Using System Dynamics to Explore the Water Supply and Demand Dilemmas of a Small South African Municipality

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Abstract

This paper explores the challenges faced by small municipalities in providing water services in a developing-world context of increasing urban demand. The paper uses a case study of the Sundays River Valley Municipality (SRVM) in South Africa. The municipality faces multiple dilemmas in reconciling its available water supply with growing demand for potable water in the primary urban settlement in the area, in a struggle that is typical of the broad category of South African municipalities to which the SRVM belongs. These dilemmas are explored using a system dynamics model, referred to as the 'Kirkwood water demand system dynamics model' (*K-DEM*). This paper specifically introduces the *K-DEM* structure, which is aimed at investigating the impacts of households progressively receiving full water and sanitation services; the use of rainwater harvesting as an alternative form of water supply; and the possible effect of a household-level water conservation / water demand management programme. Baseline results are discussed, and areas for future research identified.

Keywords: Water demand management; water service provision; municipalities; local government; South Africa; mathematical model.

1. Introduction

Recent years have seen a sharp increase in the number and severity of service delivery protests across South Africa, which many analysts broadly credit to the failure of decentralisation in South African local government (e.g. Muller, 2014; Siddle & Koelble, 2012). In this paper, the challenges faced by a small municipality attempting to provide water services in the face of growing demand are investigated. A system dynamics model is developed for the town under examination, called the 'Kirkwood water demand system dynamics model', herewith referred to as *K-DEM*.

As discussed in a review of system dynamics in the water sector (Winz et al, 2009), the themes that have traditionally garnered the greatest attention from system dynamicists are those of regional planning and river basin management, and flooding and irrigation (for e.g. Fernández & Selma, 2004; Guo et al., 2001; Xu, Takeuchi, Ishidaira, & Zhang, 2002). Whilst the overall use of system dynamics as a form of quantitative policy analysis is increasing within the international water sector, its use in investigating challenges associated with urban water supply has particularly expanded in recent years. Examples of some specific applications are in municipal water conservation policies (Ahmad & Prashar, 2010); urban water supply in Singapore (Xi & Poh, 2013) and Korea (Park, Jeon, & Jung, 2013); and urban wastewater management (Rehan, Knight, Unger, & Haas, 2013). By comparison, the application of system dynamics to urban water management in the developing world in general, and Africa in particular, has been limited: the few applications of systems dynamics in the South African water sector – for example – include the relation between a municipality and the physical dynamics of an estuary (Slinger, 1996), and as part of modelling the South African Green economy (DEA & UNEP, 2013; Musango, Brent, & Bassi, 2014). The particular suitability of system dynamics as a methodology for exploring the challenges facing South African municipalities is discussed in greater detail in section 3 of the paper.

2. Description of the case study

The Sundays River Valley Municipality (SRVM) is located in the Eastern Cape Province of the Republic of South Africa (see Figure 1). With a combination of multiple small towns and commercial farming, the SRVM is a primarily rural or prototypical 'Category B3' municipality. Over a third of the 278 municipalities in South Africa can be classified in this category (World Bank, 2009: 10-11). The SRVM is the responsible authority for water service provision to all urban water users. Many of these users are living in impoverished conditions where unemployment and dependency on social grants are endemic: on average, 47% of the SRVM population has a household income of less than R800 per month, with unemployment estimated at 44% (Sundays River Valley Municipality, 2010).

In 2010, several national and regional government departments initiated intervention processes in the SRVM, following an extended period of financial mismanagement and bankruptcy in which the provision of water services in the municipality had suffered. The *K-DEM* model described in this paper was developed as part of an action research project that participated in the wider intervention processes in the SRVM. The research was funded by the South Africa Netherlands Research Programme for Alternatives in Development (SANPAD) and was entitled 'From policy to practice: enhancing implementation of water policies for sustainable development' (Palmer, de Wet, Slinger, Linnane, & Rogers, n.d.).

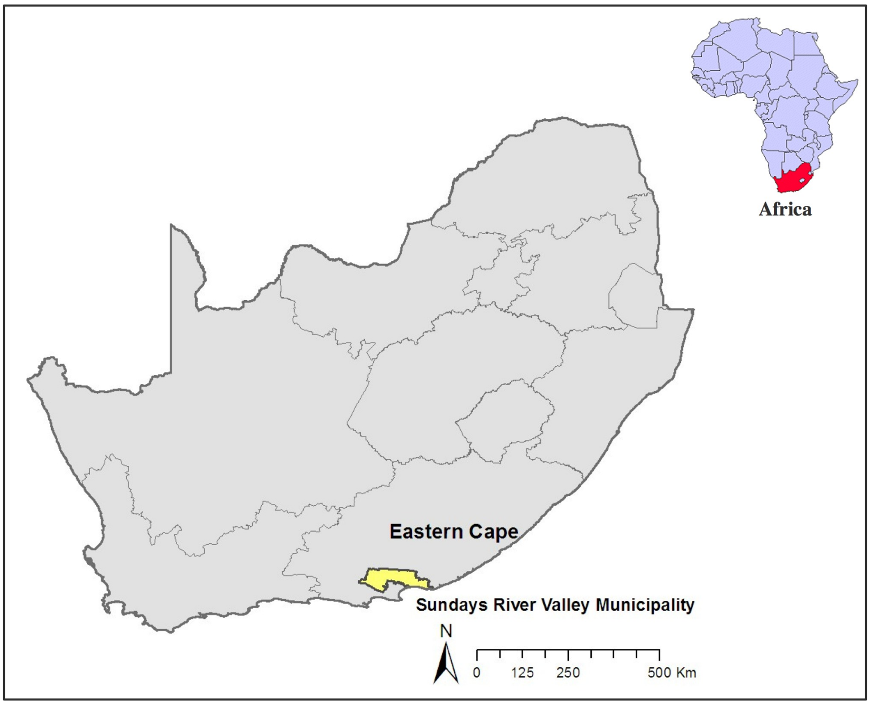

Figure 1: Map of the Sundays River Valley Municipality, shown located within the Eastern Cape province of the Republic of South Africa, in Africa.

