Improving Potable Water Accessibility And Sustainability Through Efficient Management Of Pipe Water Supply System

A Case Study Of Uganda-Kampala Region.

A System Dynamics Approach. Can we make water systems Smarter?!!

Stella Nakabugo Mirembe

Thesis

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System dynamics Group, Department of Geography,

University of Bergen.

Supervised by: Pål Davidsen

Professor of System Dynamics

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Abstract

This paper discusses how to improve potable water accessibility and sustainability through efficient management of pipe water supply system a case study of Uganda, Kampala region. Kampala the capital city of Uganda still faces a challenge to access clean potable water. Water supply coverage is 77.5 % showing at least 22.5 % of the total population has limited access to potable drinking water causing a gap between water supply and water demand. Hypotheses of the paper were that the city's population is increasing rapidly with an annual urbanization rate of 4.8% this has put pressure on the pipe water infrastructure in terms of expansion and maintenance. Also the functioning pipes in place are too few to provide enough water for the growing population demand. The paper aimed at identifying and prioritizing possible policies on how the gap between the water supply and consumer water demand could be reduced .In that respect a review of both the current pipe water supply system was modelled using a system dynamics approach to allow model and policy testing through computer simulations as well as to validate the different hypotheses. The results showed that the increase in functioning pipes would greatly improve potable water supply however this can only be done with enough available funds. The water board management can achieve this through donations from non-government organizations, loans and customer support in terms of paying their water bills.

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1 INTRODUCTION

Water supply systems are one of the most successful engineering accomplishments in history and their existence has greatly contributed to the wellbeing and welfare of human being globally**.**

In developing countries, urban areas are growing rapidly. The expansion is not only affecting the city planning but also the urban water in aspect of inadequate quantity of water supply. Kampala pipe water supply infrastructure is no exception. Increase in Kampala population has led to a rapid increase in water demand and put more pressure on the pipe infrastructure.

This chapter presents an insight of Kampala water supply system characteristics and challenges in terms of water demand.

Kampala greatly uses pipe water system as its main water distribution network of clean potable water however this has proposed challenges to the water supply in the region in terms of accessibility and sustainability to the increasing water demand of the fast growing population. The challenges include pipe rehabilitation, expansion and replacement. One cannot ignore the significance of pipe maintenance on water supply services. Access to piped water has been a significant factor in health improvements in most developing regions. As opposed to other water sources, piped water can provide water to homes, plots, and yards and is thought to be the safest drinking water source, provided that the pipes are maintained to ensure water quality. Over the past years Kampala's main policy has been to expand the water supply sector with low investments in pipe rehabilitation and replacement but the problem has not been resolved which can be significantly seen in the increase in water leakages in **U**ganda **W**ater **A**nd Environment **S**ector **P**erformance **R**eport (*UWEPSPR 2012*)

Given the international standardization of water and wastewater services **U**nited **N**ations **C**hildren's **F**und organization (*UNICEF*) Kampala has to improve the efficiency of its water supply system. They hope to accomplish this by putting in place different strategic policies to reduce the gap between the water demand and water supply and also evaluating system performance based on the level of water supply system and financial management.

Research question

What is causing the limited accessibility to potable drinking water in Kampala city?

1.1 Research objective

1.1.1 General objectives.

The aim of this study is to assess urban water supply system using a case study of Kampala region in order to improve accessibility to potable water and sustainability issues in developing countries through recommended policies.

1.1.2 Specific objectives:

- To improve accessibility and sustainability to domestic potable water supply in Kampala region through efficient management of the pipe water infrastructure.
- To identify the main factor causing the growing gap between water supply and water demand.
- To forecast the future demand and supply of potable water.
- To identify which policies can be put in place to make the pipe water supply system more effective and adequate.
- To estimate the cost effectiveness for putting the proposed policies into place.

Grigg and Bryson (*1975*), Lee and park (*2007*) modeled water supply service management using SD(System Dynamics) methodology however didn't explicitly consider modeling the effect of pipe maintenance on aspects of system management.

In this context an SD computer simulation model has been developed to aid the efficient management of water supply system mainly exploring the pipe supply water system mechanisms and then the casual feedback loop relationships showing the interactions between water demand and water supply.

The paper also presents the literature done on previous studies in relation to the topic at hand, the current case study, description of the problem at hand, dynamic hypothesis explaining the possible reasons behind the cause of the problem. The paper also presents model description where the model boundary and assumptions are defined. An analysis of the model is present to discuss the results of the model simulations. Different policies are suggested in the paper of how to alleviate the water supply gap problem as well as how they can be implemented and what challenges will be faced as well as the costs and benefits of having the policies in place.

2. LITERATURE REVIEW AND CASE STUDY BACKGROUND

This chapter presents different studies done on water dynamics .The different studies made in Kampala are found in this section. The current situation of water supply and demand is also presented. The use of System Dynamics is explained later in the chapter. The different researches done in different topics in the System Dynamics that were of interest and use in this paper are mentioned as well.

2.1 Water Demand Management

The water scarcity situation will get worse in the world's urban areas, it is projected there will be a population increase of 2.12 billion between 2000 and 2030 and 95% of this increase is expected to be in low –income countries (*UN-HABITAT, 2004*). There is a need for policy makers to rethink how to manage water resources. Instead of focusing on only supply options there is need to apply water demand management (WDM) at the utility and end-user sides.

Water demand refers to the amount of water that consumers are expected to use. A more economic definition refers to water demand as an expression of desire for a particular water service level, measured by the consumer's willingness and ability to pay for it (*Deverill, 2001*).

WDM has been described as the development and implementation of strategies aimed at influencing demand patterns so as to achieve efficient and sustainable use of water. (*Turner et al, 2007*).

(*Brooks 2006*) uses operational definition to define water demand management (WDM) where he focuses on the quantity and quality of water, usage of the water, system operations and drivers of water saving. In his introduction he points out that lack of clarity about what constitutes water demand and how it can be effectively introduced in sectors is blocking the ability in effectiveness of water policies. (*Brooks 2002*) simply states water demand management as getting the most from water.

With the challenges associated with attempting to meet the growing demand for water in Kampala, a more feasible policy would be by increasing the water supply; water control managers are finding possible ways of balancing the water demand and water supply in the hope of supplying water in more sustainable way.

A clear understanding of water use patterns in Kampala and the factors that affect water consumption is critical to the effective management of water supply and demand as well as effective design of related public policies. Water use patterns are highly complex processes that are influenced by many factors, including seasonal variability and water availability, water supply restrictions, tariff structure and water consumption which depends on household characteristics and attitudes such as incomes and household size as well as intentions regarding water conservation. Kampala's average household size is 5 as per Uganda national House Hold survey 2005/2006(*UBOS 2006*) and Per Capita water consumption estimates for three categories (high, medium and low) obtained from a consultancy study by beller Consult and associates (*2004*) These factors both directly and indirectly drive water consumption and usage behaviors. In investigating the fore mentioned issues, researchers have focused on water demand in urban regions.

2.2 Water Distribution Networks

The water supply services in Kampala and 21 other urban areas in the country are provided by the National Water and Sewerage Corporation (*NWSC*) a corporatized public –owned utility, and currently managed under the public law. NWSC draws raw water for the Kampala water treatment plant from Lake Victoria. The water quality has detoriated because of the unplanned settlements around the lakeshore as well as the unreliable water pipe system. Even then, NWSC estimated that by 2006,it provided water services to 76% of the city's, population (*NWSC, 2006*). Non-Revenue Water increased from 21% in 2009/10 to 24% in 2011/12. This is mainly attributed to the aging facilities in a number of towns, some of which have exceeded their design life and are in need of major rehabilitation or replacement. (*UWESPR 2012*).

Current asset management frameworks for water distribution networks involve analysis of water main pipe data to predict remaining service life; comparison of costs of repair/rehabilitation alternatives over the pipe life cycles; and, prioritization of rehabilitation activities such that available financial resources can be leveraged to achieve maximum benefits (*Grigg, 2012*).

In his book "Decision support for the distribution system pipe renewal" (*Arun, 2002*) a more detailed insight in given about priotization. He looks at pipe priotization as a way of addressing the most critical pipes first, he also points out how the pipe priotization process can be subjective or objective. The priority can be based on the inventory of the pipe on the system and estimated life expectancy for each category of the pipe. Some utilities have developed scoring systems, which include age, Number of breaks, critical customers served, water quality concerns (customer complaints). Individual pipes can be evaluated and scored for the different factors. The utility subjectively determines the relative importance of each factor and thus resulting into pipe priotization as a subjective process.

2.2.1 Reorganization or re strengthening of existing water supply systems

Another important aspect of water distribution system design is strengthening or reorganization of existing systems once the water demand exceeds the design capacity. Water distribution systems are designed initially for a predefined design period, and at the end of the design period, the water demand exceeds the design capacity of the existing system on account of increase in population density or extension of services to new growth areas. To handle the increase in demand, it is required either to design an entirely new system or to reorganize the existing system. As it is expensive to replace the existing system with a new system after its design life is over, the attempt should be made to improve the carrying capacity of the existing system. Moreover, if the increase in demand is marginal, then merely increasing the pumping capacity and pumping head may suffice. The method for the reorganization of existing systems (*Swamee and Sharma, 1990b*) is covered in Chapter 13.

2.3 The piped water network

The existence of piped water in Kampala goes back to 1929. Since 1974 NWSC has been responsible for the water supply and distribution system. Private connections and standpipes are not included in NWSC's scope of responsibility. The corporation is parastatal, and follows the directions of the Ministry of Water, Energy, Minerals and Environment Protection. The majority of distribution mains were installed in the 1940s, and until 1994 non substantial repairs, rehabilitation or extension had been done (*van Nostrand 1994*). This has resulted in many bursts of pipelines causing both a danger of contamination and loss of water. *Adopted from Anders Tønnerson (water choice in a low income area).*

2.3 .1 Effects of pipe quality on potable water

In countries with weak piping systems and maintenance, a large proportion of water (up to 70% in some developing countries) leaks through pipes and makes quality water coverage more costly.

Kampala city uses PVC pipes for its pipe water supply system. The presence of lead in drinking water is more prevalent and serious than many people realize. Despite common perceptions, lead is not restricted to inner-city communities, but rather is a problem that affects many water systems across the country. Lead is used in 95 percent of PVC pipe in India, 86 percent in the Middle East and Africa, and 61 percent in South America, according to figures from German stabilizer maker (*Baerlocher GmbH, 2013*), presented at the at the 2013 International Plastic Pipe Exchange Conference, held Sept. 5-6 in Xi'an.In Europe, by contrast, 29 percent of all PVC pipe systems use lead, while in North America, the figure is less than 1 percent, because nearly 100 percent of vinyl pipe systems use tin as a stabilizers, Baerlocher said Europe's PVC industry has committed to eliminate lead by 2015, and has eliminated lead stabilizers in 80 percent of its applications, according to Rainer Grasmuck, chairman of PVC 4 Pipes, a pan-European trade association and an executive at Baerlocher, in an interview at the conference. To help reduce the lead problem water board systems should put in place a very efficient pipe management policy of maintenance, repair, replacement and Installation. Removal of old pipes is costly but the most effective measure to reduce lead exposure from water. (*WHO, 1993 p49-50*)

All water utilities should deliver to the consumer an adequate supply of high-quality drinking water at a cost commensurate with the needs of each individual water system. To achieve this objective, the water should come from the highest quality source of supply available and be appropriately treated to meet regulatory and water supply industry criteria. Drinking water quality criteria should be based on documented health effects research, consumer acceptance, demonstrated treatment techniques, and effective utility management. The minimum criteria should be as defined by federal, state, and provincial regulations that take into account appropriate health and cost considerations.

2.3.1 .1 Water Quality assessment in Uganda.

Uganda has mainly two classes of drinking water:

Class I potable water available from conventional treatment processes such as chlorination, filtration; and is used in food establishments or distributed through the water distribution systems. This water is comparable to current international standards for water quality. This water is considered to be acceptable for lifetime consumption, and is the recommended compliance limit.

Class II (untreated water) potable water available for water consumers through boreholes, protected springs, shallow wells, gravity flow schemes and harvested rainwater, which may be used for consumption in accordance with the guidelines, provided by the Directorate of Water Development (DWD). This class specifies a water quality range that poses an increasing risk to consumers depending on the concentration of the determinant within the specified range and the possibility of monitoring its quality. It is considered to represent drinking water for consumption for a limited period

2.4 Relationship between dynamic systems and water resources

The Dynamic Systems (DS) methodology is based on and derived from the Theory of Control developed by Forrester (*1961*). The fundamental principle of this methodology is that every dynamic behavior is a consequence of the system structure (*Powersim, 1996*). It is characterized by changes occurring along time.

DS simulation models are real-world abstract descriptions. They allow the modeler to represent complex problems characterized by its dynamics, non-linearity, feedback relationships, and discrepancies in time and space (*Wiazowski et al., 1999*). A DS model should capture only the essential factors of a real system, disregarding all other factors. The main use of the models is to communicate a point of view of the world on specific problems; they do not try to be the reality, but to be as close as possible to it, and predict its behavior *(Pérez Maqueo et al., 2006*). The user should always be conscious of the model limitations he/she is using.

When focusing on a problem, there are several ways by which simulation models can be used. The objectives that guided the dynamic systems simulation model to manage water resources at the RB-PCJ (WRM-PCJ) construction defined the structure. Considering this, and based on other countries' experiences and other watershed development trends, a DS simulation model was developed and run in order to define the RB-PCJ developmental stage to date, and assess the availability of water resources and agriculture sustainability for the next 50 years.

WRM-PCJ uses DS on an object oriented simulation environment, the STELLA 9.0 (I see systems Co., Lebanon, NH, USA) platform. The model relates environmental, physical, social and economic elements to explain the dynamic behavior of water resources supply and demand, and wastewater generation by several existing consumers in the RB-PCJ. *Simonovic & Fahmy (1999)* also integrated object-oriented system dynamics modeling approach to conduct a long-term water resource planning and policy analysis for the Nile River basin. The WRM-PCJ is a tool to aid policy and decision makers to seek out for different alternatives to manage water resources at RB-PCJ.

To analyze the sustainability impact of water resources due to water supply and demand, WRM-PCJ uses: the Sustainability Index (*Xu et al., 2002*), which defines the relationship between total consumption and total available water; and the Falkenmark Index (*Falkenmark, 1989; Falkenmark et al., 2007*) which relates use-to-availability (Level of exploitation) and the number of people that have to share a unit of water (water shortage)

2.5. CASE STUDY

This chapter presents the case study of the paper where the research was conducted and also the backbone to the model built in this system. The case study is described in the problem description and background.

2.5.1 Background of Uganda

Uganda is a landlocked country in East Africa. It is bordered to the east by Kenya, to the north by southern Sudan, to the west by the Democratic republic of Congo, to the southwest by Rwanda and to the south by Tanzania. Uganda is the world's second largest populous country after Ethiopia. The southern part of the country includes a substantial portion of Lake Victoria, shared with Kenya and Tanzania hence situating the country in the African great lakes region. Uganda also lies within the Nile basin, and has a varied but generally equatorial climate (Wikipedia).

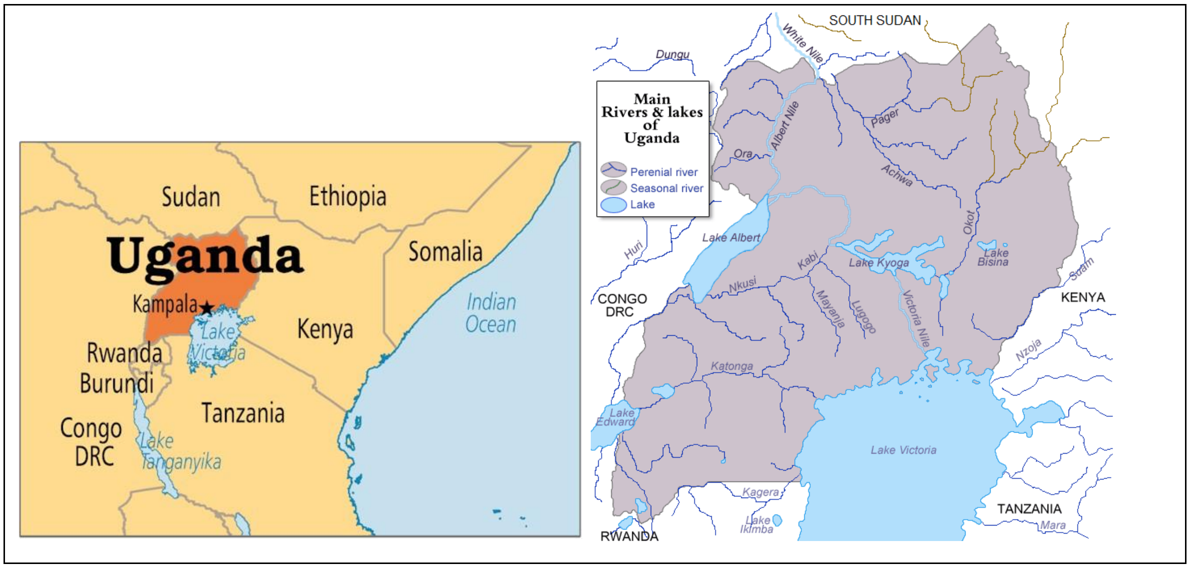

Figure 1: Uganda Geographical location and major lakes and rivers in Uganda.

2.5.5: Background of Kampala Area

Kampala is the capital and largest city of Uganda. It is located 8km north of lake Victoria. Kampala geographic features covers an of area 189 km^2 , land 176km^2 and water bodies that cover about 13km^2.

Water accessibility in Kampala

Kampala Water is the largest Area of NWSC operations and accounts for about 63% of the Corporation's revenue. Kampala is experiencing high population increase, due to high urbanization rate of 4.8% annually (*UBOS Statistical Abstract 2012*) in addition to other demographic factors such as fertility and migration leading to an overall average population growth of 9%. (NWSC annual report 2013). The population is about 1,723,300 (*UBOS Statistical Abstract 2012*), with 75% (*UWESPR 2014*) of this population being served with water and the rest of the population having no access to the clean piped water. They fetch water from neighbors' standpipes and other open water sources such as wells, boreholes and streams whereby most of them are not hygienic.

2.6 Field Research

In order to elaborate more on this paper and establish the hypothesis, data collection this was done through interviews and literature reviews from the organizational reports and studies done before. The water organization provided general customer information on how much water was consumed on average, costumers water source preferences, water quality, water prices, how long it takes to get a new connection after moving into the area among other questions.

