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Modelling Nitrogen and Phosphorus Fluxes in Nairobi City – Kenya

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Abstract With over 3 million people, the city of Nairobi faces several water supply and pollution challenges that are exacerbated by burgeoning slums and informal settlements. This paper analyzed the existing status of urban water-pollutant flows in Nairobi city. A box-flow model was developed to identify the most important pollutants in the urbanized area. Total nitrogen (N) and phosphorus (P) loadings in water were used as indicators for water pollution. The paper found that the commercial and industrial water users are the major emitters of N (45,301 ton/yr) to the environment. This was attributed to Nairobi's majority agro-based industries which release nitrogen rich organic-compounds into the system boundary. Households were major sources of P (2,663 ton/yr) to the environment. Most of the P in wastewater results from the P-rich detergents used for cleaning and washing at the household level. Investment into improved sanitation and wastewater treatment technologies is recommended to ameliorate the amount of nutrient flows into water bodies. Further, prohibiting use of P-rich detergents is important in reducing P emissions. These actions are needed to guarantee safe drinking water supply to the city in order to keep pace with the fast emergent population. An effective multi-sectoral approach to environmental conservation can provide higher sustainability in the long-term.

Keywords: *Nitrogen, phosphorous, water flows*

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1. Introduction

Increased stress on the world's water is affecting quality, quantity, and availability and as societies develop, this tends to increase water and energy consumption [1]. According to [1,2], many cities in developing and emerging countries are expected to grow rapidly in the next decades. Climate change is a key stressor on water quality, quantity and availability with the poor populations bearing the brunt of the impacts. The emergent economies require integrating adaptation responses into development planning, which includes improvements in water and sanitation, an important way to address climate change. Human-induced changes to the cycling of water and nutrients in terrestrial ecosystems can significantly affect the sustainability of food production, the state of the natural resource base, and the health of the environment [3].

According to [4], the city of Nairobi faces an enormous challenge in providing adequate public sanitation facilities, sewage disposal, and refuse collection, a problem that is compounded as the population increases. Improperly treated sewerage and uncollected garbage have contributed to a vicious cycle of water pollution, water-borne diseases, poverty, and environmental degradation. The main drivers being increasing urbanization due to rural-urban migration, rising standards of living and rapid development associated with population growth. There is insufficient water supply and a rapid growth/sprawling of slums and informal settlements. These settlements pose a big challenge particularly in the provision of piped water and sewerage services. The high demand leads to frequent water supply failures and pipeline loses because of illegal connections particularly in the slums and unlicenced car-wash vendors. People are forced to resort to obtaining water from sources whose quality cannot be guaranteed. The sewer coverage in the city is below 40% [5]. The old and poor infrastructural conditions and lack of maintenance lead to frequent sewer out-bursts and over-flows along the streets and residential areas. The sewage finds its way into the treated water system, particularly due to cross connections between the water and sewage systems. The situation leads to grave challenges that intensify environmental degradation, pollution, deprived sanitation and a strain on the few existing sanitary facilities. The end result is the contamination of water sources including piped-water supplies. The objective of this paper was therefore to analyze the existing status of urban pollution and water flows in the city of Nairobi. Availability of this information is critical for future urban-water planning and management.

2. Study Site

The city of Nairobi has an area of about 700 km^2 at the south-eastern end of Kenya's agricultural heartland with an altitude of 1,600 to 1,850 m above sea level [6]. [4,7] reported that the city enjoys a temperate tropical climate with two rainy seasons. Highest rainfall is received between March and April, and the short rain season is between November and December. The average annual rainfall ranges from 1200 -1600 mm. The mean daily temperature ranges between 12 and 26°C. It is usually dry and cold between July and August, but hot and dry in January and February. The mean monthly relative humidity varies between 36 and 55 percent. The mean daily sunshine hours varies between 3.4 and 9.5 hours. The cloudiest part of the year is just after the first rainy season, when, until September, conditions are generally overcast with drizzle. The western part of the city is the highest, with a rugged topography, while the eastern side is lower and generally flat. The Nairobi, Ngong, and Mathare Rivers traverse numerous neighborhoods and the indigenous Karura forest spreads over parts of Northern Nairobi (Figure 1).

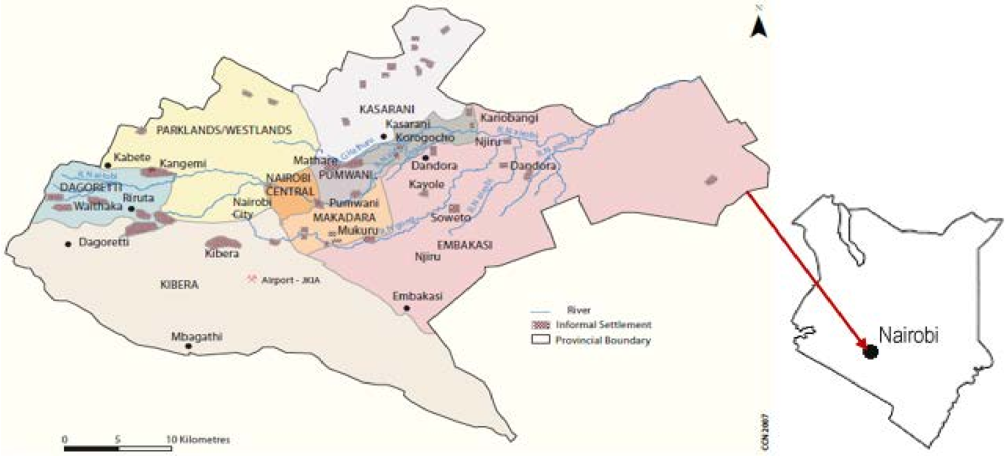

Figure 1. Study area - Nairobi Watershed and City Boundary

Nairobi's fast growth increased the demand for land has led to land speculation, forcing the poor to settle in fragile and unsavory areas where they face hardships due to a lack of proper housing and public services and where they are vulnerable to natural hazards.

Urban poverty, lack of employment opportunities, and inadequate urban planning have also conspired in the gradual growth of informal settlements in Nairobi since the city's founding. There were a total of 134 informal settlements with 77,589 structures with population of over 1.8 million by 1995 [4,7,8]. The water supply and sewerage services are provided by the Nairobi Water and Sewerage Company (NWSC) under the supervision of the Athi Water Services Board (AWSB). The NWSC pumps piped-water from Ndakaini, Ruiru, and Susumua dams which are the principal sources of drinking and industrial water for Nairobi. These dams are all on rivers emanating from the Aberdare Forest about 50 km away, and are important water sources in Kenya. Disposal of untreated waste from domestic, commercial, and industrial premises into unprotected surface watercourses and wetland areas pollutes subsurface water posing a danger to human health and leading to eutrophication, deoxygenation and habitat modification of the riverine system [7,8]. Surface water is heavily polluted with a variety of pollutants such as agro-chemicals, heavy metals, and microbial as well as persistent organic pollutants [7]. The domestic water users with proper water supply connections are a paltry 42 percent of households [7,8]. Residents living in slum areas bear the brunt from the lack of piped-water supply. In such neighborhoods, water is obtained from water vendors, with often illegal connections or directly from the water bodies. Several factors compromise the city's water quality, ranging from natural phenomena such as the high fluoride content in groundwater, to anthropogenic factors such as poor wastewater treatment and environmental degradation both within the city and in the surrounding countryside.

The NWSC ability to manage the city's wastewater has been overwhelmed by the increasing demands from the growing population and its inadequate capacity to treat the amount of domestic, industrial and municipal effluent entering the Nairobi River and other surface waters. Nairobi River and its tributaries are no longer potable or fit for many other useful purposes. Wastes from the slums and a number of factories in Nairobi's industrial area discharge directly into the Ngong River, making it the most polluted river in Kenya. Simply put, the river is an open sewer (Figure 2).

Figure 2. Trash and garbage wash down the Nairobi River that cause pollution of the water here and downstream

Effluents from industry include petro-chemicals and metals from micro-enterprises and so called "Jua-kali". Run-off from the city's road networks and paved areas also contribute oil and grease into adjacent waters [4]. Solid wastes from households and the informal settlements that have no public waste collection services also ends into the river as does sewage from pit-latrines and other on-site sewerage-disposal methods. Inadequately treated effluent from the Dandora Sewage Treatment Plant (DESTW), burst sewer systems and several drainage channels that gather storm water from Nairobi City worsen the situation. Sanitation infrastructure and facilities in most slums is either very basic or simply lacking. In many informal settlements, the water supply and sanitation system consists of open earth drains, communal water points, shared pit-latrines, and no systematic solid-waste disposal. In addition to locally generated water pollution, further effluents enter the river tributaries from anthropogenic activities further afield. Future sanitation planning by authorities in Nairobi need to pay attention to the “Bellagio Principles for Sustainable Sanitation” endorsed by the members of the Water Supply and Sanitation Collaborative Forum in November 2000 [9].

[9] reported major pollution points of organic, solid waste, and heavy metal pollutants within the Nairobi River Basin. Polluted water carries both environmental and health risks to communities within Nairobi, especially the poor who may use untreated water in their homes and to irrigate their gardens. Peasants along the Nairobi River and its tributaries commonly use polluted waters and raw sewage for irrigation, exposing both farm workers and customers who consume the food crops to potential health problems such as diarrhea and helminthic infections [4]. Almost half of the vegetables consumed in the city of Nairobi are grown on the banks of polluted rivers. All these impacts affect human health and productivity and challenge Kenya’s ability to reach targets under the Millennium Development Goals”.