Whilst many of the urban areas in the SRVM face significant water challenges, *K-DEM* focuses on one of the three primary schemes operated by the SRVM, which supplies communities and suburbs of the Greater Kirkwood area. The first research efforts to explore problems affecting the Kirkwood supply scheme – using the Strategic Adaptive Planning process of Rogers and Luton (2011) – identified the bulk water supply system as a key focus. To this end, the 'Greater Kirkwood water supply model' was developed (D'Hont, Clifford-Holmes, & Slinger, 2013) and then extended (D'Hont, 2013). The initial focus of these endeavours was to use system dynamics modelling as a means of facilitating strategic conversations (Howick & Eden, 2010) between the municipality, the bulk water supplier in the region and other organs of government, with the emphasis on the operations of the supply system. These early modelling endeavours surfaced numerous issues that were not addressed within the purpose, nor in the design of the 'Greater Kirkwood water supply model'. The most critical of these issues were the determinants of the rising demand for potable water in Kirkwood and the possible alternative sources of water supply. This problem can be articulated from the perspective of different stakeholders in the following way:

- Municipal communities who currently receive full water services (in-house water connection and waterborne sanitation) want a stable water supply, with a reduction in the number and severity of current shortages and outages.
- Municipal communities who receive a 'basic supply level' of water services (i.e. residents who access potable water either from a nearby standpipe or yard connection,

but do not have waterborne sanitation or household water connections) desire the latter services as soon as possible.

- Municipal officials want to be able to supply water now, and into the future as the municipality grows – that is, providing both to current communities, and progressively meeting the water demands of future communities.
- Funding agencies and national government departments (including the national Department of Water Affairs) want the SRVM to demonstrate active water demand management, showing how the municipality is conserving and using current water resources effectively, prior to applying for funding for further water supply infrastructure.

Following the above, the problem explored using the *K-DEM* model in this study can be summarized as:

> *How can the Sundays River Valley Municipality reconcile the available water supply with the growing demand for potable water in Kirkwood, whilst minimising the gap that currently exists between the current and desired levels of potable water services?*

The motivation for selecting system dynamics and the attendant methods for exploring the above problem are provided in section 3.

3. Methodology

System dynamics is a discipline and a professional field that was initially developed in 1956 at the Massachusetts Institute of Technology. The field grew out of control theory, cybernetics, and cognate research into nonlinear dynamics that originated in the fields of mathematics, physics and engineering (Forrester, 1968, 1970; Sterman, 2000). However, one of the founders of the discipline of system dynamics – Jay W. Forrester – describes the 'four grandparents of the field' as being strategic decision making, feedback thinking, computer technology and computer simulation (Maani & Cavana, 2007).

There are several reasons why system dynamics is an ideal method for exploring the supply-demand dilemmas in Kirkwood. Firstly, on-going disputes between different water users and stakeholders in the case study were compounded by uncertainty in the basic information. This uncertainty included the size of the population of Kirkwood, the quantity of unaccounted-for water, household demand requirements for potable water, and the mechanisms of access. Where appropriate numerical data were available, technical reports were consulted in order to provide data for the model parameters and initial states (references are provided in: D'Hont et al., 2013). To address the many areas where numerical data were lacking, researchers facilitated three workshops (31 November to 1 December 2011; 10 October 2012; and 28 February 2013), which were attended by representatives from the Department of Water Affairs and the SRVM, in addition to impacted and affected stakeholders.

4. Model description

This section outlines the structure of the *K-DEM* model in four sub-sections. Firstly, the model boundary is described by means of a 'boundary chart'. Secondly, the relationships between the primary variables are discussed using an aggregate causal loop diagram. The model settings are then summarised, after which the *K-DEM* stock-flow diagrams are explained.

4.1. *K-DEM* model boundary:

A system dynamics model strives to produce an endogenous explanation of the problem under examination (Forrester, 2007; Sterman, 2000). This is to say that the primary driving forces of the system, and the feedbacks between these driving variables, should be included within the model. Other variables that affect the system, but are not affected *by* the system, can be included in the model as 'exogenous' variables. Given that a model is a simplification of reality in order to gain analytical purchase on a particular problem, variables that are held to be less important for the system under examination are excluded from the analysis. A description of which variables are treated endogenously and exogenously in relation to those that are excluded is therefore a central part of stipulating the model boundary. This is presented in the 'model boundary chart' in Table 1.

Table 1: *K-DEM* model boundary chart

Endogenous	Exogenous	Excluded
Potable water supply	Raw water sources	Raw water allocations from the Orange-Fish Sundays inter-basin transfer scheme.
Urban domestic potable water demand drivers (households)	Population fluctuations	Possible population drivers + commercial demand + water quality + wastewater
Treatment from raw to potable water	Bulk water losses	Operational and capital budgets affecting supply infrastructure and maintenance
Rainwater harvesting infrastructure	Hydrological dynamics affecting the sub-catchment	Global and regional climatic variations
Transitions from informal households, to households with basic supply to fully-connected households	Aggregate increase in lifestyle expectations in the Greater Kirkwood area, with regards to water and sanitation	National prerogatives and directions regarding 'free basic water' and 'free basic sanitation'

4.2. Aggregate causal loop diagram:

An aggregate causal loop diagram (CLD) is provided in this section in order to describe the relationship between the primary variables of interest (Figure 2). The driver of the system is the 'gap between current and desired levels of potable water services' in Kirkwood. This gap exists between two variables: the 'current potable water demand' and the 'desired level of potable water services' (with the determinants of the desired levels excluded from this analysis). The 'current potable water demand' variable acts as the linking point for all the other variables in the aggregate CLD. The relationships between these variables are described in greater detail in sub-section 4.4.

