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Exploring the Water-Nutrient-Food Nexus for an African City Region: Linking the Chivero Lake and Harare City Region, Zimbabwe

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Abstract: Some of the most important challenges in the city regions of Africa are related to food, energy, water, and nutrients. To meet these challenges, arguments have emerged that cities should become regenerative, resource-efficient and arrest the decline of ecosystems. Therefore, a case study was performed by considering the linkage between Lake Chivero, and the Harare city region to conceptualize a framework of the water-nutrient-food nexus and to examine how nutrients from the wastewater that is disposed to Lake Chivero can assist in contributing to the food production in the Harare city region. An Applied Systems Analysis (ASA) linked System Dynamics (SD) modelling methodology was used. It is observed that the water supply in the city region, wastewater generation and disposal to Lake Chivero, nutrients, food production, food consumption and wastewater generated from consumption in the city, all work in a feedback mechanism. Premised upon the feedback mechanism, the ASA linked SD model estimates that Lake Chivero has already accumulated about 19,800 tonnes of Nitrogen (N) in its sediments, of which over half can be extracted. To comprehend the significance, it is estimated that 100 tonnes of N might assist in the production of over 35,000 tonnes of food if extracted and utilised in the city region. Therefore, the waste generated in the city region needs to be considered as a resource and recovered, which might turn a recalcitrant problem of pollution into the benefits of resource recovery and environmental and socio-economic wellbeing of the city region.

1. INTRODUCTION

One underlying aspect that is a pre-condition for the well-functioning of the city regions is the issue of resources (food, energy, water, and nutrients). Besides, arguments have emerged that the cities should become regenerative, which while focusing on achieving resource efficiency should ensure that there is no undermining of the ecosystems. Thus, using the case study of the linkage between Lake Chivero and Harare city region, this study conceptualised a framework of the water-nutrient-food nexus and examined how the nutrients from the wastewater, which is disposed to Lake Chivero, can assist in contributing to the food production in the Harare city region - a proposal that is sought to address the challenges of African cities in general, and the challenges of Harare, in particular. In this context the specific research questions investigated are:

- What is the interlinkage between water, nutrient and food in the context of disposal of wastewater from the Harare city region to Lake Chivero?
- How much Nitrogen is available in Lake Chivero, how much can be extracted, and to what extent can it contribute to food production in the Harare city region?

This research intends to provide the city region with a framework to address the challenges for sustainable development considering the particular aspects of water supply, wastewater disposal, nutrient recovery and food production based on Applied Systems Analysis premised on systems theory. In this context, the city region was considered as the system and Lake Chivero, the water, wastewater and agriculture system are the subsystems of the larger city region system. It was envisaged that nutrient recovery (Nitrogen) that is available in the lake because of wastewater disposal can assist in the reduction of pollution of the lake and contribute to food production, thereby contributing to the sustainability of the city region. However, while doing so, only the endogenous factors related to the city region such as water supply, wastewater disposal, lake and food production and consumption system were considered. The exogenous factors such as the impact of climate change, change in socio-economic, industrial systems, etc., were kept out of the scope of the study.

In a city region, there is a defined interaction between what the natural environment produces and how human beings harvest, process, consume and deposit their waste in the landscape (Beck, Villarroel Walker, & Thompson, 2013). For example, food is 'imported' into cities and 'exported' in the form of sewage into rivers and seas. Based on this premise, it becomes apparent that resources tend to get back into the system by ways of recycling or re-use. This realisation has sparked the recent debate that realises the need to re-use the waste produced by humans and their processes so that the so-called waste then finds itself back in the system as inputs to vital processes of life. In this regard, it is argued that there is a need to view Nitrogen (N), Phosphorus (P), Potassium (K) and Carbon (C) related elements from water as resources to be recovered, rather than as pollutants and waste (Beck, Villarroel Walker, & Thompson, 2013)

Harare city region, with the plethora of its energy, water, food and climate change challenges, typifies an African city needing attention to arrest these challenges. The rapid population growth and waning infrastructure have ushered a great mismatch between the supply and demand of infrastructure and services - housing, water and transport being the dominant needs. Besides, the environmental problems of the city region have increased. The range of such challenges includes, but is not limited to waste management, sewer and water systems, and sanitation and urban agriculture. There is also a problem with industrial and raw sewage effluent. Consequently, one of the major sources of water supply and irrigation, Lake Chivero, is polluted because of the unrestricted sewage disposal to it, that however, contains nutrients, such as N, P, K and C and related materials. However, it is argued that the wasted resources of the city, such as those in Lake Chivero, can be viewed as significant environmental assets for the good of the city (Beck, Das et al., 2018).

The water and wastewater reticulation systems in Harare are predominantly centralised. The sewer system is separated, where the sewage is collected and treated before discharging to the watercourses. The domestic wastewater, along with the industrial wastewater that enters the sewerage system with or without pre-treatment or after-treatment, and stormwater and runoff containing nutrients, fertilisers, pesticides, etc., eventually enter Lake Chivero. The lake has a volume of 250,000 megalitres (being 250 × 106 m2) with an average depth of 9.3 meters. The surface area of the lake is 26 square kilometres. The catchment of the lake has an area of about 2,632 hectares. Besides, several small rivers provide the lake with approximately 160,000 cubic metres of treated and untreated sewage effluent almost daily. This effluent is the main cause of pollution including eutrophication in the lake and a rise in water temperature. However, the lake is envisaged to have contained a significant amount of nutrients such as Nitrogen and other elements that can be recovered. Since the lake is an integral part of the Harare city region's metabolism, and influences the water and wastewater system of the city region significantly, it is argued that the protection of the lake from pollution, and recovery of resources from within it, would contribute to the sustainable development of the city region significantly.

An Applied Systems Analysis (ASA)-linked System Dynamics (SD) modelling methodology was used for the study. Findings revealed that the water supply in the city region, wastewater generation and disposal to Lake Chivero of nutrients, food production and consumption, and wastewater generated from consumption in the city, work in a feedback mechanism. Availability of nutrients in the system allows its production and application in the system for food production. Wastewater generation due to water supply and discharging to the lake make a possibly higher availability of nutrients in Lake Chivero. Computation based on an ASA-linked SD model estimated that the lake already has sediment of 19,800 tonnes of N, of which 9,900 tonnes can be extracted. The extraction of these resources will not only reduce the pollution level of the lake but also assist in the production of an extra 35,000 tonnes of food per 100 tonnes of reuse of the nutrient in the city region. Thus, the waste that is generated in the city region, if considered as resources and recovered, would then contribute to the environmental and socio-economic wellbeing of the city region and strengthen its sustainable development agenda.