3. Methodology

3.1. Mass Flow

A mathematically conceptualized material flow analysis (MFA) implemented in Microsoft Excel was used in this paper. It quantifies and models the material flows of the system considered based on MFA [2]. The method of MFA describes the fluxes of resources used and transformed as they flow through a region, through a single process or via a combination of various processes. It analyzes the flux of different materials through a defined space and within a certain time. In industrialized countries, MFA has proved to be a suitable instrument for early recognition of environmental problems and development of solutions to these problems [2]. The significance of the method lies in the overview that can be obtained on the entire system [10]. The scientific basis is the law of conservation of mass [2]. The MFA procedure was iterative and required stepwise checking and continuous adaptation during the whole procedure as summarized in Figure 3.

[2,11,12,13] provided the definitions of terminology as used in this paper:

Substance: Any compound (chemical) composed of uniform units. All substances are characterized by a unique and identical constitution and are thus homogeneous. Example, N and P considered in this paper are substances.

Good: Substances or mixtures of several substances with functions valued by men. Example, drinking water, solid waste and wastewater.

Process: The transformation, transport, or storage of substances or goods. Example, private households where inputs are converted to excreta, solid waste, emissions, etc. A wastewater treatment plant (WWTP) in which wastewater is transformed to treated effluent, sewage sludge and gases. Agriculture is also a transformation process in which, among others, N from the atmosphere is fixed as organic-N in crops. Example of storage process is the landfill where most of the wastes are stored.

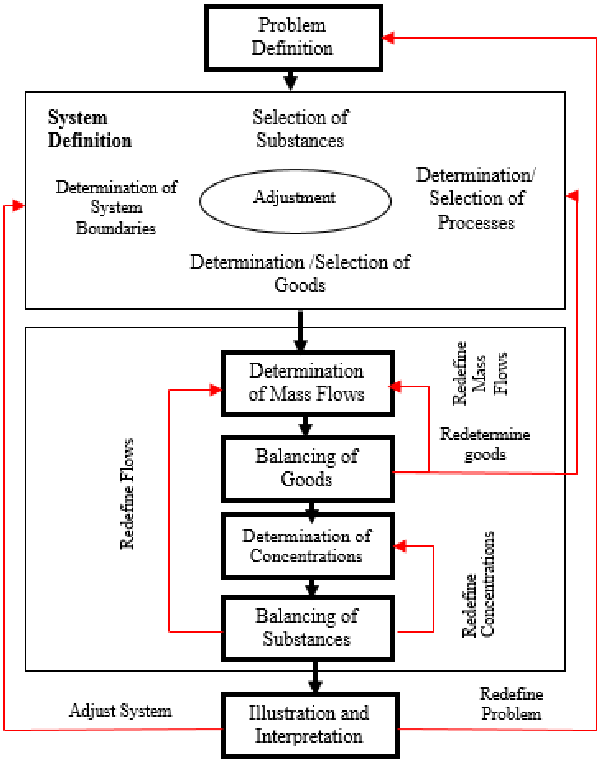

Figure 3. Flow Chart for MFA Procedure

3.2. Water Balance

A water balance of the system was derived by water inflows and outflows from the system boundary (Figure 4). For an urban system the following equation applies:

$$R + P + I = ET + D + O \pm \Delta S \qquad (1)$$

Where R=Rainfall, P= Pipe-water supply, I= other system inflows, ET=Evapotranspiration, D= Drainage of stormwater, O= other system outflows, and ΔS= Storage change of soil and aquifer.

Equation (1) provided the basis for the model development and was applied in the computation of subsequent flows expressed in million cubic meters per annum (MCM/yr).

3.3. Substance (Pollutant) Flows

Two indicator substances; N and P which also formed the main pollutants found in wastewater were chosen for simulation in order to derive annual pollutant loads [tons/yr] into the environment, groundwater and surface waters. Large inputs of nutrients especially N and P arising from human activities into rivers can lead to eutrophication, adversely affecting the ecology and limiting the use of rivers for drinking water supplies and recreation [14]. N and P could possibly be correlated with other pollutants in wastes, e.g. pathogen growth is limited by N and P levels, and increased nitrate levels in drinking water are a risk to human health. N and P are easier to model (especially P). Even though N is dynamic, it is more practical to model than highly dynamic pollutants such as pathogens. Flows provided in the defined system matrix were as follows: **input flows, I_j, internal flows $F_{i,j}$** and **output flows O_i**; where: i and j denoted balance volumes at origin and destination. Figure 4 shows all the possible mass flows i.e. rainfall, groundwater, and surface-water and piped-water supply which constituted inflows. These were used by the various processes before leaving the system in different forms as groundwater, surface water and ET. The defined system considered the pollutants within its boundary.

3.4. Model Selection and Development

The method of MFA was selected for the case study. MFA is a tool used for the analysis and description of the material balances of a system [2]. At the beginning of a MFA, the following questions were addressed for the system analysis:Which goods and processes are considered? What are the system boundaries? and What time period should be modelled?

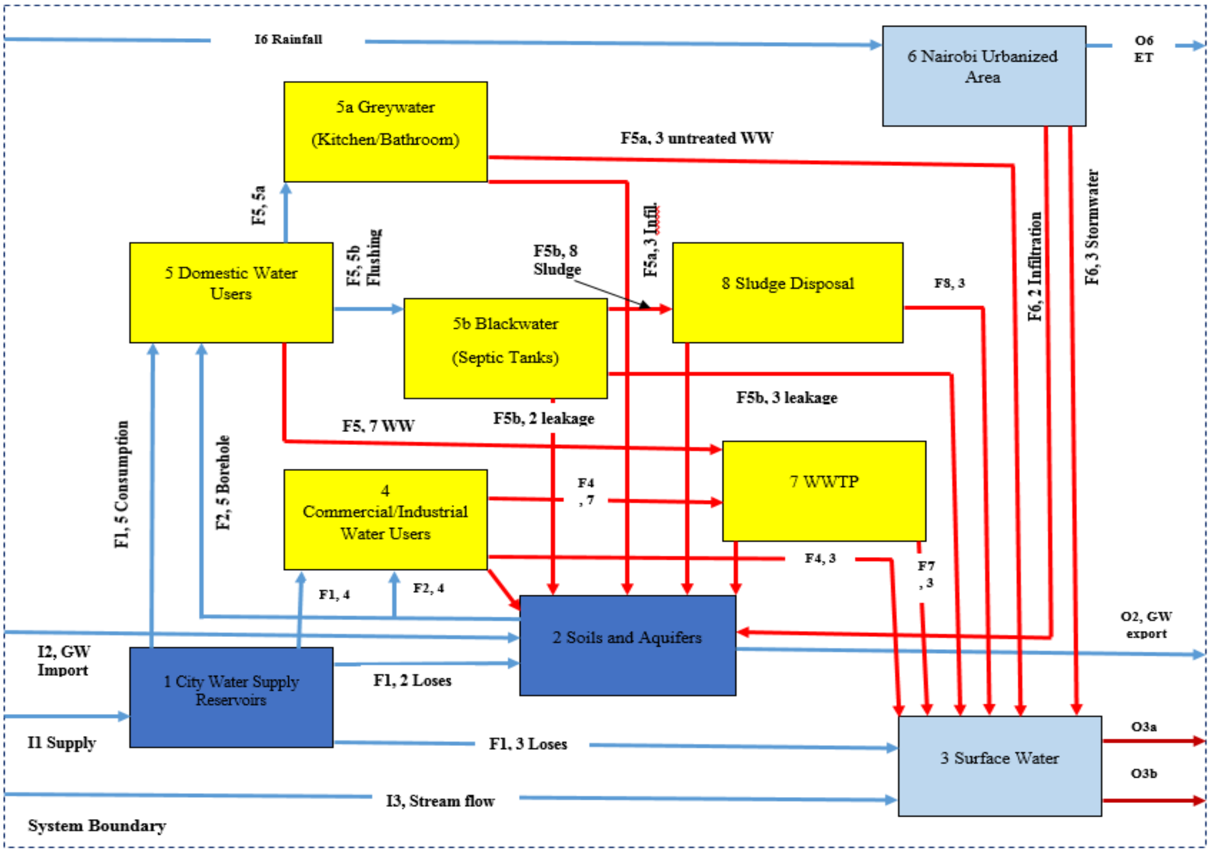

Figure 4. Nairobi MFA Scheme and system boundary

Key: Yellow box – water utilization processes, **blue box** – fresh water sources, **light blue box** – processes with potential outflow points, **blue arrow** – freshwater flows and **red arrow** – potentially polluted water flow.

A material flow matrix based on N and P elements was developed in order to get insight into anthropogenic water pollution by nutrients for a period of one year. Even though this time step fails to capture seasonal changes, it is important since storage change for most goods is basically assumed zero. The modeled system was conceptualized as a process of flows containing boxes and arrows. Figure 4 shows the Mass Flow Scheme for the urbanized area of Nairobi.