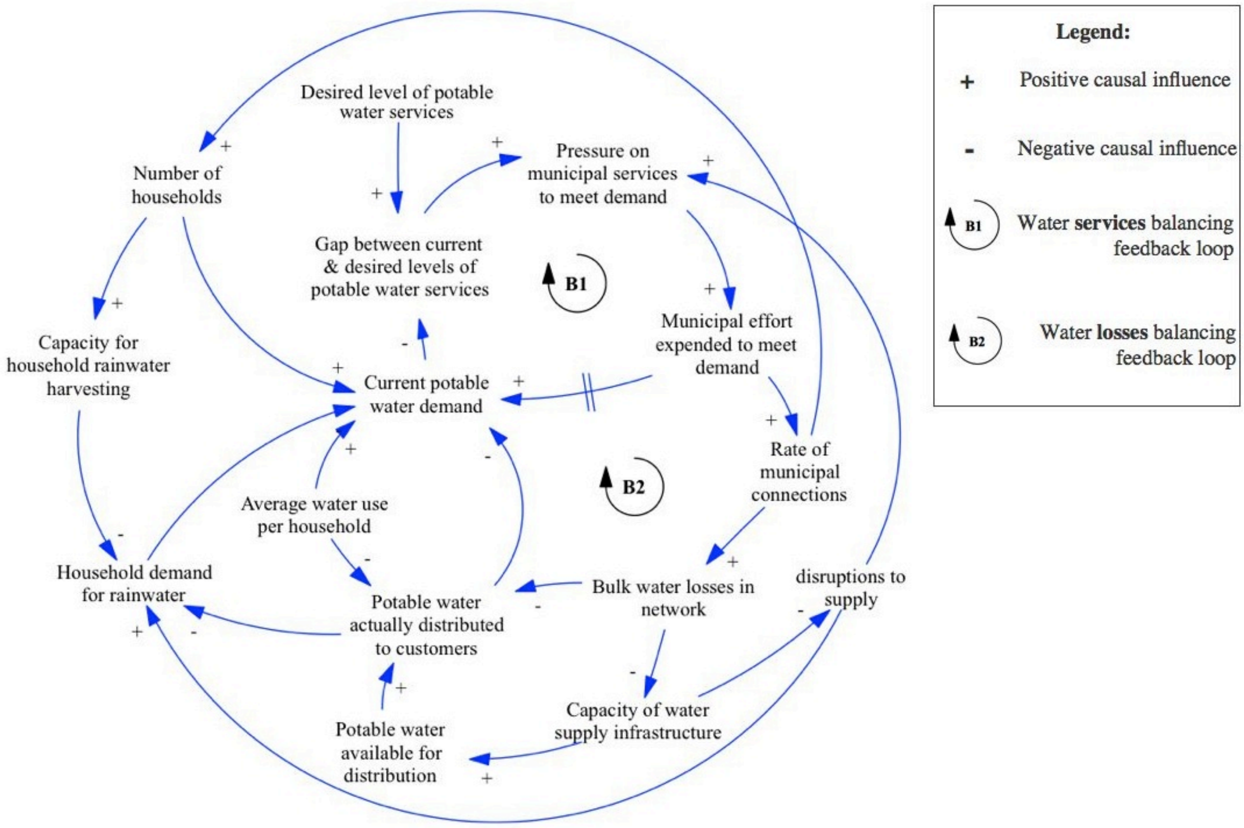

Figure 2: Aggregate causal loop diagram, with legend identifying two balancing feedback loops

4.3. Model settings:

K-DEM simulates a 20-year period, equating to a time horizon of 2005-2025. The period between 2005 and 2013 was used primarily for model calibration purposes, whilst the period between 2013 and 2025 was used for projection and simulation purposes. A time step of 0.0625 years (a little less than a month) was selected. The model was simulated using the time unit of years. The Euler method was selected for numerical integration purposes. The level of data uncertainty, and the inclusion of the decision rule used in the water treatment process within the model (an if-then-else construction) are the primary reasons for selecting Euler over Runge-Kutta4. The model was constructed and simulated using Vensim PLE (Personal Learning Edition) system dynamics software for Macintosh, Version 6.1c (Ventana Systems, 2013).

4.4 K-DEM sub-models:

This section describes the simulation model by introducing the *K-DEM* sub-models that were developed. The model consists of four sub-models: a simple population sub-model (top-left of Figure 3), which is linked to a rainwater-harvesting sub-model (bottom left) and to a household sub-model (top-right). All three of these are linked with the fourth sub-model (which is the potable water supply system: bottom-right). The link between these sub-models is the sum of the demand for water from 'informal households', 'households with basic supply' and 'connected households'. This 'total household demand' is represented by the variable enclosed in a circle in the middle of Figure 3.

Each sub-model is described in detail in the following section. These descriptions provide an overview of the functions utilised in each sub-model whilst surfacing the assumptions (and some of the limitations) associated with each part the model.

