cities have come to the limits of water availability from natural sources. This has been discussed by Fang et al. (2007) through the concept of Water Resources Constraint Forces (WRCF). In addition, the quality of sources may degrade due to uncontrolled discharge of waste(water).

Surface waters may be depleted as well when their capacity is fully exploited. Many of the rivers in Northern China are fully or partially dry, so that they cannot fulfil their functions in transporting salt and sand, groundwater recharge and local water supply, and their ecological role. In Northern China, 40% of the total river length of 10,000 km is temporarily or permanently dry.

Another example is Lake Haromaya in Ethiopia, situated in the eastern part of the country in the mountains, in the densely populated regional state of Oromia (Alemayehu et al. 2007). Together with Lake Adele, Lake Haromaya is serving as the primary source of drinking water for 150,000 people in cities like Harar, Awoday and Alemaya. Lake Haromaya had a surface area of 33.2 km^2 in the 1970s, with an average depth of 7 m. Lake Adele was more shallow (2 m depth) but had a similar surface area at 28.2 km^2. Both lakes were characterized by a naturally closed hydrological environment, with inflows exclusively from rainfall in the area of the lakes. Extraction for human consumption and evaporation are the only processes that reduce the volume in the lakes. The rate of human extraction was 35 l/s for 25 years, but during the last 10 years, this was increased to 60 l/s due to higher water needs in the expanding cities served by the water of the lakes. In addition, groundwater is extracted from wells close to the lakes, putting even more pressure on the water levels in the lakes since they are hydraulically connected with the groundwater layers. Furthermore, local residents use the same sources for irrigation of surrounding fields for *khat* production (which is legal in Ethiopia), especially in the dry season. By doing this, they further degrade the lake's water quality since large quantities of pesticides are used for growing *khat*, which are leached to the lake and to the wells.

The use of water from the lakes should be seen as an intervention in the natural rainfall-evaporation cycle. Indeed, evaporation accounts for the largest loss of water, as calculated by Alemayehu et al. (2007). Sediments also reduce the lakes' volume in a natural way, at a rate of 1.2% per year (10 cm sludge sedimentation per year). It should be remarked that this is in fact largely due to deforestation, which is a side effect of population growth and urbanisation in the region.

However, the additional non-natural abstractions on top of this make the lakes unsustainable. The ever increasing abstraction has led to a complete disappearance of the Lake Haromaya (in 2005) and Lake Adele (in 2003). Urban water supply now depends on exploitation of non-renewable groundwater layers, and is about to lead to a water crisis.

In this case, it should be concluded that the local urban population exceeds the capacity of available natural water resources. The situation is currently dramatic in Harar, where hardly any urban water supply is still functioning (UN Habitat 2009).

A further example of natural limits to population growth and urbanization is Lake Chad in Northern Africa, once bordered by four countries (Chad, Niger, Nigeria and Cameroon). After Victoria Lake this is the largest fresh water reservoir in Africa. Its size is naturally variable because it is highly sensitive to the amount of precipitation; between 1400 and 1910 four periods of drought occurred. Its hydrological system covers a total land area of 2.5 million km^2 and used to border the Sahara desert in the north. The local climatological conditions lead to evaporation of ca. 2,300 mm/year. Salts are leached to underlying groundwater layer, which are extensively used for consumption (Odada et al. 2005).

Since the middle of last century, the yearly precipitation has declined, and contributing rivers are smaller. At the same time, exploitation of the water from contributing rivers and the lake itself has increased drastically. At the beginning of the twenty-first century, the lake had a surface area of 1,350 km^2, compared to 25,000 km^2 in 1963 (Coe and Foley 2001). In 1991, approximately 22 million people were living in the Lake Chad area in major cities such as N'Djamena, Kano, Maiduguri and Maroua. At a growth rate of 2.4 to 2.6%, the population is now estimated to be 37 million (Odada et al. 2005). It is anticipated that this number will grow to 56 million in 2020. N'Djamena, capital of Chad, is a typical example for this region. Urbanisation started very slowly, with little or no population growth or economic progress until Chad's independence in 1960. In 1958 the total population was 53,000, but in 1960 this was already 90,000. The civil war urged many people to the cities. The number of inhabitants continued to increase, to 130,000 (1973), 531,000 (1993) and 728,000 (2000). The infrastructure in N'Djamena dated back to colonial times and had no chance to be upgraded due to the speed of population growth and lack of a good economic and political climate (Zeleza and Eyoh 2003).