Boxes either represent water bodies, water users or a compartment involving water pollution or treatment. Arrows represent the water and pollutant flows between two boxes. Water flows were expressed in MCM/yr, N and P in metric tons per year (ton/yr or simply as t/yr), respectively. In this context, processes were denoted either as system inflows (I), internal flows (F) or outflows (O) and were shown as arrows in the schematic showing the system analysis (Figure 4). The elements called "goods" by [11], were visualized as boxes and represent an imaginary unit where materials were stored, consumed or produced.

3.5. Definition of Processes

Processes in the system (Figure 4) considered were represented by boxes, also referred to as balance volumes. These are system segments in which flows were computed and are basically pathways for water and pollutants/substances. They included the following:

Drinking water from piped supply- the four main reservoirs supplying Nairobi with drinking water as shown in box marked 1 (Figure 4), namely; Ndakaini, Ngethu, Sasumua dams and Kikuyu Springs abstraction points. All the drinking water supply is pumped into the Kabete treatment works from where it is distributed to the rest of the city. The supply volume used in this paper was therefore the sum of the four reservoirs into the treatment works at Kabete.

Soil and Aquifers (box 2) receive, infiltrate and constitute the groundwater source. The soil adsorbs pollutants/nutrients on its particle surfaces, while water infiltrates to the aquifers and therefore acts as a sink for pollutants/nutrients.

Surface water (box 3) is the Nairobi River Basin constituting Ngong, Mathare and other small tributaries. These are subjected to extreme levels of pollution ranging from agricultural fertilizers (agricultural sector was not considered in this paper) and raw domestic sewage, to industrial waste. In a number of cases, solid and liquid waste from these sources are reportedly discharged directly into the river system having undergone no pre-treatment whatsoever, thereby severely damaging the river ecology as well as posing serious risks to human health. The rivers themselves are now considered an environmental health hazard due to the high concentrations of chemical and bacteriological pollution. However, despite this, nearly half of the urban population one way or another, dependent on them as a source of water for especially urban agriculture, domestic use and in the worst cases, for drinking [[4]]. Due to relatively short retention time assumed to be one day, de-nitrification is negligible (which is a fairly quick process especially under these conditions). The flow of groundwater between processes may be difficult to ascertain and thus requires a detailed hydro-geological assessment. Hence, the mass stock change found in this paper is only an indicative value which needs to be used carefully.

Non-Domestic water users (box 4) include wastewater generated from industries, institutions, commercial sector and agriculture. A component of which, may also be used for domestic purposes and can be accounted for if the per capita consumption is calculated to include domestic water.

Domestic water users (box 5) refers to water use at the household level. It constitutes sullage mainly from sanitation and other households' purposes such as cleaning, cooking, washing, bathing, watering, etc. [15] reported that 60 per cent of the total wastewater generated from households' world over is greywater (box 5a). The other component is blackwater (box 5b) which refers to wastewater resulting from use of water closets (WC) and other forms of toilets. Its main inputs are feces and urine while the outputs include constituents of N and other pollutants such as P. Pollutant sources from both grey and blackwater include organic wastes, detergents, and soap among other compounds. In 1995 the rural per capita water demand for sub-Sahara Africa, with households connected to the water supply system was 18.8 m^3/yr while for urban households was 29.2 m^3/yr translating into 51.5 liters/capita-day (l/cap/d) and 80 l/cap/d, respectively [16]. For Nairobi, per capita water consumption can be estimated at 60-80 l/cap/d depending on the social class of individuals [7]. In this paper, the value of 60 l/cap/d was chosen since Nairobi faces inherent and unreliable water supply to populations. Water supply failure and rationing is a norm to residents. Records showed that water consumption in 2007 was 476,603 m^3/day [5].

The Nairobi urbanized area (box 6) generates surface run-off (stormwater) and groundwater recharge from precipitation. Pollutants emanate from atmospheric deposition, washed out pollutants of organic nature (resulting from open defecation), run-off from small scale agriculture around the city and the illegal solid waste dumping. The urbanized area can contribute extraneous water into sewer flows during wet weather of 10 % to 100% of total sanitary flows (Qs), (Krebs, 2007, personal communication). For this study, an estimated value of 94 MCM/yr was used for wet weather of the total annual precipitation runoff of 313 MCM/yr.

Fecal sludge disposal (box 8) constitutes sludge from on-site treatment systems and dry sanitary systems. The Nairobi sludge disposal involves underground or emptying into the main sewer line. Other sources of sludge include the dry sanitation systems such pit-latrines, ventilated improved pits (VIP) toilets, pour flush among other technologies.

The Nairobi WWTP (box 7) is situated about 33 km from the city center and receives wastewater from the approximately 40 percent population connected to sewers. However, a considerable portion of the collected sewage is lost through sewer outbursts and infiltration to soils and aquifers. Hence, the final yearly amount of treated wastewater is far less than what can be expected from the connected population.

3.6. Modeling Procedure

A model was developed and implemented in Microsoft Excel for the simulation of material flows. Eight-seven equations were developed to model water, N and P flows. These equations are discussed in section 3.12.

3.7. Model Plausibility

Sensitivity analysis is important in identifying sensitive parameters in a model. It shows the change of a variable upon change of a parameter (model input). If the value of a material flow reacts strongly on the change of a certain parameter, this parameter is called sensitive. Analysis of sensitive parameters is important in scenario modelling and more attention should be devoted to the selection of sensitive parameters to improve model predictions. System equations are described in the preceding chapters. An analysis of parameter sensitivity and plausibility was simulated and assessed. It showed the change of box stock rates and material flows when all parameters are increased or decreased. This was helpful in assessing the behavior of non-linear relationships and to prepare and improve the system for the development of scenarios. However, scenario development was not the goal of this paper, thus sensitivity analysis will not be discussed any further in this paper. Additionally, this model was not a dynamic MFA model and parameter conditions were assumed static.

3.8. Data Acquisition and Calibration

For the anthropogenic system boundary considered in this paper, a one year investigation data provides adequate steady state simulation [2]. The primary data were acquired through personal interviews with the NWSC staff. Secondary data were requisitioned through existing literature search on Nairobi and elsewhere in Sub-Sahara Africa from cities with similar characteristics as Nairobi. The NWSC [5] provided data on water demand, distribution, sewer network and the wastewater treatment.

The modelling data were analyzed to provide input for important model parameters and coefficients for the simulation, and where no data were available reasonable assumptions and estimations were made. This was due to the fact that MFA can be assessed based on assumptions and cross-comparisons between similar systems and the law of mass conservation of matter applied on each process [2,10]. Following the above, in MFA the reliability of data must be carefully questioned.

3.8.1. Water Supply Data

Table 1 shows the NWSC water demand for the year 2007 [5]. The actual water demand in Nairobi is 640,00 m^3/day, however for the last several years the production capacity of the NWSC has remained at about 476,000 m^3/day [5,15]. Of the 476,000 m^3/day nearly 40 percent is lost due to illegal connections and leakages [15].

Table 1. Summary of Nairobi Piped-water Demand

Year	Ngethu	Kabete	Sasumua	Kikuyu	Average
2007	[m3/d]	[m3/d]	[m3/d]	[m3/d]	[m3/d]
Jan	398,440	22,318	2,283	4,000	427,041
Feb	368,998	22,854	60,663	4,000	456,515
Mar	413,024	21,755	-	4,000	438,779
Apr	388,452	22,070	54,792	4,000	469,314
May	409,818	18,804	54,792	4,000	487,413
Jun	415,488	22,247	49,490	4,000	491,225
Jul	409,084	21,411	54,792	4,000	489,288
Aug	414,801	23,134	53,266	4,000	495,201
Sep	413,267	22,308	53,967	4,000	493,543
Oct	410,834	21,866	55,509	4,000	492,209
Nov	404,077	21,045	55,737	4,000	484,860
Dec	412,804	20,116	56,928	4,000	493,848
Average production Jan. 2007 - Dec. 2007					476,603

3.8.2. Baseline Pollutant Data

Some of the secondary data and other valuable information used to derive certain parameters and transfer coefficients for the simulation runs are discussed in Table 2 and Table 3 (presented later in section 3.10).

3.9. Derivation of Key Parameters and Coefficients

3.9.1. Run-off

The water balance was computed using equation (1). The typical values of runoff coefficient were obtained from [16] and used to estimate the run-off /stormwater. The run-off coefficient for the improved/developed area of Nairobi (which includes all the paved surfaces and roads) was estimated at 0.5 and for unimproved 0.2 constituting the unpaved residential areas and informal settlements and vegetated areas was estimated at 0.2. Since there were no data for the impervious surface, stormwater generating surface was estimated at 0.5. The value took into consideration the fact that in developing cities like Nairobi, streets are not well paved and are generally characterized by bare ground beyond the road shoulders and sometimes around buildings.

3.9.2. Groundwater Recharge and Abstraction

According to [17], the estimated upstream groundwater re-charge was estimated at 25 MCM/yr and rate of abstraction at 31 MCM/yr, respectively This translates to a daily abstraction rate of 84,932 m^3/day. However, across and within the city boundary the soil infiltration is highly variable depending on soil type, so this value should be used with care and a more certain figure needs further detailed investigation.