2. PERSPECTIVES OF NUTRIENTS IN WASTEWATER, AND NUTRIENT RECOVERY AND REUSE FOR FOOD PRODUCTION

The nexus between water and food has been identified and established. Such a nexus entails a reduction in water consumption and increasing the efficiency of water resources for food production (Endo et al., 2017). For this purpose, improvement in the utilization of rainwater held in the soil profile, prevention of depletion of residual soil moisture in the field after crop harvest, and shifting to low water consuming crops have been attempted (Cai et al., 2018; Endo et al., 2017). Similarly, the water-energy-food nexus has been prompted. This is conducted through integrated water resource management (IWRM), producing alternative energy such as biofuel from woody biomass, sugar bagasse, and concentrated solar power, and investigating the land and water requirements for producing bioethanol from maize (Cai et al., 2018; Endo et al., 2017; Lehmann, 2018; Mutanga et al., 2016). In this context, food, energy, and water are governed by separate but interconnected physical, biophysical, and chemical processes, and work through a dynamic interaction among these systems (Cai et al., 2018). Furthermore, the water-nutrient-food nexus has been promoted (Beck et al., 2013; Villarín & Merel, 2020; Villarroel Walker, Beck, & Hall, 2012). However, since the focus of this study is on the water-nutrient-food nexus the theoretical perspectives are confined to this aspect only.

According to scholars such as Beck, Villarroel Walker, and Thompson (2013), the dominance of urban agglomerations is becoming a permanent feature of the globe today and consequently, humanity and its relationship with natural ecosystems are also changing. This is particularly prominent in the system linking water, wastewater, nutrients and food production. For example, large cities in Europe such as Paris and London grew much of their food supplies in swamps or fields where human wastes were dumped (Lee-Smith & Cole, 2008). Water has been the primary input in the process of urban food production as in the countryside. Farmers, besides relying on the natural hydrologic cycle for water and quality of soil embedded with nutrients, have also been innovative to channel the water resource through different innovative forms of irrigation and transforming wastes into useful resources for food production.

Generally, cities in the global South (third world countries in Africa, Latin America and developing countries in Asia) are experiencing a rapid transformation with Africa being the fastest urbanising now (Centre for African Studies Basel, 2010). Apparently, it is observed that depending on the availability or non-availability of critical resources, city landscapes tend to emerge. Cities have a mammoth task to transform themselves into self-regulating systems and to be sustainable, that is connected to their dependency on resources like food, water, manufactured products and energy (Chelleri & Olazabal, 2012; Kumar et al., 2014; Mason & Lang, 2017). It is also argued that at a localised scale, households and institutions have to be innovative to capitalise on resources and hence devise ways to capture limited resources (Vairavamoorthy, 2011). In this regard, water (wastewater) offers three fundamental resources which include water, nutrients, and energy, which could aid the food production in cities if harnessed and used effectively (Gremillion & Avellán, 2016). Evidence has shown that wastewater that is generated in the cities and disposed to watercourses contains a significant amount of nutrients such as N, P, K and C-related matters that are considered as pollutants and contaminants, that essentially pollute the water resources (D'Angelo & Wiedenmann, 2014; Villarín & Merel, 2020; Villarroel Walker, Beck, & Hall, 2012). However, Villarroel Walker, Beck, and Hall (2012), while examining the challenges and benefits deriving from adopting a broader, multi-sectoral system perspective on addressing water-nutrient-energy systems in city watershed management, argued that the elements such as N, P, K, and C that are historically being viewed as pollutants can be considered as resources that can be gainfully recovered allowing them to be reused in the agricultural food sector, and as bio-fuels in the energy sector or nutrient supplements in the ecosystems services sector. For example, a toilet's waste of 520 kg/person/year generates 7.5 kg of N, P, and K, and some micro-nutrients in a form that can be useful for plants. Similarly, about 4.5 kg nitrogen and 0.6 kg phosphorus per person per year can be produced from human waste (Mateo-Sagasta, Raschid-Sally, & Thebo, 2015). These nutrients can be extracted and reused (Gjesteland, 2013; Niwagaba, 2009). Similarly, in the case of urine from human excretions, which contains 98% of the N, 65% of the P, and 80% of the K, these nutrients can be substantially recovered and reused for food production. For example, according to Villarroel Walker et al. (2014), with the use of appropriate technology, urine separation has the potential to recover 47% of N related materials that is available in the food consumed in London, and revenue of $33 million per annum from fertiliser production. Therefore, there is a need for changing the existing perceptions of wastes and to reconceive these as valuable resources, which can be an integral part of the water, nutrients and food nexus for the sustainable development of cities.

3. CASE STUDY CONTEXT

For this study, the Harare city region and its linkage with Lake Chivero were taken as the case study context. Harare is the capital city of Zimbabwe, which was established in 1890 is a fast-growing city in the Southern region of Africa. Harare city region comprises the city of Harare and its satellite cities (Chitungwiza, Ruwa, Epworth and Norton). The human population on the watershed is doubling every 12.5 years, that is attributed largely to rural-urban migration and natural increase. The estimated population of this region is about 4 million (ZIMSTATS, 2012). For a long time, the Harare city region has been experiencing challenges with regards to urban infrastructure and services. Consequent upon the troubled urban infrastructure and service delivery sectors, the city region experiences environmental malaise and the major troubled subsectors influenced are water, energy and sanitation. In this regard, the challenge of managing water and wastewater is enormous. The urban water challenge in the Harare city region is both a supply and demand issue. From the supply side, the issue centres around the Harare city water system, which is largely over-reliant on a centralised system whose infrastructure is badly maintained. The water when supplied is also of poor and unreliable quality. Lake Chivero, the major source, is 'heavily polluted'. On the demand side, migrants from the rural areas are increasing and settling into peri-urban areas, a development that has seen the sprawling of the city region. The bulk of these areas do not access the Chivero water hence rely upon 'decentralised' systems designed by the households, which have to tap largely underground water by drilling boreholes or digging shallow wells.