Currently the water crisis in the region is evident. Fishing and agriculture on the land that is inundated in wet seasons are the main sources of income for the local population. People moved along with the receding water. However, too many people try to get hold of a too small land strip; and on top of this, the fact that Lake Chad bordered four different countries in the past makes this a problem with international dimensions. The 'prior in time is prior in right' principle is now causing increased tensions in the region, and between countries. Niger and Nigeria today have already conflicts on the use of water from the Komadougou-Yobé river system.

The water balance of the lake is quite simple, although extremely variable: the total inflow in recent times has varied between 7 km^3/year (1984/1985) and 54 km^3/year (1955/1956). The inflow comes from the Chari-Logone river system (90%) and the Komadougou-Yobé river system (10%) in the south (Onyekakeyah 2008). The outflow is only due to evaporation and human abstraction. However, it is extremely difficult to pinpoint the cause of the drastic decline of the lake. In a UN report (Fortman and Oguntola 2004), mass balances were made and it can be concluded that at all times the natural inflow equals the sum of evaporation and infiltration (in the period before 1970 and in the period 1971–1991). Details are given in Table 3. This should lead to the conclusion that the lost water is entirely due to human activity. This may not be entirely correct; another report (Coe and Foley 2001) suggests that human impact causes 50% of the effect, whereas climate change would be responsible for the remaining 50%. The effect of climate change on urban water use has also been outlined by O'Hara and Georgakakos (2008), in the case of San Diego, CA, USA.

Table 3 Mass balance of Lake Chad in the period before 1970, and in the period 1971–1991 (Fortman and Oguntola 2004)

	Inflow/outflow (in km^3/year)	
	Average before 1970	Average 1971–1991
Inflow		
Chari/Logone	37.8	21.8
Komadugu/Yobé	1	0.4
El Beid and other rivers	1.2	0.2
Total inflow from rivers	40	22.4
Precipitation on the lake surface	6	2.1
Total inflow	46	24.5
Outflow		
Evapotranspiration	43	23.1
Infiltration	3	1.4
Total outflow	46	24.5

Human extraction is not included in this table

Taking into account that ca. 10 km^3 of water is used for irrigation, the human impact can be understood. Furthermore, water from contributing rivers is also increasingly used for human consumption; while the average value for the contribution of the Chari-Logone river system in 1971–1991 was still above 20 km^3/year, it went down to 10–15 km^3 in the 1990s (Coe and Foley 2001). A possible approach for estimating the impact of water abstraction from the lake and rivers is through simulation of different scenarios. On this basis, Coe and Foley conclude that the decreased surface of the lake is significantly fastened, in addition to the climatological effects It can also be clearly seen that the flow of Chari River is drastically influenced by water abstraction since 1985 (Coe and Foley 2001). In fact, the inflow from the Chari/Logone river system has steadily increased again since the mid-1980's until 2008, to reach the level of the early 1970's (Mana 2009). This is a clear evidence of the impact of human abstraction on the size of the lake, since the shrinking process did not stop or reverse after the mid-1980's.

It could be argued that the human impact is only partly due to urbanization and population growth; the remaining part is linked to agricultural and industrial activities. However, population growth causes more other activities as well, so that they are intrinsically linked.