3.9.3. Evapotranspiration

Nairobi has very tall buildings were assumed to interfere with normal Evapotranspiration (ET) and wind movement processes. Thus, the tall buildings act as windbreaks which significantly reduce the actual ET. The Real Evapotranspiration (ETR) refers to the sum between the quantity of water evaporated from soils and the quantity of water evaporated from the vegetation, when the soil is at actual specific humidity and vegetation being at real physiological and sanitary growing stages. From the foregoing definition, it is rather difficult to ascertain the ETR for a large basin like Nairobi. It receives an annual rainfall range of 1200 – 1600 mm (the upper watershed areas receive rain up to 2400mm) [4,7]. The actual ET therefore depends on the location in the basin. Across the city, one can observe high variability of climatic zones eastwards, with the western side being wetter than the eastern. The meteorological data for the 2007/08 simulation period were obtained from the Kenya Meteorological Station and used to estimate the ETR. A pan coefficient of Kc-Pan = 0.7, was applied to find a ETR currently estimated at 1190 mm per annum (developed areas) and for forested areas (510 mm). Based on this information, an estimated actual ET value of 580 mm/yr was determined and used in this paper.

3.10. Mass Flow from Households

Data on population distribution across the city suburbs were obtained from [8,18,19,20]. The data were useful in estimating the substances flows across the city.

3.11. Model Parameters and Transfer Coefficients

Transfer coefficients describe important ratios and constants required in the computation of the material flows within the model system. These provided the apportioning of the substances in the different processes that gave the percentage of the total throughput of the considered substance transferred into specific output goods. Most of the fundamental parameters and coefficients necessary for this simulation are presented in Table 2 and Table 3. Where no data were available, reasonable assumptions were made or data were adapted from similar research in other fast growing African mega cities elsewhere.

3.12. Derivation of Flow Equations

The different mass flows considered were denoted as Parameter P_n^j, for j= W, N and P.

Where: W=water for all balance volumes n, N= total nitrogen, P= total phosphorous.

All mass flows were developed based on the schematic in Figure 4, and parameters and coefficients used to derive equations discussed in the next sections are all defined and presented in Table 2 and Table 3.

Table 2. Model Parameter values and description for pollutant flow

No	Name	Description of Parameter	Unit	Mean	Source
P01	k_blackwater_GW	GW percolation of blackwater	-	0.58	Est
P02	k_runoff_dev	Run-off coefficient for developed area	-	0.5	Est;[21]
P03	k_runoff_undev	Run-off coefficient for undeveloped	-	0.2	Est;[21]
P04	k_dom_ WW_GW	Fraction of greywater to GW (GW)	-	0.3	Est
P05	k_GW_dom	GW consumed by households from total GW abstracted	-	0.45	Est
P06	k_GW_recharge	Coefficient of GW re-charge	-	0.14	Est;[17]
P07	k_non-dom_WW_GW	Fraction of non-domestic waste to GW	-	0.25	Est
P08	k_perc_TP	Percolation of effluent at WWTP	-	0.1	Est
P09	k_pipe_dom	Fraction of pipe water to domestic users	-	0.42	Est [5]
P10	k_pipe_non-dom	Fraction of pipe water to non-domestic users	-	0.38	Est
P11	k_pipe_surf_loss	physical losses to surface water	-	0.1	Est;
P12	k_dom_WW_SW	Fraction of domestic WW to surface	-	0.6	Est;
P13	k_non_dom_treated	Fraction of Non-domestic WW that is treated	-	0.6	Est
P14	k_pop_sewage	Fraction of the population connected to the sewer system	-	0.4	Est;[5]
P15	k_open_defaecation	Fraction of population practicing open and indiscriminate defecation	-	0.03	Est;[22]
P16	P_actual_ET	Estimated actual evapotranspiration	mm/yr	580	Est;[23]
P17	P_black_water	Per capita blackwater generation	m³/cap/yr	5	Est;[24]
P18	P_per_cap_GW	Per capita GW consumption	l/cap/d	30	Est
P19	P_per_cap_tap	Per capita pipe water consumption	l/cap/d	60	Est;[24]
P20	P_GW_non-dom	Non-domestic fraction of GW use	MCM/yr	15.48	Est
P21	P_no_trucks	Registered number of sewage exhausters	yr-1	1000	Est
P22	P_pop	Population living within the boundary system	millions	3.15	[25]
P23	P_rainfall	Average mean annual rainfall	mm/yr	1400	[4, 26]
P24	P_truck_vol	Average volume of a desludging truck	m³	7	Est
P25	P_upstr_WS	Area of watershed upstream of study area ref. base point	ha	47,300	Est;[8]
P26	P_urb_area	The Nairobi urbanized area	ha	22,330	[8]
P27	P_Kabete_prod	Treated drinking water supply from the Kabete reservoir less losses	MCM/yr	175.7	[5]
P28	P_pipe_ GW_loss	Physical losses to GW	-	0.18	Est;[5]
P29	Qe	Extraneous water into sewer line	MCM/yr	94.31	Est
P30	P_coeff_soil_storae	Coefficient of soil-water storage	-	0.525	Est
P31	k_pollutant_GW	portion of pollutants to GW	-	0.3	Est
P32	k_sanitat_GW	pollutants from sanitary flows to GW	-	0.2	Est
P33	k_sanitat_SW	pollutants from sanitary flows to SW	-	0.35	Est;[4]
P34	k_uncollect_garbage	Fraction of uncollected solid waste (incl. Illegal dumping)	-	0.4	Est;[4]
P35	k_Swaste_SW	Fraction of solid waste to surface water	-	0.3	Est
P36	P_per cap_waste	Amount of solid waste per cap per day	kg/cap/yr	146	[4]

Key: GW- groundwater, WWTP- Wastewater Treatment Plant, SW- Surface water, WW-wastewater and MCM/yr- million cubic meters per year, Est- Estimation refers author´s results

Table 3. Transfer coefficients

Transfer coefficients			Unit	Mean		Source
No	Name	Description of parameter		N	P	
P37	k_pollutant_waste	pollutant fraction of solid waste	-	0.01	0.01	[2,26]
P38	P_storm_water	pollutant conc. in stormwater	mg/l	3	0.3	[2,26]
P39	P_FS_effluent	pollutant conc. in FS effluent	mg/l	1600	24	[27,28]
P40	P_faecal_sludge	pollutant conc. in faecal sludge	mg/l	3500	650	[28,29,30,31]
P41	P_conc_reservoir	pollutant conc. in tap water	mg/l	0.5	0.56	[32]
P42	P_non_dom_users	pollutant conc. in non-domestic flows	mg/l	620	18	Est; [33]
P43	P_nairobi_upstream	Average pollutant conc. in Nairobi river upstream	mg/l	5	3	Est; [32]
P44	P_conc.sewage	pollutant conc. in sewage including effect of extraneous water	mg/l	40	21	[32]
P45	P_conc.GW	pollutant conc. in GW	mg/l	5	1.5	Est
P46	P_effluent_WWTP	unbiodegraded pollutant conc. in effluent	mg/l	16	10.92	Est; [32]
P47	P_cap_yr	Pollutant excretion per cap/yr	kg/cap/yr	3.5	0.52	[30,34,35]
P48	P_detergents	P use per capita from detergents	kg/cap/yr		0.18	
P49	P_deposition	N and P deposition from Atmosphere	kg/ha/yr	7.5	0.7	
P50	P_conc_dom_ww	Conc. of domestic WW for the given consumption	mg/l	159.82	23.74	Est

The different inflows into the system boundary relate to inputs of the considered parameters. Where necessary, units were converted using conversion factors to form the stated units in the results. The inflow into the urbanized (developed) area was mainly as a result of rainfall and atmospheric deposition of N and P, thus:

$$I_6^W = P\_rainfall*P\_Urb\_Area/10^5 \qquad (2)$$

$$I_6^N = P\_N\_deposition*P\_Urb\_Area/10^3 \qquad (3)$$

$$I_6^P = \text{P\_P\_deposition*P\_Urb\_Area}/10^3 \quad (4)$$

Run-off from upstream of the system boundary was derived by use of a run-off coefficient for undeveloped area:

$$I_3^W=\text{P\_upstr\_WS*P\_rainfall*k\_runoff\_Undev}/10^5 \quad (5)$$

$$I_3^N = I_3^W * \text{P\_N\_Nairobi\_upstream} \quad (6)$$

$$I_3^P = I_3^W * \text{P\_P\_Nairobi\_upstream} \quad (7)$$

The upstream groundwater recharge for Nairobi was estimated as 25 MCM/yr, with transmissivity of 5 – 50 m²/day [[17]]. It can then be assumed that the average groundwater flow cannot be higher than groundwater recharge in the upstream area. This is true for a long-term groundwater recharge with a change in storage equal to zero within one year flow regime:

$$I_2^W = P_{\text{\_upstr\_WS}} * P_{\text{\_rainfall}} * k_{\text{\_GW\_recharge}}/10^5 \quad (8)$$

$$I_2^N = I_2^W * P_{\text{\_N\_GW}} \quad (9)$$

$$I_2^P 2= I_2^W * P_{\text{\_P\_GW}} \quad (10)$$

Water supply to the main treatment works at Kabete was simply given by its production to the distribution system:

$$I_1^W= \text{P\_kabete\_prod} \quad (11)$$

Whereas the NWSC conducts surveillance on leakages within the distribution system and carries-out repairs, a substantial amount of water is lost through undetected leakages for a pipe network buried underground, illegal connections by car wash and other vendors. Physical losses and illegal connections within the distribution system describe losses to soils and aquifers (F1, 2) and surface water (F1, 3) computed as follows:

$$F_{1,2}^W = \text{k\_pipe\_ GW\_loss* P\_kabete\_prod} \quad (12)$$

$$F_{1,3}^W = \text{k\_pipe\_surf \_loss* P\_kabete\_prod} \quad (13)$$

Losses due to transmission were assumed to occur outside the boundary system since the abstraction points are about 50 km away, while treatment works losses were considered negligible. The water demand data provided by [[5]] were used during the estimation of piped-water supply to non-domestic (F1,4) and domestic (F1,5) water users, respectively:

$$F_{1,j}^W = x * I_1^W - (F_{1,2}^W + F_{1,3}^W) \quad (14)$$

$$F_{1,j}^N = F_{1,j}^W * \text{P\_N\_res\_upstream} \quad (15)$$

$$F_{1,j}^P = F_{1,j}^W * \text{P\_P\_res\_upstream} \quad (16)$$

Where j = mass flows to box 4, 5 (Figure 5) and x = k_pipe_non_dom (box 4) and k_pipe__dom (box 5), respectively.