In terms of the water and wastewater reticulation systems (system of sanitation), the regional system is predominantly waterborne and centralised. The water eventually gets to Lake Chivero, which has a volume of 250,000 megalitres (being 250 × 106 m3). The average lake depth is 9.3 meters. The surface area of the lake is 26 square kilometres. In terms of elevation, the lake is 1,300 meters above the mean sea level (MSL). The catchment of Lake Chivero is called the Manyame Catchment, which has a size of some 2,632 hectares (*Figure 1*).

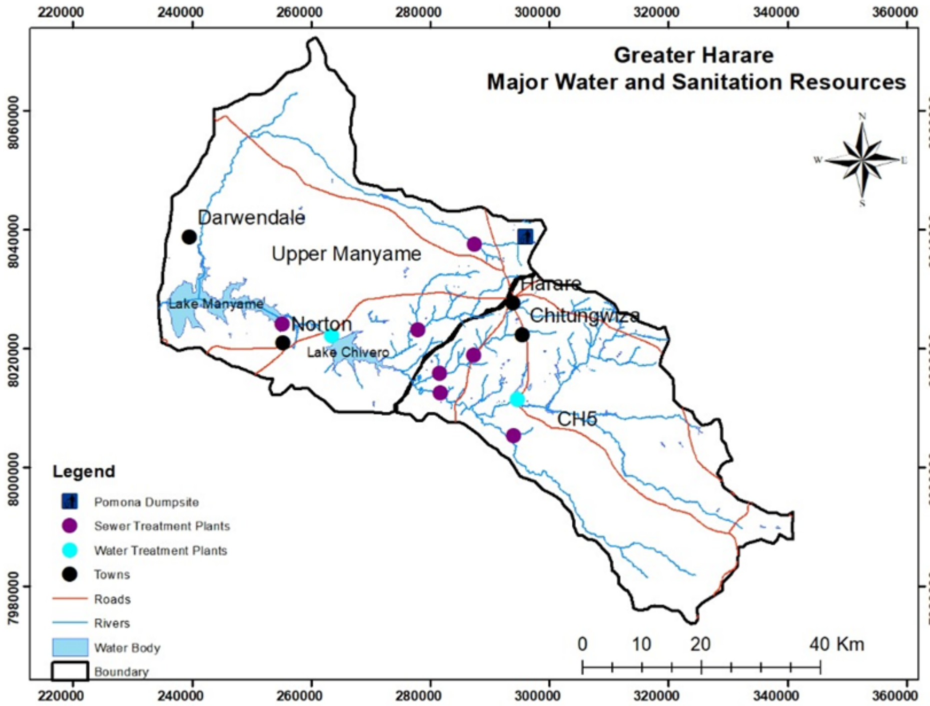

Figure 1. The Manyame Catchment

Figure 2 presents the areas of food production in the Harare metropolitan region. The majority of the food production areas are located in the Southern part of the region in and around Goromonzi. The Northern part contains very limited food production areas around Norton.

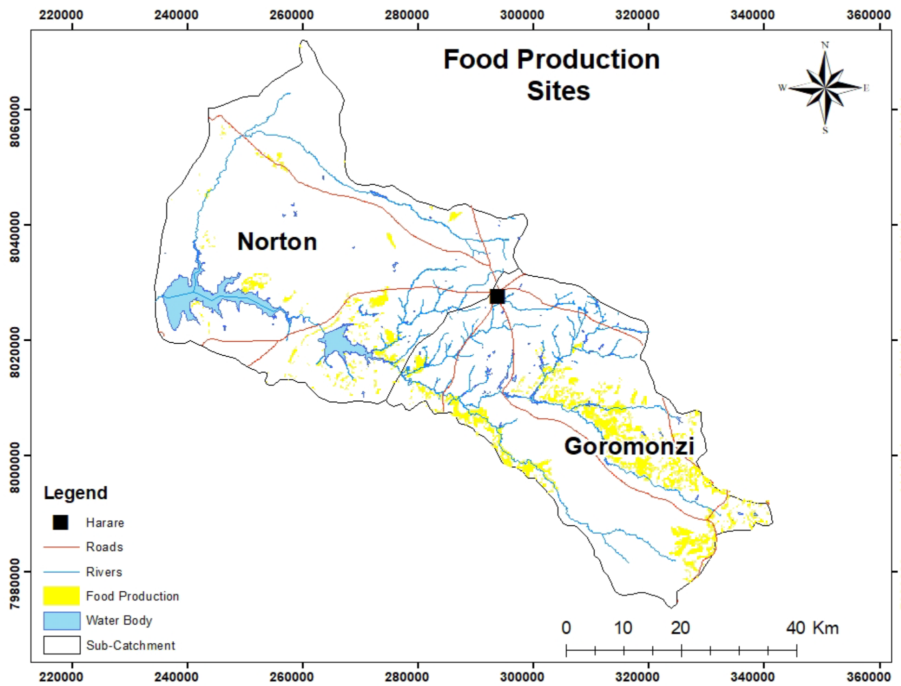

Figure 2. Food production areas in the Harare city region

The region receives average precipitation of 830 mm/per year. The rainfall received translates to 750 m3/ year, of which 16% flows into Lake Chivero. Lake inflows are observed throughout the year. Runoff in Harare is collected by a combined drainage system of open ditches and pipelines, associated with the municipal road structure, and are conveyed directly to natural watercourses that discharge into Lake Chivero (Hranova, 2003). The spillway at Lake Chivero rarely releases water in the dry months of July to November. There are no regulated outflows from Lake Chivero into the Manyame River as the floodgates are permanently closed. The lake inflow/outflow regime mainly dictates seasonal water quality and, to some extent, the self-purification capacity of feeding rivers and of the lake itself.