A partial answer could be in increasing the efficiency of urban water supply. For example, in the city of Kano (Nigeria), the urban water supply system relies on a large reservoir that is filled every year in the rainy season. By doing this, much of the water is lost during the rest of the year by evaporation. In Kano as well as in growing cities like N'Djamena, better infrastructure is needed to improve the situation and stop the shrinking of the lake (second cause of water shortage identified in this manuscript). However, the main conclusion in this case is that there is an upper limit to the water extraction from Lake Chad and the catchment area of the contributing rivers systems, and this limit is insufficient to provide water to the current population in the cities in the area of the lake.

A large scale plan for saving Lake Chad, the Lake Chad Replenishment Project (LCRP), has been developed by the Lake Chad Basin Commission (a collaboration between Niger, Nigeria, Chad and Cameroon), which involves a water transfer from the Congo River to the Fafa-Ouham River in the Central-African Republic, and further on to Lake Chad. This would involve a dam on the river Oubangui in Palambo, and a long canal. From the analysis made in this paper it is clear that this is not a sustainable solution. The real causes, i.e., population growth and lack of infrastructure, should be considered. The natural limits imposed by the availability of water should be acknowledged, and the social and ecological impact of large projects such as the LCRP should be well known beforehand. At this moment, financial support for the LCRP is missing.

5 Interaction Between Factors: Comparative Study of London, Los Angeles and Kinshasa

The three factors that influence the availability of clean water in urbanized regions in developing countries are, as discussed above, the rate of population growth, the lack of infrastructure and the upper limits to naturally available sources. When considering the expansion of a city, these three factors will interact in a complex interplay. This is particularly the case in large urban centres in developing countries, but the same analysis can be made for the development of western cities. This will be shown through a comparison of three cities that developed in a totally different context, i.e., London, Los Angeles and Kinshasa.

The recorded history of London (UK) started in the thirteenth century, when it was a settlement with 40,000 inhabitants. By 1666 this number reached 500,000; it was then the largest city in Europe. Bristol, the second city in England, had a population of 30,000 (Hansen 2009). Further growth of the city was relatively slow: the population was 630,000 in 1715 and 740,000 in 1760 (see Table 4). High mortality rates tempered population growth.

The city developed along the Thames and local side rivers of the Thames. Streets were narrow and were used as an open sewer. Daily life was centered around the river, which was to be considered London's main street. Public latrines were on bridges over the Thames. The water from the river was used for all purposes, including drinking; anyone who could afford it, bought water taken upstream by carriers.

A change occurred in the nineteenth century: better hygiene and sanitation came together with better housing and food supply, so that life expectancy grew steadily. In the nineteenth century, London's population increased by a factor of 6.5.

Throughout the centuries many large waterworks have been carried out. 'The Great Conduit', a pipeline that brought fresh water from sources outside London, served the city, including the first public fountain. Another large scale project was a canal that carried water from the Herfordshire-source of Chadwell and Amwell over a distance of 60 km, the 'New River'. Although changed, the New River still plays a role in London's water supply. In the nineteenth century a water supply network was set up over a total length of 1,000 km, carrying 550 Mm^3/day.

The sewerage system started more recently, after cholera outbreaks in 1832 and 1849. Much of the system is still Victorian, although it has been continuously expanded.

The history of Los Angeles (USA) is totally different. The city was only founded in 1781, by 44 Spanish colonists. In 1845, Los Angeles took over from Monterey as the capital of Mexican Alta California; in 1850, after the American–Mexican war, it became part of the USA. In 1860, Los Angeles had a population of 4,399 (Brief History of El Pueblo de Los Angeles 2009). At the end of the nineteenth century,

Table 4 Population of London through the history (www.londononline.co.uk)

Year	Population
1666	500,000
1715	630,000
1760	740,000
1801	1,096,784
1821	1,378,947
1841	1,948,417
1861	2,803,989
1881	3,815,544
1899	6,528,434
1939	8,615,245
2006	7,512,400

exponential population growth began (Table 5; LA Almanac 2009). From 1900 to 2000, the population increased by a factor 37.