The following were the key performance highlights of Kampala area during the year of review. (Information gathered from NWSC organization)

Water Production and quality: Water production averaged 181,466m3/day during the financial year 2012/2013 compared to 160,606m3/day in the previous year thus improving supply reliability. All the three water treatment plants produced final water with good bacteriological and physiochemical quality that was maintained in the distribution at all times.

Meter Management: Kampala Water has a Meter workshop with a capacity of 100 meters per day (where 75 meters are repaired and 25 forwarded for testing). Currently there are 3-meter test benches in total and proactive meter servicing that consists of central teams. Meter servicing is a strategy that is aimed at reducing water losses caused by erroneous meter readings hence increasing water sales. In addition, modern electronic handheld meter devices are used in all the branches to increase meter reading accuracy.

Training: In regard to training, staff was trained in different courses such as customer care, team building, surveying techniques and principles, and ethics and integrity. This was intended to improve the quality of services offered by staff and the level of productivity.

Mains extensions, intensifications, reinforcements and replacements: During the year, a total of approximately 44.8kms of pipes were laid increasing the total pipe network to 2,343km.

Debt recovery: A number of firms were contracted to improve debt collection, which helped with the collection of 0.795 million Uganda shillings during the year**.**

3. PROBLEM DESCRIPTION

Kampala uses a piped water supply system as its main source of provision of potable drinking water among other sources such as protected springs but these are not considered very safe for providing drinking water. NSWC(National Water and Sewerage Corporation) a utility service provider that is owned by the government is responsible for water supply. Over the years the pipe supply system has become insufficient to meet the growing consumer water demand. The mains concerns are with the water pipe system management especially with new installations having to go through bureaucratic steps to be approved, repairs are improving but even so some customers complain that it can take weeks or even longer to get a fault repaired. Particularly if more than one meter in a neighborhood is out of order, during this time residents may resort to unprotected water sources at wells, or buy water from vendors or neighborhood resellers with yard taps. This goes the same for pipe maintenance and replacements. The increasing water demand would not be a problem if the government had enough resources but the hiring of workforce for pipe management and ordering for new pipes are constrained by lack of funds.

The increase in population in the city is an additional constraint to the pipe water supply system as it has resulted in the city's water supply system being placed under a lot of pressure as the available pipes in place are unable sustain the growing population also the total pipe Network length in place is not enough to serve the increasing water demand from the population.

The average water supply has been growing at an average rate of 6% for the past 7 years. This has caused the water accessibility to increase, but not fast enough to cover the increasing consumer water demand causing a gap between the water demand and water supply.

The National target made in the last development budget (June 2014) was to have 100% water accessibility by 2015, but since the current water supply growth rate is not able to sustain the fast growing population. So meeting the proposed target is unlikely to happen.

The water management board needs to find diverse means to reach the target as soon as possible.

3.1 Reference mode

The graph represents the reference mode used in this paper. The reference mode is the problem represented in a time graph that shows the development of the problem over time. The reference mode shows the water supply has been growing over the past 6 years. The graph below **(figure 2)** shows how the water supply in Kampala has grown over the years. The water supply growth rate is growing at an average of 75%, which means about 25% of the water demand is not being met. (*NWSC annual report 2012-2013 pdf pg. 56*)

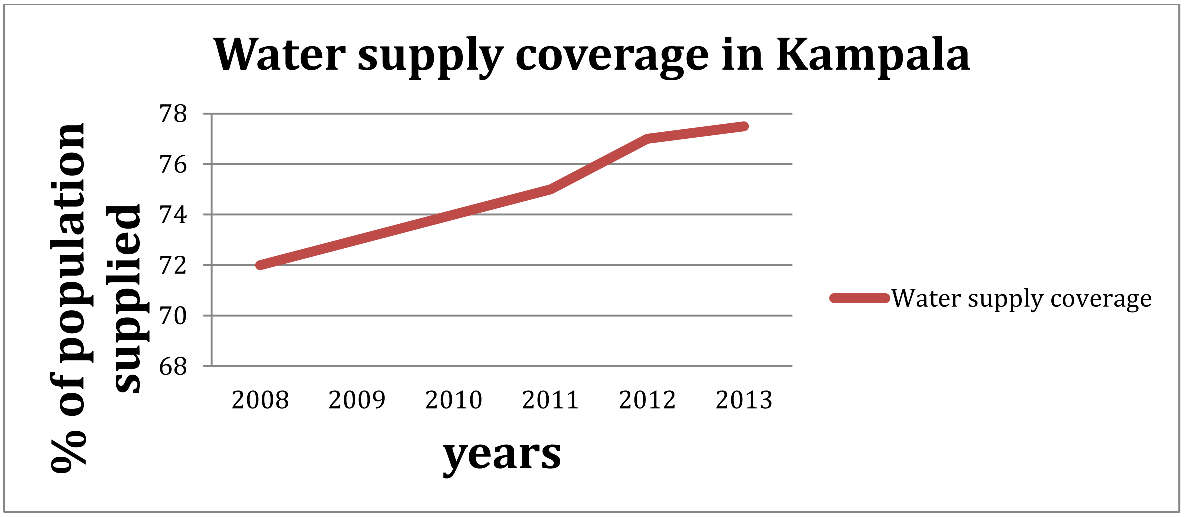

Figure 2: reference mode water supply growth coverage.

3.2 Dynamic hypothesis

Different hypothesis are discussed to explain the cause of the gap between water demand and water supply in Kampala. A description of various hypothesis is presented .A casual loop diagram (**figure 3**) is used to illustrate the hypothesis and the different feedbacks how they are assumed to affect water supply gap.

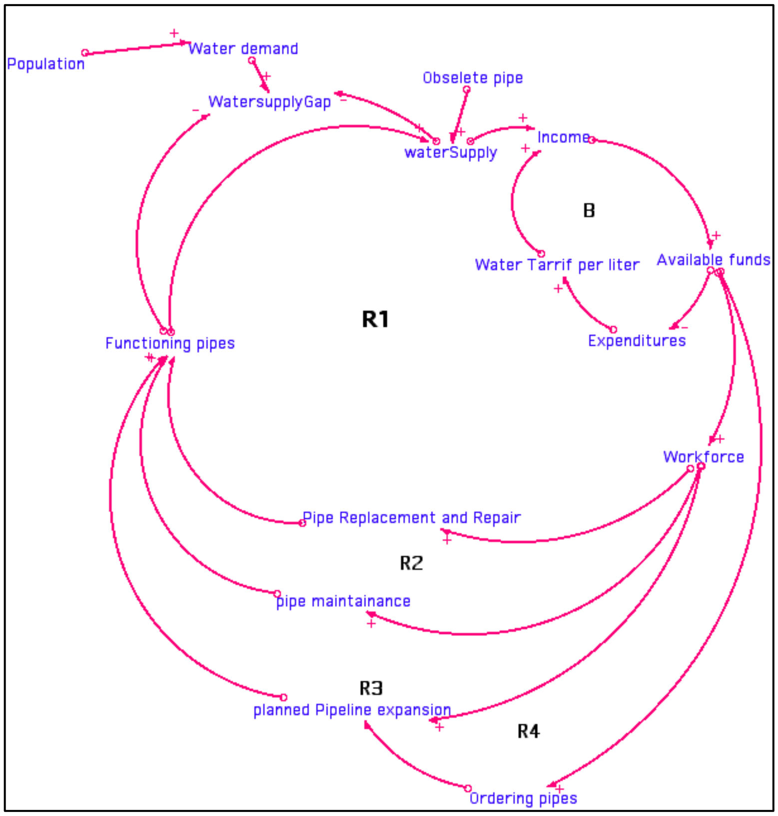

Figure 3.Casual loop diagram showing different hypothesis

H1: Few functioning pipes in place to supply enough water to meet consumer water demand.

Uganda mainly uses a pipe water system as its main source of potable water supply, the functioning pipes in the system are the pipes that working very well with no damages that could possibly lead to leakages. The Pipe infrastructure over the years has become less efficient to sustain the water demand from the consumers due to the constraints from the growing population and the pipe infrastructure itself.

In the casual diagram above (figure 3) the reinforcing loops (R1, R2, R3, R4) show how the functioning pipes are influenced. The pipes can be increased through new installations determined by the planned pipeline expansion, through repair and maintenance of damaged pipes as well as replacing the old pipes. It has been hypothesized that when the functioning pipes in place are few, the water supplied is not enough to meet the water demand. The cause of the few pipes can be explained with the long time delays taken on maintenance, repairs and replacements and the fact that there are low available funds to purchase new pipes as well as to hire enough manpower for efficiency management ***(balancing loop (B)***. The table below shows that 43% of technical breakdown of pipes is causing non-functionality.

Table 1. Reasons for non-functionality of urban drinking water sources (adopted from UWESPR report)

Reasons for non-functionality	June 2012	June 2013
Technical Breakdown of pipes	43%	44%
Dry/Low yielding	17%	17%
Vandalism	10%	9%
Alternative water source nearby	8%	8%

Water quality	8%	8%
Water source committee not functional	5%	5%
Other	4%	4%
Leaking	4%	4%

H2: Increasing water demand from the growing Kampala population.

Kampala being the capital city it’s bound to experience a population increase. The current annual urbanization growth rate is 4.8%. The population increase has resulted into the city’s pipe water infrastructure being placed under pressure to sustain the growing water demand.

The water board management is doing its best to keep up with the growing demand through infrastructure expansions but this is being limited by the funds available within the organization, The pipe density is 150 people per pipe but these numbers have increased over the years hence the consumers are being forced to cut down on the water consumption in order for other people to get some water. Other people are resorting to other water sources such as unprotected springs, wells to meet their demand.

4. MODEL DESCRIPTION

This chapter presents an overview of how the model interacts and works, the model boundaries and level of aggregation are defined and the general assumptions about the model are listed.

Method used is a system dynamics approach .A computer software (I think version 10.0.6) was used to aid in the analysis and test different model and policy behaviours through simulation graphs.

4.1 Model boundary

The model scope and focus are reflected in the model boundary; **figure 4** shows the primary features included (endogenous), assumed (exogenous) and the and excluded (ignored) from the development of the model.

Exogenous

- Births
- Deaths
- Current Water Tariff
- Net migration
- Adjustment times

Endogenous

- Water supply
- Water demand
- Income
- Expenditures
- Available funds
- Workforce
- Population
- Functioning pipes
- Desired water tariff

Ignored

- Water production
- Competing projects
- Project

environment.

Figure 4 shows exogenous, endogenous and ignored variables.

4.2: Model Assumptions

Boundary assumption: The environment for development is assumed to be stable throughout the project life. An example of assumption of stable environment is the use of constant (exogenous) variables to describe average durations to complete development activities.

The time for the model is measured in weeks and the reference mode runs from 2010 to 2012 (approximately 156 weeks). The other assumptions have been grouped and explained according to the sectors they influence. The assumptions for each sector are described below.

Water demand sector (population sector)

The region of interest in this study is Kampala city located in Uganda. The Kampala population is increased by births, 40% of the women are assumed to be fertile. The population is increased through net migration rate where the urbanization growth rate is assumed to be 0.028 per week. The population is reduced by death rate, death fraction is estimated at 0.035.

The Average water consumption per week is estimated to be 29 liters per person per week.

Water supply sector

The supply sector has been subdivided into two categories

a) **Pipe supply control sector** responsible for controlling pipe inventory and pipes on order. The time to adjust pipes on order and inventory is assumed to be 18weeks and time taken for pipes to be delivered from Pipes On order stock to Inventory stock is estimated to be 6 weeks. Workforce productivity is assumed to be 3 pipes per person per week (number of pipes each worker can repair or install per week).

b) **Functioning pipe management sector**

This part of the sector looks at how the pipes are managed that is to say how they are installed, repaired, replaced and maintained.

Adjustment time for new pipes is estimated to be 1 year (52 weeks) this is the time it takes to plan and prepare. Expansion implementation period is estimated at 25 weeks (time to install new pipes).

Damaged pipes repair time is estimated at 2 weeks and it is assumed that 0.01 of the functioning pipes get damaged per week.

Obsolete damaged repair is estimated at 3 weeks, fraction of obsolete damaged pipes is considered 10 times much higher than damaged functioning pipes because the obsolete pipes are at a much risk of getting damaged since they are old.

Obsolete pipes replacement time is estimated at 5 weeks this is because these pipes are old but not damaged so sometimes the management gives priority to the other pipes. Pipes lifetime is 20 years (1040 weeks). Time to report pipes for regular maintenance is estimated at 6 weeks and time it takes to maintain the pipes is 4 weeks.

4.3 Model structure.

The model has three sectors .The first sector is the population sectors which determines Kampala water demand, Secondly we look at the Pipe sector (water supply system) which structures of the way the water board manages the pipes in the system, from the moment they are reported to when they are ordered and replaced, how the pipe supply system is controlled. The third sector is the Finance Sector in this sector both major Sources of income and expenditures are structured. *The Structure of the Entire model is shown is Appendix A.* The figure below shows the three sectors interact.

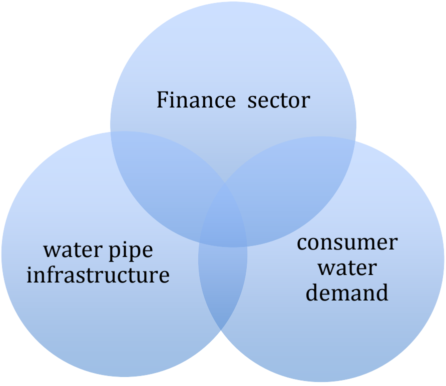

Figure 5 shows the relationship between the different sectors.

4.3.1 How the model works (model dynamics overview)

The main role of the model is to understand what is causing a limitation to accessibility of drinking potable water that has resulted into a water supply gap in Kampala, which is a dynamic problem as described in the problem description. The water supply gap is the difference between the desired water demand and actual water supply.

The total population of Kampala and the Average water domestic consumption determines the desired demand per capita (liters/week/person). On the other hand, the water supply defined by the functioning pipes, average water domestic consumption and pipe density (pipe density is the total number of people supplied per pipe).

The hypothesized reason why there is a water supply gap is because of poor and ineffective pipe water management system in place. The explanatory model aims to assist in identifying the different existing dynamic systems that could be behind the ineffective pipe system management.

The model works in a way that there are already a certain number of functioning pipes in place. These are the pipes supplying water to the entire Kampala population. These pipes are maintained on a regular basis (Regular maintenance stock). There is also a probability that these pipes could get damaged or obsolete (Damaged and obsolete pipe stocks). The obsolete pipes can also be defined as depreciated pipes but they are not damaged but just old. The average life time of pipes used in Kampala is 20 years and after this life time these pipes are expected to be replaced but sometimes some of the pipes get damaged while awaiting to be replaced, which calls for obsolete damaged pipes emergency replacement rate. These pipes are accumulated into the obsolete damaged stock.

There is a continuous weekly pipes maintenance and replacement because of pipe breakages and leakages, which have become very expensive. In addition due to the growing water demand from the increasing population, the pipe system has to be expanded. This implies that the management water board needs to buy new pipes and hire a workforce for the installation and maintenance of the pipes. The finance sector in the model helps to understand how much funds are available. The reliable funds come from within the water pipes system itself so if the system is poorly managed the water board management won’t have much funds especially if all the pipes breakdown and are not replaced in time. The income is determined by how much revenue water we have in relation to expenditure (actual water supplied-water lost) so if there are too many pipes not replaced, income is going to be low because water supply will be low.

The expenditures in the system are total sum of investment costs in new pipes, total workers costs and weekly maintenance costs. With the finance in place, the management is able to know how much workforce can be hired and how many new pipes can be ordered. So in a nutshell the funds have a great impact on the pipe supply effective management.

The damaged and old pipes are supposed to be replaced and also new pipes for expansion planning as regards to the growing population to keep the water supply system balanced. In order to do this, a pipe supply control system is needed.

In the pipe supply control system new pipes can be ordered. In order to do so, we need to know how many pipes are needed in the system (total pipes renewal and installation demand). This demand for the pipes is determined by capacity demand for the pipes to be replaced and added (obsolete, obsolete damaged, damaged, planned pipeline expansion pipes). Each of these stocks has its capacity demand determined by using the accumulated stock divided by the normal repair time. The repair times differ from each stock pipe.

With the total demand determined, the pipes are ordered but there is a constraint faced from the funds at times (effect of Available funds on ordering rate, which is explained later). The ordered pipes take approximately 6 weeks to be delivered to the inventory stock.

For pipes to be finally installed we need a workforce in place, the hiring rate for this workforce depends on the total pipes demand and workforce productivity estimated at (3pipes/person per week) and also if there is enough funds to pay the workers (workforce budget). Pipe installation also depends on pipe installation capacity.

Finally pipes are installed according to urgency .The management needs to know how much capacity is available for each stock that has pipes for installation or replacement. This is done by getting capacity residual minus available capacity for the stock. Capacity residual is what is left after a certain capacity has been deducted. The management replaces the damaged pipes first, obsolete damaged pipes, new pipes for pipeline expansion and lastly obsolete pipes. (more description is done in individual sector discussion).