Besides, Chivero has two inflowing rivers - Mukuvisi and Marimba. These small rivers provide the lake with approximately 160,000 m3 of treated and untreated sewage effluent almost daily, which is the main cause of eutrophication and pollution in the lake. Only about 30% of the Lake Chivero inflows are abstracted for urban use. The rest either evaporates or flows downstream where some of it is abstracted for agricultural irrigation. In terms of water losses, water processed and treated at Lake Chivero amounts to 35% to 40 % (210 to 240 megalitres) of the production lost as Non-Revenue Water (NRW) because of the infrastructure dilapidation and the poor reticulation system.

Harare's sewer system is separated, where the sewage is collected and treated before being discharged to watercourses. Harare operates five sewage treatment works, wastewater stabilisation ponds, biological (trickling) filters and biological nutrient removal (BNR) plants at Marlborough, Donnybrook, Hatcliffe (BNR), Crowborough (two Biological Filters and one BNR) and Firle (two Biological Filters and two BNR units). The Firle plant, for example, is meant to process 72 megalitres of effluent per day. The effluent is retained in points for cattle feeding (hence peri-urban cattle ranching). The Firle plant is a plant for removing BOD at a 70% rate (Nhapi, 2009; Nhapi & Hoko, 2004).

Sources of pollutants of Lake Chivero are many. For example, many industries do not have effluent pre-treatment facilities so they let obnoxious waste enter the sewer system, or even worse into the stormwater drainage system. Furthermore, all domestic and industrial wastewater in Harare goes into the sewerage system and all wastewaters in the sewerage system are adequately treated. Farming is also a source of pollution from runoff containing nutrients and various noxious substances from the use of fertiliser, herbicides and pesticides. Concerning water treatment, residues are discharged directly into the river systems in the catchment, especially the Manyame River from Chitungwiza.

It has been noted that the use of chemical fertilisers by informal urban and peri-urban cultivators has decreased raw water pH from 9.5 to between 8.5 and 9.0. It is found that the biological nutrient removal (BNR) cannot cope with the current phosphate loads, which is about an average of 15 mg/ℓ. The non-point source of nutrients (300t of P and >1 000t of N) can maintain the lake in a hypereutrophic state, as the total of non-point nutrient sources exceeds 1967 levels when the lake was hypereutrophic.

Further, although statistics from the Food and Agriculture Organisation (FAO) of the United Nations (UN) indicate that the contribution of food production in the region (Harare and its peri-urban area) could be some 20,000 tonnes, that is highly inadequate to serve the region. Food production suffers from challenges related to water and nutrients. Therefore, it is argued that if the nutrients are recovered from the lake it can assist in the food production and reduction in the pollution of Lake Chivero.

4. METHODOLOGY

4.1 Data and ASA-linked SD modelling approach

A quantitative research method that includes ASA-linked SD modelling was used in the study. Data used in the simulation model were collected from both primary and secondary sources and processed before their use in the model. Primary data were collected through a household survey by using a random sampling process and statistical data were collected from secondary sources, such as literature and various organisations, which included the Zimbabwe National Water Authority (ZINWA), Zimbabwe Statistical Agency (ZIMSTATS), Food Agriculture Organisation (FAO) and Harare Water. The primary data was collected from 500 households by use of a questionnaire survey. The respondents were selected randomly from different suburbs and satellite towns of the Harare city region. While collecting data, no discrimination among the various households, such as race and socio-economic strata, was made to avoid any bias and prejudice. The survey questionnaires included the various parameters relating to the water, supply, demand, consumption, wastewater generation, wastewater treatment and wastewater disposal system. It also included various types of wastes generated in the households and disposed of through the waterborne disposal system.

The data was then reduced and analysed to initialise the various variables that are used to develop and simulate the SD model. Both primary and secondary data were analysed by use of descriptive statistics, mean, percentages, and rates to obtain the initial values that are used in initialising the model. Following this, the SD model was developed by following a five-step process: (A) Problem identification; (B) Identification of the system, its environment, and the system's sub-systems—Prelude to formal analysis; (C) Preliminary analysis of logic of visual-analog representation; (D) Computational analysis with a model; (E) Screening and analysis of computational results; and (F) Implementing the decision and handling uncertainty (Beck et al., 2018). While doing so, the concern was to develop an understanding of the mechanics of how one thing relates to another within the system. Subsequently, a more or less complex computational model of those mechanics was constructed and run in various ways, forecasting the future behaviour of the measured variables for evolving policy-technology interventions, from that a specific decision can be arrived at and implemented in practice (Beck et al., 2018).

The SD model is critical for complex, messy and interdisciplinary problems (Patterson et al., 2004). SD has now been applied in various fields including urban and social-ecological systems (Borshchev & Filippov, 2004; Das, 2019; Patterson et al., 2004). One, while applying SD, must know the behaviour of that system. The behaviour is explained by several interacting feedback loops, balancing or reinforcing, and delay structures (Mohammadi, Tavakolan, & Khosravi, 2018; Sterman, 2000). Two types of variables are outstanding: stocks or levels (for example, inventory and perceived risk) and flows or rates (for example, production rate, deaths per thousand per year). It has the ability to combine both qualitative and quantitative aspects (Sterman, 2000). In the qualitative dimension, there is "...construction of 'causal maps' or 'influence diagrams' in that the system structure and the interrelations between the components of a system are explored (Beck et al., 2018; Srijariya, Riewpaiboon, & Chaikledkaew, 2008; Sterman, 2000).

Entailed in the quantitative aspect is the development of a computer model in which flows of material or information around the system are modelled and scenario mapping is done. A scenario refers to "a set of assumptions about the environment" and this allows for the simulation of the reality on the ground. Further, through sensitivity analysis, it is possible to reduce the reducible uncertainties and accept the existence of irreducible uncertainties and take the existence of these irreducible uncertainties into account when interpreting the results and designing robust policies and systems (Beck et al., 2018; Pruyt, 2007).