Groundwater abstraction in Nairobi was estimated at 31 MCM/yr [[17]]. Certain sectors within the non-domestic users such as schools, industries abstract their own water from the groundwater sources and thus, it was imperative that groundwater use is accounted for:

$$F_{2,4}^W = P_{\text{\_GW\_non-dom}} \quad (17)$$

$$F_{2,4}^N = F_{2,4}^W * P_{\text{\_N\_GW}} \quad (18)$$

$$F_{2,4}^P 4 = F_{2,4}^W * P_{\text{\_P\_GW}} \quad (19)$$

For domestic water users groundwater is commonly used especially by households not connected to piped-supply and some neighborhoods use borehole water for back-up in the event of municipal water supply failure:

$$F_{2,5}^W = P_{\text{\_Pop}} * k_{\text{\_GW\_dom}} * k_{\text{\_per\_cap\_GW}} * 365/1000 \quad (20)$$

$$F_{2,5}^N = F_{2,5}^W * P_{\text{\_N\_GW}} \quad (21)$$

$$F_{2,5}^P 4 = F_{2,5}^W * P_{\text{\_P\_GW}} \quad (22)$$

The infiltration and ex-filtration of surface water into the ground and vice versa depends on the seasonal variation between wet days and dry days of the year. Ex-filtration is predominant when flow F3,2 is negative and thus, the following equation was applied to flows between the ground and surface waters:

$$F_{3,2}^W = I_3^W + \Sigma(F_{1,k}^W + F_{l,3}^W) - \Sigma O_m^W \quad (23)$$

where k = 2,3; l = 4, 5a,b, 6,7,and 8; and m = 3a,b.

$$F_{3,2}^N = F_{3,2}^W * P_{\text{\_N\_GW}} \quad (24)$$

$$F_{3,2}^P = F_{3,2}^W * P_{\text{\_P\_GW}} \quad (25)$$

The following equations explain the mass flows associated with the internal flows and discharges into the soil and aquifers and surface water:

$$F_{4,2}^W = (F_{1,4}^W + F_{2,4}^W) * \text{k\_non} \\ -\text{dom\_WW\_GW} * (1 - \text{k\_non} - \text{dom\_treated}) \quad (26)$$

$$F_{4,2}^N = F_{4,2}^W * \text{k\_non\_dom\_WW\_GW} \\ * (1 - \text{k\_non} - \text{Dom\_treated}) * \text{P\_N\_non} - \text{dom} \quad (27)$$

$$F_{4,2}^P = F_{4,2}^W * \text{k\_non\_dom\_WW\_GW} \\ * (1 - \text{kNon} - \text{Dom\_treated}) * \text{P\_P\_non} - \text{dom} \quad (28)$$

$$F_{4,3}^W = (F_{1,4}^W + F_{2,4}^W - F_{4,2}^W - F_{4,7}^W) \quad (29)$$

$$F_{4,3}^N = = F_{4,3}^W * P_{\text{\_N\_non-dom}} \quad (30)$$

$$F_{4,3}^P = F_{4,3}^W * P_{\text{\_P\_non-dom}} \quad (31)$$

$$F_{4,7}^W = (F_{1,4}^W + F_{2,4}^W) *) * k_{\text{\_non-dom\_treated}} \quad (32)$$

$$F_{4,7}^N = = F_{4,7}^W * P_{\text{\_N\_non\_dom}} \quad (33)$$

$$F_{4,7}^P = F_{4,7}^W * P_{\text{\_P\_non\_dom}} \quad (34)$$

Box 5 (domestic water) provides the sub-boxes box 5b (black water) and box 5a (greywater generated from the remaining domestic supply). Quantity of blackwater produced by households connected to a sewage system is allocated to the box 5b. The corresponding substance flow equations are:

$$F_{5,5b}^W = \text{P\_black\_water*P\_Pop} / 10^6 \quad (35)$$

$$F_{5,5b}^N = \left(\frac{F_{5,5b}^W}{F_{1,5}^W + F_{2,5}^W}\right) * (F_{1,5}^N + F_{2,5}^N) \quad (36)$$

$$F_{5,5b}^P = \left(\frac{F_{5,5b}^W}{F_{1,5}^W + F_{2,5}^W}\right) * (F_{1,5}^P + F_{2,5}^P) \quad (37)$$

$$F_{5,5a}^W = F_{1,5}^W + F_{2,5}^W - F_{5,5b}^W \quad (38)$$

$$F_{5,5a}^N = \left(\frac{F_{5,5a}^W}{F_{1,5}^W + F_{2,5}^W}\right) * (F_{1,5}^N + F_{2,5}^N) \quad (39)$$

$$F_{5,5a}^P = \left(\frac{F_{5,5a}^W}{F_{1,5}^W + F_{2,5}^W}\right) * (F_{1,5}^P + F_{2,5}^P) \quad (40)$$

Flows and substances from the domestic box (5a) were then derived and apportioned into different destinations- surface water, groundwater or WWTP:

$$F^{W}_{5b,2} = F^{W}_{5,5b} * \text{k\_blackwater\_GW} \tag{41}$$

$$F^{\mathbf{N}}_{5b,2} = F^{W}_{5b,2} * \text{k\_N\_sanitat\_GW} * \text{P\_N\_cap\_yr} * \text{P\_pop} * 1000 \tag{42}$$

$$F^{\mathbf{P}}_{5b,2} = F^{W}_{5b,2} * \text{k}_{\text{\_P\_sanitat\_GW}} * \text{P}_{\text{\_P\_cap\_yr}} * \text{P}_{\text{\_pop}} * 1000 \tag{43}$$

Flows and substance into groundwater from greywater are derived as follows:

$$F^{W}_{5a,2} = F^{W}_{5,5a} * \text{k}_{\text{\_dom\_ WW\_GW}} \tag{44}$$

$$F^{N}_{5a,2} = \text{P\_percap\_waste} * \text{P\_pop} * \text{k\_Swaste\_SW} * \text{k\_N\_waste} * 1000 * \text{k\_dom\_ WW\_GW} \tag{45}$$

$$F^{P}_{5a,2} = \begin{pmatrix} \text{P\_detergents} + \text{P\_percap\_waste} \\ * \text{k\_Swaste\_SW} * \text{k\_P\_waste} \end{pmatrix} * \text{P\_pop} * 1000 \; * \text{k}_{\text{\_dom\_WW\_GW}} \tag{46}$$

Flows and substances into Surface water result from:

$$F^{W}_{5b,3} = (F^{W}_{5,5b} - F^{W}_{5b,2} - F^{W}_{5b,8}) * \begin{pmatrix} 1 - \text{k\_black\_water} \\ - \text{k\_pop\_sewage} \end{pmatrix} \tag{47}$$

$$F^{N}_{5b,3} = \text{k\_N\_sanitat\_SW} * \text{P\_N\_cap\_yr} * \text{P\_pop} * 1000 \tag{48}$$

$$F^{P}_{5b,3} = \text{k\_P\_sanitat\_SW} * \text{P\_P\_cap\_yr} * \text{P\_pop} * 1000 \tag{49}$$

$$F^{W}_{5a,3} = F^{W}_{5,5a} * (1 - \text{k\_dom\_WW\_GW}) * (1 - \text{k\_pop\_sewage}) * (1 - \text{k\_pop\_septic}) \tag{50}$$

$$F^{N}_{5a,3} = \text{P\_percap\_waste} * \text{P\_pop} * \text{k\_Swaste\_SW} * \text{k\_N\_waste} * 1000 * (1 - \text{k\_dom\_WW\_GW}) \tag{51}$$

$$F^{P}_{5a,3} = \begin{pmatrix} \text{P\_detergents} + \text{P\_percap\_waste} \\ * \text{k\_Swaste\_SW} * \text{k\_P\_waste} \end{pmatrix} * \text{P\_pop} * 1000 * (1 - \text{k\_dom\_WW\_GW}) \tag{52}$$