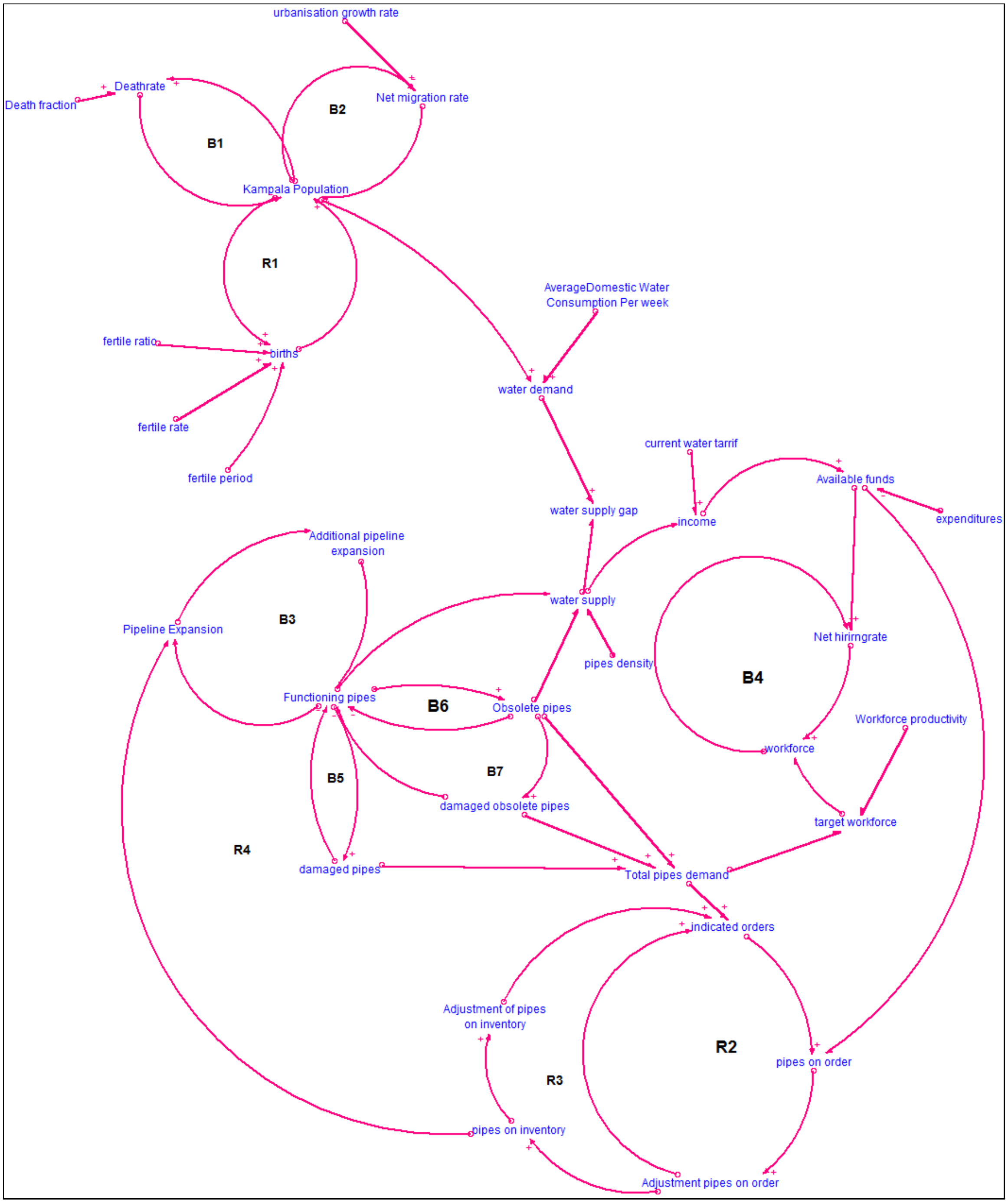

Figure 6 : Casual loop diagram for the entire model

4.4 Sector description

The model is comprised of both linear and non linear equations a list of them is shown in the appendix C. The equations are arrayed to allow simulation of a flexible number of development phases and manage the modeling of the different model sectors, definition of some of the parameters used are explained within the sector description.

Water demand. (Population sector).

The Population sector in the model is associated with the water demand in Kampala. The dynamics behind the population include births, deaths and migration as seen and explained below.

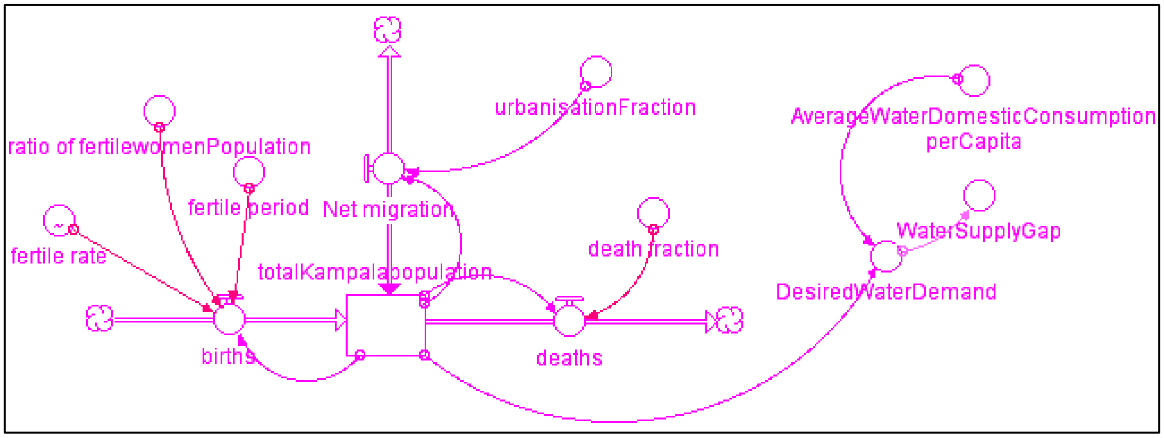

Figure 7: Population sector structure

The population is initialized to 1597800(year 2010 reference mode) and it is increased by birth rate.

Equation= (KampalaPopulation*ratio_of_fertilewomenPopulation*(fertile_rate/fertile period))/52

The birthrate has been determined by the above equation. The ratio of fertile women is assumed to be 40%, fertile rate (average children born per woman) is calculated over time and the fertile period is 35 years (Time a woman can stay fertile). The rate is divided by 52 to determine births per week.

Net migration rate also increases population and this has been determined by

Equation= (KampalaPopulation*urbanisationFraction)/52

The urbanization fraction is assumed to be 0.028 and the rate is divided by 52 to determine the migration increase per week. The population is decreased by deaths.

Equation= (KampalaPopulation*death fraction)/52, death fraction is assumed to be 0.035 .The rate is divided by 52 to determine deaths per week.

The water demand is determined by

Equation=AverageWaterDomesticConsumptionperWeek*KampalaPopulation

The domestic consumption is how much water each person consumes per week (liters per person per week). It estimated at 29 liters.

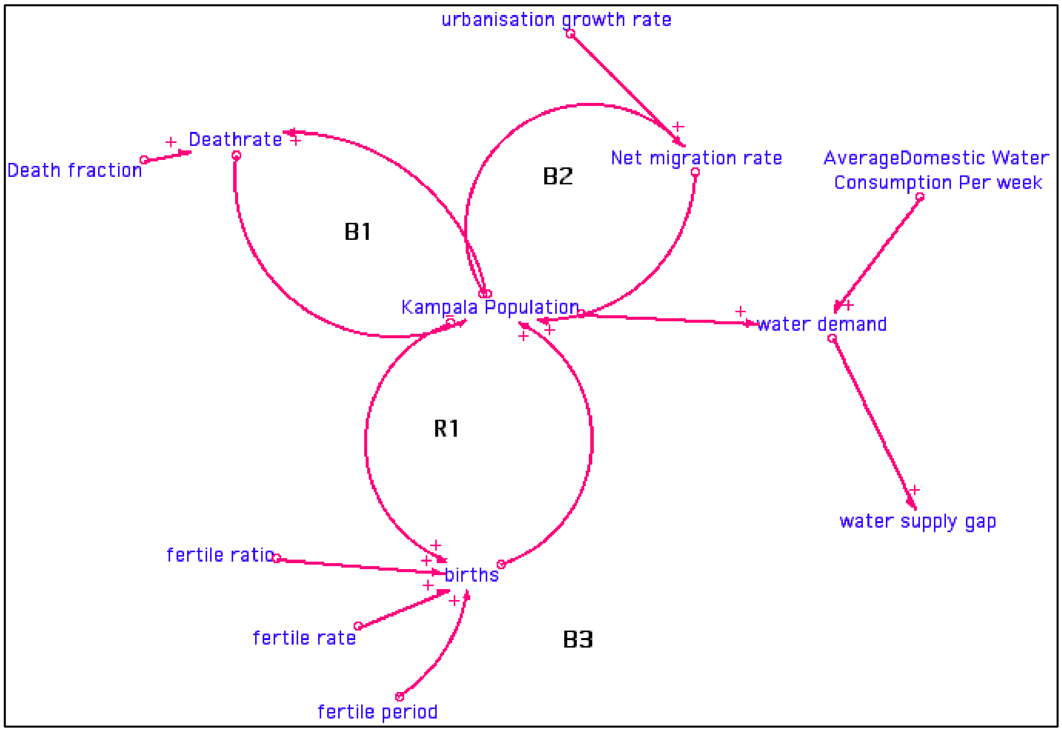

Figure 8: casual loop diagram for population sector.

Pipe Sector (Water supply sector)

The pipe sector is currently the main water source distribution for potable drinking water. The Pipe sector is divided into two parts a) pipe supply control system and b) functioning pipes management system.

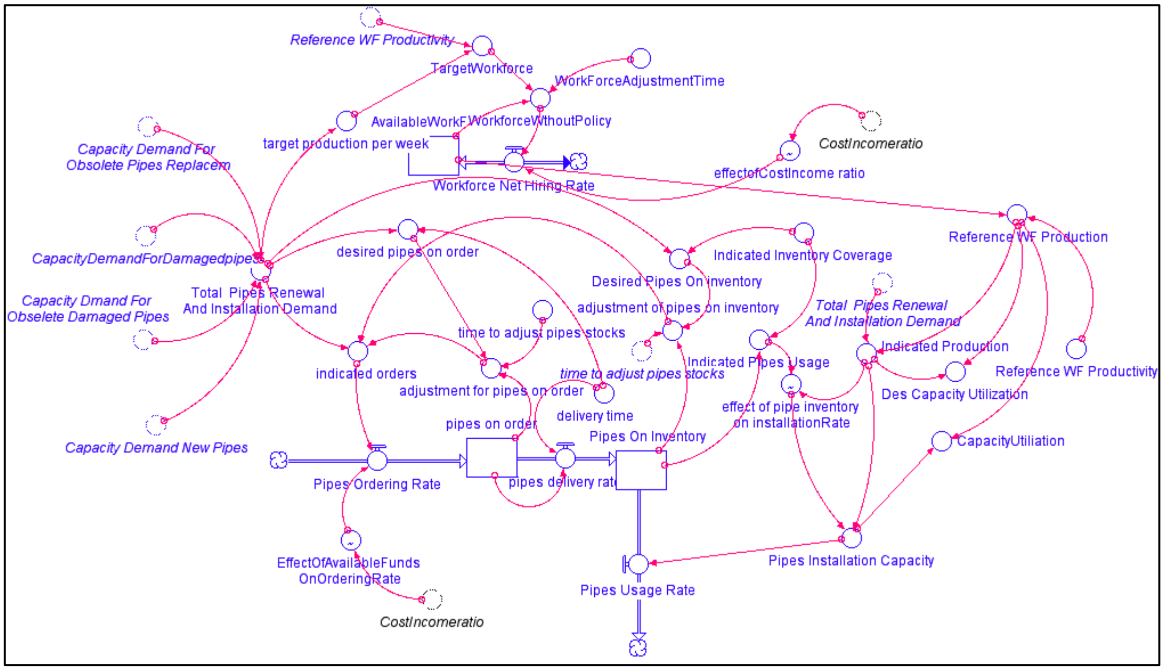

Figure 9: Pipe supply control system

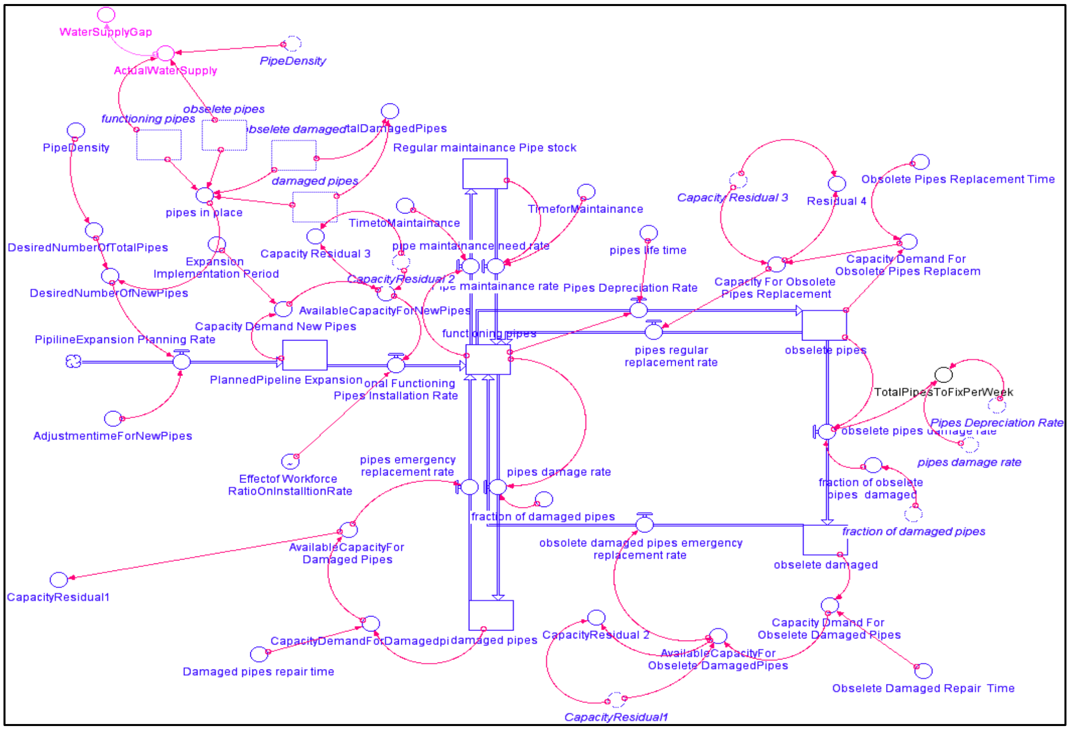

Figure 10: functioning pipes management system.

The pipe sector focuses on management and efficiency of pipes in the Kampala Water System. Therefore the main stock in this sector is the Functioning Pipes, which are currently the pipes in the system, and has been initialized to 7882 pipes.

This number was determined from the reference data initialized from 2010. That is using the population served with water /pipe density. Since in 2010, 74% of Kampala population was receiving water, 74% of the total population is 1,182,372 persons with water in 2010. And pipe density is 150 (1,182,372/150) is 7882 pipes in place.

There are two ways of increasing pipes in the water supply system. 1) Through installation of new pipes using the expansion pipeline or through Repair, maintenance and replacement of pipes that are damaged or obsolete. All these pipes are accumulated in a stock called Functioning Pipes. These are pipes in place.

The Functioning pipes are increased in different ways:

1.Through new installations, when there is an increase in the consumer demand the water management is obliged to expand the water system to meet the demand. A planned pipeline stock in this system helps in the regulation of the functioning pipes. The stock is increased by the ***PipelineExpansionPlanningRate,*** *which* is determined by

Equation= ***DesiredNumberOfNewPipes/AdjustmentTimeForNewPipes.***

This is a nonlinear equation that helps to determine how many new pipes are added per week for over a period of time.

DesiredNumberOfNewPipes = DesiredNumberOfTotalPipes - PipesInPlace. The equation determines the gap between total required pipes and how many pipes are actually available. **TheDesiredNumberOfTotalPipes** is derived from Kampala **Population/Pipe density** where pipe density is the number of persons per pipe. **Pipes InPlace** are all the pipes in the system. In this case a summation of all the stock pipes is done under an assumption that all pipes old and damaged need to be replaced at some given point of time. If the damaged pipes and obsolete pipes are not included there will be double counting because the pipes in need of replacement will be considered in the pipeline Expansion Rate and later will be also replaced after regular replacement times hence too many pipes in the system and thus heavy expenditures on maintenance.

The PlannedPipelineExpansion stock is decreased by the **Additional Functioning Pipeline Installation rate** which at the same time increases the functioning pipe stock.
This rate is determined by the equation below:
Equation=
(AvailableCapacityForNewPipes)*Effectof_Workforce_RatioOnInstalltionRate.
This effect is captured by using a graphical function because under the assumption that it is a non-linear relationship. The equation works in a way that if the workforce is a lot more pipes are installed and vice versa. (**Effects explained later in this section)**

2. Through repair, replacement and maintenance of pipes.

Functioning pipe to be managed efficiently have to go through regular maintenance thus the need for the maintenance stock. It takes about 6 weeks to report pipes for maintenance and about 4 weeks to work on the pipes.

Repairs from bursts that could lead to possible leakages. Old and broken pipes must be replaced. Different stocks categorize the repairs and replacements; obsolete **pipes, ObseleteDamagedPipes** and **DamagedPipes.** For each of the replacement rate from each stock capacity demand is determined by dividing the each stock by the repair time. First the total demand has to be determined which leads to the **pipe supply control sector**.

The pipe supply control sector is responsible for pipes orders and inventory. The **Pipe ordering rate** accumulates the **Pipes on order stock** and it determined by the **IndicatedOrders**
Equation=(MAX(0,indicated_orders))*EffectOfAvailableFundsOnOrderingRate.A max function in this case is used so that the rate can pick the highest number as the indicated demand however if the number is negative the rate takes 0 as the indicated demand. Once the pipes are ordered its takes 6 weeks for them to be delivered to the **pipes on Inventory stock** the **pipes delivery rate** is determine how many pipes are on order divided by the time they will take to be delivered. **Equation=pipes_on_order/delivery_time.** The Pipes on order stocks and pipe on inventory stock are both adjusted over a period of time approximately 18 weeks.

With pipes on Inventory the **IndicatedPipesUsage** (how pipes are used from the inventory) is the number of pipes available to be installed this depends on the normal inventory coverage that is the number of weeks it normally takes to receive the inventory divided by pipes on inventory

Equation=Pipes_On_Inventory/Indicated_Inventory_Coverage

A workforce is needed to install or replace the pipes and the Target workforce is determined by

Equation=target_production_per_week/Reference_WF_Productivity) where by TargetProduction=TotalPipesRenewalAndInstallationDemand and **Reference workforce productivity** is the number of pipes installed or repaired per worker per week. The **Workforce Net Hiring rate** is adjusted over a period of 12 weeks and the rate is constrained by the availability of funds. (***EffectOfAvailablefunds OnNetHiringRate which explained later in this section***)

IndicatedProduction=Min(Total__Pipes_Renewal_And_Installation_Demand,Reference_WF_Production) Indicated production takes the minimum of reference workforce production , what actually is produced and total demand (what we actually need)

(Indicated_Production*effect_of_pipe_inventory_on_installationRate) is a linear equation that determines the pipe installation capacity. The effect works in a way that if the desired production is high and the pipe consumption rate will be high, however in this case the pipe usage is controlled by the inventory .So the pipes can increase to any number but as the inventory reduces despite the desired production the pipe usage has to reduce in order to avoid depleting the inventory. (***Explained later in this section***)

Once the total pipe installation capacity is determined the available capacity for each replacement rate is calculated by taking the minimum capacity for example to determine the replacement rate for damaged stock replacement rate, the minimum of the demand and the available capacity is determined using Minimum function.

Equation=MIN (CapacityDemandForDamagedpipes,PipesInstallationCapacity)

After capacity residual is calculated to determine how much capacity is available for the next replacement rate. The replacement rates have been priotized in a way that damaged pipes are replaced first followed by obsolete damaged pipes, new installations and lastly obsolete pipes.