4.2 Model development

4.2.1 Critical assumptions in model building

The benefit in developing the SD model(s) at this stage is to derive from observing the eventual results of the computations, learn from them, and compare how the model behaves with the belief around what is happening in the real world of Harare. The key questions to be answered include having the ability to establish the technical feasibility of recovering nutrients from the lake- beginning with first establishing the "theoretical maximum" of the nutrients that might be recoverable from the lake. The next stage involved developing a model to differentiate between the nutrient content of the lake water and the nutrient content of the lake sediment. This is especially important for the recovery of N, most of which (historically) will have been deposited with and in the lake's sediments. Leakage from the lake means (in part) the outflow of water to the river downstream. Also, there is the role of "industry", in a variety of ways: in producing fertilizers for agriculture, whose nutrients (N) end up being consumed by citizens, thereby entering the sewerage system; and in producing materials, consumer products, and waste by-products containing N, some of which enter the sewerage system in one way or the other (pre-consumption or post-consumption). However, the purpose of the present model is to focus exclusively on the role of some of Harare's citizens (those connected to the sewer network) and to establish how much N flows around the cycle of fertilizer-agriculture-food-people-wastewater-lake-fertilizer. The wastewater that enters the lake through the sewers constitutes the wastewater from the lavatories and showers (human excreta, urine, shower water, etc.,) as well as from the kitchen. Overall in Harare, the nutrients that enter the lake from the city are a function of the population that is connected to the centralised sewerage and wastewater infrastructure. Nevertheless, not all of the nutrients generated by the (sewer-connected) population will reach the lake. In this particular study, the scope of the modelling is limited to computations relating to nutrient N.

4.2.2 Conceptualisation and causal feedback loops

Feedback loops represent a chain of causality. They are responses created by the system that will change the current pattern. Flows are the movement of contents throughout the system (Forrester, 1968, 1969; Sterman et al., 1983). Therefore, in this investigation, it is envisaged that the total N available in the lake is a function of two causal feedback reinforcing loops and one balancing loop (*Figure 3*).

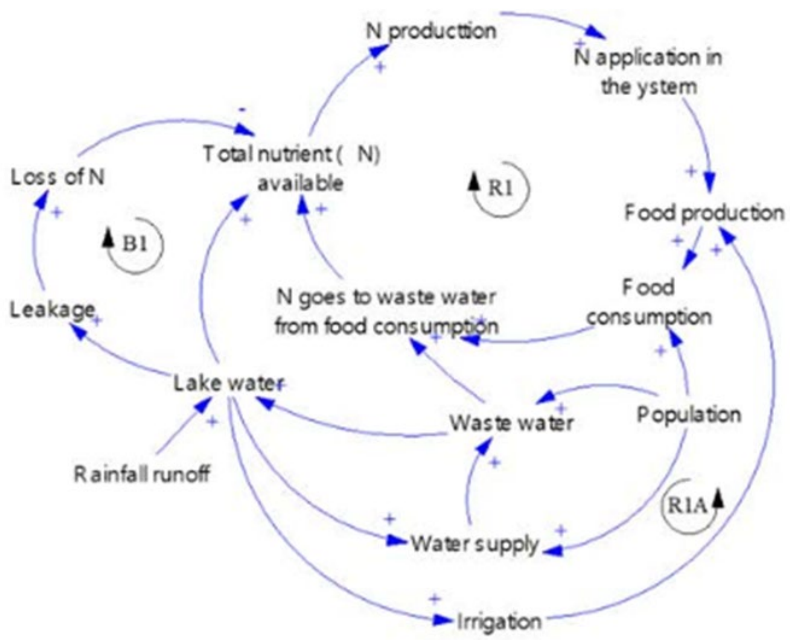

Figure 3. Causal feedback loop diagram for Nitrogen in the lake

Resources in the form of water, nutrients and food are essential for the sustainability of a city (Kumar et al., 2014). They are interlinked to each other and their efficient use assists in the sustainability of the whole ecosystem (Olewiler, 2006; Park et al., 2013). In this context, the wastewater, nutrient and food system has been divided into three components (subsystems), such as the wastewater subsystem linking population, water supply, generation and disposal of wastewater to Lake Chivero, which is also influenced by irrigation and leakage. The second subsystem constitutes resources (N) in the lake that are generated from disposed wastewater and also lost due to leakage from the lake. The third subsystem is the food system. Nitrogen enters the wastewater system because of consumption of the food by people, however, on the other hand, the availability of nitrogen in the city region system because of nitrogen recovery from the lake would enhance food production. Thus, nitrogen and wastewater play a crucial role in food consumption and food production systems in the city region. Thus, these three different subsystems are interconnected to each other and if they work in an integrated manner then they can contribute to the sustainability of the city region significantly (Allenby, 2012; Beck and Villarroel Walker, 2011; Fink, 2012; Hall et al., 2012).

In this context, there is a positive feedback relationship among the total nutrients (N) available in the lake, N production, application of N for food production in the system, food production, food consumption, N going to wastewater from food consumption and total nutrient available (R1) in the Chivero lake and Harare city region system. The lake water makes the water available for irrigation that assists in food production, food consumption, and nutrients from food consumption go back to wastewater (R1A) (Beck, 2013; Beck & Villarroel Walker, 2011; Beck, Villarroel Walker, & Thompson, 2013) and then to the lake, reinforcing the feedback mechanism R1, enhancing the availability of N in the lake. Further, wastewater generation due to water supply, population and discharging to the lake makes it possible to have a higher availability of N (Beck, 2013; Beck &

Villarroel Walker, 2011; Beck, Villarroel Walker, & Thompson, 2013). Thus, the lake water, availability of N, its production, its application in the system for food production, food consumption, and wastewater generation are interconnected through reinforcing mechanisms to produce the nutrient N in the system. However, on the other hand, the availability of the N in the system is balanced by leakage (Bouwman et al., 2005; van Puijenbroek, Beusen, & Bouwman, 2019) (in this case from lake water through a feedback mechanism B1 involving lake water, leakage, loss of N and total availability of N in the lake system generated by the reinforcing feedback mechanism R1). Thus, while feedback mechanisms R1 supported by R1A enhance the availability and consequent production of N in the system, the feedback loop B1 acts as a reducer.

4.2.3 Developing the model

An SD model was developed to simulate the behaviour of the variables in the system based on the interaction of the variables and causal feedback relations to predict the total nutrient (N) that can be produced, available and extracted based on Lake Chivero, water supply to the city, and wastewater generation and discharging to the lake, food production and consumption in the city and nutrients available from all sources in the lake as discussed in the following sections. The model was built by using the Powersim software and algorithms developed as per the interaction of the stocks, rates and auxiliary variables (Sterman, 2000) for a projected period of 120 months from its initial values.