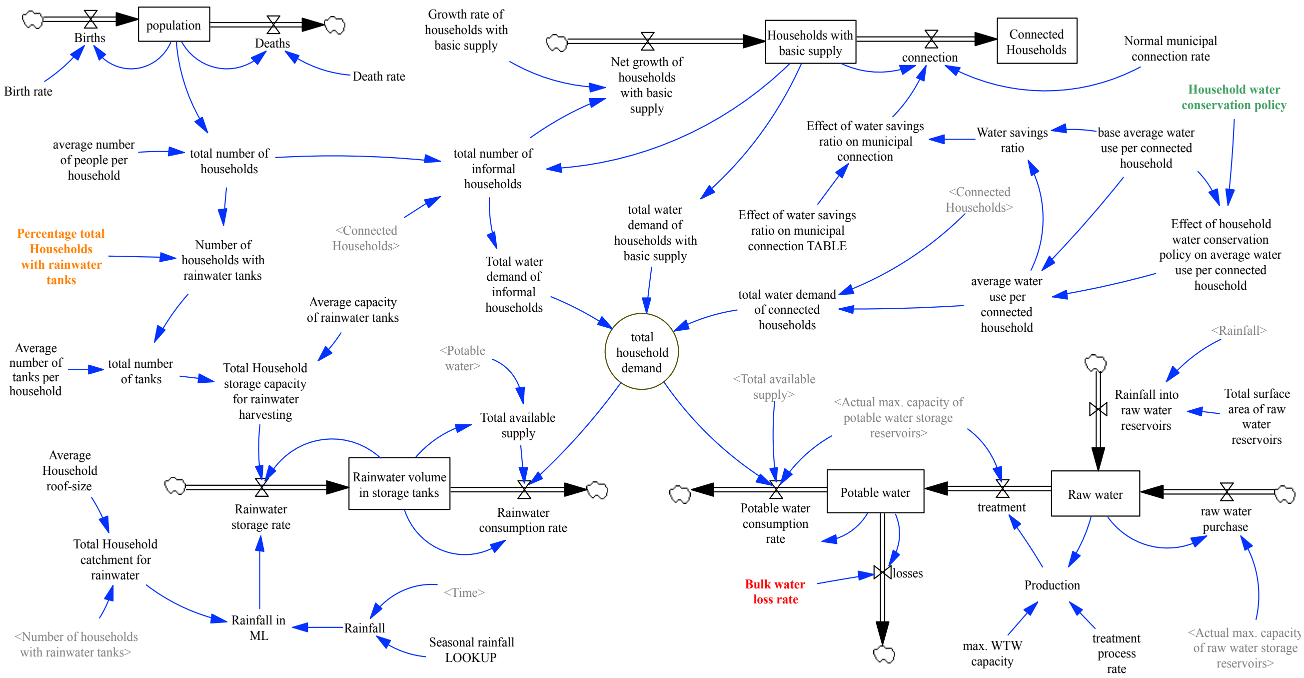

Figure 3: Overall *K-DEM* sub-models

4.5. Population sub-model

This sub-model represents the population of the Greater Kirkwood region of the Sundays River Valley Municipality. It is a simplified one consisting of one stock 'population' (*P*), which is increased by births (r_b) and decreased by deaths (r_d) (refer Figure 3). The population at time *t* is mathematically represented as:

$$P(t) = P(0) + \int [r_b - r_d] dt$$

4.6 Households sub-model:

The households sub-model consists of two stocks, namely, households with basic supply (*HBS*) and connected households (*CH*) (refer Figure 3). These two stocks are connected using an 'aging chain' model structure (Sterman, 2000: 485-490). The first stock (*HBS*) is influenced by the net growth of households with basic supply (r_{gbs}) and the household connection rate (r_c):

$$HBS(t) = HBS(0) + \int [r_{gbs} - r_c] dt$$

In 2005 (the start of the time horizon used in this model), the majority of the households in the Greater Kirkwood area received a 'basic supply level' of water services. The inflow into this stock – the net growth of households with basic supply (r_{gbs}) – is influenced by the total number of informal households (*TIH*) and the growth rate of households with basic supply (*GRBS*). The total number of informal households is given as the total number of households (*TH*) minus the sum of households with basic supply (*HBS*) and connected households (*CH*). This is mathematically represented as follows:

$$TIH = TH - (HBS + CH)$$

The key driver of demand in *K-DEM* is the water demand from connected households, which are the households that are connected to the municipal bulk water supply and waterborne sanitation network. The stock of connected households (*CH*) is influenced by the connection rate (r_c), represented as:

$$CH(t) = CH(0) + \int [\ r_c\ ] dt$$

The rate that households move from the *HBS* stock to the *CH* stock (i.e. the connection rate) is the single most important driver of behaviour in *K-DEM* and is represented as:

$$r_c = HBS * NMC * EWSR$$

Where, *HBS* is households with basic supply stock; *NMC* is the normal municipal connection rate; and *EWSR* is the effect of water savings ratio on municipal connections. *NMC* is equal to the average time that it takes the municipality to connect households under normal conditions. The connection rate deviates from the norm given the effect of water savings on municipal connections (*EWSR*). *EWSR* is based on two interrelated assumptions: the first is that the *less* the water use per connected household per year, the *more* potable water will be made available for use by new connected households. The second assumption is that the municipality will use the resulting 'water savings' on connecting additional households to the bulk water supply and sanitation network. The water savings are estimated through a 'water savings ratio' (*WSR*), which is calculated as the 'average water use per connected household' (*AWCH*) divided by 'base average water use per connected household' (*BAWCH*):

$$WSR = \frac{AWCH}{BAWCH}$$

In order to account for the non-linear nature of the interactions between water savings ratio (*WSR)* and the municipal connection rate (r_c), *K-DEM* employs a LOOKUP function, demonstrated in Figure 4.

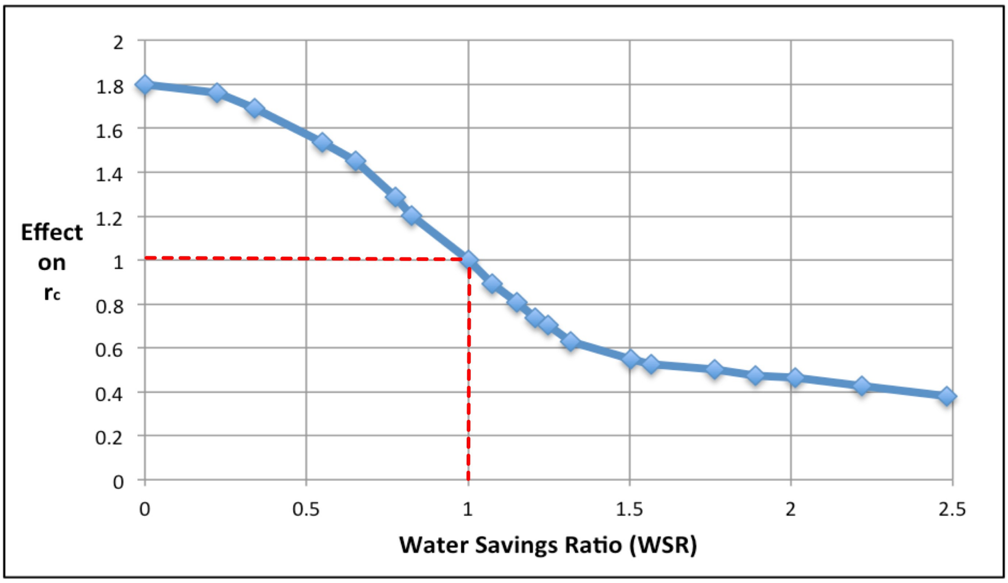

Figure 4: LOOKUP function for effect of water savings ratio (WSR) on municipal connection rate (r_c)

The water savings ratio (*WSR*) would be within the bounds of the box created by the dotted red lines in Figure 4 with a household water conservation policy. The ratio would only be greater than 1 if the type of domestic water uses changes. As the water savings ratio (*WSR*) exceeds 1, the number of houses that can be connected decreases sharply (as demonstrated by the sharp decline between 1 and 1.5 on the x-axis). On the y-axis, 1 denotes the standard municipal connection rate (*MCR*). At the upper bound of 2 on the y-axis, the standard municipal connection rate (*MCR*) would double (hence twice as many houses per year could be connected than the 'normal' connection rate would allow). The variability of the municipal connection rate (*MCR*) is controlled by the presence of a 'Household water conservation policy' (in green in the top right of the stock-flow diagram in Figure 3). The latter is one of three policies that are planned for testing in the model in the future development of the work.