In the early days of Los Angeles, the small local L.A. River was sufficient. However, this could not sustain the exponential population growth in the twentieth century. Large waterworks were initiated, transporting water from Owens Valley through an aqueduct (1913), extended to Mono Lake (1940) and further extended in 1963. Many other initiatives were taken to transport water to the region, including the Colorado River Aqueduct, the Central Valley Project and the State Water Project. All of these served to make the unlimited population growth in Los Angeles necessary, by providing water to the city and to the agricultural land in Southern California (Carle 2000). Today the climate for these large infrastructure works has changed in the sense that people are aware of potential adverse effects, and more attention is going to water recycling (recharge of aquifers with treated wastewater) and desalination projects. The philosophy, however, remains the same: water is a key commodity and requires (large) investments. A similar approach, but much earlier in history, has been seen in Tokyo (Japan). This city, formerly called Edo, developed in the sixteenth century as a so-called castle town for samurai (the high city) surrounded by the low city built along canals on reclaimed delta land, referred to as the 'city of water'. The low city was not built in a totally unaltered natural setting, but made possible by diverting dangerous rivers like Tone River to the eastern seaboard (De Graaf and Hooimeijer 2008). Further land reclamation resulted in a planned, checker-board style urban organisation of units with a fixed size. Thus, the current city is the result of large scale infrastructure and expansion works that have taken place a long time ago, in the period from the sixteenth century until the Second World War. The non-organized way of urban development, related to the private ownership of paddy fields, is therefore supported by existing infrastructure for water supply that has been developed during many centuries. Challenges for Tokyo are therefore different than for the three cities under consideration here: water supply is secured, but lack of inundation areas—which may entail flooding in urban areas—is a risk. Sanitation infrastructure is more recent; enormous problems with water pollution appeared in the 1960's. As a result, a sewage system was initiated, but only 16% was connected in 1970. The number of connections grew steadily, to reach 64.7% in 1998 (De Graaf and Hooimeijer 2008).

Table 5 Evolution of the population of Los Angeles, CA (LA Almanac 2009)

Year	Population
1900	102,479
1910	319,198
1920	576,673
1930	1,238,048
1940	1,504,277
1950	1,970,358
1960	2,479,015
1970	2,816,061
1980	2,950,010
1990	3,485,398
2000	3,694,820
2006	3,849,378

Kinshasa, capital of the Democratic Republic of Congo (D.R. Congo), is located on the southern bank of the Congo River, 350 km inland. The river was navigable up to this point, further to the Atlantic Ocean, rapids and waterfalls made navigation impossible. Similar to Los Angeles, it is a very young city. In 1889 the population was barely 500, but more people moved in when the railroad to the coast was finished in 1898. By 1919, the population reached 14,000 (Kimbuta 2007). A large increase started in the period 1940–1960, when the population was already at 443,000. During the following decades, the population was close to doubling in every decade. Due to political instability and civil wars no exact numbers are available, but an estimate is given in Table 6, with a projection until 2025 (UN-ESA 2008). From ca. 1920 to 2020, the population will have increased by a factor 1,000.

Kinshasa depends on the Congo River for its water supply. The Congo has a total length of 4,370 km and a catchment area of 3.68 million km^2. The average runoff is 1,320 km^3/year, which makes it the largest river in Africa and the third worldwide. The average flow is 41,250 m^3/s, to be compared with the Nile at 1,700 m^3/s (Shiklomanov and Rodda 2003).

The responsibility for water supply in urban regions lies with REGIDESO (Régie de Distribution d'Eau de la République Democratique du Congo). Much of the infrastructure dates back to colonial times (1930–1960) and is archaic. In the 1960s, international support allowed doubling of the number of connections to the water supply system, and the hydraulic infrastructure was extended in the period between 1970 and 1990. However, international development programmes were suspended in the beginning of the 1990s due to civil wars and instability. Recent numbers for Kinshasa indicate that 85.5% of the population have access to safe water and 78.2% to sanitation (UN-ESA 2008). However, these numbers are unreliable. Furthermore, an estimated 40% of the water is lost through defects in pipes and connections, and the quality of the supplied water is doubtful. Installations are old and not well entertained, in some parts of the city the infrastructure is absent, and many people cannot afford connecting. A sewage system is non-existing; open ditches transport storm water to the river. These ditches are generally blocked by waste so that stagnant pools develop, which are ideal breeding places for malaria mosquitoes. This water is, although heavily contaminated, used for clothes washing and even drinking.