4.2.4 Variables and data used in the model development and simulation

The various variables used in the model are presented in *Table 1*. There are four stocks in the system, such as the quantity of lake water in Chivero Lake, the population in the city, food production and water used for irrigation from the lake. The rate variables are natural birth rate, death rate, immigration rate and emigration rate relating to population; runoff rate, irrigation rate and leakage rate relating to the lake water; and food production rates relating to the food production in the system. The auxiliary variables are related to water supply, wastewater generation, and nutrient availability and production. The rates and auxiliaries are functions of the constants and fractions as shown in *Table 1*. *Table 2* presents the data used for the simulation of the model.

Table 1. Variables used in the SD modelling

Stocks	Rates	Auxiliaries	Constants/ fractions
Population (Harare city region) (P)	Birth rate (BR), Death rate (DR), Immigration rate (IMR), Emigration rate (EMR)		Birth rate fractions (BRF), Death rate fractions (DRF), Immigration rate fractions (IMF), Emigration rate fractions (EMF)
Lake water (Lake Chivero) (LW)	Runoff rate (RR), Irrigation rate (IR), Leakage rate	Water supply (WS)	Runoff rate fraction (RRF), Irrigation rate fraction (IRF), leakage rate fraction (LRF)
Water used for irrigation (IW)		Wastewater generation (TWW)	Fraction of population receiving water supply

		Wastewater goes to the lake by sewers (WW) Total lake water	(PF) Water supply rate fraction (WSRF), Wastewater generation fraction (WWF)
Food production in the city (FP)	Food production rate (FPR)	Total food available (TFA)	Food production fraction (FPF)
		Total food consumption (FC)	Food coming from outside fraction (FCOF) Food going out of system fraction (FGOF) Food waste fraction
		Total nutrient available (TNA)	Nutrient fraction from lake water without wastewater
		Total nutrient extraction (TNE)	Nutrient fraction from wastewater (NWWF)
		Nutrients generated from the lake without wastewater (TNLW)	Nutrient fraction from food consumption going to wastewater (EMFF)
		Nutrients generated from wastewater (TNWW)	Nutrient fraction for application (AFE)
		Nutrients available from food consumption and entering wastewater (ENF) Nutrient application for food production	Nutrient fraction for extraction (NFE)

Table 2. Data Used for Simulation of the Model

Variables	Source	Initial Value	Units
Lake water	ZINWA	250,000,000,000	Litres
Population	ZIMSTATS, (2012)	4.000,000	Number
Irrigation water	ZINWA	75,000,000	Litres
Food production	FAO	20,000,000/12	Kilograms
Birth rate fractions	ZIMSTATS	0.0333/12	
Death rate fractions	ZIMSTATS	0.0077/12	
Immigration rate fractions	ZIMSTATS	0.03252/12	
Emigration rate fractions	ZIMSTATS	0.02906/12	
Runoff rate fraction	ZINWA	2.18/12	
Irrigation rate fraction	ZINWA	0.0075	
leakage rate fraction	Harare Water	1.936/12	
Fraction of population receiving water	Harare Water	0.3	
Water supply rate fraction	Harare Water	0.9	
Wastewater generation fraction	Harare Water	0.70	
Food production fraction	FAO	0.05	
Food coming from outside fraction	FAO	0.50	
Food going out of system fraction	FAO	0.01	

Food waste fraction	FAO	0.03
Nutrient fraction (N) from lake water without wastewater	Harare Water	10/100000
Nutrient fraction (N) from wastewater	Harare Water	0.8
Nutrient fraction (N) from food consumption and entering wastewater	Harare Water	0.02

The SD model was developed by using equations (equations 1 to 13) and their related algorithms based on the feedback mechanisms and then simulated for computing the measured variables, such as population, lake waste, wastewater discharging to the lake, total lake water, food production, food available and food consumption, total N available, N that can be extracted and N that can be used for food production.

The stock variable population is a function of rate variables: birth rate, death rate, immigration and emigration in the system. It is represented in equation 1.

$$= Pi + \int_{t0}^{t} \mathrm{Pi(BR - DR + IMR - OMR)dt}$$

The lake water is dependent on the initial quantity of water available in the lake and run-off rate from rainfall, leakage due to evaporation and overflow, and outflow due to irrigation (equation 2). The wastewater discharged to the lake is the portion of water supplied to the city, used and discharged through the sewerage system (equation 3). The water used for irrigation is dependent on the irrigation rate (equation 4). However, the total water in the lake is the sum total of the water in the lake and wastewater discharge from the city and water used for irrigation purposes (equation 5).

$$= LWi + \int_{t0}^{t} \mathrm{LWi(RR - LR - LR)dt}$$

$$i = Pi * WSR * WWGF$$

$$= IWi + \int_{t0}^{t} \mathrm{IWi * IRdt}$$

$$= LW + WW - IWi$$

Similarly, food production is a function of food production rate and the effect of irrigation (EFI). Food availability is the summation of food production, food going out of the system and food quantity imported from outside. However, food consumption is a function of total food availability and the food wasted in the system. They are represented by the following equations (equations 6, 7 and 8) respectively.

$$= FPi + \int_{t0}^{t} \mathrm{(FPi * FPR * EFI)dt}$$

$$= FP + FO - FI$$

$$= TFA(1 - FWF)$$

The nutrient N available in the system is dependent on the availability of nutrients in the lake water, and nutrients from wastewater and the effect of food consumed that enters to the wastewater (ENF). The total N available in the wastewater is a function of wastewater quantity and nutrient content in fractions and the effect of food consumed and discharged to wastewater. In other words, the total N available in the wastewater constitutes N in wastewater from showers and lavatories (human excreta, urine and shower water) and N in wastewater from the kitchen. The N content in lake water is a function of lake water quantity and the fraction of N content per litre of lake water. They are represented by equations 9, 10 and 11. The total N extracted is dependent on the method of extraction and fraction possible for extraction (NFE) and is shown in equation 12. The N application in the system for food production is dependent on the quantity of N extracted and the fraction utilized for the food production, which is given in equation 13.

$$= TNL + TNW$$

$$W = WW * (NFW + ENF$$

$$= LW * (NFLW$$

$$= TNA * (NFE$$

$$= TNE * (AFE$$

For simulating the model, a sensitivity analysis was conducted by use of table functions and initialising the variables. However, before the model was employed for measuring the variables and deriving policy interventions, it was validated by the structure verification test, algorithm tests and behavioural tests of the variable in past years. The validated model is then used to develop simulated scenarios for the projected period of 120 months (10 years) from the base year based on the causal feedback mechanisms.