4.7. Potable water supply sub-model:

Given that potable water supply system in Kirkwood has been the subject of previous modelling endeavours (D'Hont et al., 2013; D'Hont, 2013), the water supply sub-model in *K-DEM* is relatively simple. The water supply system was modelled in *K-DEM* using two stocks: raw water and potable water. The raw water stock (*RW*) is influenced by three flows, raw water purchases (r_{rwp}), rainfall into raw water reservoirs (r_{rf}) and water treatment rate (r_{tm}). The mathematical representation of this is:

$$RW(t) = RW(0) + \int \left[(r_{rwp} + r_{rf}) - r_{tm} \right] dt$$

The potable water (*PW*) stock is influenced by water treatment rate (r_{tm}), potable water losses (r_{lo}) and potable water consumption (r_{pwc}), represented as:

$$PW(t) = PW(0) + \int \left[r_{tm} - r_{lo} - r_{pwc}) \right] dt$$

Portable water losses (r_{lo}) are determined by bulk water loss rate (*BWL*), which is set exogenously as a constant (and is adjusted for policy analysis purposes).

The rate of potable water consumption (r_{pwc}) is influenced by the total household demand (*THD*), the amount of potable water (*PW),* maximum capacity of the potable water reservoirs (*MPW*), and total available supply of water (*TAS*) – which is the sum of available rainwater and potable water. This is mathematically represented as:

$$r_{pwc} = \min\,(MPW, (THD * \frac{PW}{TAS}))$$

This model structure reflects the real-world problem that the amount of potable water available is subject to the amount of raw water available and the treatment capacity. As described above, raw water availability increases with raw water purchases (r_{rwp}) and rainfall into raw water reservoirs (r_{rf}). The latter is described in detail in the rainwater harvesting sub-model in 4.8. The primary determinant of raw water availability is raw water purchases (r_{rwp}). Raw water purchases (r_{rwp}) are calculated as the difference between the maximum capacity of the raw water reservoirs (*MRW*), corresponding to the situation in the town of Kirkwood, and the amount of raw water (*RW*) at a particular point in time. This is given as:

$$r_{rwp} = MRW - (RW / t_{rw})$$

Where, t_{rw} is time to adjust raw water stock.

Maximum capacity of raw water reservoirs (*MRW*) is calculated as a sum of the capacity of raw water reservoirs, as demonstrated in Figure 5 below. This sub-model calculates the sum of the four raw water reservoirs and includes an additional storage facility – the old storage canal. As illustrated in Figure 5, *MRW* caters for the entire possible storage infrastructure in the model (*phrased as* 'theoretical max. capacity of raw water storage reservoirs'), with the dysfunctional reservoirs then subtracted from it.

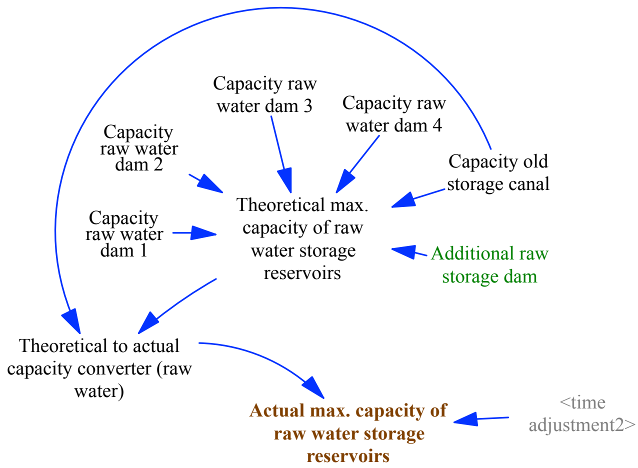

Figure 5: Maximum capacity of raw water storage reservoirs (MRW) sub-model

Given increasing water demand in the Greater Kirkwood area, the municipality has been operating its water treatment works at its maximum capacity (*WTC*). To reflect this reality, production (*PR*) is represented as a decision rule influenced by the maximum capacity of the water treatment works (*WTC*), the treatment process rate (*TPR*) and the available raw water (*RW*). The model simulates the current operating rule of the municipality. Producing potable water is, however, still reliant on there being sufficient raw water available to support this function, so in situations when there is insufficient raw water to support maximum capacity, then the water treatment works will process everything available. As such, this is mathematically presented as:

$$PR = IF\ THEN\ ELSE\ (RW < (WTC * TPR), RW,\ (WTC * TPR))$$

The amount of potable water available for use by Greater Kirkwood residents is constrained by the storage capacity of the potable water reservoirs (i.e. for practical purposes, more water cannot be treated than can be stored in these reservoirs). The maximum capacity of the potable water reservoirs (*MPW*) is calculated using an equivalent model structure for potable water storage to the one outlined for raw water storage in Figure 5. The water treatment rate (r_{tm}) is therefore determined by production (*PR*) and the maximum capacity of the potable water reservoirs (*MPW*). A minimum function is utilised for the treatment rate (r_{tm}) calculation, where:

$$r_{tm} = \min(MPW, PR)$$

4.8. Rainwater harvesting sub-model:

This sub-model consists of one stock, namely rainwater volume in storage tanks (*RWT*), which is increased by rainwater storage (r_{rs}) and reduced by rain water consumption (r_{rwc}). This is mathematically represented as:

$$RWT(t) = RWT(0) + \int [\, r_{rs} - r_{rwc} \,] dt$$

The rainwater storage rate (r_{rs}) is determined by the amount of rainfall in ML (*RFA*) available for rainwater harvesting, total household storage capacity for rainwater (*THStR*), and the rainfall volume in storage tanks (*RWT*). This was represented as a minimum function as follows:

$$r_{rs} = \min\left((THStR - RWT), RFA\right)$$

The rainwater consumption rate (r_{rwc}) is determined by the total household demand (*THD*), the rainwater volume in storage tanks (*RWT*) and the total available supply of water (*TAS*), and is expressed as minimum function as follows:

