Sequential Budget Allocation for Multi-Region Integrated Water and Sanitation Systems: Case Study of Siuna, Nicaragua

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Abstract

This research proposes a solution to the problem of allocating centralized municipal budgets for drinking water supply (DWS), wastewater and sewage treatment (WST), and municipal solid waste management (MSW) services simultaneously across multiple service areas or jurisdictions. The goal of the allocation is to ensure that resources are available to each jurisdiction to continue short-term operation and maintenance, and provide for capital improvements to sustain services in the long term. The approach treats the three services and multiple jurisdictions as components of a Multi-Region Integrated Water and Sanitation System (MR-IWSS). Then, I use *system dynamics* to determine a *sequential budget allocation* regime that balances short term, multi-region continuity of services with long-term capacity expansion for sustained satisfaction of demand for each service.

Introduction

Safe drinking water is vital for human health and poverty reduction, yet over one billion people lack regular access to safe water, and 1.8 million (mostly under 5 years of age) die every year from diarrhoeal disease (WHO, 2007). Over two billion people live without improved sanitation facilities (WHO, 2013). The connections between water contamination, sanitation, hygiene and health are well established in developing countries (Pruss et al, 2003; Esrey et al., 1985; UN, 2005); a “lack of safe water perpetuates a cycle whereby poor populations become further disadvantaged, and poverty becomes entrenched” (WHO, 2007). Illnesses caused by contaminated water (e.g. acute respiratory infections, and schistosomiasis (Mara et al., 2010; Fewtrell et al., 2005)) force patients to miss schools/work, which result in loss in opportunities/incomes (Hutton et al., 2004).

The traditional approach to improving water and sanitation systems involves improving the four services within the water and sanitation system independently (Marsalek et al., 2001; Vlachos and Braga, 2001; Mitchell et al., 2003). The four services include Drinking Water Supply (DWS), Wastewater and Sewage Treatment (WST), Municipal Solid Waste management (MSW), and Stormwater Management (SWM). Historically, engineers designed the system so that each service can operate as an “independent entity” with its own engineering, administrative, and customer service line (Tarr, 1996). Here engineering refers to the design, implementation, operation, maintenance and expansion of the service. Administration refers to the legal, financial, and human resources functions of the service. Customer service refers to service connections, billing and accounts management, advertising and marketing of the service.

However, there are many adverse economic and environmental impacts associated with the traditional approach to improving the water and sanitation system (Marsalek et al., 2001; Vlachos and Braga, 2001; Mitchell et al., 2003). Drinking water eventually becomes wastewater, both DWS and WST processes generate sludge for MSW, and MSW landfills produce leachate to be treated by WST plants. Failure to accommodate these material flow interdependencies can result in inefficient gaps in capacity across the services, particularly if one expands before the others have the capacity to accommodate its additional new flow. Furthermore, in most municipalities, the three services are funded from a single municipal administration. DWS, WST, and SWM services each produce solid waste (sludge) that requires treatment as solid waste; while the MSW services produce leachate. If the sludge in not managed appropriately or the leachate gets into water sources without treatment, human health and the environment can be adversely affected.

Many researchers have considered various integrated combinations of the four services in order to manage their interdependence more effectively. For instance, Harremoes (1997) considered Drinking water supply services (DWS) and Wastewater and sewage services (WST) together, using Material Flow Analysis (MFA) and analysis of the life cycle of water flow (Harremoes, 1997). Louis and Magpili (2007) integrated DWS, WST, and MSW services. They excluded the Stormwater management (SWM) as a separate service because systems with combined sewers include stormwater as part of their wastewater and sewage treatment system. More recently, many systems are moving to separate stormwater and wastewater sewers, with stormwater collected and stored for treatment in wastewater treatment plants. Thus Louis and Magpili included stormwater in the WST category, and this paper will continue that nomenclature (Vesilind, 2011).This integrated water and sanitation system (IWSS) proved to be beneficial in terms of “administrative/finance, engineering, and customer service/marketing functions” (Louis et al., 2013). The Polk County, Georgia (Polk County Water Authority, 2013) and Seattle, Washington (Seattle Public Utilities) (SPU, 2013) show two successfully integrated water and sanitation systems.

I propose a Multi-Region Integrated Water and Sanitation System (MR-IWSS) model. It extends the integrated Municipal Sanitation System model of Magpili (2005, PhD dissertation), and Louis and Magpili (2007, 2013) to include the multiple administrative regions that are usually served by these systems (Louis and Magpili, 2007; Louis et al., 2013). For example there are the five boroughs of New York City or the 129 municipalities in the ALCOSAN service district of Allegheny County Sanitation Authority in Pittsburgh, PA. I will build and test my model on the community of Siuna, Nicaragua. Here there is a single decision maker for the three services, which are provided to three major regions, each with different levels of service. The service areas in Siuna are, the urban core or commercial district of roughly 1 km radius, the peri-urban of neighborhoods surrounding Siuna hospital. This is roughly a 6 km radius, which encompasses the urban core. Finally there are the rural areas, which extend for roughly 15 km outside the peri urban areas, or 21 km from the urban core. While the urban and peri-urban areas have DWS and MSW services, their MSW services operate differently. The peri-urban areas practice open burning, while the urban core has municipal collection and a controlled dump or landfill. The rural areas have no municipal DWS, WST, or MSW service.