Illustration of the different effects used.

The effect graphical functions are based on logic and assumptions.

1. Effect of Available funds on ordering rate

The effect is determined by the **costIncome ratio** (Expenditures/income).

The cost Income ratio helps to measure how costs are changing compared to the income. It shows the efficiency of a firm minimizing costs while increasing profits. The lower the cost to income ratio the more efficient the firm is running, the higher the ratio, the less efficient the management is at reducing costs.

This effect is captured by using a graphical function under the assumption that it is a non-linear relationship, when the cost Income ratio increases the effect of the available funds on the Ordering rate reduces showing that there is limited funds to order for new pipes and when the cost income ratio is low the effect is high.

This effect is created because most of the times the management board is constrained by funding, there is never enough money to purchase the pipes required for installment. So in this case the effect works in a way that if there are enough funds the needed pipes can be purchased but lack of enough funds will limit the number of pipes ordered.

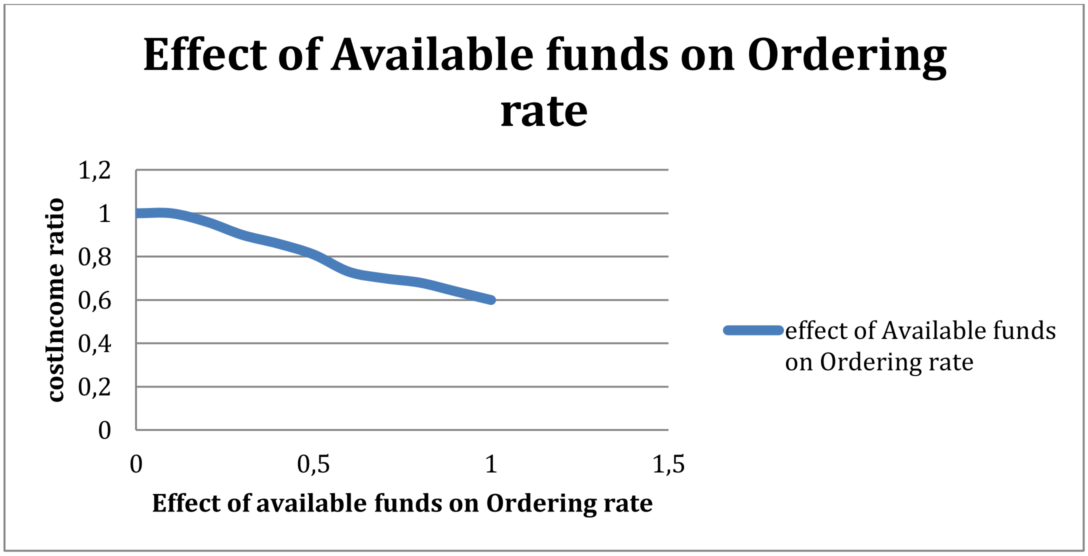

Figure 11: shows the effect of available funds on ordering rate

2. Effect of Available funds on Net Hiring rate

This is a non-linear effect determined by the cost Income ratio. When the cost Income ratio increases the effect of the available funds on the Net hiring rate reduces showing that there is limited funds to hire new workers.

This effect is created to show what happens if the funds are low to finance the workforce budget. So if the funds are low the management board will be forced to cut back its hiring rate. And also if the funds are high then more workforce can be hired but only if there are many pipes to be installed.

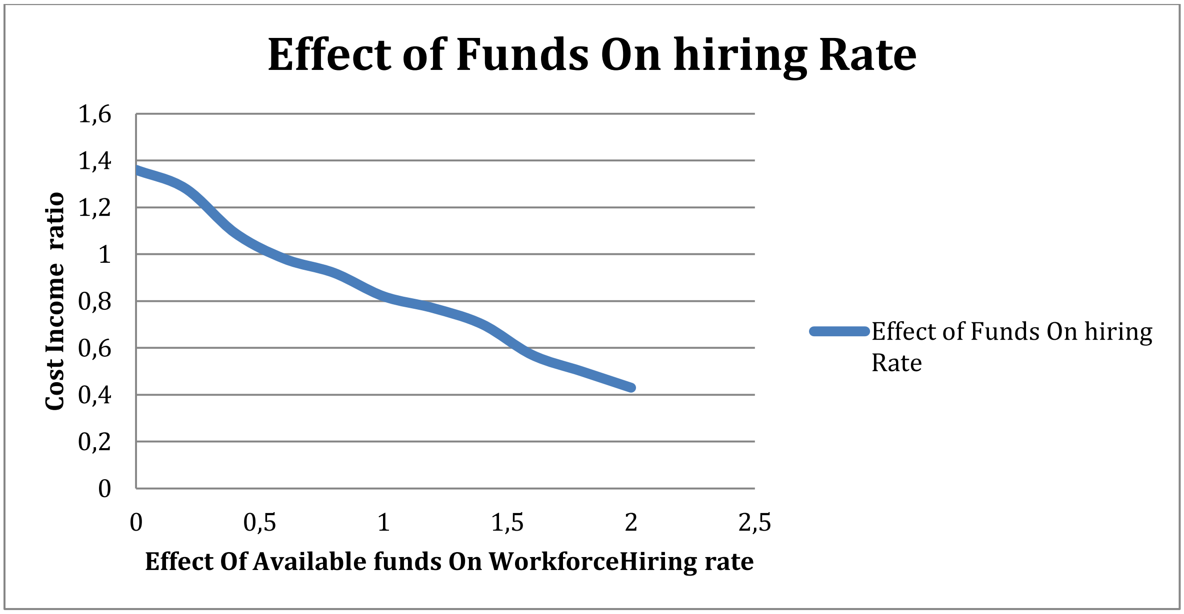

Figure 12: shows the effect of available funds on hiring rate

3. Effect of pipe inventory on installation rate

This is a linear effect determined by a ratio of indicated usage/indicated production. When the ratio is high this implies that there are pipes available for installation hence the effect will be high and vice versa.

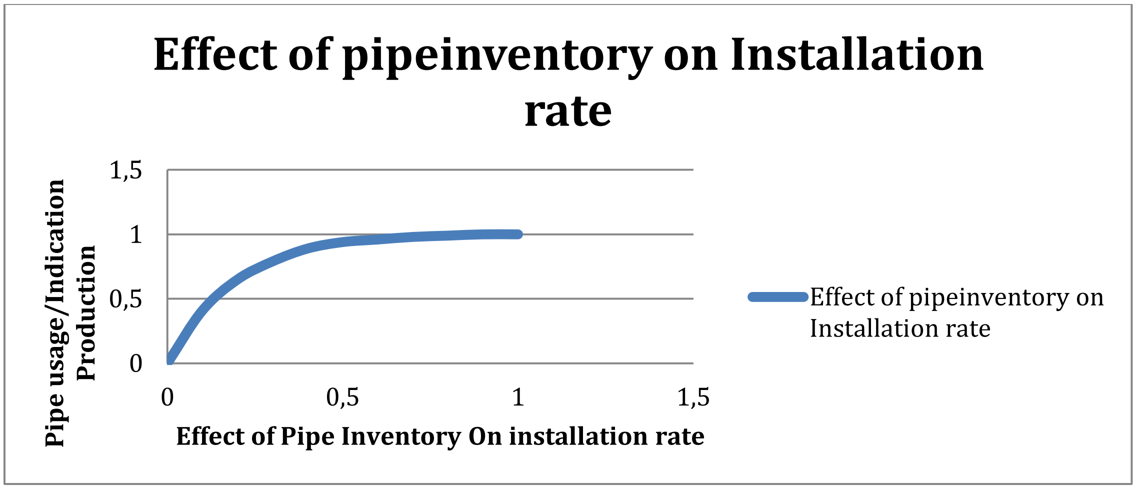

Figure 13: shows the effect of pipe inventory on installation rate

4. Effect of workforce on Installation rate

The effect is determined by the workforce ratio (**Available Work Force/desired workforce**). This ratio helps the management to determine if they need more workers .If the ratio is small that means the Available workforce is less than the desired so the production is low. If the ratio is big that means the available workforce is greater than the desired staff so in this case production is high but so are the expenditures. If the ratio is one the available workforce and desired staff are more less equal which is the ideal situation.

The effect works in a way that if the ratio is low few pipes are installed and a high ratio gives a high pipe installation.

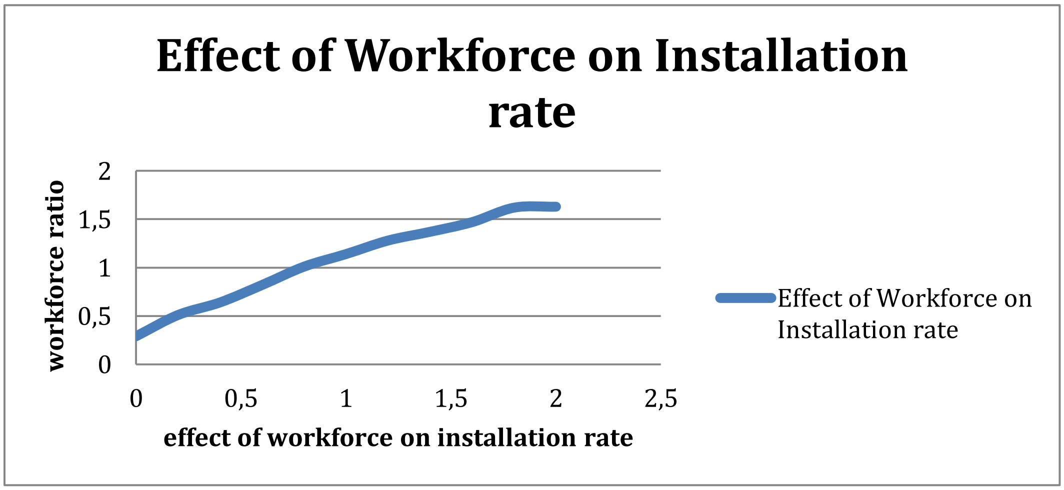

Figure 14 shows the effect of workforce on installation rate

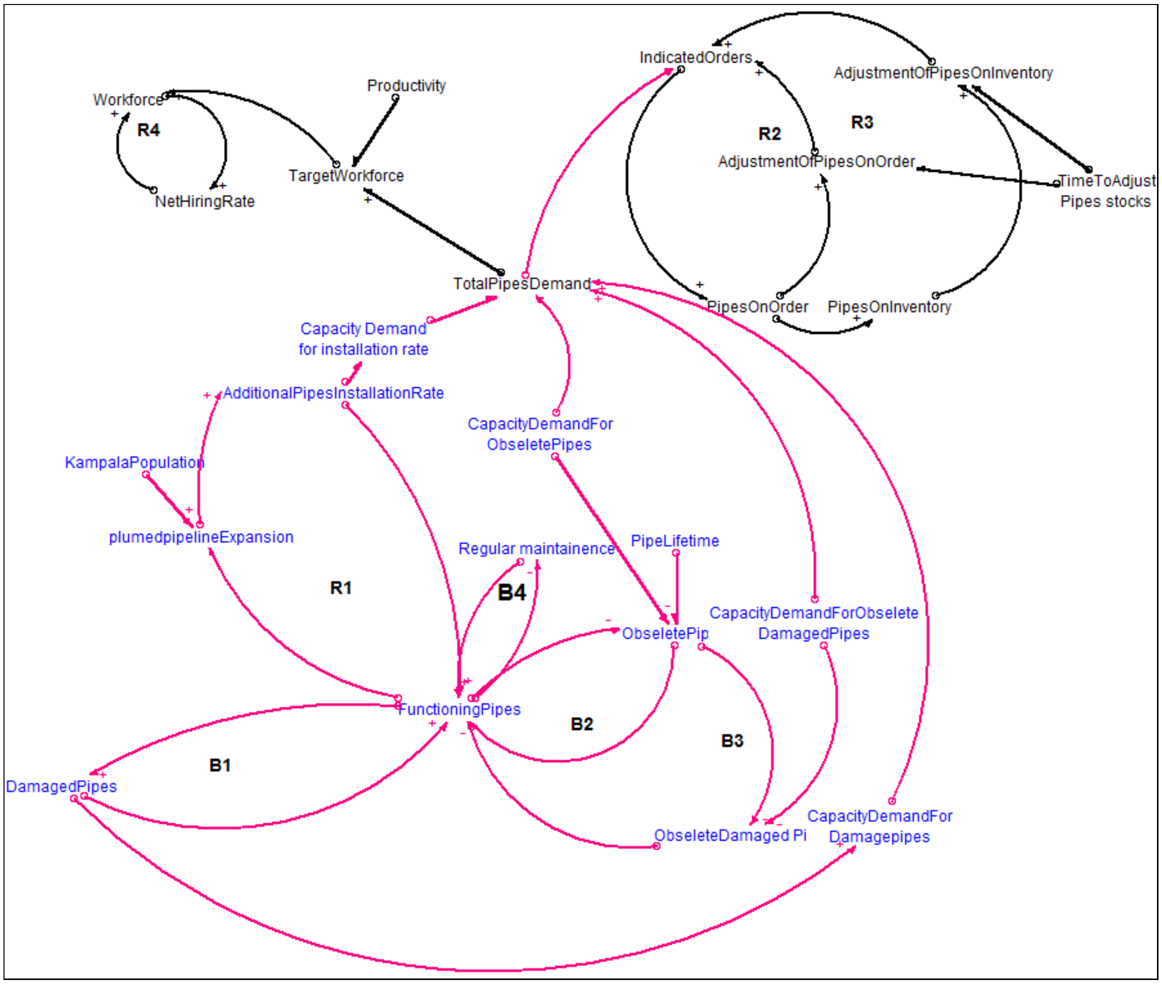

Figure 15 casual loop diagram for pipe sector

Finance sector

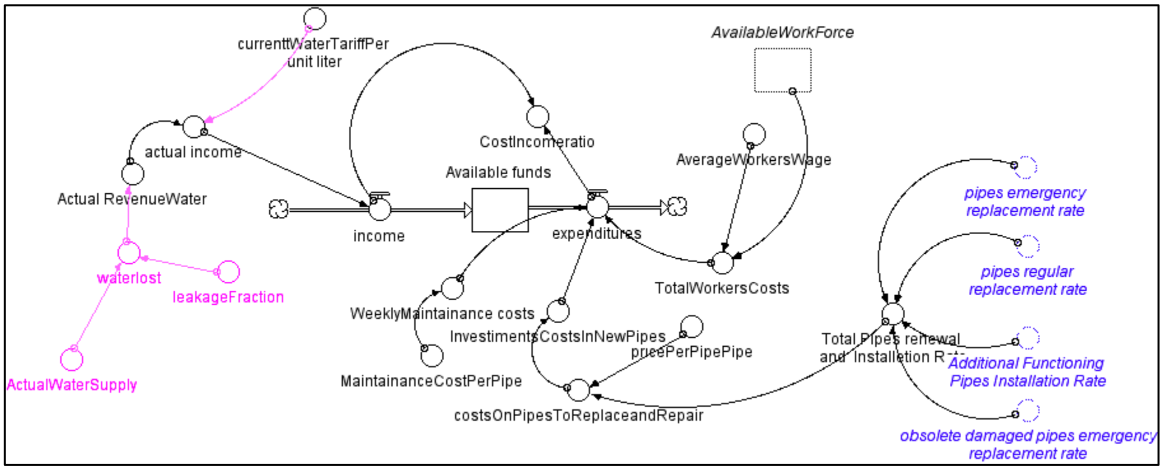

Figure 16: shows the model structure of the finance sector

The finance sector in this model shows the actual income and expenditures of the water board management. This sector is crucial since for effective and efficient management of the pipe infrastructure sector availability of funds is necessary.

The funds are represented by a stock (**available funds**); this stock is accumulated by income rate and decreased by expenditures.

The Income rate input is the actual income, which is determined by the **Equation=ActualRevenueWater*CurrentWaterTariffPerunitLiter .**The actual revenue water is the actual water billed minus the leakages .The water tariff is normally pre-determined by the water board management. This equation provides a linear relationship between the water tariff and the actual revenue water.

The expenditure rate is determined by **Investment costs in new pipes**, which are **costs on pipe to replace and repair** defined by the equation below:

IF(Total_Pipes_renewal_and__Installation_Rate>0)then(Total_Pipes_renewal_and__Installation_Rate*pricePerPipePipe)else 0 .This means that if there are no pipes to renew or install then there will be no investiment costs incurred other than that the model calculates costs using price per pipe multiplied by total pipes that need to be renewed or installed.

Other expenditures include is the Total worker costs

Equation=(available Workforce*AverageWorkersWage)

and weekly maintenance costs (Maintenance Cost – This is the amount of money spent on the preventive and corrective maintenance)

Equation=Pipe_maintainance_rate*MaintainanceCostPerPipe.

5. BEHAVIOUR TESTING

This section intends to test the different hypothesis that have been proposed, modeled and explained in the previous sections . This is done through simulations methods as seen in different graphs below. The hypotheses go through various tests also the problematic behavior of the current situation is recreated by the model. The results run for 150 weeks (approximately 3 years).

5.1 Types of tests done on the model

Various Ways of Testing a model are suggested by Sterman (*2000*). He identifies simulation as the only practical way to test the model as a way of understanding the model implications. And build confidence in the model hence the various tests were carried out through simulation to test hypothesis and evaluate likely effects of policies.

Dimensional Consistency

Each variable has been checked with their respective equation. The unit consistency was part of checking the equations. They have also been checked comparing them to the real life case, making sure that they are concurrent.

Extreme Condition Test

This was mainly Equation focused.it was done to make sure each equation makes sense even when its inputs take on extreme conditions.

Sensitivity Analysis Test

This is more of uncertainty analysis that was done to build confidence; it was done to demonstrate that each variable of interest does not change significantly if parameters are varied within reasonable ranges even if marginal and justifiable changes in model boundary are made. The sensitivity test identifies the parameter which deserves special attention. This test was done both on the explanatory and policy model.

Forecasting

This was done with the predicting future patterns of behavior, changes in the patterns, and event prediction. This was in policy model testing.

Integration error test.

Here the time step was tested the model behaved the same when different time steps where input.

parameter assessment

All parameters were conformed to real life situations and showed consistency with relevant descriptive and numerical knowledge of the system.

As explained in the problem description there is a gap between water supply and demand which means that some of the population is having limited accessibility to potable water in Kampala. **Figure 17** below show how the gap has been developing over the past 3 years. There are different hypotheses proposed to explain why this gap exists.