$$r_{rwc} = \min\left(RWT, (THD * \frac{RWT}{TAS})\right)$$

The total household storage capacity for rainwater harvesting (*THStR*) is given as the total number of tanks (*TNT*) multiplied by the average capacity of rainwater tanks (*ACR)*:

$$THStR = TNT * ACR$$

Similarly, the available rainfall in ML (*RFA*) is given as the product of rainfall (*RF*) and the total household catchment for rainwater (*THCR)*:

$$RFA = RF * THCR$$

Rainfall (*RF*) is influenced by the seasonality of rainfall in the Greater Kirkwood area, which was represented as a LOOKUP. In representing the seasonality, the months of the year were translated into values between 0 and 1 via dividing the value of the midpoint of each month (in days) by the total number of days in the year (i.e. a value for January was created by dividing 15 by 365, resulting in a value of 0.041). These values were used as the <u>inputs</u> for the LOOKUP table. Secondly, rainfall data was disaggregated into monthly rainfall (using data collected on a monthly basis, at the local level in the SRVM, between 1969 and 2012). The average rainfall per month (i.e. January to December, from 1969-2012); and average monthly rainfall (calculated as the sum of all the monthly averages, divided by the number of months (i.e. 12)) were then calculated. The rainfall <u>outputs</u> for the LOOKUP table were then calculated by dividing average rainfall per month with average monthly rainfall. For example, the average rainfall for the month of January in the Greater Kirkwood area is 38.41mm. The annual average monthly rainfall is 36.96mm. Hence, the effect of seasonality on rainfall is given as 38.41 mm divided by 36.96 mm, which is equal to 1.039. The resulting LOOKUP function from this table of inputs and outputs is graphically represented in

Figure 6 below.

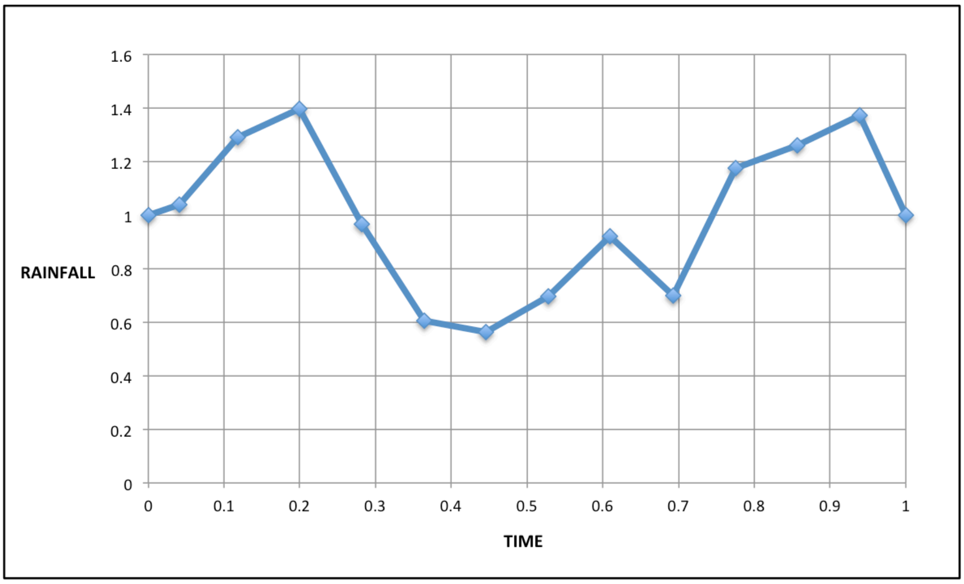

Figure 6: LOOKUP function for rainfall

4.9. Supplementary variables used in model:

K-DEM employs one 'supplementary' variable that has no causal effect on any other variable, and so is itself redundant within the model other than as a source from which information can be derived. This variable is the 'Water security index', the equation for which is as follows:

$$\texttt{Water security index} = \frac{\texttt{total available supply}}{\texttt{total household demand}}$$

The formulation of this index follows an 'Adequacy of water' index employed in an system dynamics model on water supply in Singapore (Xi & Poh, 2013; Xi, 2012). The goal of the Kirkwood system is to have sufficient water supply to meet the demand in any particular year, and at any point throughout the year. Hence, the supply-demand ratio should be larger than, or equal to, 1. However, whilst a value of 1 on the index might suffice as an annual indicator, having demand=supply (i.e. 1) fails to provide any buffer in the event of a system failure affecting water supply *or* a sudden (and unexpected) spike in demand. On a short-term basis, the index needs to exceed 1. The Department of Water Affairs specifies that a municipal water service provider must ensure a minimum of two days' potable water supply (i.e. two days worth of storage in its potable water storage reservoirs), and a minimum of 14 days storage in the raw water storage reservoirs. This requirement is interpreted in the model as requiring that the water security index should ideally lie between 2 and 6.

4.10. Model verification and validation:

Prior to use in policy analysis, the *K-DEM* model was tested through processes of 'model debugging', 'model verification' and 'model validation'. The first stage, 'model debugging', sought to trace and correct errors preventing the model from simulating properly (or at all). Once the obvious bugs such as floating point overflows were eradicated from the model, other verification processes were undertaken to further test whether the model was coded correctly and whether it simulated correctly. Following Pruyt (2013), verification can be distinguished from debugging in that the former looks for errors without knowing whether they are present (whilst the latter addresses errors that are obviously present). Particular attention in model verification was paid to achieving consistency between the conceptualisation of the model and its specification. Unit consistency and the numerical accuracy of the simulation were checked. By performing simulation runs throughout the model-building process, structural errors were identified and addressed iteratively.

The aim of model validation is broadly understood as striving to increase confidence in the model under development, thereby increasing confidence in the robustness of the simulated results and the policy analysis arising out of the modelling process (Sterman, 2000). Validation processes used in this study included direct structural tests and extreme condition tests, which are briefly introduced below.

Direct structural tests assess the "validity of the model structure by directly comparing the simulated reference mode with knowledge about the real system" (Barlas, 1996). These tests were particularly useful given that the modeller had in-depth experience of the real-world problem environment (as a participant in a multi-year action research case study using the SRVM (Palmer et al., n.d.)). Rather than relying on one data set, the model was tested against historical data from a range of sources, collected by national, provincial and local authorities. The results presented below reflect the model outcomes that accord with these different data sets.