The United Nations support for water and sanitation development projects had declined from 1997 to 2008, from 8% to 5% of the total development aid (United Nations, 2013). Nicaragua has received support from many international organizations regarding water and sanitation. However, the major support has come from the World Bank, which has supported a total of nine projects since 1972. The first four projects, between 1972 and 1983, focused on improving water supply system in the capital city of Nicaragua, Managua. Those projects are Managua Water Supply Project I, Managua Water Supply Project II, Managua Water Supply Project III, and Managua Water Supply Engineering Project. Another project, started around 1977, focused on sanitation systems in rural areas. This project considered both water supply and sanitation together, in addition to providing “latrines, sanitary house improvements, health education, and child immunization” (The World Bank, 1988). Later in 2008, the following three projects – namely, NI Rural Water Supply and Sanitation Project (PRASNICA), NI Greater Managua Water and Sanitation (PRASMA), and Rural Water Supply and Sanitation Additional Financing – fully integrated water and sanitation systems. Out of the recently mentioned three projects, the two focused on water and sanitation systems in rural areas. These three projects focused more on creating small-scale technological solutions, such as boreholes, springs catchment, conduction lines, water tanks, piped potable water, and septic tanks (The World Bank, 2012; The World Bank 1, 2008; The World Bank 2, 2008). Lastly, the final project is quite specialized, and not so much about basic improvement of water supply. The project, “Adaptation of NicaraguasWater Supplies to Climate Change,” has just started in 2012, focusing on the system’s durability to climate change. *My project has the similar goal of developing a sustainable integrated water and sanitation system; however, my focus is more on budget allocation that helps decrease the deficit in as short a time period as possible*.

Yet, due to Siuna’s limited budget, it is not sufficient only to have a good working system without effective budget allocation systems. Researchers have proposed various ways to allocate budgets for water and sanitation systems. Louis and Magpili (2007) proposed a life-cycle capacity-based approach to allocating investments in municipal sanitation infrastructure (Louis and Magpili, 2007). Kao, Pan, and Lin (2009) invented a budget allocation system for use in regional water quality management. The system supported sustainability goals and aimed for the best water quality, and utilized the Driving-Force-State-Response (DSR) framework to classify indicators in the budget allocation process and evaluation (Kao et al, 2009).

MR-IWSS

Several public agencies manage water and sanitation services across multiple jurisdictions. For instance, The Rivanna Water and Sewer Authority manages the water and sanitation services in Charlottesville and Albemarle County, Virginia (Rivanna, 2013); while the District of Columbia Water and Sewer Authority manages in the District of Columbia, Montgomery and Prince George's counties in Maryland, and Fairfax and Loudoun counties in Virginia (District of Columbia, 2013). Thus DWS, WST, and MSW services are integrated to various degrees in practice, though not widely addressed in the literature. This leads me to consider integrated water and sanitation systems across multiple regions, namely MR-IWSS, as a way to model a growing practice in the industry. As noted earlier, I will build the MR-IWSS from Louis and Magpili (2007)'s integrated water and sanitation system (IWSS) (Louis and Magpili, 2007). The IWSS alone cannot represent a holistic view of the water and sanitation system if there are different service levels among sub-regions or if sub-regions (jurisdictions) specialize in one or more services which they provide to other sub-regions in the system. The MR-IWSS model is more appropriate in this case. It assumes a single authority responsible for allocating the budget for the three services in all sub-regions or jurisdictions in its domain.

Suppose there are N sub-regions—instead of one region (Figure 2)—in a particular municipality, and each region shares a source and sink (Figure 1).

In an integrated water and sanitation system (IWSS), DWS, WST, and MSW services are interrelated (Figure 2).

1. If the budget is allocated to DWS services, supply of DWS will increase, thus increasing demand of WST and MSW.
2. If the budget is allocated to WST services, supply of WST will increase, thus increasing demand of DWS and MSW.
3. If the budget is allocated to MSW services, supply of MSW will increase, thus increasing demand of WST.

Figure 1: A Multi-Region Integrated Water and Sanitation System (MR-IWSS) in a particular municipality, with N sub-regions.