Material flows due to sludge disposal from on-site sanitation facilities:

$$F^{W}_{5b,8} = \text{P\_truck\_vol} * \text{P\_no\_trucks} / 10^{6} \tag{53}$$

$$F^{N}_{5b,8} = F^{W}_{5b,8} * \text{P\_N\_faecal\_sludge} \tag{54}$$

$$F^{P}_{5b,8} = F^{W}_{5b,8} * \text{P\_P\_faecal\_sludge} \tag{55}$$

Material flows to the WWTP:

$$F^{W}_{5,7} = \text{P\_per\_cap\_tap} / 10^{9} * 365 * \text{k\_pop\_sewage} * \text{P\_pop} \tag{56}$$

$$F^{N}_{5,7} = F^{W}_{5,7} * \text{P\_N\_conc.sewage} \tag{57}$$

$$F^{P}_{5,7} = F^{W}_{5,7} * \text{P\_P\_conc.sewage} \tag{58}$$

Phosphorus deposition by rainfall onto the soil surface was assumed near equal to the accumulation of the same from stormwater, hence:

$$F^{W}_{6,2} = I^{W}_{6} - O^{W}_{6} - F^{W}_{6,3} \tag{59}$$

$$F^{N}_{6,2} = F^{W}_{6,2} * \text{P\_N\_stormwater} + \begin{pmatrix} \text{P\_per\_cap\_waste} * 1000 * \text{P\_pop} \\ * \text{k\_N\_waste} * \text{k\_uncollect\_garbage} \\ * \text{k\_dom\_WW\_GW} \end{pmatrix} + (\text{k\_open\_defaecation} * \text{P\_pop} * \text{P\_N\_cap\_yr}) \tag{60}$$

$$F^{N}_{6,2} = F^{W}_{6,2} * \text{P\_P\_stormwater} + \begin{pmatrix} \text{P\_per\_cap\_waste} * 1000 * \text{P\_pop} \\ * \text{k\_P\_waste} * \text{k\_uncollect\_garbage} \\ * \text{k\_dom\_WW\_GW} \end{pmatrix} + (\text{k\_open\_defaecation} * \text{P\_pop} * \text{P\_p\_cap\_yr}) \tag{61}$$

Some uncollected domestic waste finds its way into open drains and surface waters. These include open defecation, uncollected garbage, market waste and industrial waste etc. are washed to surface waters during rainfall. Run-off therefore washes significant N and P loads to surface water:

$$F^{W}_{6,3} = I^{W}_{6} - O^{W}_{6} * \text{k\_runoff\_dev} \tag{62}$$

$$F^{N}_{6,3} = F^{W}_{6,3} * \text{P\_N\_stormwater} + \text{P\_per\_cap\_waste} * 1000 * \text{P\_pop} * \text{k\_N\_waste} * \text{k\_uncollect\_garbage} * (1 - \text{k\_dom\_WW\_GW}) + (\text{k\_open\_defaection} * \text{P\_pop} * \text{P\_N\_cap\_yr}) \tag{63}$$

$$F^{P}_{6,3} = F^{W}_{6,3} * \text{P\_P\_stormwater} + \text{P\_per\_cap\_waste} * 1000 * \text{P\_pop} * \text{k\_P\_waste} * \text{k\_uncollect\_garbage} * (1 - \text{k\_dom\_WW\_GW}) + (\text{k\_open\_defaection} * \text{P\_pop} * \text{P\_p\_cap\_yr}) \tag{64}$$

At the wastewater treatment plant there is percolation to the groundwater:

$$F^{W}_{7,2} = (F^{W}_{5,7} + F^{W}_{4,7}) * (\text{k\_Perc\_TP}) \tag{65}$$

$$F^{N}_{7,2} = F^{W}_{7,2} * \text{P\_N\_FS\_effluent} \tag{66}$$

$$F^{P}_{7,2} = = F^{W}_{7,2} * \text{P\_P\_FS\_effluent} \tag{67}$$

Effluent discharge into the Nairobi River is given by the following:

$$F^{W}_{7,3} = (F^{W}_{5,7} + F^{W}_{4,7}) * (1 - \text{k\_Perc\_TP}) \tag{68}$$

$$F^{N}_{7,3} = F^{W}_{7,3} * \text{P\_N\_effluent\_WWTP} \tag{69}$$

$$F^{P}_{7,3} = F^{W}_{7,3} * \text{P\_P\_effluent\_WWTP} \tag{70}$$

Percolation from buried sludge into groundwater ultimately occurs. Nairobi has no sludge treatment plant but the sludge collected from pit latrines, septic tanks and the WWTP is usually buried into the ground or in some cases released into the sewer lines. The impact of this is that there will be percolation and discharge into groundwater and the surface waters. Percolation can be assumed to occur at a rate equal to infiltration of undeveloped land as all the water within the buried sludge finally gets its way into groundwater. Hence the corresponding flows were estimated as follows:

$$F_{8,2}^{W} = F_{5b,8}^{W} * (1\text{-k\_runoff\_undev}) \quad (71)$$

$$F_{8,2}^{N} = F_{8,2}^{W} * \text{N\_effluent\_WWTP} \quad (72)$$

$$F_{8,2}^{P} = F_{8,2}^{W} * \text{P\_N\_effluent\_WWTP} \quad (73)$$

According to Figure 4, there are four outflows from the boundary system: O_6 is the outflow from the urbanized area due to ET, O_2 is outflow due to groundwater export to the peri-urban areas, O_{3a} and O_{3b} are surface water outflows due to system boundary discharge into the Nairobi River and the river upstream flow, respectively. The ET of rainfall within the system boundary is the only flow that transports water but no pollutants.

$$O_6^{W} = \text{P\_actual\_ET*P\_urb\_area}/10^5 \quad (74)$$

$$O_6^{N} = 0 \quad (75)$$

$$O_6^{P} = 0 \quad (76)$$

Groundwater export from the aquifers was estimated as:

$$O_2^{W} = F_{1,2}^{W} + F_{4,2}^{W} + F_{6,2}^{W} + F_{5a\&b,2}^{W} + F_{7,2}^{W} + F_{8,2}^{W} + I_2^{W} - F_{2,4}^{W} - F_{2,5}^{W} * (1 - \text{P\_coeff\_soil\_storage}) \quad (77)$$

$$O_2^{N} = O_2^{W} * P_{\text{\_N\_GW}} \quad (78)$$

$$O_2^{P} = O_2^{W} * P_{\text{\_P\_GW}} \quad (79)$$

Outflow due to the discharge from the urbanized area and other compartments of the boundary system:

$$O_{3a}^{W} = F_{4,3}^{W} + F_{6,3}^{W} + F_{5a\&b,3}^{W} + F_{7,3}^{W} + F_{8,3}^{W} \quad (80)$$

$$O_{3a}^{N} = O_{3a}^{W} * \text{k\_N\_nairobi\_river} \quad (81)$$

$$O_{3a}^{P} = O_{3a}^{W} * \text{k\_P\_nairobi\_river} \quad (82)$$

$$O_{3b}^{W} = I_3^{W} \quad (83)$$

$$O_{3b}^{N} = I_3^{W} * \text{P\_N\_nairobi\_river} \quad (84)$$

$$O_{3b}^{P} = I_3^{W} * \text{P\_P\_nairobi\_river} \quad (85)$$

3.13. Mass Balance

3.13.1. Mass Stock Exchange

The stock change for a one year period for all boxes is assumed zero. However, in the short-term, soils and aquifer store some soil water which was reflected as a mass stock change. The stock change for all processes was defined as the mass balance of inputs minus outputs.

$$B_I^{m} = \sum_{j=1}^{n} I_{j.i}^{m} - \sum_{k=1}^{n} O_{j.k}^{m} \quad (86)$$

n = 10, m=W, N and P, j=number of box; i= box of origin and k = destination box. Stock change of boxes was denoted as B_I^m , with i=number of box, and m=W, N, and P.

The definition of each of the stock exchange is as follows:

Water

The mass stock exchange for water (box1) gets incorporated in the treatment plant, gets lost through ET or infiltrated. However, stock change data was not available and therefore only outflows were considered in the computations.

Nitrogen and Phosphorous

B_2^N and B_2^P → Accumulation of immobile N and P in the top-soil layer. Part of the N stock is lost to the atmosphere, another part to run-off.

B_3^N and B_3^P → Consumption of N by processes such as de-nitrification, ammonia, volatilization and to lesser extent, sediment mineralization and plant incorporation. Some P is adsorbed to clay particles or bound to metallic compounds.

B_4^N and B_4^P → N and P input from imported pollutant sources such as industrial wastes.

B_{5a}^N, B_{5a}^P, B_{5b}^N and B_{5b}^P → N and P that results from excrements and organic wastes with a large fraction of P stock exchange emanating from detergents.

B_6^N and B_6^P → N and P that results from organic wastes within the urbanized area.

B_7^N and B_7^P → N and P accumulating from buried fecal sludge

B_8^N and B_8^P → N and P that accumulates from the fecal sludge in the WWTP, the stabilization ponds call for regular desludging.

4. Results and Analysis

4.1. Water Balance

Table 4 provides detailed modeled mass stock exchange and mass flows across the entire system boundary. For one-year period, the water balance between inflows and outflows was estimated at zero for all the process boxes except for box 2 representing soil and aquifers. The box for the soil and aquifers had a mass storage change of approximately 122 MCM/yr. This value represents the soil moisture content/storage change due to aquifer recharge and soil infiltration.