A comparison of the three factors identified in this paper for London, Los Angeles and Kinshasa is summarized in Table 7. The first point of comparison is the rate of population growth. In London, population growth was relatively slow. Compared to Kinshasa, it took over 200 years to have the same increase (from ca. half a million to ca. four millions) as was obtained in 30 years in Kinshasa. Los Angeles comes in

Table 6 Estimate of the population of Kinshasa, DR Congo, since 1950, and prediction of the population until 2025 (UN-ESA 2008)

Year	Population
1950	202,000
1960	443,000
1970	1,070,000
1980	2,053,000
1990	3,448,000
2000	5,485,000
2010	9,052,000
2020	13,875,000
2025	16,762,000

Table 7 Comparison of factors causing water supply problems for London, Los Angeles and Kinshasa

	London	Los Angeles	Kinshasa
Population growth	Relatively slow	Fast	Very fast
Infrastructure for water supply	Gradual extension	Large-scale projects	Failing and outdated infrastructure
Availability of water sources	Feasible with external sources	Alternative solutions needed (desalination, water recycling)	Unlimited

between (ca. 100 years). In this period, London had high mortality rates due to the absence of clean water and hygiene. This, however, was due to ignorance and was gradually improved after the discovery of the infection mechanisms of e.g., cholera. Today this knowledge is present, but yet no plans for improved water supply and sanitation in Kinshasa are made. Kinshasa today is much like nineteenth century London, and not even up to this point: REGIDESO supplies 213 Mm^3 water to 19.14 million people in (all) cities, while 550 Mm^3 was supplied in 1876 London to ca. three million people. This is a lesson to be learnt from the London case: action is required to transform the city into a modern, sanitized centre. It should be remarked that the gradual construction of infrastructure in London combined with privatisation has left behind a historical heritage where many pipes are old and leaking; an estimated 28% of the water in London is wasted through leaking pipes (London Assembly Committee 2006). Furthermore, London is still faced with population growth: there were almost 600,000 more people living in London in 2004 than 1991, and the population is due to rise by a further 800,000 by 2021. This makes new investments necessary to avoid new droughts; currently, a large-scale desalination plant under construction in Newham, East London to supply 140 million litres of water per day to meet the daily needs of up to one million people in case of droughts (Thames Water 2009). Large scale waterworks such as this desalination plant, or as carried out in Los Angeles, are beyond the financial possibilities of a city like Kinshasa, but a more gradual approach, similar to nineteenth century London should be feasible. Lessons to be learnt from the case of London are certainly related to maintenance of the system, which has not been carried out well in London. Keeping this in mind, the gradual approach should be of great use for Kinshasa. International funding and collaboration are required, but when looking at the third factor discussed in this paper, water availability, it is evident that Kinshasa can be self-supporting on condition that the infrastructure is there. Looking at the Los Angeles case, it is clear that the exponential growth could only be handled because of large investments in water infrastructure. At this moment, the question is raised even in Los Angeles whether the rate of population growth is sustainable. Comparing with Kinshasa, it should be concluded that measures to stop the expansion of the city are necessary, allowing to go at a more realistic pace.

The potential of Kinshasa as a large city in terms of water supply and sanitation is undisputable. A simple calculation, assuming a daily consumption of 100 l of fresh water per person per day and recalculated to total use by assuming that 58% of the water is used for households (WHO 2000), yields a total volume of 2,890,000 m^3/day for the projected number of inhabitants for Kinshasa given in Table 6. This is only a tiny fraction of the 3.56 billion cubic meter flow of the Congo River.