5. RESULTS AND DISCUSSION

The results in terms of behaviours of the system, such as population growth, wastewater generated in the system and wastewater entering the lake, the total nutrient in terms of N available and N that can be extracted and the amount of N that can be used for food production as a feedback to the system, and the amount of food that can be produced by the use of the extracted N over the next 120 months (10 years), are presented in Figures 1 to 5. As part of the behavioural presentation of results, it is observed that there will be steady population growth in the city region over the next ten years, reaching up to a 5.35 million (*Figure 4*). The population is the source of nutrients as it consumes food, which goes as waste via the sewer. The wastewater generation will increase commensurately and about 3,025 megalitres of wastewater per year by the end of 10 years (120 months) will reach the lake (*Figure 5*). Similarly, the deposition of N will increase non-linearly over the next ten years to reach about 19,800 tonnes out of which only about only 9,900 tonnes can be extracted (*Figure 6*). Some N will be lost through leakages including natural processes. In other words, the nutrients that enter Lake Chivero from Harare are delivered there by the city's water-based sub-system of sewerage and wastewater infrastructure. Their quantity in the lake is highly significant. As mentioned above, the model results indicate that some 19,800 tonnes of N-based materials (estimated as elemental N) have already accumulated in the lake's sediments, of which over half could be extracted and recovered over a 10-year period. To gauge the significance of this, it is estimated that 100 tonnes of these materials (as N) (*Figure 7*) might assist in the production of an extra over 35,000 tonnes of food in the city region over the business-as-usual scenario (if no Nitrogen is extracted and reused in the system for food production and the current system of food production continues). Looking at the severe gaps between consumption of food and food production in the system, this extra production of food can plausibly contribute to closing the gap between production and consumption to a significant level. In other words, there shall be a gradual increase of food production ranging between 17% to 44% from production under the business-as-usual scenario over a period of 4 to 10 years, although towards the later period of the time (towards 9th and 10th years), the food production and consumption might grow exponentially because of the reinforcing causal feedback relations and given there are no scenarios of uncertainties or other dampeners arising. Consequently, it will reduce the shortfall between food production and consumption by 27% during the same period. Such impressive quantities, when checked and further verified, emphasise rather dramatically the significance of turning a recalcitrant problem of pollution into the benefit of resource recovery—provided the economic and institutional aspects thereof are conducive to such strategic change (see, for example, Beck (2016) and the Afterword in Thompson (2017), and Beck et al. (2018)).

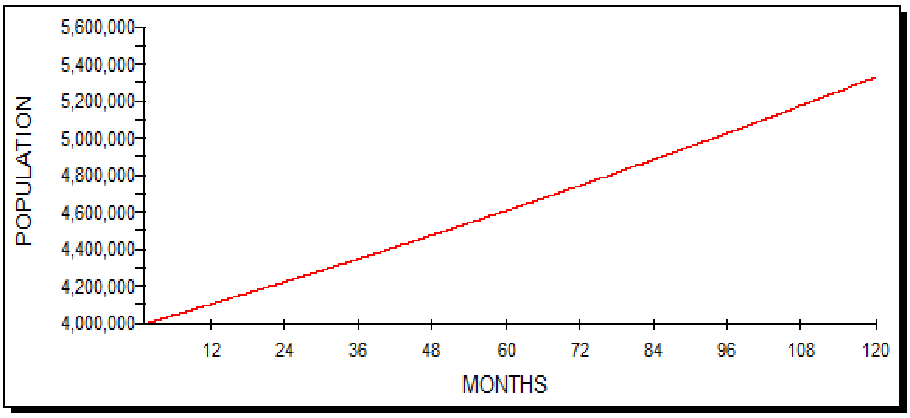

Figure 4. Population growth in the Harare city region

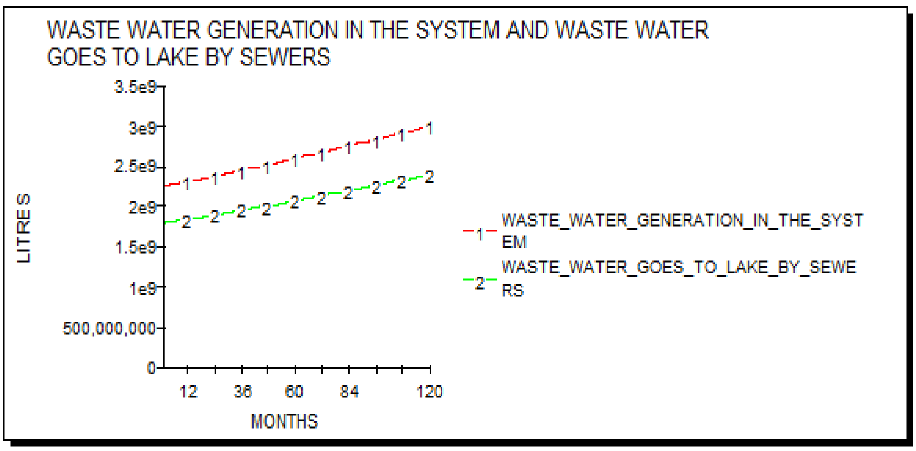

Figure 5. Wastewater generation and wastewater entering Lake Chivero

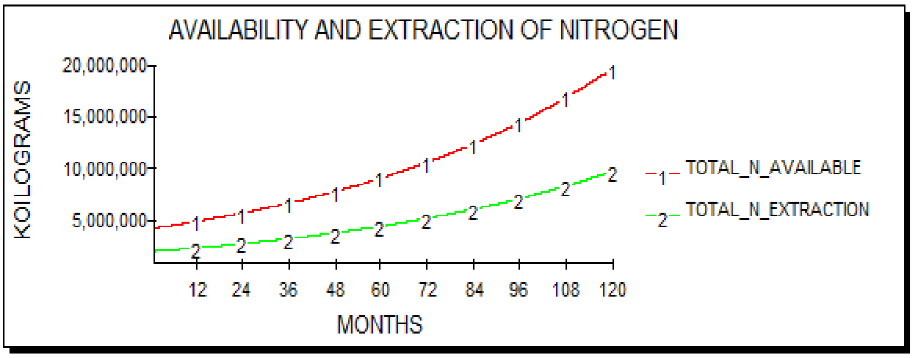

Figure 6. Availability of Nitrogen in the lake and possible extraction of Nitrogen from the lake