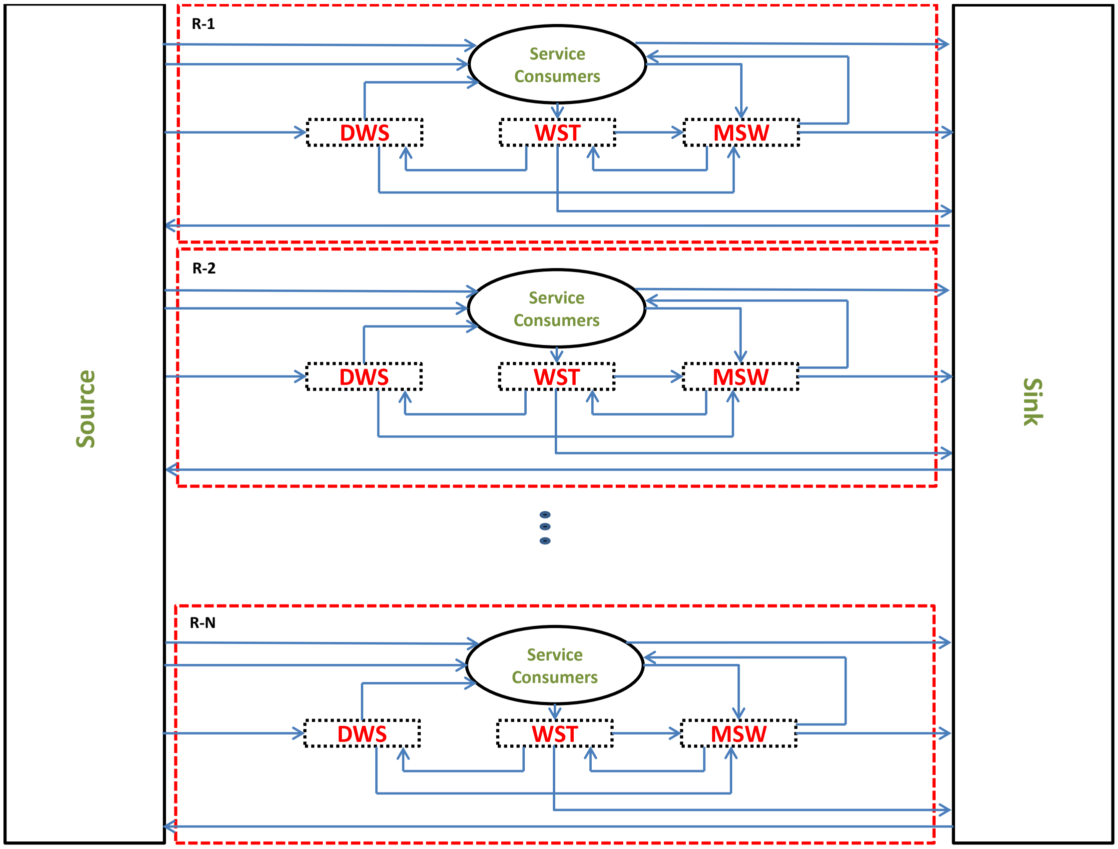
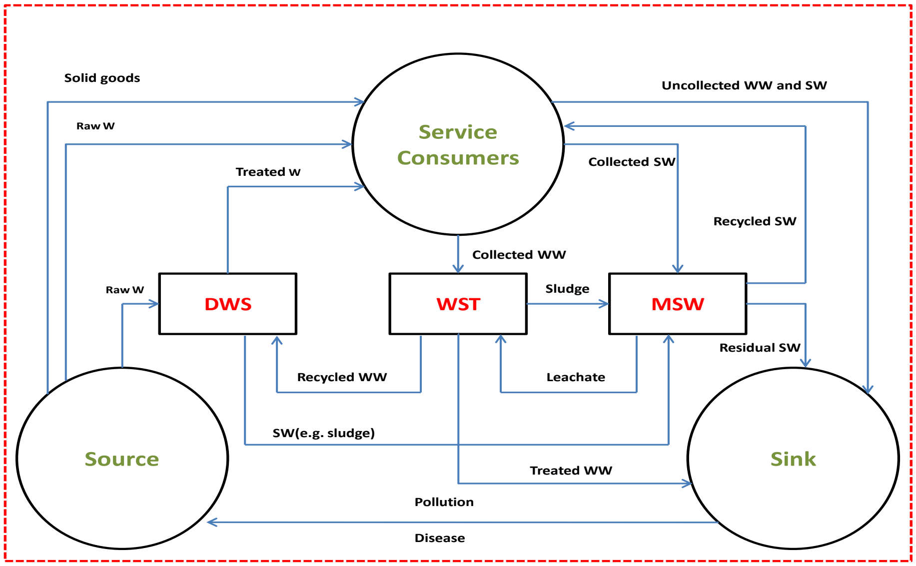


Figure 2: A Multi-Region Integrated Water and Sanitation System (MR-IWSS) in the municipality with one region.