6 Conclusions

The challenge of water supply and sanitation in urbanized regions in developing countries is evident. Causes are not easy to pinpoint, since they are a complex interaction between various factors. In this paper, three interrelated factors have been identified: (1) a high rate of population growth, (2) lack of infrastructure and investments in infrastructure, and (3) limitations to natural water resources. It must be understood that these factors can be significantly influenced by e.g., political decisions, instability, poverty, and (civil) wars. The latter two tend to make people flee to large cities. Therefore, control of urbanization and water supply and sanitation in urbanized regions is only possible in the context of political and military stability, which is often not the case in developing countries. Once this is achieved, plans for investments with international support are feasible and can be carried out at steady pace, keeping sustainability in mind and in conjunction with programmes to reduce population growth. Furthermore, a realistic estimate of the upper limit of the natural sources should be made.

References

Alemayehu T, Furi W, Legesse D (2007) Impact of water overexploitation on highland lakes of eastern Ethiopia. Environ Geol 52:147–154

Amacher GS, Ersado L, Grebner DL, Hyde WF (2004) Disease, microdams and natural resources in Tigray, Ethiopia: impacts on productivity and labour supplies. J Dev Stud 406:122–145

Biswas AK (2006) Water management for major urban centres. Int J Water Resour Dev 22(2):183–197

Carle D (2000) Drowning the dream—California's water choices at the millennium. Westport, Connecticut

City of Los Angeles (2009) Brief history of El Pueblo de Los Angeles. http://www.ci.la.ca.us/elp/media/mycity/MyCityPgs9_12.pdf

Coe MT, Foley JA (2001) Human and natural impacts on the water resources of the Lake Chad basin. J Geophys Res 106(D4):3349–3356

Cohen B (2006) Urbanization in developing countries: current trends, future projections, and key challenges for sustainability. Technol Soc 28:63–80

De Graaf R, Hooimeijer F (2008) Urban water in Japan. Urban water series vol. 11. Taylor & Francis, London

Dejenie T, Asmelash T, De Meester L, Mulugeta A, Gebrekidan A, Risch S, Pals A, Van der Gucht K, Vyverman W, Nyssen J, Deckers J, Declerck S (2008) Limnological and ecological characteristics of tropical highland reservoirs in Tigray, Northern Ethiopia. Hydrobiologia 610:193–209

Fang CL, Bao C, Huang JC (2007) Management implications to water resources constraint force on socio-economic system in rapid urbanization: a case study of the hexi corridor, NW China. Water Resour Manag 21(9):1613–1633

Fortman MP, Oguntola JA (2004) Lake Chad basin, GIWA regional assessment 43. University of Kalmar, Kalmar

Gleick PH (2009) The world's water: the biennial report on freshwater resources 2008–2009. Island Press, Washington

Hansen RD (2009) Water-related infrastructure in Medieval London. http://www.waterhistory.org/histories/london/london.pdf