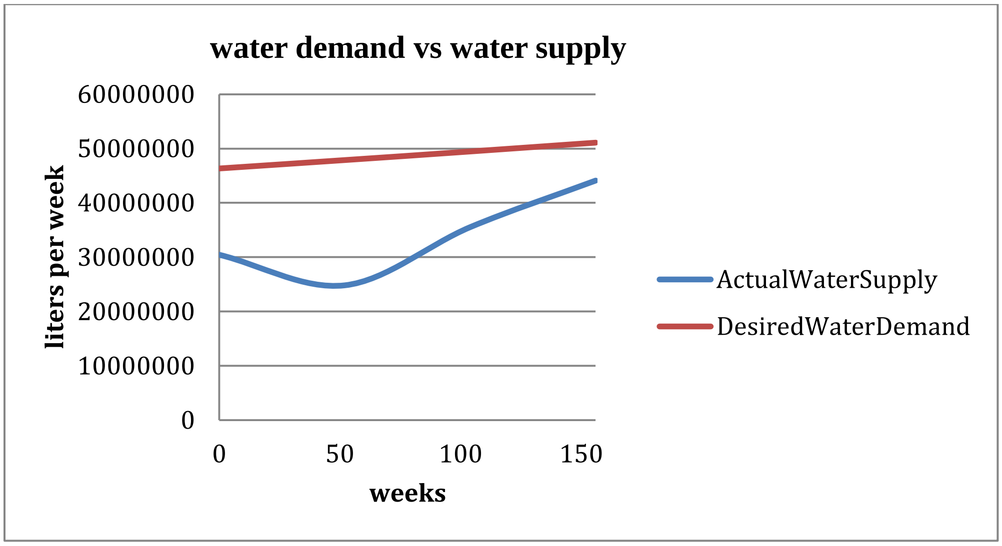

Figure 17: shows water demand vs water supply in Kampala city

5.2 Testing H1 Few functioning pipes in place .

Figure 18 below shows how the pipes have been developing over the past 3 years. There has been an increase in the functioning pipes but not fast enough to meet the rapid growth of water demand. Each pipe serves a total number of 150 people so the ideal pipes for the city would have to be the desired number of total pipes (Total population /150(pipe density)) so the gap between the desired number of pipes and actual pipes in place could explain the problematic behavior .

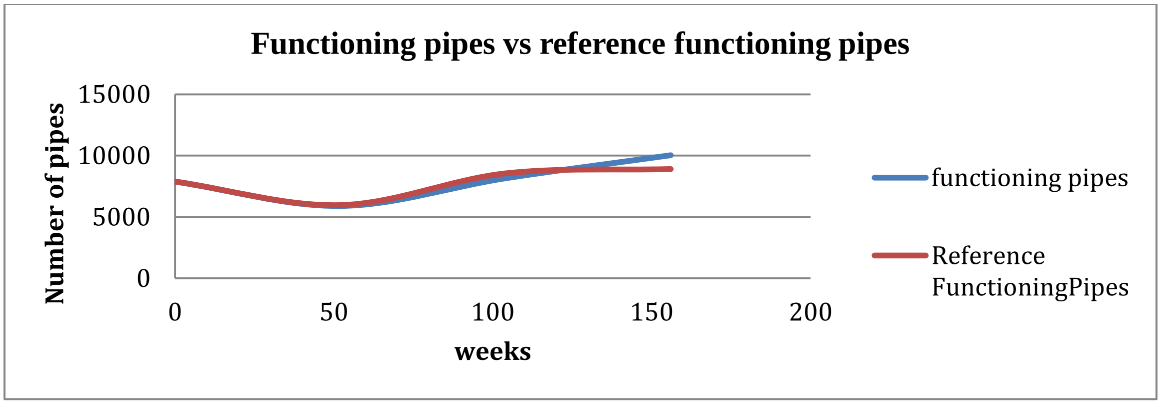

Figure 18: shows the Functioning pipes vs reference functioning pipes

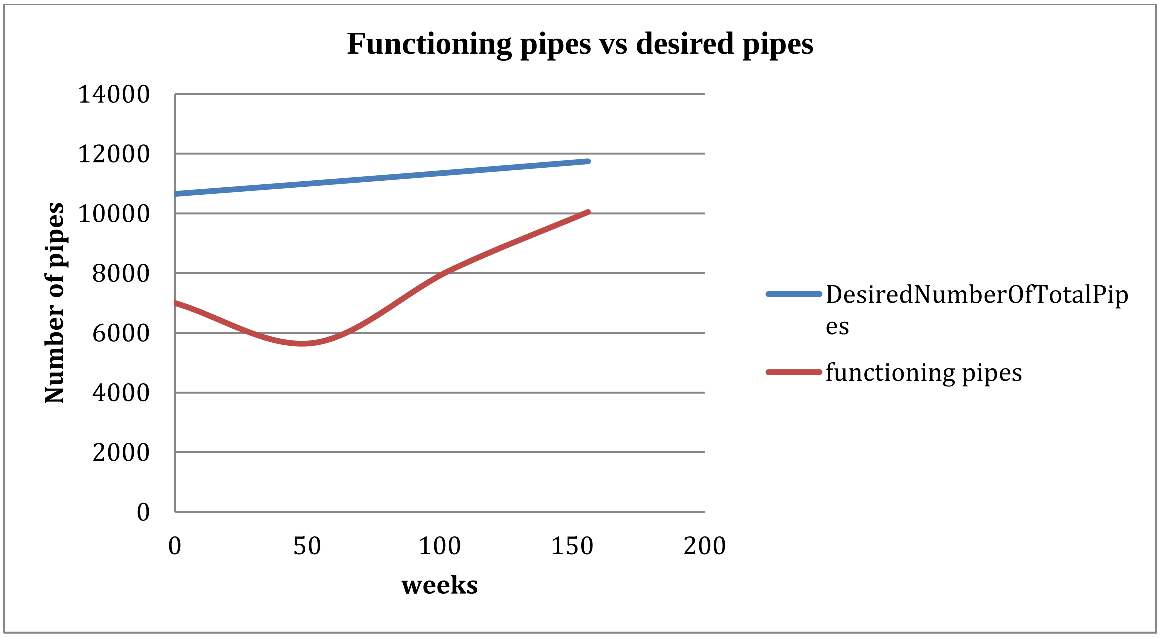

Figure 19: shows the functioning pipes in place vs the desired pipes.

Some of the possible reasons to explain why the functioning pipes are not increasing fast enough as desired.

1. Too many pipes are getting damaged as seen in **figure 20** below, these pipes reduce the number of functioning pipes in place since it takes some time for them to be repaired and replaced.

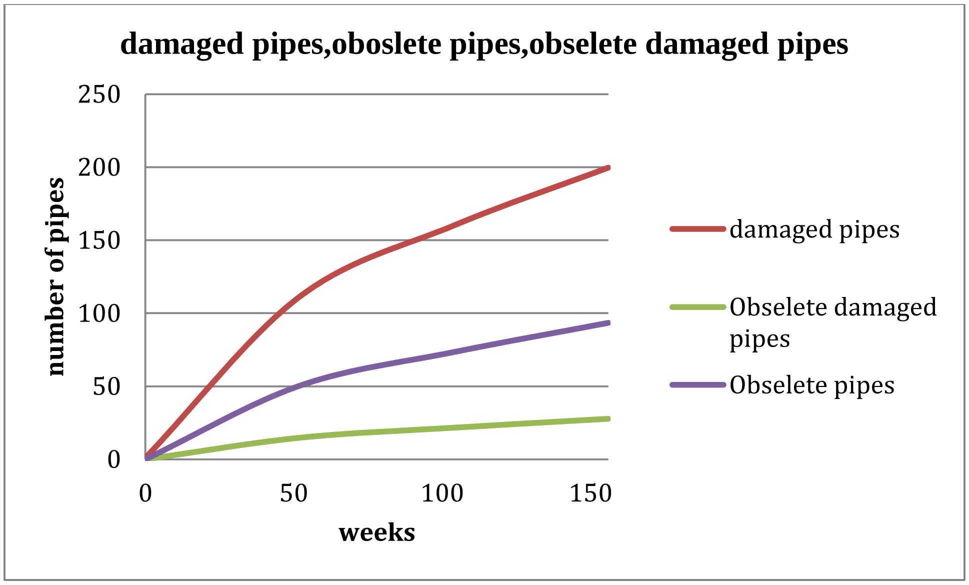

Figure 20: shows the pipes in need of replacement.

It takes time to repair and maintain the pipes the average repair time is 4 weeks, a sensitive analysis and extreme condition testing has been done on time taken for regular maintainance and it can be seen the longer the time taken the fewer the pipes in place , this applies to all the repair and replacement times.

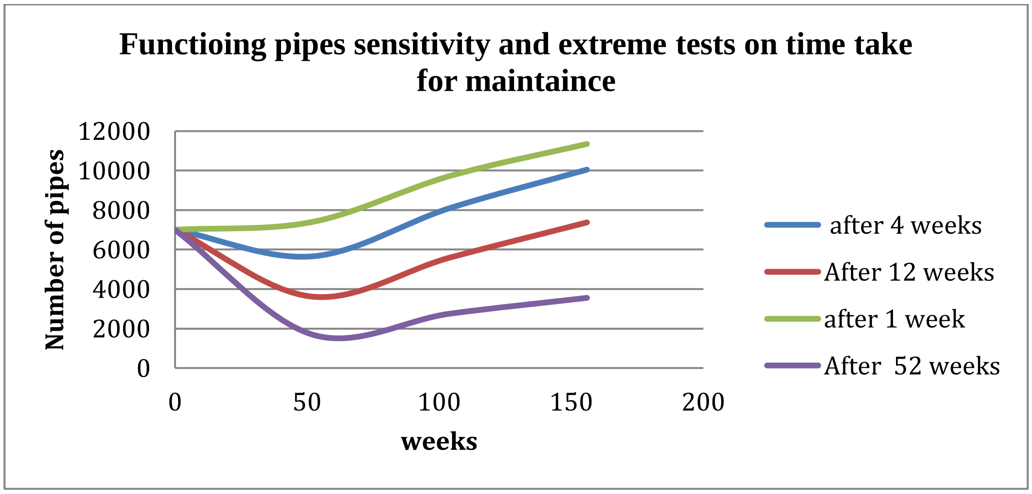

Figure 21: shows functioning pipes behavior under sensitivity and extreme testing on maintenance time.

2. Few available workers to help in new installations ,repairs and maintainance, when the workforce is increased ,there is an increase in functioning pipes and water supply (week 100-150) but when the workforce is low the gap is much bigger (week 50) because few pipes are installed or maintained reducing water supply.

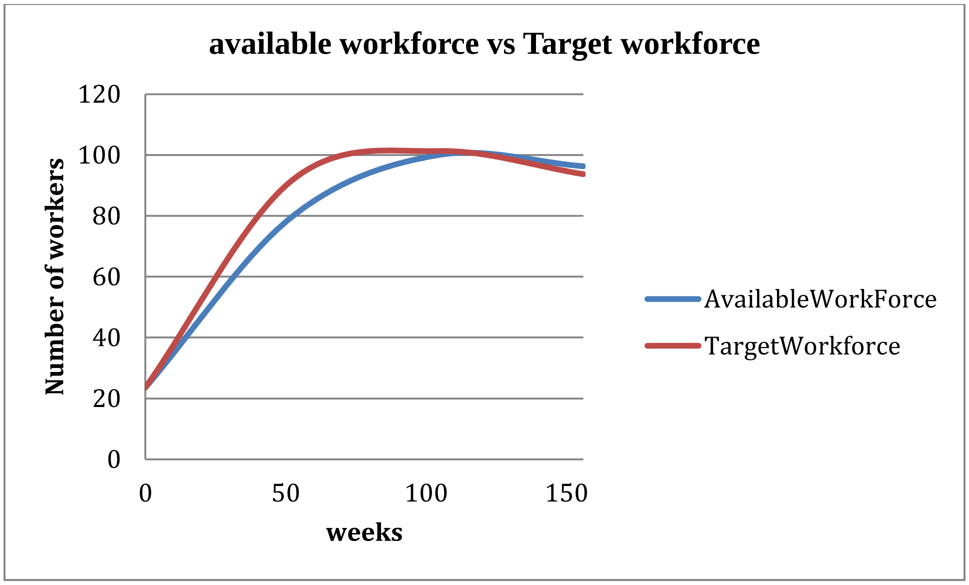

Figure 22: shows available workforce vs target workforce.

The normal adjustment time for workforce is 12 weeks ,if the workforce is adjusted after 1 year(52 weeks) the functioning pipes reduce and if it is adjusted after 100 weeks(almost2 years) there will be fewer pipes .so the adjustment time should not be too long.

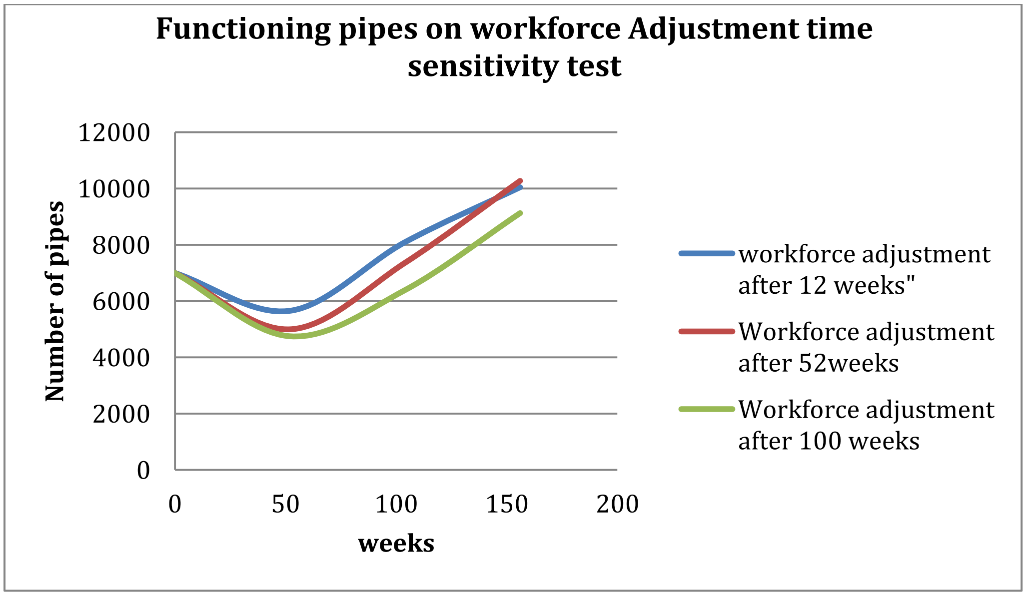

Figure 23: shows behavior of functioning pipes after sensitivity tests on workforce adjustment time.

3. Few pipes on inventory could explain the few functioning pipes. The pipes on order increase linearly to total demand of pipes. It takes 18 weeks to order for pipes and 6 weeks for the pipes to be delivered however pipes on order are limited due to funds hence accumulate until enough are available for purchase and delivery. The inventory received is not enough to satisfy the demand hence the few functioning pipes in place.

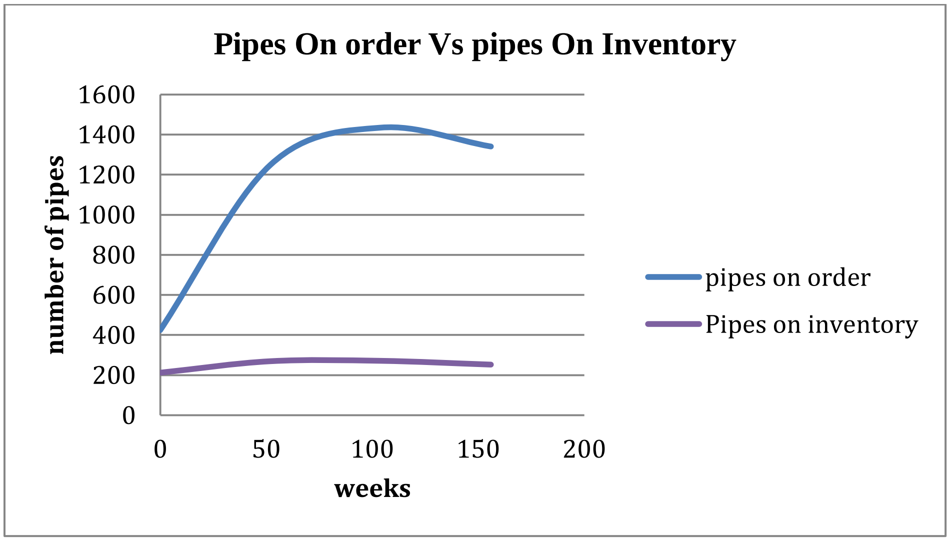

Figure 24 : shows pipes on order vs pipes on inventory

4. The availability of enough funds to order for new pipes, hire workers could also explain why there are few functioning pipes in place. The available funds = income but over the past 2 years as seen in the graph below expenditures have been increasing due to the increased purchase of new pipes to increase water supply. This is not efficient management so the board need to find a solution of increasing the pipes in place but as well as cutting down on the costs.

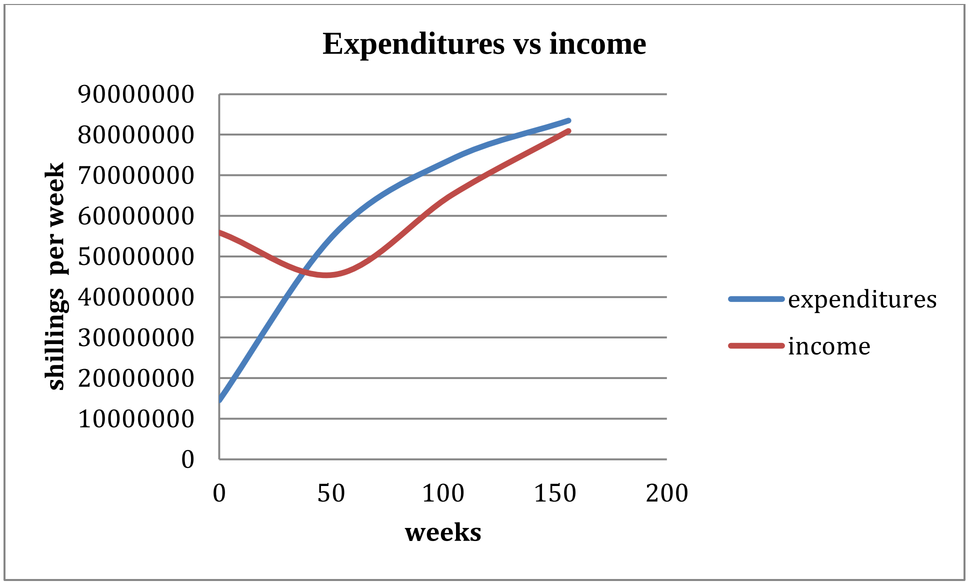

Figure 25: shows expenditure and income.