Source: IWSS by Louis and Magpili (2007)

Sequential Budget Allocation

Sequential budget allocation is a financial management strategy to fund the capital and operating expenses of DWS, WST, and MSW within each region of a MR-IWSS, with an eye to minimizing any deficits in service across the region.

The Sequential budget allocation concerns with uncertain budget. Many countries normally receive fund from international organizations that finance private companies involved in improving water and sanitation services of the countries. The countries very much rely on this process because public sectors rarely have the fund that matches that of the private companies—whose earn about three times as much money as the public sectors (Hall and Lubina, 2010). Yet, the private companies' budget is still not enough and does not meet the demand because the companies fail to receive compensation from people who receive the services. People neither have money to pay for the services nor are they able to help maintaining the services (Hall and Lubina, 2010).

Next, I summarize various budget allocation strategies that have been used for improving water and sanitation services. The common strategy used for improving water services is called "a portfolio approach" (Neely, 1976). This approach uses benefit-cost ratio (BCR) that does not concern with "uncertainty in economic selection of projects" (Neely, 1976). Later in 1994, "multiobjective multicriteria sequential decision making" was developed to improve water services as well. However, this approach concerns with the uncertainty (Bector et al., 1994; Goulter, 1995). The approach has been used in many countries. For instance, Thailand used the approach to allocate budget for infrastructure planning in water sectors (Robak et al., 2007). Lastly, Magpili (2005) proposed a life-cycle capacity-based approach that concerns with both water and sanitation services (Magpili, 2005).

A life-cycle capacity-based approach is used in this paper. The strategy was used in Louis and Magpili's IWSS, so I would like to test its effectiveness with the extended IWSS, i.e., MR-IWSS.

A Life-cycle Capacity-based Approach

As mentioned earlier, the approach was proposed by Louis and Magpili (2007) for use in an IWSS (Louis and Magpili, 2007). I extend the approach for use in multiple regions, and the following is the extension of the water demand-supply model, from one region into multiple regions, within the municipality:

Table 1: Demand and Supply Notations in the Three Services across Regions

	DWS (1)	WST (2)	MSW (3)
Region#1	(D_{11t}, Q_{11t})	(D_{21t}, Q_{21t})	(D_{31t}, Q_{31t})
Region#2	(D_{12t}, Q_{12t})	(D_{22t}, Q_{22t})	(D_{32t}, Q_{32t})
		…	
Region#N	(D_{1Nt}, Q_{1Nt})	(D_{2Nt}, Q_{2Nt})	(D_{3Nt}, Q_{3Nt})

Deficit (G): $D_{ijt} - Q_{ijt}$ for I =1(DWS), 2(WST), 3(MSW), and j=1,2,…,N

where D_{ijt} is the demand of service i, in region j, at time t, and

Q_{ijt} is the supply of service i, in region j, at time t.

The model considers both demand and supply in different regions. The difference between supply and demand, called deficit, is translated to impacts in economic, environment, social, and inter-service.

T_{ij} is the total impact of service i in region j, and is defined as

$$T_{ij}(t) = \sum_j \xi_{ijk}(t) \qquad (1)$$

where ξ_{ijk} is the associated set of impacts of the gap in a given service, G_{ij} for (j=1) economics, (k=2) social, (k=3) environmental, (k=4) inter-service impacts from lack of service, and (k=5) inter-region impacts from lack of service in other regions.

Next, we define ψ_i as an impact impression.

$$\psi_{ij}(t) = T_{ij}(t) / \sum_j \sum_i T_{ij}(t) \qquad (2)$$

An impact impression displays the ratio of each service in each region total impact, to the total impact of three services in all regions combined.

The budget invested in service i, in region j, in year t, $B_{ij}(t)$ defined as

$$B_{ij}(t) = \psi_{ij}(t) * (B(t) + \mu(t-1)) \qquad (3)$$

where $\mu(0) = 0$ when $\mu(t-1)$ is the remaining budget from the previous period.

where $B_{ij}(t)$ denotes the allocation of budget for service i, in region j, in year t. Thus, the budget allocated to a given service i, in region j, in any year t is proportional to the relative size of the impact that a deficit in that service has—when comparing to the other services.

That is to say, the budget allocation of *capacity expansion* depends on the proportional impacts of deficits.

The updated gap between the demand and supply for service i, in region j, in year t+1, $G_{ij}(t+1)$ defined as

$$G_{ij}(t+1) = G_{ij}(t) - E_{ij}(t) + d_{ij}(t) \qquad (4)$$

where $E_{ij}(t)$ is an expected capacity expansion in year t from using $B_{ij}(t)$

$d_{ij}(t)$ is the demand that has grown during year t.