He B, Wang Y, Takase K, Mouri G, Razafindrabe BHN (2009) Estimating land use impacts on regional scale urban water balance and groundwater recharge. Water Resour Manag 23(9):1863–1873
Hoekstra AY, Chapagain AK (2008) Globalization of water: sharing the planet's freshwater resources. Blackwell, Malden
Khatri KB, Vairavamoorthy K (2007) Challenges for urban water supply and sanitation in the developing countries. Symposium: water for a changing world—enhancing local knowledge and capacity. UNESCO-IHE, Delft
Kimbuta A (2007) Programme du gouvernement provincial de Kinshasa 2007-2011. République Democratique de Congo, Ville de Kinshasa
LA Almanac (2009) Historical resident population 1850–2000. http://www.laalmanac.com/population/po02.htm
London Assembly Committee (2006) www.london.gov.uk/assembly/reports/health/londons-drought.rtf
Mana B (2009) Inter basin water transfer project from the Oubangui River to Lake Chad. Presented at the World Water Week, Stockholm, pp 16–22
National Research Council (2003) Cities transformed: demographic change and its implications in the developing world. National Academies Press, Washington
Odada EO, Oyebande L, Oguntola JA (2005) Lake Chad—experience and lessons learned brief (Lake Basin Management Initiative). http://www.iwlearn.net/publications/ll/lakechad_2005.pdf/view
O'Hara JK, Georgakakos KR (2008) Quantifying the urban water supply impacts of climate change. Water Resour Manag 22(10):1477–1497
Okbazghi Y (2008) Water resources and inter-riparian relationships in the Nile Basin. State University Press, Albany
Oki T, Kanae S (2006) Global hydrological cycles and world water resources. Science 313(5790):1068–1072
Onyekakeyah L (2008) Lake Chad: a study of a drying fresh water body. http://riversymposium.com/index.php?element=ONYEKAKEYAH
Sharma SK, Tyagi PK, Upadhyay AK, Haque MA, Adak T, Dash AP (2008) Building small dams can decrease malaria: a comparative study from Sundargarh District, Orissa, India. Acta Trop 107(2):174–178
Shiklomanov IA (1999) World Water resources and their use. Intergovernmental programme in water resources. http://webworld.unesco.org/water/ihp/db/sh5iklomanov/
Shiklomanov IA, Rodda JC (2003) World water resources at the beginning of the 21st century. University Press, Cambridge
Singh N (2000) Tapping traditional systems of resource management, vol 6, no 3. Habitat Debate UNCHS
Tanawa E, Tchapnga HBD, Ngnikam E, Temgoua E, Siakeu J (2001) Habitat and protection of water resources in suburban areas in African cities. Build Environ 37:269–275
Thames Water (2009) http://www.thameswater.co.uk/cps/rde/xchg/corp/hs.xsl/2802.htm
Thomas S (2009) Urbanization as a driver of change. In: Gospodini A, Brebbia CA (eds) Sustainable city V: urban regeneration and sustainability. WIT transactions on ecology and the environment, vol 117. WIT Press, Ashurst, pp 95–104
UNDP (2006) Human development report 2006: beyond scarcity: power, poverty and the global water crisis. Palgrave Macmillan, New York
UNEP (2008) Vital water graphics—an overview of the state of the world's fresh and marine waters. UNEP, Nairobi
UN-ESA (2008) World urbanization prospects—the 2007 revision highlights. United Nations, Department of Economical and Social Affairs, New York
UN Habitat (2008) State of the world's cities 2008/2009—harmonious cities. Earthscan, London
UN Habitat (2009) Water for African cities, Ethiopia: Hara City programme. http://www.unhabitat.org/categories.asp?catid=499
UN Population Division (2007) World urbanization prospects: the 2007 revision population database. esa.un.org/unup/index.asp
Van der Zaag P, Gupta J (2008) Scale issues in the governance of water storage projects. Water Resour Res 44(10):W10417
Varis O, Biswas AK, Tortajada C, Lundqvist J (2006) Megacities and water management. Int J Water Resour Dev 22(2):377–394

WHO (2000) Water supply & sanitation sector assessment 2000, part II—Democratic Republic Congo. http://www.afro.who.int/wsh/countryprofiles/demrepcongo.pdf
WHO/UNICEF (2006) Meeting the MDG drinking water and sanitation target, the urban and rural challenge of the decade. WHO Press, Genève
Yewhalaw D, Legesse W, Van Bortel W, Gebrie-Selassie S, Kloos H, Duchateau L, Speybroeck N (2009) Malaria and water resource development: the case of Gilgel-Gibe hydroelectric dam in Ethiopia. Malaria J 8:21
Yohannes M, Haile M, Ghebreyesus TA, Witten KH, Getachew A, Byass P, Lindsay SW (2005) Can source reduction of mosquito larval habitat reduce malaria transmission in Tigray, Ethiopia? Trop Med Int Health 10(12):1274–1285
Zeleza T, Eyoh D (2003) Encyclopedia of twentieth-century African history. Taylor & Francis, London