The income increases linearly to functioning pipes assuming other factors are constant .If the functioning pipes in place increase as seen in (**Figure 21),** more water is supplied hence increase in the amount of water billed.

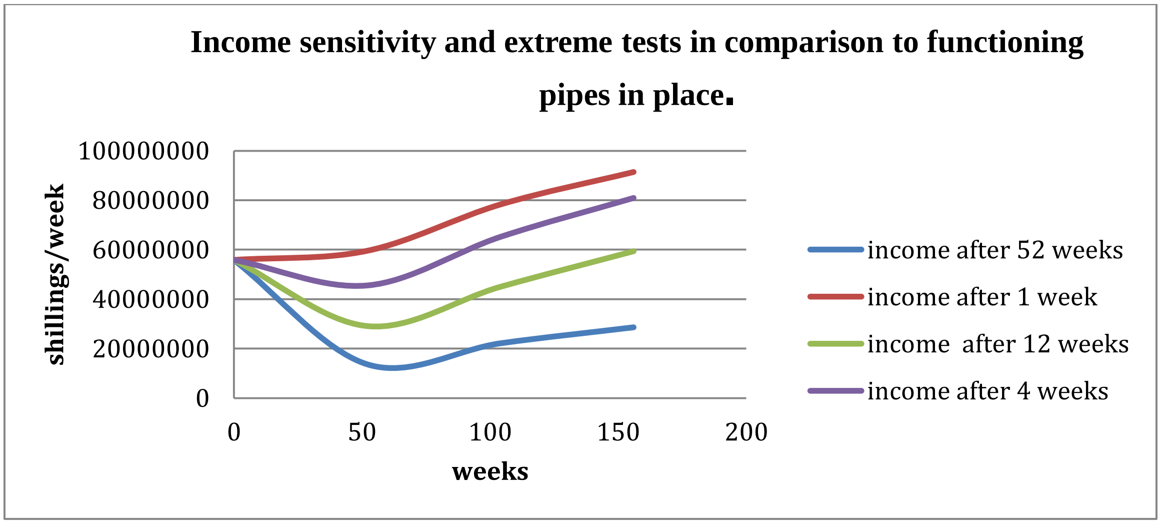

Figure 26: shows sensitivity and extreme tests on how income behaves in comparison to changes of functioning pipes.

Figure 27 below shows sensitivity and extreme condition testing done on expenditures it is observed that when the functioning pipes (**Figure 21**) increase the expenditures increase as well this is because more maintainence costs are incurred, more workers needed and more investment costs in repairs and replacements.

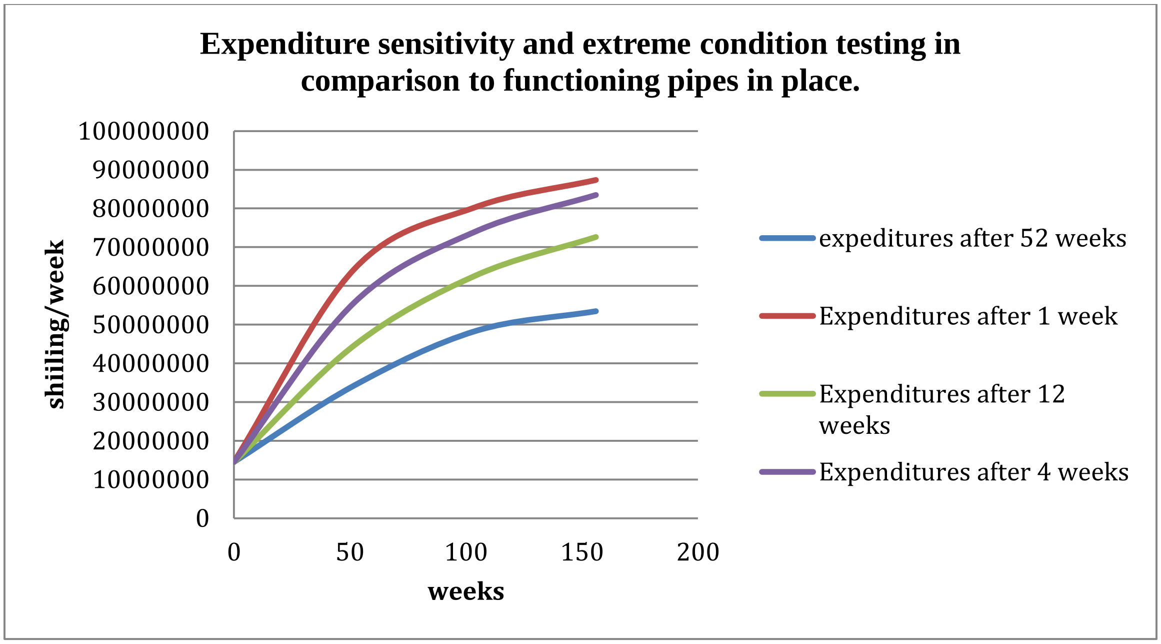

Figure 27: shows sensitivity and extreme tests on how Expenditures increase in comparison to changes of functioning pipes

5.3 Testing H2: Increasing water demand from the increasing population.

The Kampala population is increasing day by day. The simulated population has been compared to the base run (using reference data).This rapid increase in population explains the increase in demand as well as the gap between the demand and supply of water in Kampala city.

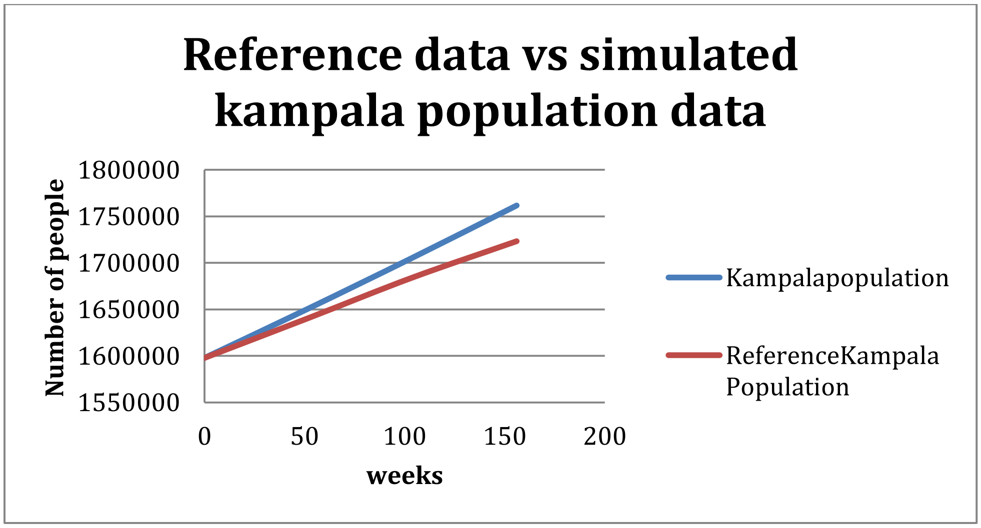

Figure 28: shows reference population compared to population simulated by the mode

6. POLICY TESTING AND IMPLEMENTATION

The explanatory model after going through various tests has been proven to being robust and useful enough to use for policy analysis. The purpose of this section is find policies that will help to resolve the problem of limited accessibility to clean potable water in Kampala Region. The policies will be tested to see which of them is the most effective in reducing the gap between the water demand and water supply.

6.1 Policy assumptions

The time horizon for the simulation in the policy testing is 7 years (364 weeks). The policies are activated after 3 years (156 weeks).

Each policy is tested to show the effect it has on the water supply gap and also determine which policy is the most effective for the management to adopt.

The explanatory model that replicates the Reference mode has determined the base run. (Policy switch off)

6.2 Policy 1: Adjustment of water tariff on each unit liter.

The first policy suggests is to increase the water tariff. A water tariff is a price assigned to water supplied by a public utility through a piped network to its customers. The water board management is responsible in setting the fee. The fee is determined by the water board depending on the expenses required for proper management of the pipe water infrastructure.

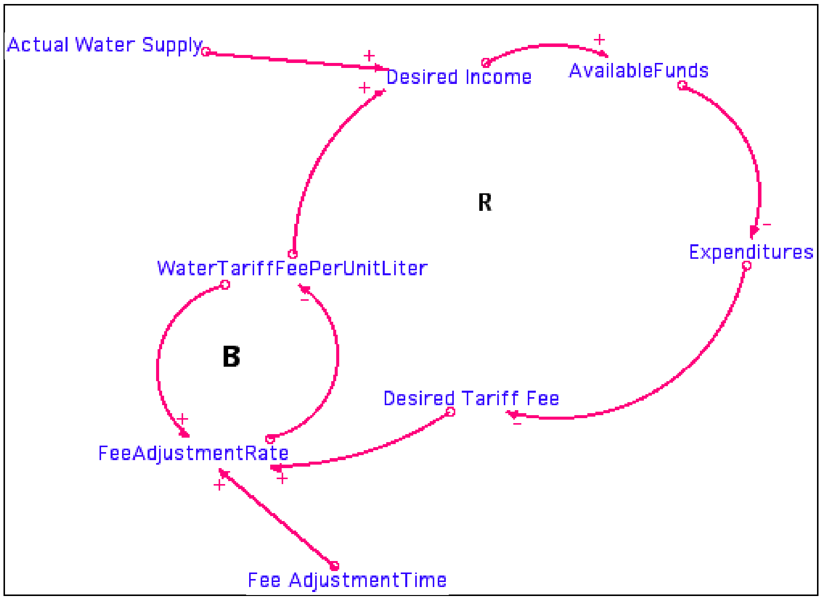

Figure 29:Policy 1 Casual loop Diagram

Policy 1 consists of setting a goal (Desired Water Tariff fee.) and actually using this goal. In this case the water board management finds an ideal fee that can generate enough funds to cover the water system management expenses. The current fee is adjusted over a period of time 4 months to the new desired fee. So as to give the water consumers time to perceive the new price and make a gradual change.

So the increased water tariff is multiplied by the *ActualWaterSupply* under the assumption that the pipes are repaired and fixed so all water initially supplied is consumed to help determine the *DesiredIncome*.

The policy when activated after week 156 it works in a way that with an increase in Income the management has enough funds to cover the expenses. So the water board management can order for more pipes to help increase the water supply and reduce the water supply gap. After simulations there is increase in functioning pipes and available funds .The water supply gap is also reduced.

6.3 Policy 2: Additional workforce

The workforce is an important factor in managing the pipe water supply system. The workforce is responsible for maintenance, repairs and replacement of damaged and old pipes as well as installing new pipes. However the workforce hiring depends on the availability of funds and how pipes need to be installed, replaced, repaired or maintained. So for policy 2 the flow of Net workforce hiring rate was regulated.

Currently the management uses the same workforce for replacement, repair, new installations and maintenance of pipes in order to cut down hiring expenses. As a result there is low productivity resulting into low accumulation of functioning pipes due to long delay periods resulting from few workforce.

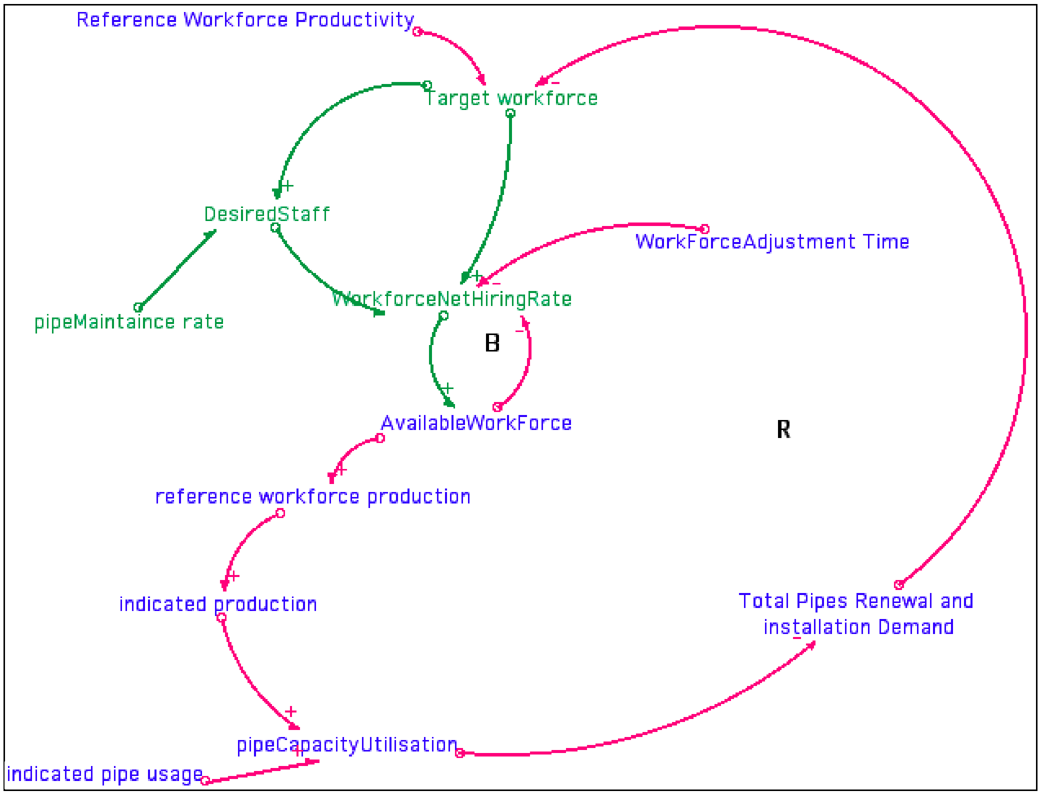

Figure 30:policy 2 casual loop diagram

Policy 2 (The additional green structure). Before week 156, the water board management was using the target workforce that was determined by the capacity demand of obsolete pipes, damaged pipes, obsolete damaged pipes, and new installations but also used workforce was used for pipe maintenance which was not sufficient enough as there was low production.

The workforce policy suggests an additional of workforce ***(Desired Staff)*** determined by the ***Pipe maintenance rate*** and the ***TargetWorkforce*** so if the water board management divides the workforce by hiring workforce for repair, replacements and installations and also workforce for maintenance there is an increase in production. The policy is activated after week 156 .Simulation results show that there is an increase in functioning pipes because more pipes are repaired, installed and maintained due to increase in the work force, the water supply gap is reduced .However the expenditures increase as well.

6.4 Policy 3 Migration policy

The main factor causing insufficient water supply is the increasing population from births and migration. Kampala being the capital city attracts lots of people it has an urbanization fraction of 0.028 people per week.

Policy 3 is a parameter suggestion policy of what would happen if the population was more controlled. However the policy is limited as will be discussed in the implementation sector.it may be harder to implement since it goes beyond the management influence of the water board however if a fraction of 0.01 is maintained on the migration the water board management will alleviate some of their problems such as reduction on expenses on pipes and workforce. Also the gap between the demand and supply will definitely reduce because of the reduced water demand.

6.5 policy 4 .New pipes adjustment time

With the increasing population in Kampala city every day, the Water board has to consider the possibility of pipeline expansion. Each pipe (100m) currently serves a total number of 150 people. However if the number of people increases the consumption of the people is reduced since the capacity of the pipes is limited.

Policy 4 suggests that if the water board management reduces the time it takes to install a new pipe, which is 1 year to at least 4 months, then the water supply gap can be closed much faster. The policy simulations with a new adjustment time of 4 months shows an increase in functioning pipes, reduction in the water supply gap to almost 0 in week 290 but also an increase in the expenditures since much workforce has to be hired within a short time and also the expenses on the new pipes.

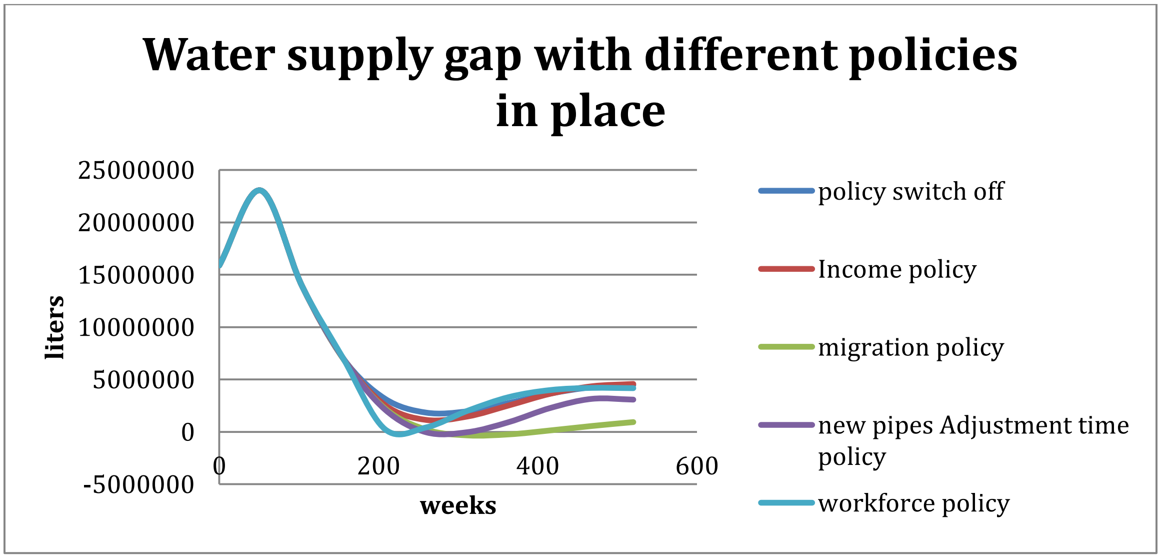

Figure 31: shows water supply simulation behavior with different policies

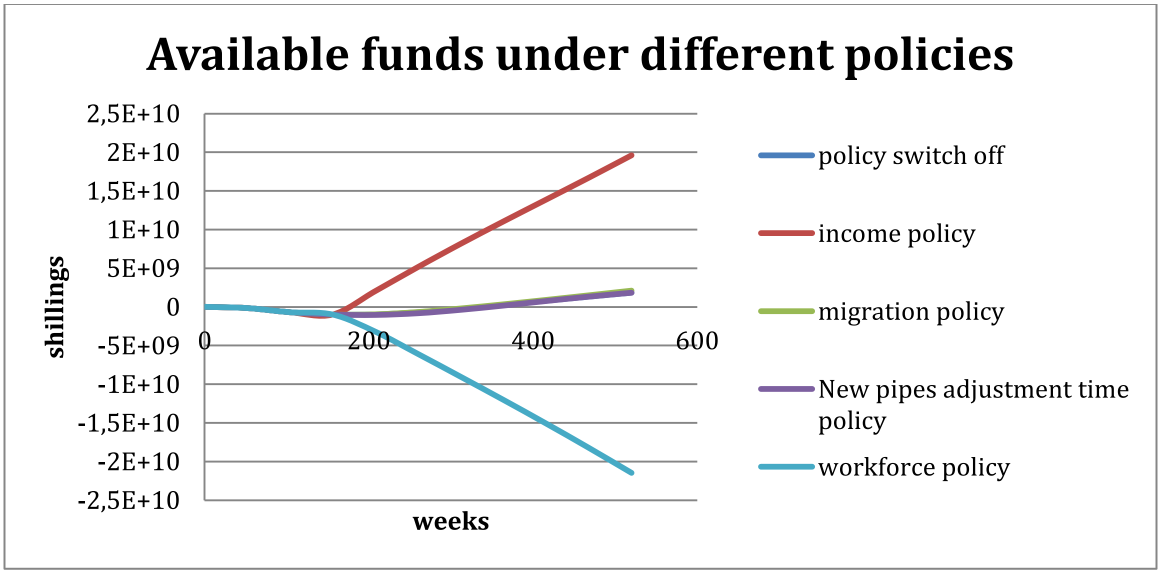

Figure 32: shows available funds under different policies (clear analysis is shown in *table 2 appendix B*)