An updated non-service ratio for year t+1:

$$\varphi_{ij}(t+1) = G_{ij}(t+1) / D_{ij}(t+1) \qquad (5)$$

An updated total impact for year t+1:

$$T_{ij}(t+1) = T_{ij}(t) * \{\varphi_{ij}(t+1) / \varphi_{ij}(t)\} \qquad (6)$$

An updated impact impression for year t+1:

$$\psi_{ij}(t+1) = T_{ij}(t+1) / \sum_{j}\sum_{i} T_{ij}(t+1) \qquad (7)$$

The last equation (7) updates the proportional impacts of each service and each region. Now, we have a complete life cycle budget allocation that has a potential to reduce the deficit of water and sanitation demand and supply to zero over time. The service in the region where most impact of deficit occurred will receive the highest amount of fund to improve its infrastructures.

General Budget Allocation System

I start by creating budget allocation system using STELLA software and system dynamics approach (Figure 3).

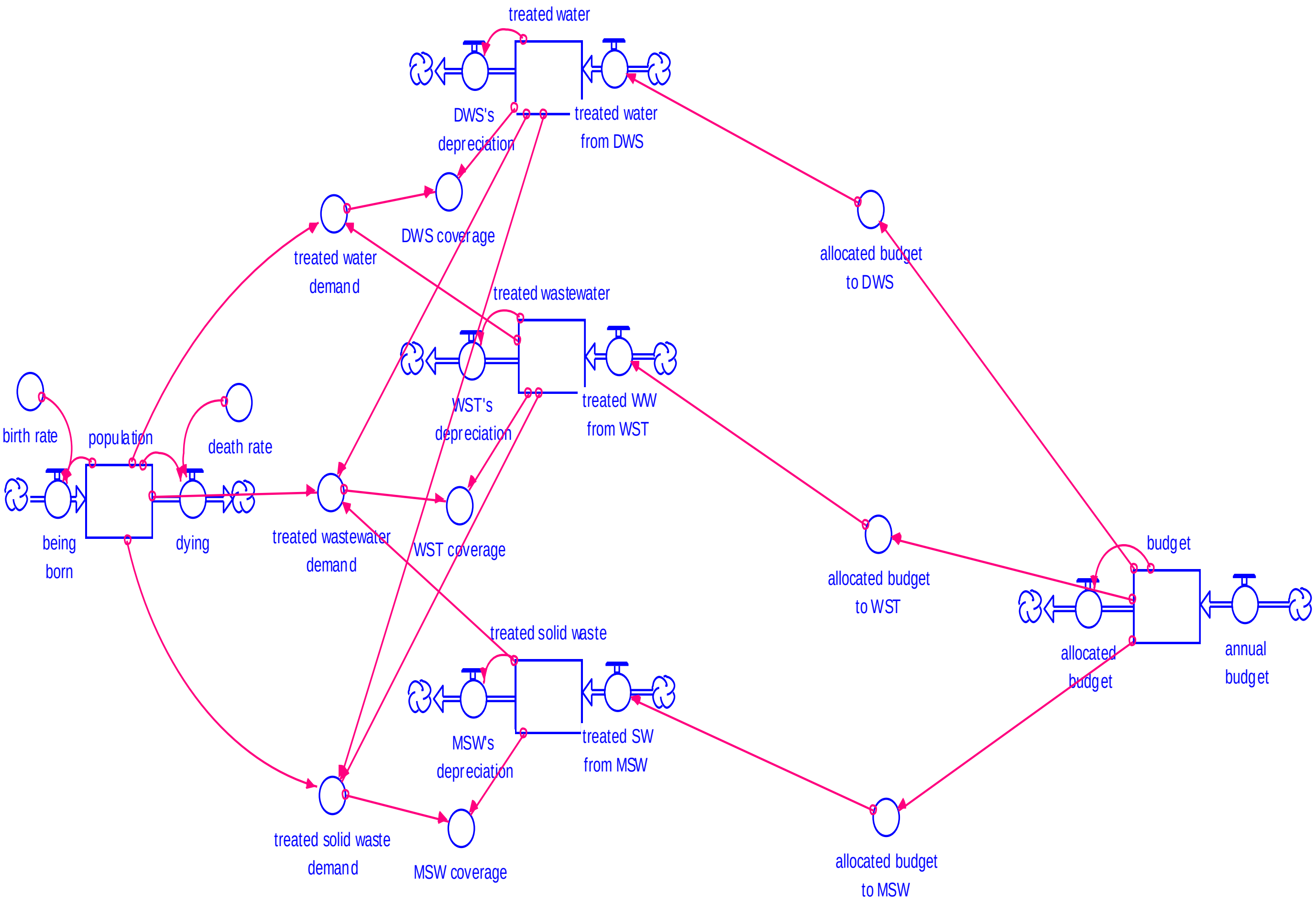
The model consists of 5 stocks: 1) Treated water, 2) Treated wastewater, 3) Treated solid waste, 4) Population (Note: Increases in demand of DSW, WST, and MSW can be due to population growth), and 5) Budget.