According to Table 4, the sum of all inflows into the system boundary was 714 MCM/yr which included piped-water supply (I_1 = 176 MCM/yr), groundwater (GW) import (I_2 = 93 MCM/yr), upstream (u/s) inflow (I_3 = 132 MCM/yr) and runoff due to rainfall (I_6 = 313 MCM/yr). In addition to the soil and aquifer storage of 122 MCM/yr, the system discharge to surface water (SW) was 220 MCM/yr, ET (130 MCM/yr), downstream (d/s) flow due to upstream inflow (132 MCM/yr) and GW export (110 MCM/yr). Visualization of these flows are presented in Figure 5.

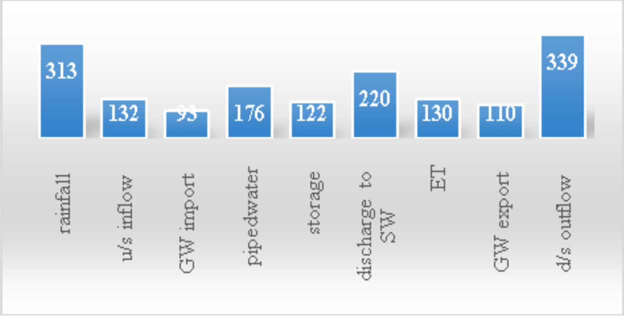

Figure 5. Systems inflows and outflows

u/s = upstream, GW =groundwater, SW =surface water and d/s =downstream.

Table 4. Mass stock exchange and flows from the system boundary

No.	Description	W-flows	N-load	P-load
		MCM/yr	ton/yr	ton/yr
B 1	Kabete reservoir	0	0	0
B 2	Soil and aquifer	122	22,420	949
B 3	Surface water	0	20,273	1,739
B 4	Non-domestic users	0	(45,301)	(1,258)
B 5	Domestic users	0	(15,680)	(2,663)
B 6	Urbanized area	0	(2,406)	(1,174)
B 7	WWTP	0	22,762	1,520
B 8	Sludge disposal	0	5	4
I6	Rainfall	313	167	16
I3	Upstream inflow	132	662	397
I2	Groundwater import	93	464	139
I1	Pipe water supply	176	88	98
F1,3	Losses to surface water	14	7	8
F1,2	Losses to soil and aquifers	21	11	12
F1,4	Pipe water supply to non-domestic users	67	33	37
F1,5	Pipe water supply to domestic users	74	37	41
F2,4	Groundwater abstraction to non-domestic users	15	77	23
F2,5	Groundwater abstraction to domestic users	16	78	23
F5,5a	Greywater discharge	54	52	2
F5,5b	Water supply for sanitation	16	20	11
F4,3	Non-domestic wastewater flow to surface water	31	19,121	555
F4,2	Non-domestic wastewater infiltration	10	797	23
F4,7	Non-domestic wastewater flow to WWTP	41	25,494	740
F5,7	Domestic wastewater flow to WWTP	36	4,876	2,560
F5a,3	Greywater direct flow to surface water	23	166	976
F5a,2	Greywater direct infiltration	22	455	418
F5b,2	Blackwater direct infiltration	9	20,143	2,993
F5b,3	Blackwater direct flow to surface water	0.01	3,859	573
F5b,8	Blackwater carried in sludge	0.01	25	5
F8,3	Sludge effluent flow to surface water	0.01	10	0.15
F8,2	Sludge effluent infiltration	0.01	9	0.13
F7,2	WWTP effluent infiltration	16	261	178
F7,3	WWTP effluent flow to surface water	61	2,347	1,602
F6,3	Stormwater flow to surface water	92	1,691	800
F6,2	Stormwater infiltration	92	882	359
F3,2	Extra-filtration from surface water	21	105	32
O3a	System discharge to surface water	220	27,410	4,515
O3b	Downstream flow due to upstream inflow	132	7,848	1,373
O6 ET	Evapotranspiration	130	-	-
O2	Groundwater export	110	551	165
(O3a + O3b)	Nairobi River downstream outflow	339	35,258	5,888
Note: Quantities under brackets () indicate negative load				

Therefore, the total outflow from the system boundary including the Nairobi River downstream flow was 582 MCM/yr. Together with the soil and aquifer storage this summed up to 714 MCM/yr which is equal to the inflow into the system. The balance confirmed plausibility between system flows and storage.

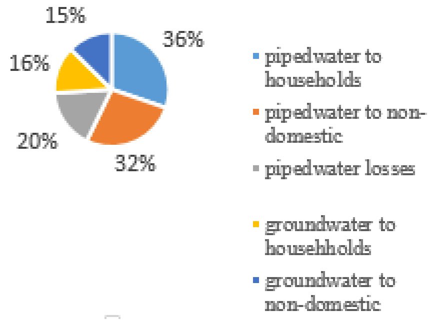

Figure 6. Percent consumption by different sectors

Besides the annual piped-water supply of 176 MCM/yr, an additional 31 MCM/yr of groundwater supply is required to supplement the piped-water. Thus, the overall water supply to the city amounts to 207 MCM/yr (575,000 m^3/day), of which 85% is piped-water and 15% from groundwater sources. Analysis of Table 4 shows that piped-water supply to households and to non-domestic users constitute 36% and 32%, respectively. Piped-water losses to surface water (including illegal connections) amount to 14 MCM/yr (8%) while undetected physical losses to soils and aquifers add to 21 MCM/yr (12%), adding to 20% of total water losses of piped-water. Domestic groundwater consumption is 16 MCM/yr (8% of 207 MCM/yr) and the non-domestic groundwater consumption is 15 MCM/yr (7% of 207 MCM/yr). Based on the current piped-water supply and per capita consumption of 60 l/cap/d of 476, 000 m^3/day; there is presently a deficit of about 36 MCM/wwwyr (99,000

m^3/day). Figure 6 presents a summary of water consumption by the different sectors in the city.

4.2. Wastewater Generation

A total of about 89 MCM/yr of piped and groundwater are used domestically (box 5) annually. Of this amount, approximately 15 MCM yr is used for sanitation purposes and 74 MCM/yr for other domestic activities such as drinking, cooking, cloth-washing, watering and bathing. The wastewater generated by households (grey- and blackwater) collectively add to about 36 MCM/yr (29 MCM/yr: greywater and 7 MCM/yr: blackwater) from the 40% of households connected to sewers. About 23 MCM/yr of greywater generated from the domestic activities (box 5a) flows as untreated wastewater directly into the surface water while 22 MCM/yr either infiltrates directly into the groundwater sources or lost via ET, cooking, house-cleaning, etc. On the other hand, 9 MCM/yr of blackwater infiltrates directly into groundwater sources particularly from households via septic tanks and pit-latrines. A paltry 0.14 MCM/yr is lost directly to surface water or with the sludge disposal from the septics. Overall, wastewater that is treated domestically averages 40%, and 26% is lost as untreated wastewater directly into surface water. About 34% disappears into groundwater sources. However, this value needs to be used only for wet weather flow as during dry weather flow the situation changes drastically and flows may be quite small for dry weather. Due to inadequate information, it was difficult to estimate the dry weather value.

The modeled water supply to the non-domestic users (box 4) from the piped and groundwater sources was 82 MCM/yr of which 31 MCM/yr (38%) of wastewater flows direct to surface water and 10 MCM/yr (12%) to groundwater sources. The remaining 41 MCM/yr (50%) is estimated to flow to the WWTP. The average extraneous water (Qe) during the wet season into the sewer-lines was estimated at 94 MCM/yr. That means that during wet season, the WWTP is subjected to accumulative shock-load of up to 171 MCM/yr from Qe, domestic and non-domestic water users. This value is likely to result into an overflow from the WWTP, further increasing direct loading of pollutants into surface water.

4.3. Pollutant Loadings and Fluxes

In Table 4, values in bracket imply that processes within the boxes 4 through 6 (that is, domestic and non-domestic water users, and urbanized area) pollutant loadings generated within the box are more than the inflow loadings. Pollutants loads flowing into the system boundary are summarized in Table 5.

Table 5. Mass flux in inflows into the system boundary

Mass flux	N (ton/yr)	P (ton/yr)
Rainfall	167	16
GW import	464	139
Piped water	70	78
Upstream inflow	662	397
Total	1,363	630

The N and P loads (Table 5) are mainly emanating from natural processes. For example, the presence of pollutant substances in rainfall is because of atmospheric deposition of these particles in the atmosphere. When it rains pollutants fall to the ground dissolved in rain droplets or adsorbed on dust particles. Upstream inflows and groundwater import get contamination from and anthropogenic activities upstream of the boundary system. Extraneous water from runoff upstream gets its way into piped-water via leaking pipes, and burst pipes. Total N inflow into the system amounts to 1,363 ton/yr, and P load of 630 ton/yr from the upstream is observed.

Anthropogenic processes within the system boundary exacerbate the situation leading to more output at the downstream outflow. In Table 4, N load in the outflow increased twenty six times to a total of 35,258 ton/yr (the sum of load due to upstream and wastewater discharge and stormwater). Likewise, P multiplied itself nine times to 5,888 ton/yr due to anthropogenic influences. It is clearly seen that within the system boundary over 35,000 ton/yr N and almost 6, 000 ton/yr, respectively find their ways into the water cycle of Nairobi City annually. Most of these N and P loadings s in Table 4 are not transported downstream to the outflow. Given the nature of these substances, certain amounts are absorbed by the soil particles particularly P while some N evaporates to the atmosphere. Further, in Table 4 shows that over 27,000 ton/yr of N and 4,500 ton/yr P accumulate into surface water.