The second validation test – extreme condition testing – examined the degree to which the model "responded plausibly when subjected to extreme policies, shocks, and parameters" (Sterman, 2000: 860). The model was tested by drastically increasing the key stocks driving demand in the model (like population), and decreasing the key stocks driving water supply in the model. The outcome of these tests resulted in water demand greatly exceeding available supply, with system behaviour that agreed with the dynamic hypothesis, thereby confirming the validity of K-DEM.

5. Results

The results of *K-DEM* are predominantly summarised in this section by using the outputs from the model, with supplementary explanations supplied where necessary. The emphasis is on simulating the problem situation know to, and experienced by, the Sundays River Municipality. This is referred to as the 'Base' scenario in *K-DEM* and provides the reference mode against which policies and scenarios can be assessed.

In Figure 7 below, the total number of households rises: connected households rise as the number of 'households with basic supply' and 'informal households' drops. The resulting rise in overall water demand is demonstrated in Figure 8.

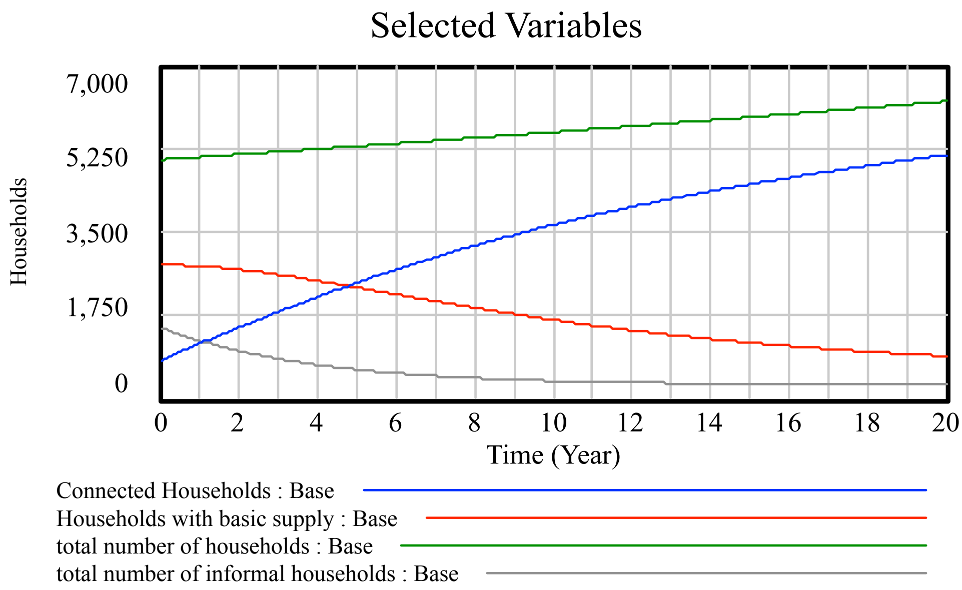

Figure 7: Base- total number of households

Additionally in Figure 8 the household demand is disaggregated into the three contributors ('connected households', 'households with basic supply' and 'informal households'), illustrating how the rise in 'total water demand of connected households' – in red – mirrors the 'total household demand' – in blue – whilst the total household demand for basic and informal households declines and remain insignificant contributors to total demand.

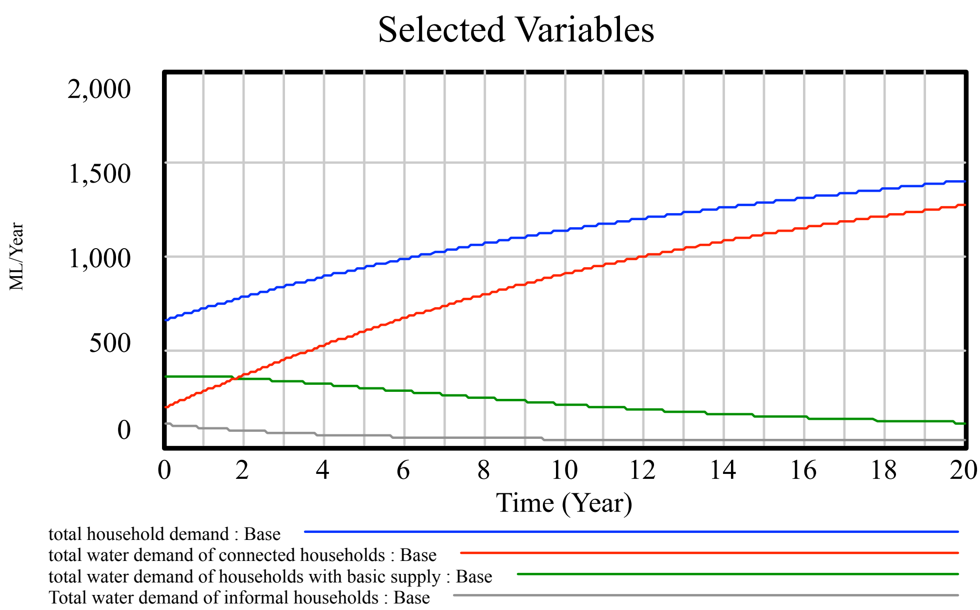

Figure 8: Base – water demand

As water demand rises, the stock of potable water falls (Figure 9). In Figure 10, the potable water consumption rate is compared against the total household demand. This demonstrates the fact that by Year 9 in the simulation, total household demand exceeds the ability of the water supply system to provide water. At this point, potable water consumption levels out – meaning that the water supply system is functioning at maximum and, as such, the supply system cannot meet the demand. The 'gap' between 'total household demand' (in red) and the 'potable water consumption rate' is the supply and demand gap that is one of the key phenomena of interest in *K-DEM*. Figure 10 fits with the municipal experience in Kirkwood, where residents observed that the number of water outages per year rose dramatically in the period between 2012 and 2013 – as total household demand exceeded the maximum design capacity of the water supply system (with no concomitant restriction in supply – in the form of water restrictions – nor constriction in demand, in the form of conservation or water demand management programmes).