Each stock is explained as follows:

1. Treated water: amount of water that DWS can possibly treat.
2. Treated wastewater: amount of wastewater that WST can possibly treat.
3. Treated solid waste: amount of solid waste that MSW can possibly treat.
4. Population: the number of population in a particular municipality affected by birth and death rates only. Population will serve as the source of demand in this model.
5. Budget: amount of money that municipality receives for use in water and sanitation service improvement projects in each budget period. For this study the budget period is 1 year.

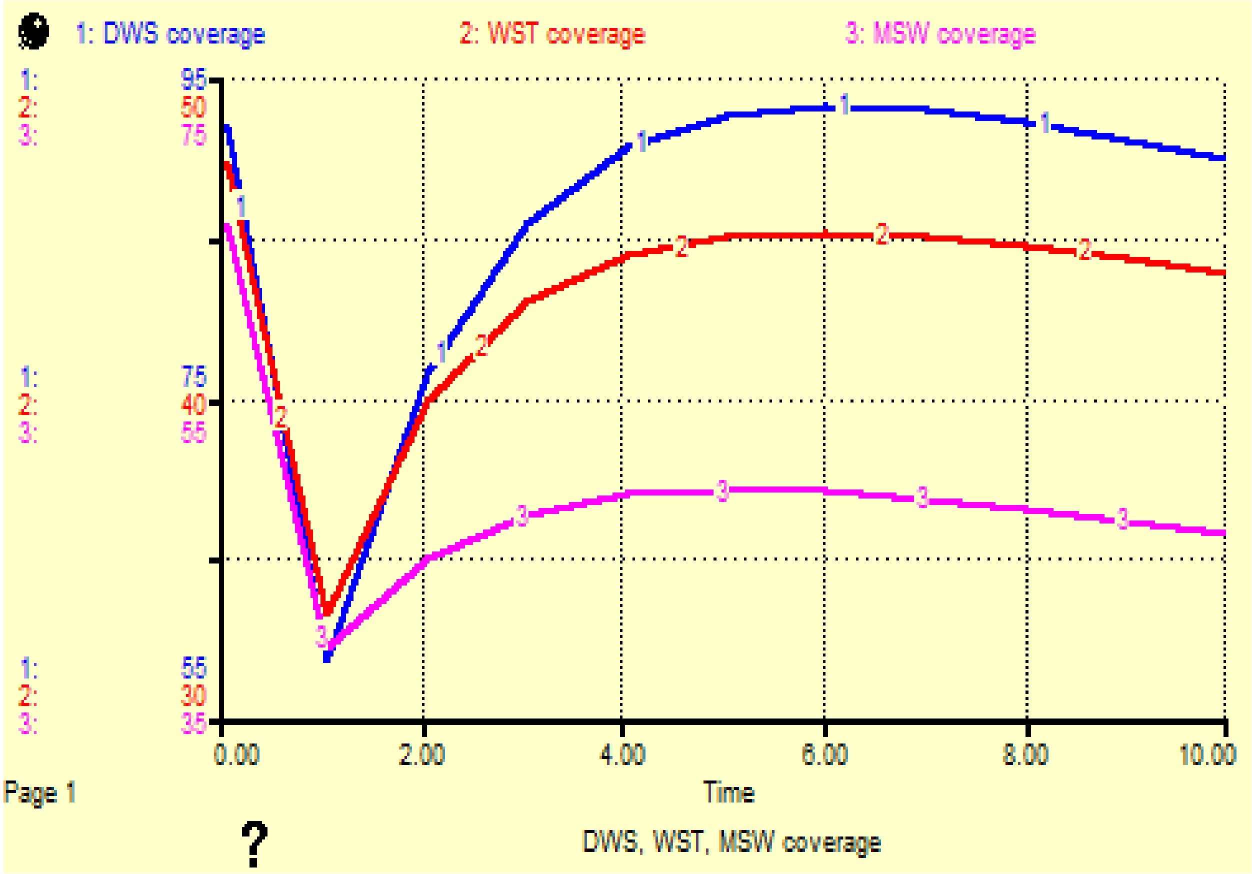
The goal is to observe the difference between demand and supply of DWS, WST, and MSW each year. Then, the gap between supply and demand (the deficit) is reduced by increasing the supply of the DWS, WST, and MSW. However, the supplies can only be increased to the extent of the budget of each service system.

Figure 3: A system dynamic budget allocation model



Below are graph examples, showing the coverage of DWS, WST, and MSW over a 10-year period.

Figure 4: Graph example, showing the coverage of DWS, WST, and MSW.