4.4. Mass Stock Changes

The mass stock changes occurring between the pollutant producers and consumers within the system are discussed in this section. Table 6 provides an overview of the mass stock changes in the different process boxes.

Table 6. Mass stock changes for the different processes

Process	Box No.	Water (MCM/yr)	N (ton/yr)	P (ton/yr)
Kabete reservoir	1	0	0	0
Soil and aquifers	2	122	22,420	949
Surface water	3	0	20,273	1,739
Non-domestic water	4	0	(45,301)	(1,258)
Domestic water	5	0	(15,680)	(2,663)
Urbanized area	6	0	(2,406)	(1,174)
WWTP	7	0	22,762	1,520
Sludge disposal	8	0	5	4

Note: Quantities under brackets () indicate negative load.

For the domestic, non-domestic water users and the urbanized areas there was generally mass production of N and P loadings within the boxes. These are generally processes within the system where mass is added into the process as solid wastes (garbage) or via greywater, blackwater, fecal waste and open defecation, and urinating in the street alleys. The rate of mass production generally exceeds inflow accumulation within the process and is therefore referred to as producers (quantities under brackets). The soil and aquifers, surface water, WWTP and sludge disposal boxes shows positive stock changes mainly due to load accumulation within the boxes (known as sinks). For instance, the positive stock change in the WWTP occurs because of accumulation of substances from domestic and non-domestic boxes and accumulation of sludge (which in this case acts as a sink).

Producers have accumulative loadings of 63,387 ton/yr N and 5,095 ton/yr P, respectively. The non-domestic, domestic water and stormwater from urbanized area released approximately 71, 25 and 4% of the total N loading, respectively as shown in Figure 7. The reason for the high N produced by the non-domestic water is mainly attributed to the fact that Nairobi has more agro-based industries and would be expected to release nitrogen rich compounds into the system.

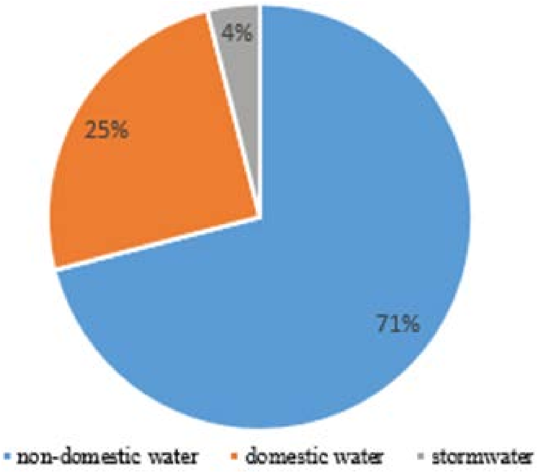

Figure 7. N sources from the different sectors

However, domestic, non-domestic water and stormwater from the urbanized area released 52, 25 and 23% of the total P loading to the system, respectively (Figure 8). The high P load from the domestic water results from use of P-rich detergents at household level for cleaning and washing.

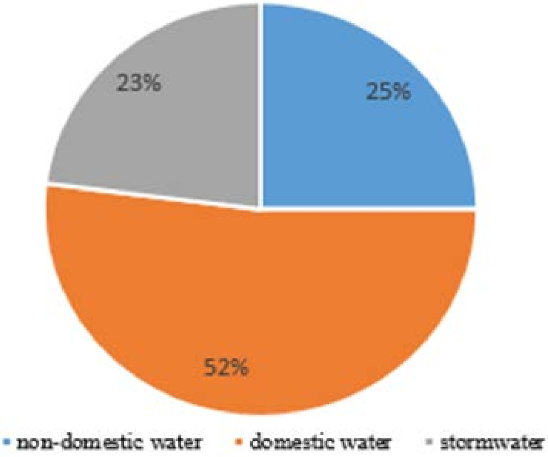

Figure 8. P sources from the different sectors

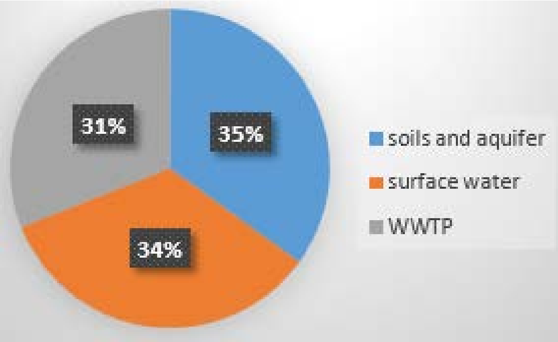

Figure 9. N sinks for the different sectors

When sinks are considered, WWTP, soil and aquifers, and surface water accumulate 35, 34, and 31% of the total N load, respectively (Figure 9).

Similarly, P accumulation is disproportionately apportioned as 22, 41, and 36% for soil and aquifers, surface water, and WWTP, respectively (Figure10).

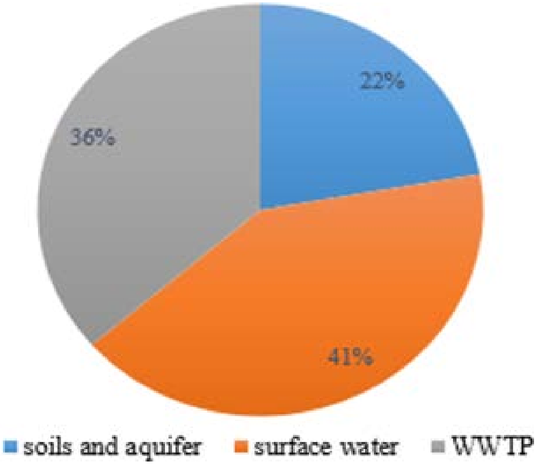

Figure 10. P sinks for the different sectors

A small amount of pollutants was observed to accumulate in sludge due to the fact that there is little adsorption to the sludge surface as most pollutant are dissolved in wastewater that flows to other sinks. For N, WWTP forms the largest sink while surface water forms the biggest sink for P.

4.5. Model Limitations

Access to data was a major factor contributing to the limitations of the model. Limited secondary data on Nairobi city was a big impediment. The unavailability of secondary data implies either little research has been carried out before about the topic on Nairobi or is completely shelved from the public domain. However, the model fairly quantified and captured the magnitude of the relevant mass flows and compared the extent of magnitude of different flows. The trade-off between the quantity of flows and the level of detail of each flow is clear but information on detailed analysis of single flows is not explicit.

5. Conclusions and Recommendations

The current urbanization processes are driven by three global trends: (i) the continued growth of megacities in the developing world, (ii) most population growth occurring in intermediate and small cities for another few decades, and (iii) 95% of the urban growth taking place in the developing world over the next two decades. The city of Nairobi will experience unparalleled population growth that far exceeds its capacity to provide water and sanitation infrastructure, public health and environmental protection. The challenge requires advancing sustainable environmental health technologies of providing sanitation while conserving water especially in the densely populated urban slums. This study found that the non-domestic water users, who include commercial and industrial entities are the major N polluters with an annual load of 45,301 ton/yr N to the environment. This load results from the fact that Nairobi has more agro-based industries and would be expected to release nitrogen rich compounds into the system. The domestic water are on the other hand the major producers of P to the environment with a loading of 2,663 ton/yr, contributed mainly from the detergents containing P, which are used in cleaning and washing at the household level.

This study recommends the following:

- The city should improve its frequency of solid waste collection and street cleaning.
- Ban or regulate detergents that contain P and reduce open urination and defecation.
- Encourage more use of dry sanitation or improved blackwater and greywater treatment to reduce the pollution footprint into the environment.

However, these require high capital investments. Nevertheless, the best options depend on factors such as sources of livelihoods, existing habits and climate, which makes the choice of a sanitation system difficult for a city like Nairobi.

Further, this study recommends future research on the following areas:

- The model did not cover all sectors that contribute to surface water and environmental pollution; it is therefore recommended that future work is required to include the pathways for urban agriculture, the Dandora landfill and other important sources of pollution.
- Future work on household survey to ascertaining the exact per capita drinking water demand in the City.
- A research on micro-organisms in wastewater flows and pollution is necessary to give an insight into the different levels of pollutants within the system boundary contributed by the biological activities.

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List of Abbreviations

AWSB	Athi Water Services Board, government agency charged with the management and licencing of water operators within the Athi River Basin
CCN	City Council of Nairobi, currently Nairobi City County which is the local government for the Nairobi City
DESTW	Dandora Estate Sewage Treatment Works
ET	Evapotranspiration, water lost through open surface and plant cover to atmosphere
GW	Groundwater sources
ha	Hectares, unit of land area
kg/cap/yr	Kilogram per capita per year, amount of substance produced in a year
l/cap/d	Liters per capita per day, amount of water consumed per person in a day
m^3/cap/yr	Cubic meters per capita per yer, amount of water consumed per per person per year
MCM/yr	Million cubic meters per year, volume of mass water flow in a year
mg/l	Milligrams per liter, concentration of a substance
mm/yr	Millimeters per year, amount of water lost through evaporation per year
N	Total Nitrogen, a chemical element
NWSC	Nairobi Water and Sewerage Company, Nairobi Sewer and Water operator
P	Total Phosphorus, a chemical element
ton/yr (t/yr)	Tonnes per year, quantity of a substance released in a year
WW	Wastewater
WWTP	Wastewater Treatment Plant

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