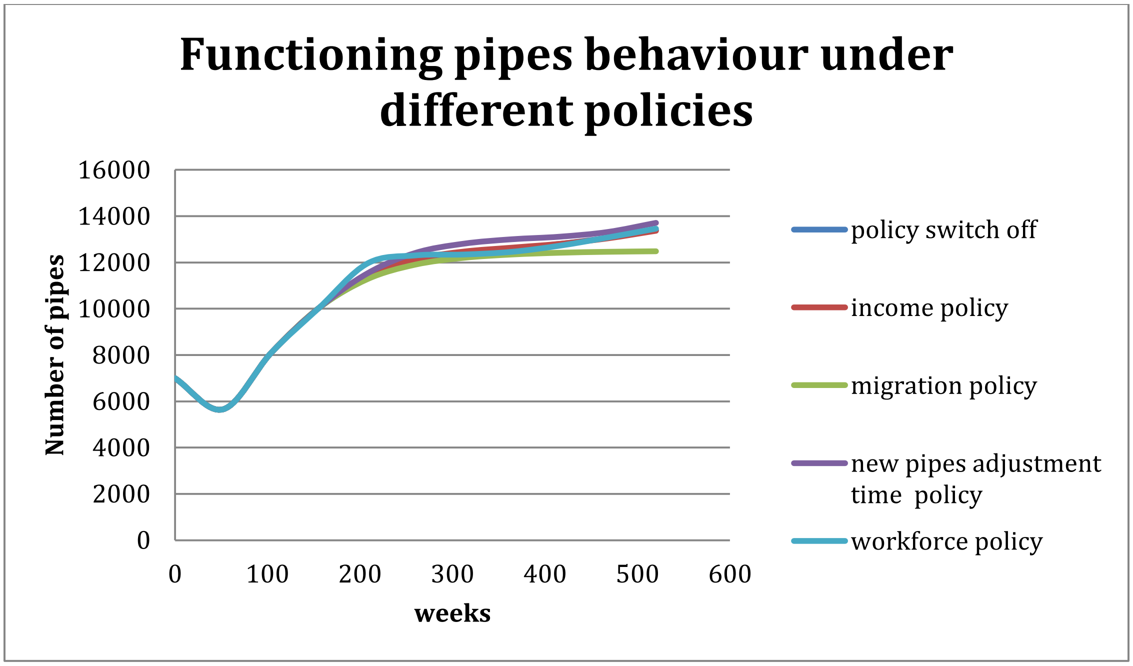

Figure 33 : shows how functioning pipes behave under different policies(clear analysis is seen *table 3 Appendix B*)

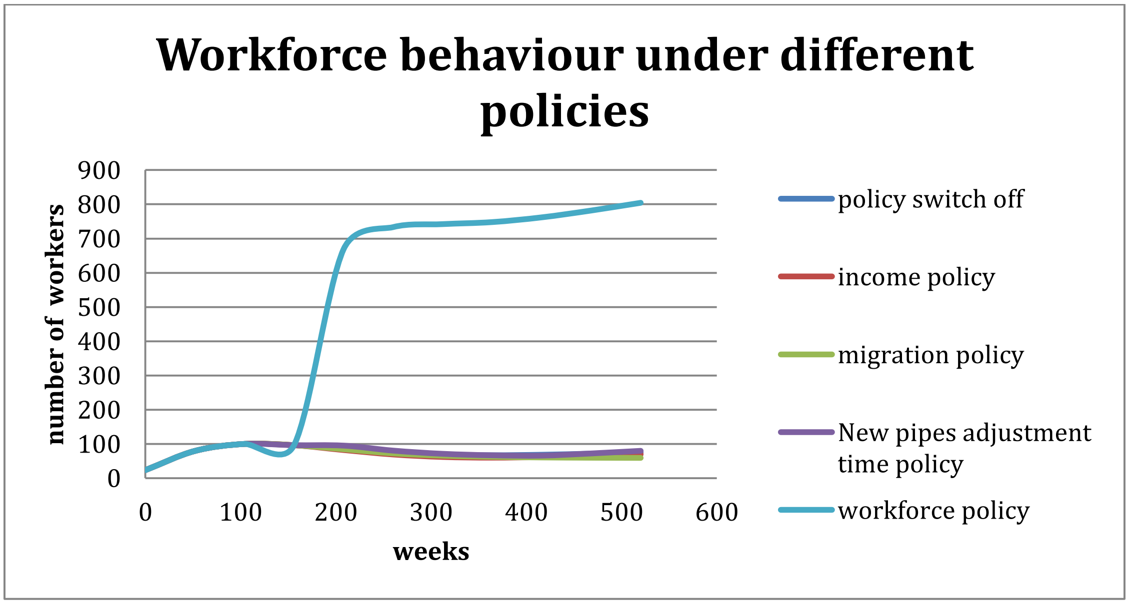

Figure 34: shows how the workforce changes when different policies are in place (clear analysis is seen in table 4 *Appendix B*)

Combination of all the policies

The water board can decide to use two policies at once to have a much more effect in resolving the water supply gap. Simulations can be seen below.

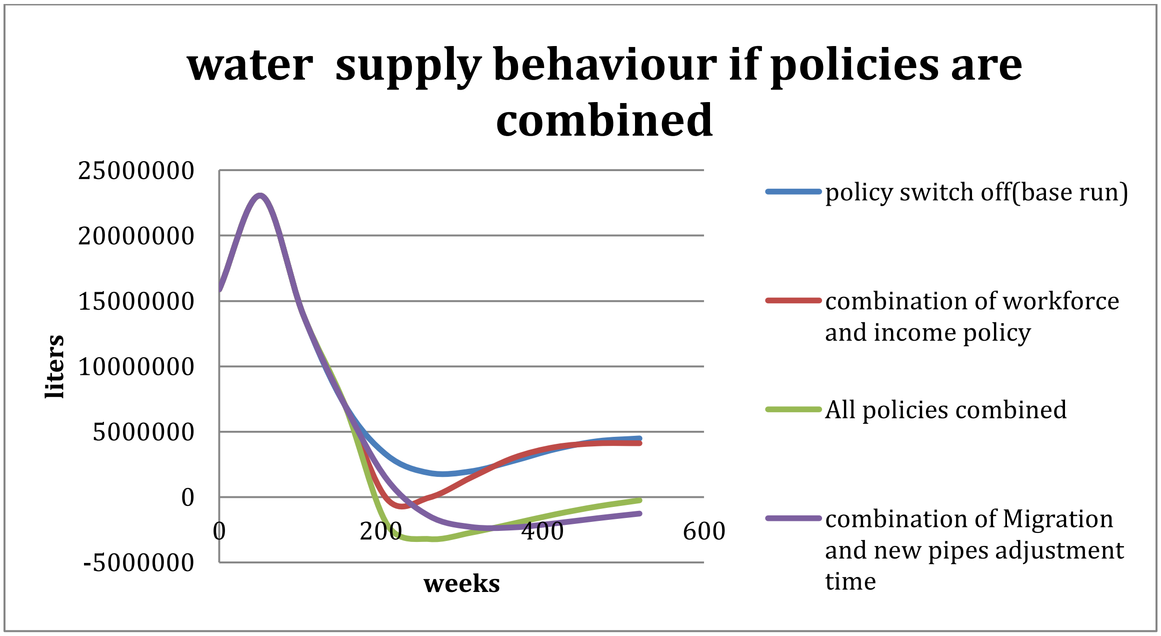

Figure 35: shows water supply gap when different policies are combined

Summary

This section presented the different policies that have been hypothesized to reduce the gap between the water supply and water demand. The different policies were explained different, tested and simulated to show how much effect they had on closing the water supply gap. They showed to be robust under different scenarios. The policies present do not fully close the gap but they could be a very great start.

6.6. Implementation of Policies

In this section the implementation of the suggested policies is discussed .The policies have been tested to make sure they are a realistic approach to the problem of the model. For the implementation to take place different conditions have been considered such as finances, manpower, time consumption, consumer behavior among others.

Implementing policy 1: Adjustment of the water Tariff

The policy suggests adjusting the current water tariff to increase income. This policy is ideal but water board has to take into consideration the consumer household income. The fee has to be reasonable so that people are not forced to resort to unprotected spring water sources because of high water prices.

One proposed way of doing this, the water board should announce the increase of the fee at least 8 months before to give time for people to perceive the new price change.

The water board should also take up the responsibility of communicating to the consumers why the price is changed .if this is not communicated very clearly to the people, the water board could end up losing credibility from the people. However if done right, people would be willing to accept any change in fee if justifiable.

Implementing policy 2. Additional workforce

The policy of increasing the workforce was seen to have an impact in reducing the gap between the water demand and water supply. The policy however didn’t favor the expenditures that have to be incurred by the management.

So the water board management could use seasonal workers for the installations, repair and replacements and permanent workers for the pipe maintenance. Therefore only incurring the high expenses once in a while. Also the water board management can use volunteers.

Implementing policy 3. Migration policy

The policy suggests reducing the number of people migrating into the city. The policy was effective as it cuts down the amount of water demanded by the consumers hence reducing on the water supply gap. The water board management cannot solely implement this policy because they don’t have the full managerial influence to do so. However it’s possible to work hand in hand with the government in place on migration restrictions. This policy is not very immediate but it’s a good policy for maintenance of the balance between the water demand and supply once put in place.

Implementation policy 4: New pipes adjustment time.

The policy suggests increasing the adjustment time for new pipes. Normally when there is an increase for water demand from the consumers the water board increases the pipes but this takes some time as it relies on availability of funds, workforce, land, among other factors. The planning time can be as long as 1 year but with a great time delay like that people resort to unclean and unsafe water sources such as wells. So if the planning and pipeline expansion can be done in a period of 4 months as the policy suggests it would be very effective on the water supply gap.

The water board has to increase its workforce and funds. The management can solicit for funding through donations from non-government organizations. To be able to purchase more pipes. A loan can also be borrowed to increase the funds and this can be repayed over a period of time.

6.7 Cost Benefit Analysis.

To determine the effectiveness of the policies in place a cost benefit analysis was done .The structure can be seen in appendix A.

Costs:

The major cost of the policies is the increase in expenditures in terms of workforce and investment costs in pipes the annual benefits is the annual cost difference of not having a policy and having a policy. The cost of having a policy is the desired income.

Equation=((actual_income+Annual_cost)-DesiredIncome)*policy_effect_on_net_present_value

Benefits:

The benefits of the policies if adopted could be increased income, water supply gap reduction.

Net benefits were determined as the difference between the benefits of having this policy in place and the associated that results.it is the gap between costs and benefits.

Annual_benefits-Annual_cost

Though there is a cost associated with this policy implementation, it is far less than the cost of having no policy. This is demonstrated by the Net present value of the policy and no policy alternatives.

Net present value is a useful tool to determine whether a project or investment will result in a net profit or a loss because of its simplicity.in this case the net present value shows if the policies put in place are effective.

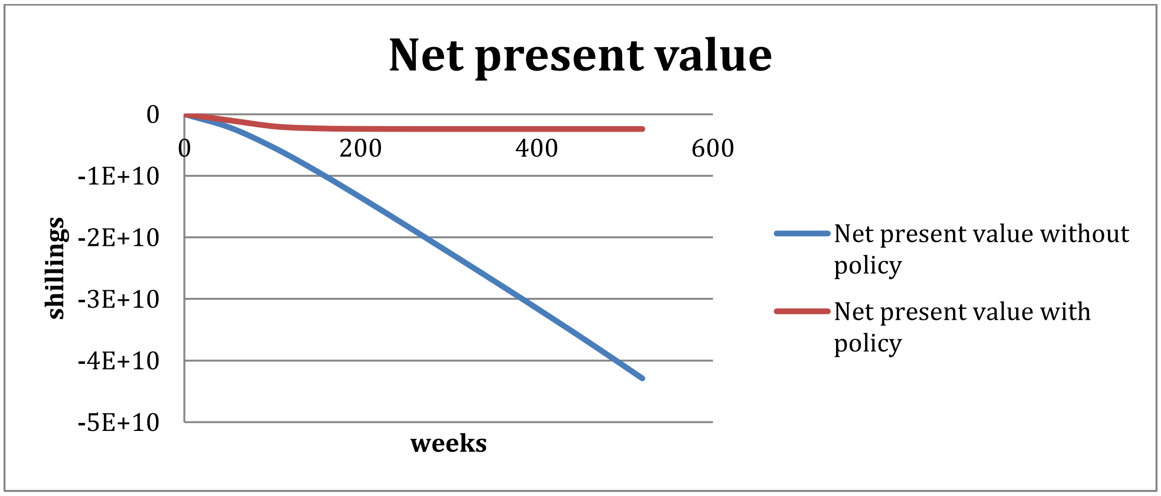

Figure 36 shows the net present value before and after policies are in place.

The net present value with policy shows a significant difference from the net present value with no policy, a difference that can be used to convince the decision makers to implement the policies.

6.8 Challenges with implementation of large piped water schemes

While the general practice is that connections are made up to50 m for the distribution pipeline, the reality is, that for those so far connected, the average distance of service pipeline to the consumers is 110 m. The challenge is that many applicants for connections are as far as 200 - 500 m from the distribution pipeline and in most cases, such consumers are denied a connection due to the distance from the distribution lines. The water board management has to invest or incur much more expenses in the new pipes.

Also resistance from people paying more water fees for the benefit of the new comers could be challenging but the management can create awareness about the benefits of clean water access for everyone.

7. CONCLUSIONS

This paper discussed how to improve potable accessibility and sustainability through efficient management of the pipe water supply system in Kampala the capital city of Uganda. There have been different studies done to explain the main cause of the gap between the water supply and consumer water demand. The model built and presented in this paper intended to represent the structure of the hypotheses thought to explain the problem. The model intended to reproduce the problematic behavior happening in real life as well. As the model was found to be useful, policies were suggested to find possible solutions to control the problem. A cost benefit analysis was done to show if the policies were useful and the results from the net present value showed that the adoption of the income policy would help alleviate the problem.

I consider that this paper has illustrated important feedbacks in the system that is possibly not being considered. Again, this paper does not intend to solve the problem completely, but it is definitely a step start to modifying the system in order to improve the water supply gap.

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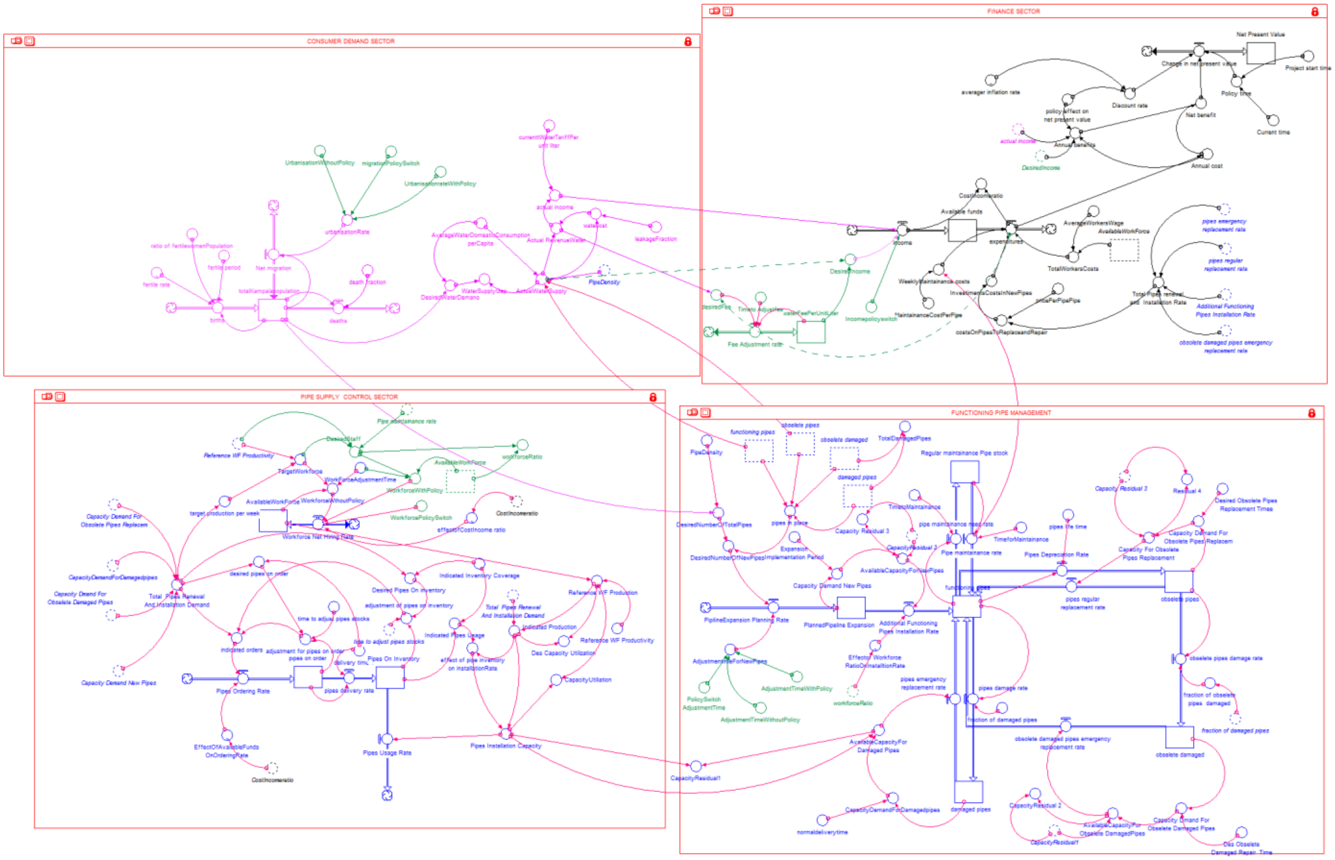
Appendix A

Overall Model structure with policies.