I use the budget allocation system (Figure 4) to observe its behavior when the demand of DWS, WST, and MSW is greater than their supply. Hypothetical data are used. Then, I use the life-cycle capacity-based approach to allocate budget to the DWS, WST, and MSW services in each region within the MR-IWSS. The eventual goal is to minimize the deficit over time, regardless of the increase in demand.

Figure 5: The system dynamic model for MR-IWSS in a particular region.

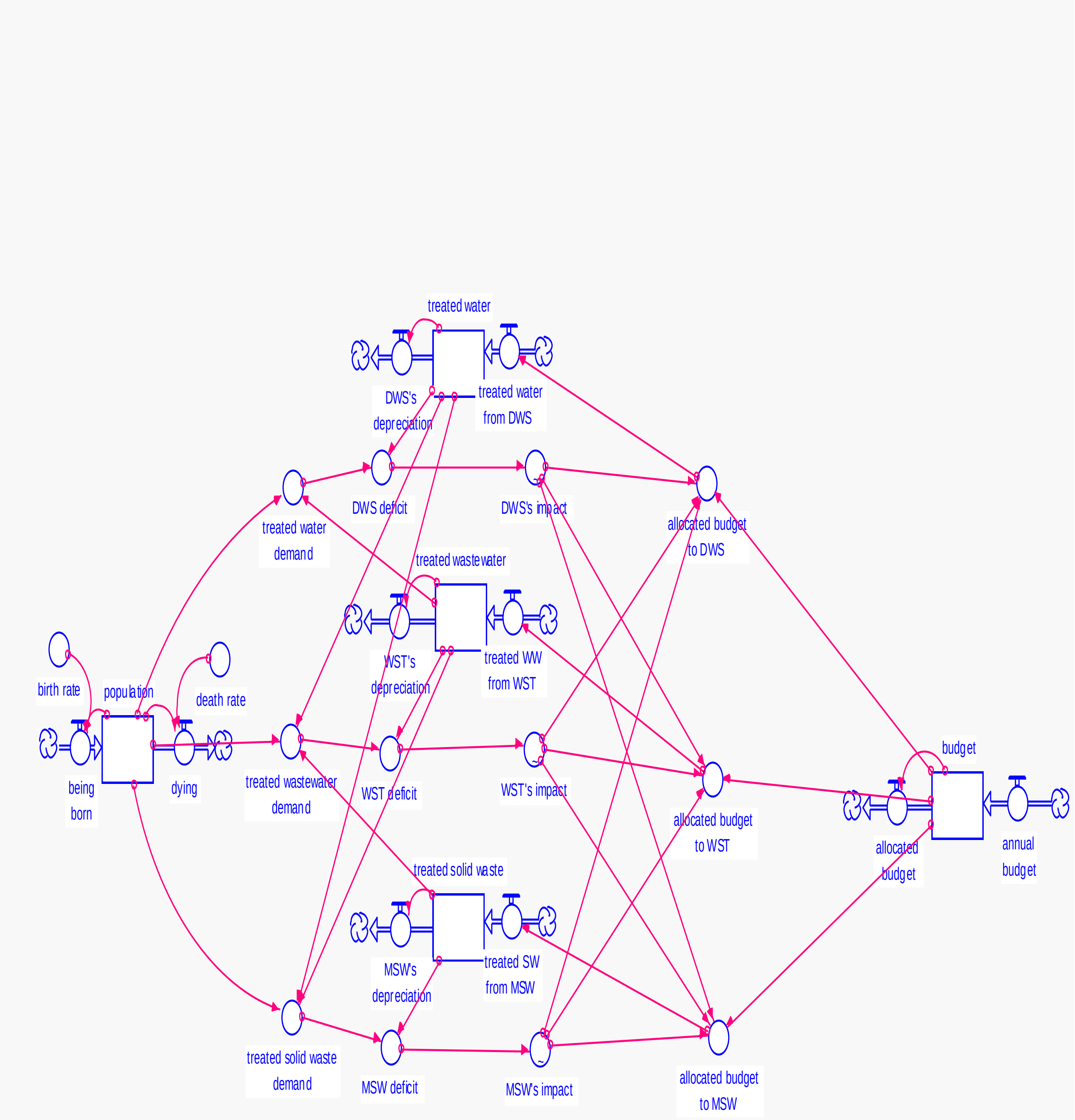
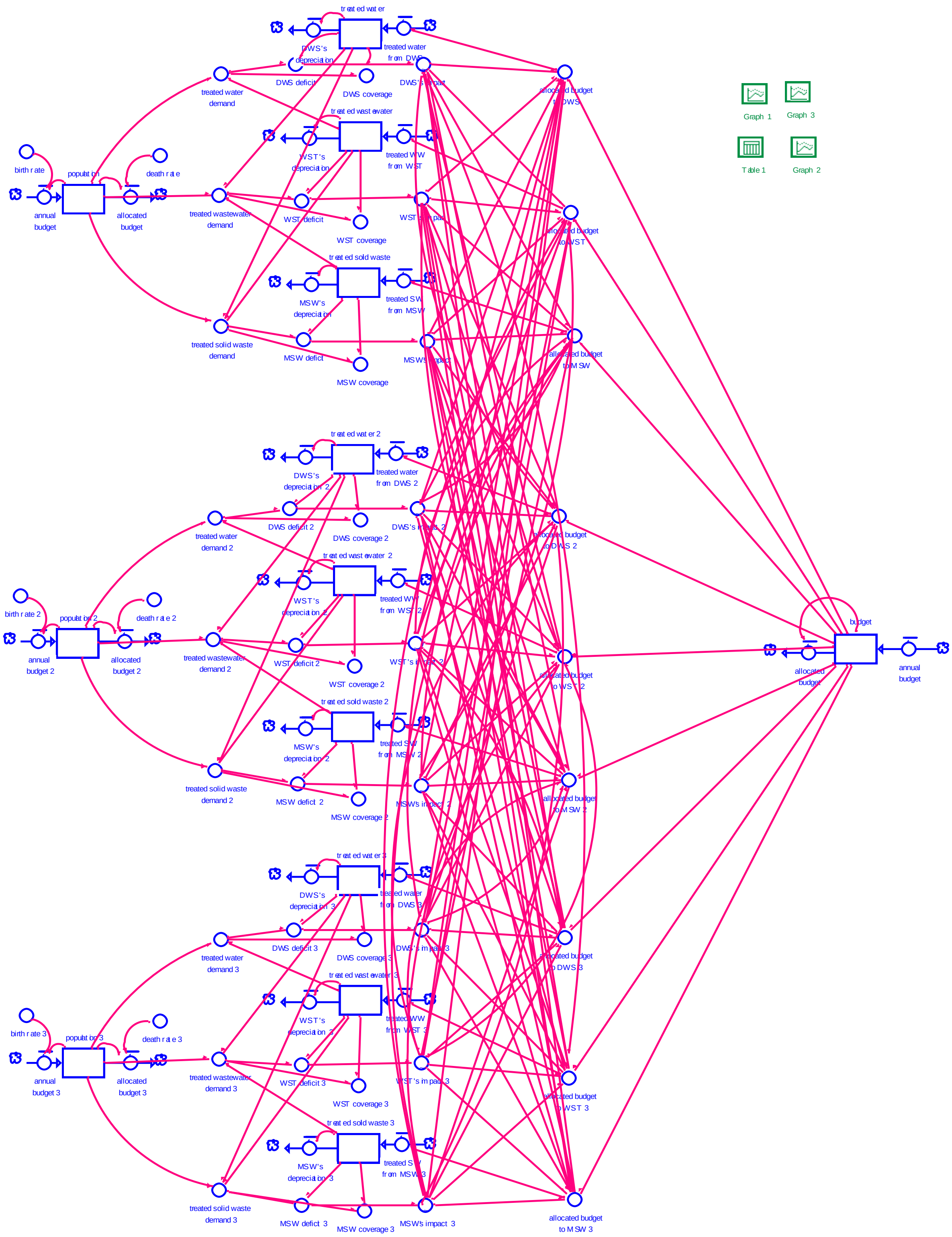