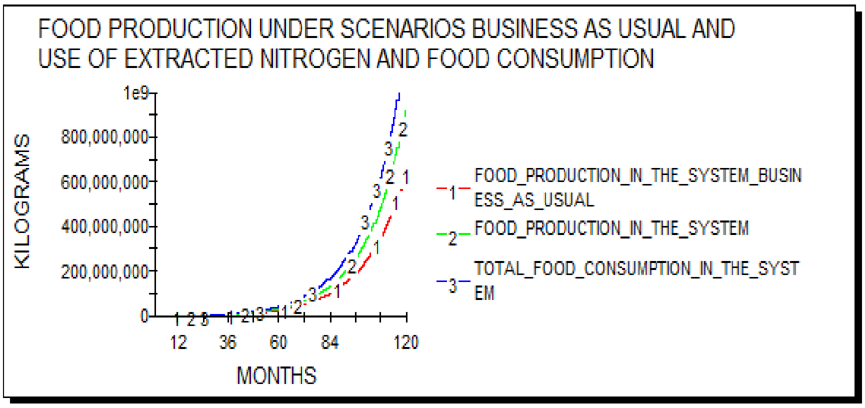

Figure 7. Total food availability and food consumption in the city region and Food production if Nitrogen extracted is used in the system

6. CONCLUSION

Harare city region has a plethora of challenges that include energy, water, food, and climate change. However, the challenge of water, wastewater and food production typifies the challenges of any African city. The wastewater generated by the city region is disposed of after treatment to Lake Chivero. Although, Lake Chivero is an important part of the ecosystem of the Harare city region and is a major source of water supply, it is getting polluted because of wastewater disposal. Also, the wastewater carries a significant amount of nutrients, such as Nitrogen-based materials, which remain wasted and contribute to the pollution of the lake. However, arguments have emerged that if the nutrients are recovered then they can contribute to the food production in the city region, albeit contributing to reducing the food challenges in the region. Therefore, using the study context of the lake, the interlinkage between Lake Chivero and the Harare city region was conceptualised as a framework of the water-nutrient-food nexus for the Harare city region that is sought to propose ways to address the challenges of African cities in general, and the challenges of Harare, in particular.

An ASA-linked SD modelling methodology was used to examine the nexus and estimate the various system variables, such as the wastewater, nutrient, and food production. Findings suggest that the nutrients that enter the lake from the city region are a function of the population that is connected to the centralised sewerage and wastewater infrastructure. However, not all of the nutrients generated by the wastewater (sewer-connected) reach the lake. The quantity that reaches the lake is however highly significant. The conceptual framework developed through causal feedback loops posits that water supply in the city region, wastewater generation and disposal to Lake Chivero, nutrients, food production and food consumption and wastewater generated from consumption in the city region, work in a causal feedback mechanism. The availability of nutrients in the water and wastewater system allows its production and application in the system for food production. Wastewater generation and discharge to the lake make the availability of nutrients in Lake Chivero higher. This, in turn, argues for the extraction of the nutrients and reuse in the system for food production. The computation based on the ASA-linked SD model estimated that the lake already has sediment of 19,800 tonnes of N, about half of which can be extracted. It is also evident from the model results that the extraction of these resources will not only reduce the pollution level of the lake but also assist in the production of an extra 35,000 tonnes of food in the city region per 100 tonnes of use of Nitrogen.

Thus, it is theorised that in a city, there is a defined interaction between what the natural environment produces and how human beings harvest, process, consume and deposit their waste in the landscape as professed by systems theory (von Bertalanffy, 1968; Coelho & Ruth, 2006; Rotmans, 2006). For instance, food is 'imported' into cities and 'exported' in the form of sewage into lakes, rivers and seas and deposited in the form of nutrients. So, it becomes apparent that resources tend to get back into the system by ways of recycling or re-use. This realisation has engendered the recent debate that realises the need to re-use waste produced by humans and their processes so that the so-called waste then finds itself put back into the system as inputs to vital processes of life. In this regard, it is argued that there is a need to view nitrogen, carbon, phosphorus or any other materials from the water as resources to be recovered, rather than as pollutants and waste (Beck, Villarroel Walker, & Thompson 2013). The wastes that are generated in the city region need to be considered as resources and be recovered, that might contribute to the environmental and socio-economic wellbeing of the city region and strengthen its sustainable development agenda. That is perhaps one of the ways forward for attaining sustainable development in many of the similar city regions in Africa.

It is also to be noted that since the scope of this work was to examine the contribution of the nutrients extracted from the wastewater towards food production, scenarios, such as uncertainties and pessimistic scenarios (if no policy measures to recover nutrients from wastewater are made and implemented at all) were not considered in the simulations.

This article is useful in that it identifies key aspects and parameters that can help in modelling and simulating a better and sustainable future for an African city region. Indeed, urbanisation entails urban population growth due to natural increase and migration and has often been considered a 'curse' to the African fabric. However, this can be tapped as an opportunity for an increased quantum of nutrients reusable for food production within the city region in keeping with the tenets of urban metabolism. The ultimate deposition of treated wastewater into the lake and tapping much of the nutrients from the wastewater will be instrumental in harvesting a great quantum of the nutrients. This calls for the application and devising of critical technology to extract the existing nutrient sediments that are available in the lake. Nevertheless, the study shows that there exists a clear linkage between water, nutrient and food in a city region system that can be appropriately utilised to attain environmental and food production sustainability in the city regions of Africa.

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