Appendix B

Table 2: shows figures of the available funds when different policies are in place.

Weeks	1: policy off	2: Income policy	3: Migration policy	4: adjustment time policy	5: workforce policy
0	10000000	10000000	10000000	10000000	10000000
52	-150065764,1	-150065764,1	-150065764,1	-150065764,1	-150065764,1
104	-688829343,5	-688829343,5	-688829343,5	-688829343,5	-688829343,5
156	-989036727,1	-989036727,1	-989036652	-989036727,1	-989036727,1
208	-966036334	2049875058	-962315682,7	-1039056642	-3203986238
260	-687087799,3	5165206626	-662154859,8	-821658140,4	-6091444493
312	-251176230,5	8166632879	-200265448,4	-378119434,9	-9038036870
364	260361382,8	11053015847	336568512,6	168855507	-12025072458
416	793151134,9	13879453486	909629662	760239811,4	-15083596883
468	1319300237	16711758151	1501805071	1327690359	-18229185572
520	1833901269	19607385402	2104184341	1833809316	-21466223295

Table 3: shows figures of the functioning pipes when different policies are in place

Weeks	1: policy switch off	Income policy	Migration policy	adjustment time policy	workforce policy
0	7882	7882	7882	7882	7882
52	5656,25316	5656,25316	5656,25316	5656,25316	5656,25316
104	8095,067694	8095,067694	8095,067694	8095,067694	8095,067694
156	10046,45056	10046,45056	10046,45011	10046,45056	10046,45056
208	11292,18486	11430,52809	11279,70186	11527,54292	11954,58818
260	11986,27279	12144,66319	11909,00302	12413,56718	12305,66924
312	12357,28148	12469,23315	12199,92111	12810,86915	12344,06124
364	12588,00345	12639,36864	12343,91822	13001,62759	12458,94171
416	12801,42386	12804,6917	12420,31526	13113,69164	12725,10386
468	13064,06803	13043,82893	12461,1715	13317,16803	13079,09955
520	13391,57003	13369,58773	12483,10182	13710,13172	13461,0146

Table 4 : shows number of workers available when different policies are in place.

Weeks	policy switch off	Income policy	migration policy	adjustment time policy	workforce policy
0	23	23	23	23	23
52	79	79	79	79	79
104	99	99	99	99	99
156	96	96	96	96	96
208	85	82	84	94	668
260	75	69	72	80	733
312	68	61	65	71	742
364	66	59	62	66	748
416	68	61	60	65	761
468	71	65	59	72	781
520	75	69	59	79	804

Appendix c

Consumer demand sector
t**otalKampalapopulation** (t) = totalKampalapopulation(t - dt) + (births - deaths - Net_migration) * dt
INIT totalKampalapopulation = 1597800
Births = (totalKampalapopulation*ratio_of_fertilewomenPopulation*(fertile_rate/fertile_period))/ 52
Deaths = (totalKampalapopulation*death_fraction)/52
Net_migration = (totalKampalapopulation*urbanisationRate)/52
ActualWaterSupply = (functioning_pipes+obselete_pipes)*AverageWaterDomesticConsumption_perCapita*PipeDensity
Actual income = Actual_RevenueWater*currenttWaterTariffPer_unit_liter
Actual_RevenueWater = (ActualWaterSupply-waterlost)
AverageWaterDomesticConsumption_perCapita = 29
currentWaterTariffPer_unit_liter = 2.912
death_fraction = 0.035
DesiredWaterDemand = AverageWaterDomesticConsumption_perCapita*totalKampalapopulation
fertile_period = 35
leakageFraction = 0.37
migrationPolicySwitch = 1
ratio_of_fertilewomenPopulation = 0.4

UrbanisationRate = UrbanisationrateWithPolicy*(1-migrationPolicySwitch)+migrationPolicySwitch*(IF TIME <154 THEN UrbanisationrateWithPolicy ELSE UrbanisationWithoutPolicy)
UrbanisationrateWithPolicy = 0.01
UrbanisationWithoutPolicy = 0.028
waterlost = leakageFraction*ActualWaterSupply
WaterSupplyGap = DesiredWaterDemand-ActualWaterSupply
fertile_rate = GRAPH(TIME)
(0.00, 6.81), (130, 6.77), (260, 6.73), (390, 6.69), (520, 6.14)

Finanace sector

Available_funds(t) = Available_funds(t - dt) + (income - expenditures) * dt
INIT Available_funds = 10000000
income = actual_income*(1-Incomepolicyswitch)+Incomepolicyswitch*(IF TIME <156 THEN actual_income ELSE DesiredIncome)
expenditures = WeeklyMaintainance_costs+InvestimentsCostsInNewPipes+TotalWorkersCosts
Net_Present_Value(t) = Net_Present_Value(t - dt) + (Change_in_net_present_value) * dt
INIT Net_Present_Value = 0
Change_in_net_present_value = Net_benefit/(1+Discount_rate)^Policy_time
waterFeePerUnitLiter(t) = waterFeePerUnitLiter(t - dt) + (Fee_Adjustment_rate) * dt
INIT waterFeePerUnitLiter = 1.912

Fee_Adjustment_rate = (desiredFee-waterFeePerUnitLiter)/Timeto_Adjustfee
Annual_benefits = ((actual_income+Annual_cost)-DesiredIncome)*policy_effect_on_net_present_value
Annual_cost = expenditures
AverageWorkersWage = 100000
CostIncomeratio = Expenditures/income
costsOnPipesToReplaceandRepair = IF(Total_Pipes_renewal_and__Installetion_Rate>0)then(Total_Pipes_renewal_and__Installetion_Rate*pricePerPipePipe)else 0
Current_time = TIME
desiredFee = expenditures/Actual_RevenueWater

DesiredIncome = ActualWaterSupply*waterFeePerUnitLiter
Discount_rate = averager_inflation_rate*policy_effect_on_net_present_value
Incomepolicyswitch = 1
InvestimentsCostsInNewPipes = costsOnPipesToReplaceandRepair
MaintainanceCostPerPipe = 30000
Net_benefit = Annual_benefits-Annual_cost
policy_effect_on_net_present_value = 1
Policy_time = Current_time-Project_start_time
pricePerPipePipe = 150000

Project_start_time = 52
Timeto_Adjustfee = 0.8*52
TotalWorkersCosts = availableWorkForce*AverageWorkersWage
Total_Pipes_renewal_and__Installetion_ Rate =
(Additional_Functioning_Pipes_Installation_Rate+obsolete_damaged_pipes_emergency_
replacement_rate+pipes_regular_replacement_rate+pipes_emergency_replacement_rate)
WeeklyMaintainance_costs = Pipe_maintainance_rate*MaintainanceCostPerPipe
averager_inflation_rate = GRAPH(TIME)
(0.00, 0.00), (0.111, 0.00), (0.222, 0.03), (0.333, 0.03), (0.444, 0.03), (0.556, 0.03),
(0.667, 0.03), (0.778, 0.03), (0.889, 0.03), (1.00, 0.03)

Functioning pipe management sector

damaged_pipes(t) = damaged_pipes(t - dt) + (pipes_damage_rate -
pipes_emergency_replacement_rate) * dt
INIT damaged_pipes = 1
pipes_damage_rate = functioning_pipes*fraction_of_damaged_pipes
pipes_emergency_replacement_rate = AvailableCapacityFor_Damaged_Pipes
functioning_pipes(t) = functioning_pipes(t - dt) + (pipes_emergency_replacement_rate
+ pipes_regular_replacement_rate +
obsolete_damaged_pipes_emergency_replacement_rate + Pipe_maintainance_rate +
Additional_Functioning_Pipes_Installation_Rate - pipes_damage_rate -
Pipes_Depreciation_Rate - pipe_maintainance_need_rate) * dt
INIT functioning_pipes = 7882
pipes_emergency_replacement_rate = AvailableCapacityFor_Damaged_Pipes
pipes_regular_replacement_rate = Capacity_For_Obsolete_Pipes_Replacement
obsolete_damaged_pipes_emergency_replacement_rate =
AvailableCapacityFor_Obselete_DamagedPipes
Pipe_maintainance_rate = (Regular_maintainance_Pipe_stock/TimeforMaintainance)
Additional_Functioning_Pipes_Installation_Rate =
(AvailableCapacityForNewPipes)*Effectof_Workforce_RatioOnInstalltionRate
pipes_damage_rate = functioning_pipes*fraction_of_damaged_pipes
Pipes_Depreciation_Rate = functioning_pipes/pipes_life_time
pipe_maintainance_need_rate = functioning_pipes/TimetoMaintainance
obselete_damaged(t) = obselete_damaged(t - dt) + (obselete_pipes_damage_rate -
obsolete_damaged_pipes_emergency_replacement_rate) * dt
INIT obselete_damaged = 0
obselete_pipes_damage_rate = obselete_pipes*fraction_of_obselete_pipes__damaged
obsolete_damaged_pipes_emergency_replacement_rate =
AvailableCapacityFor_Obselete_DamagedPipes
obselete_pipes(t) = obselete_pipes(t - dt) + (Pipes_Depreciation_Rate -
pipes_regular_replacement_rate - obselete_pipes_damage_rate) * dt
INIT obselete_pipes = 0
Pipes_Depreciation_Rate = functioning_pipes/pipes_life_time
pipes_regular_replacement_rate = Capacity_For_Obsolete_Pipes_Replacement
obselete_pipes_damage_rate = obselete_pipes*fraction_of_obselete_pipes__damaged

PlannedPipeline_Expansion(t) = PlannedPipeline_Expansion(t - dt) + (PipilineExpansion_Planning_Rate - Additional_Functioning_Pipes_Installation_Rate) * dt
INIT PlannedPipeline_Expansion = (DesiredNumberOfNewPipes/AdjustmentimeForNewPipes)*Expansion__Implementation_Period
PipilineExpansion_Planning_Rate = DesiredNumberOfNewPipes/AdjustmentimeForNewPipes
Additional_Functioning_Pipes_Installation_Rate = (AvailableCapacityForNewPipes)*Effectof_Workforce_RatioOnInstalltionRate
Regular_maintainance_Pipe_stock(t) = Regular_maintainance_Pipe_stock(t - dt) + (pipe_maintainance_need_rate - Pipe_maintainance_rate) * dt
INIT Regular_maintainance_Pipe_stock = 0
pipe_maintainance_need_rate = functioning_pipes/TimetoMaintainance
Pipe_maintainance_rate = (Regular_maintainance_Pipe_stock/TimeforMaintainance)
AdjustmentimeForNewPipes = AdjustmentTimeWithoutPolicy*(1-PolicySwitch__AdjustmentTime)+PolicySwitch__AdjustmentTime*(IF TIME <156 THEN AdjustmentTimeWithoutPolicy ELSE AdjustmentTimeWithPolicy)
AdjustmentTimeWithoutPolicy = 1*52
AdjustmentTimeWithPolicy = 0.4*52
AvailableCapacityFor_Obselete_DamagedPipes = MIN(CapacityResidual1,Capacity_Dmand_For_Obselete_Damaged_Pipes)
AvailableCapacityForNewPipes = Min(Capacity_Demand_New_Pipes,CapacityResidual_2)
AvailableCapacityFor_Damaged_Pipes = MIN(CapacityDemandForDamagedpipes,Pipes_Installation_Capacity)
CapacityDemandForDamagedpipes = damaged_pipes/normaldeliverytime
CapacityResidual1 = (Pipes_Installation_Capacity-AvailableCapacityFor_Damaged_Pipes)
CapacityResidual_2 = CapacityResidual1-AvailableCapacityFor_Obselete_DamagedPipes
Capacity_Demand_For_Obsolete_Pipes_Replacem = obselete_pipes/Desired_Obsolete_Pipes_Replacement_Timee
Capacity_Demand_New_Pipes = PlannedPipeline_Expansion/Expansion__Implementation_Period
Capacity_Dmand_For_Obselete_Damaged_ Pipes = obselete_damaged/Des_Obselete_Damaged_Repair__Time
Capacity_For_Obsolete_Pipes_Replacement = MIN(Capacity_Demand_For_Obsolete_Pipes_Replacem,Capacity_Residual_3)
Capacity_Residual_3 = CapacityResidual_2-AvailableCapacityForNewPipes
DesiredNumberOfNewPipes = DesiredNumberOfTotalPipes-pipes_in_place
DesiredNumberOfTotalPipes = (totalKampalapopulation/PipeDensity)
Desired_Obsolete_Pipes_Replacement_ Timee = 5
Des_Obselete_Damaged_Repair__ Time = 3
Expansion__Implementation_Period = 25
fraction_of_damaged_pipes = 0.01

fraction_of_obselete_pipes__damaged = fraction_of_damaged_pipes*10
normaldeliverytime = 2
PipeDensity = 150
pipes_in_place = obselete_damaged+functioning_pipes+obselete_pipes+damaged_pipes
pipes_life_time = 20*52
PolicySwitch__AdjustmentTime = 1
{unitless}
Residual_4 = Capacity_Residual_3-Capacity_For_Obsolete_Pipes_Replacement
TimeforMaintainance = 4
TimetoMaintainance = 6
TotalDamagedPipes = obselete_damaged+damaged_pipes
Effectof_Workforce_RatioOnInstalltionRate = GRAPH(workforceRatio)
(0.00, 0.292), (0.2, 0.514), (0.4, 0.641), (0.6, 0.825), (0.8, 1.01), (1.00, 1.15), (1.20, 1.28), (1.40, 1.37), (1.60, 1.48), (1.80, 1.63), (2.00, 1.64)

Pipe supply control sector

AvailableWorkForce(t) = AvailableWorkForce(t - dt) + (Workforce_Net_Hiring_Rate) * dt
INIT AvailableWorkForce = TargetWorkforce
Workforce_Net_Hiring_ Rate = (WorkforceWthoutPolicy*(1-WorkforcePolicySwitch)+WorkforcePolicySwitch*(IF TIME <156 THEN WorkforceWthoutPolicy ELSE WorkforceWithPolicy))*effectofCostIncome_ratio
Pipes_On_Inventory(t) = Pipes_On_Inventory(t - dt) + (pipes_delivery_rate - Pipes_Usage_Rate) * dt
INIT Pipes_On_Inventory = Desired_Pipes_On_inventory
pipes_delivery_rate = pipes_on_order/delivery_time_1
Pipes_Usage_Rate = Pipes_Installation_Capacity
pipes_on_order(t) = pipes_on_order(t - dt) + (Pipes_Ordering_Rate - pipes_delivery_rate) * dt
INIT pipes_on_order = desired_pipes_on_order
Pipes_Ordering_Rate = (MAX(0,indicated_orders))* EffectOfAvailableFunds_OnOrderingRate
pipes_delivery_rate = pipes_on_order/delivery_time_1
adjustment_for_pipes_on_order = (desired_pipes_on_order-pipes_on_order)/time_to_adjust_pipes_stocks
adjustment_of_pipes_on_inventory = (Desired_Pipes_On_inventory-Pipes_On_Inventory)/time_to_adjust_pipes_stocks
CapacityUtiliation = Pipes_Installation_Capacity/Reference_WF_Production
delivery_time_1 = 6
DesiredStaff = (TargetWorkforce)+(Pipe_maintainance_rate/Reference_WF_Productivity)
Desired_Pipes_On_inventory = Total__Pipes_Renewal_And_Installation_Demand*Indicated_Inventory_Coverage
desired_pipes_on_order = Total__Pipes_Renewal_And_Installation_Demand*delivery_time_1

Des_Capacity_Utilization = Indicated_Production/Reference_WF_Production

Indicated_Inventory_Coverage = 3

indicated_orders = Total__Pipes_Renewal_And_Installation_Demand+adjustment_of_pipes_on_inventory+adjustment_for_pipes_on_order

Indicated_Pipes_Usage = Pipes_On_Inventory/Indicated_Inventory_Coverage

Indicated_Production = Min(Total__Pipes_Renewal_And_Installation_Demand,Reference_WF_Production)

Pipes_Installation_Capacity = (Indicated_Production*effect_of_pipe_inventory_on_installationRate)

Reference_WF_Production = availableWorkForce*Reference_WF_Productivity

Reference_WF_Productivity = 3

TargetWorkforce = (target_production_per_week/Reference_WF_Productivity)

target_production_per_week = Total__Pipes_Renewal_And_Installation_Demand

time_to_adjust_pipes_stocks = 18

Total__Pipes_Renewal_And_Installation_Demand = CapacityDemandForDamagedpipes+Capacity_Dmand_For_Obselete_Damaged_Pipes+Capacity_Demand_New_Pipes+Capacity_Demand_For_Obsolete_Pipes_Replacem

WorkForceAdjustmentTime = 12

WorkforcePolicySwitch = 1

workforceRatio = availableWorkForce/DesiredStaff

WorkforceWithPolicy = (DesiredStaff-availableWorkForce)/WorkForceAdjustmentTime

WorkforceWthoutPolicy = (TargetWorkforce-availableWorkForce)/WorkForceAdjustmentTime

EffectOfAvailableFunds_OnOrderingRate = GRAPH(Costincomeratio)
(0.00, 1.00), (0.1, 1.00), (0.2, 0.967), (0.3, 0.905), (0.4, 0.862), (0.5, 0.81), (0.6, 0.733), (0.7, 0.7), (0.8, 0.686), (0.9, 0.648), (1.00, 0.662)

effectofCostIncome_ratio = GRAPH(CostIncomeratio)
(0.00, 1.37), (0.2, 1.28), (0.4, 1.10), (0.6, 0.984), (0.8, 0.921), (1.00, 0.825), (1.20, 0.775), (1.40, 0.705), (1.60, 0.578), (1.80, 0.502), (2.00, 0.438)

effect_of_pipe_inventory_on_installationRate = GRAPH(Indicated_Pipes_Usage/Indicated_Production)
(0.00, 0.00), (0.1, 0.418), (0.2, 0.656), (0.3, 0.797), (0.4, 0.891), (0.5, 0.949), (0.6, 0.965), (0.7, 0.981), (0.8, 0.99), (0.9, 1.00), (1.00, 1.00)