Figure 6: The system dynamic model for MR-IWSS in three regions.



Below are the behaviors of the system:

1) If deficit of the DWS was to be reduced over time, one would require allocating budget to the DWS, increasing its supply until it is greater than the sum of all demands—caused by population change and increase in supply in the WST.
2) Similarly, if deficit of the WST was to be reduced over time, one would require allocating budget to the WST, increasing its supply until it is greater than the sum of all demands—caused by population change and increase in supply in the DWS and MSW.
3) Also, if deficit of the MSW was to be reduced over time, one would require allocating budget to the MSW, increasing its supply until it is greater than the sum of all demands—caused by population change and increase in supply in the DWS and WST.

Conclusion

I propose a life-cycle capacity-based approach solution (a sequential budget allocation method) to the problem of allocating centralized municipal budgets for the Multi-Region Integrated Water and Sanitation System (MR-IWSS). This approach is suitable for the community of Siuna, Nicaragua, where there is a single decision maker for the three services, which are provided to the three major regions (the urban core, peri-urban of neighborhoods surrounding Siuna hospital, and the rural areas), each with different levels of service. This paper proposes a MR-IWSS and uses system dynamics to determine the appropriate method to the budget allocation problem. The proposed life-cycle capacity-based approach balances short term, multi-region continuity of services with long-term capacity expansion for sustained satisfaction of demand for each service.

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