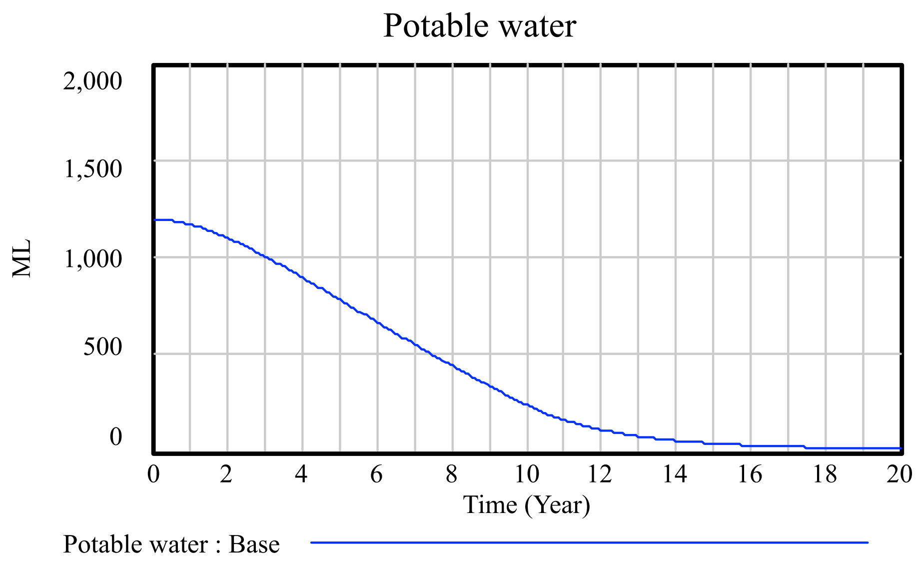

Figure 9: Base - potable water stock

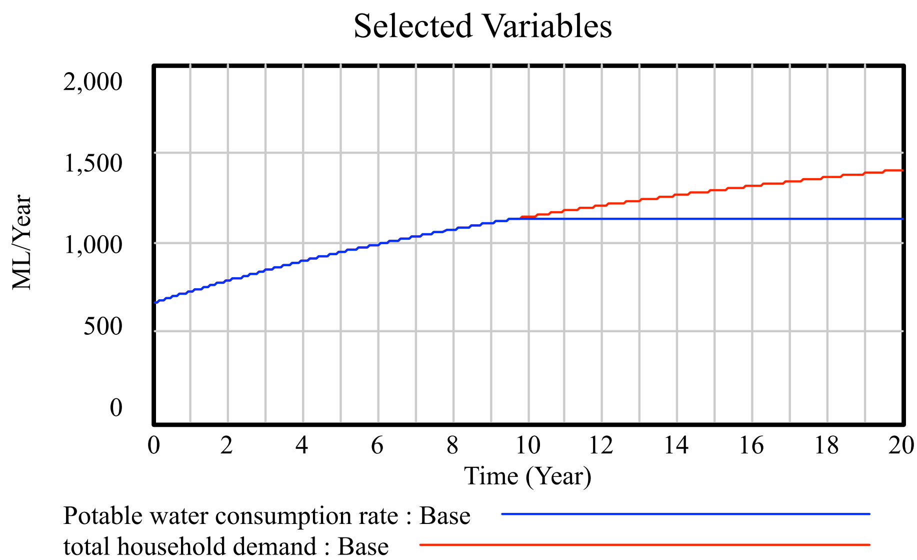

Figure 10: Base - potable water consumption rate against total household demand

The next two figures pertain to rainwater harvesting. Figure 11 demonstrates the behaviour of the stock 'Rainwater volume in storage tanks'. The initial spike in the volume of the stock can be understood as settling behaviour: for this simulation, the initial volume in the stock appears to be set too low, so that the stock takes time to fill (in the first two years), after which the stock depletes at a rapid rate (Years 3 – 5), before stabilizing and growing at a steady rate from Year 6 onwards. This behaviour is further demonstrated in Figure 12, which graphs the

'Rainwater storage rate' against the 'Rainwater consumption rate'. In addition to seeing the 'Rainwater consumption rate' rise in the initial first 4 years (in response to the Rainwater stock), we see the trend of the 'Rainwater storage rate' increasing gently (as the number of households in Kirkwood grows, thereby increasing the 'Total household catchment for rainwater').

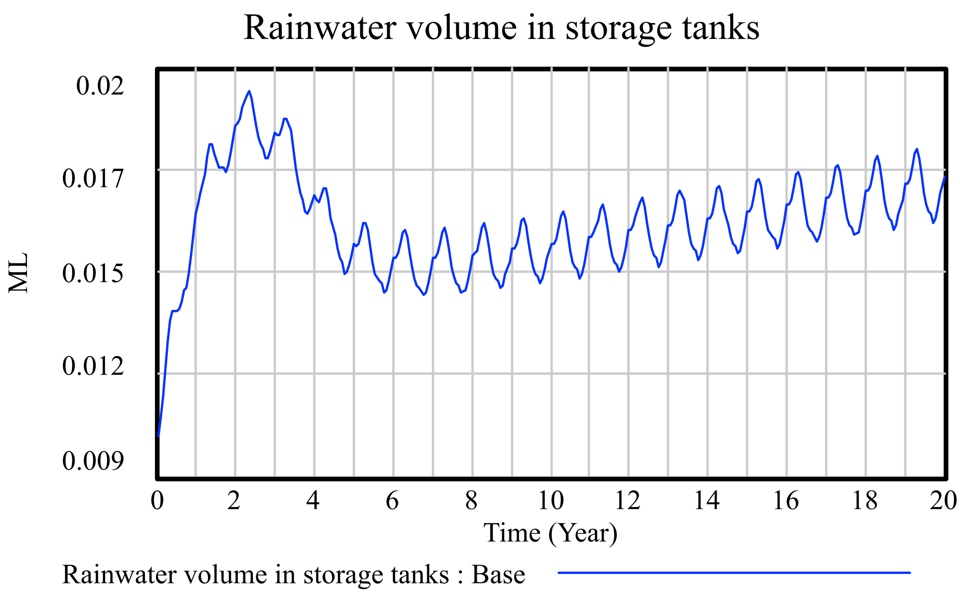

Figure 11: Base - volume of rainwater in storage tanks

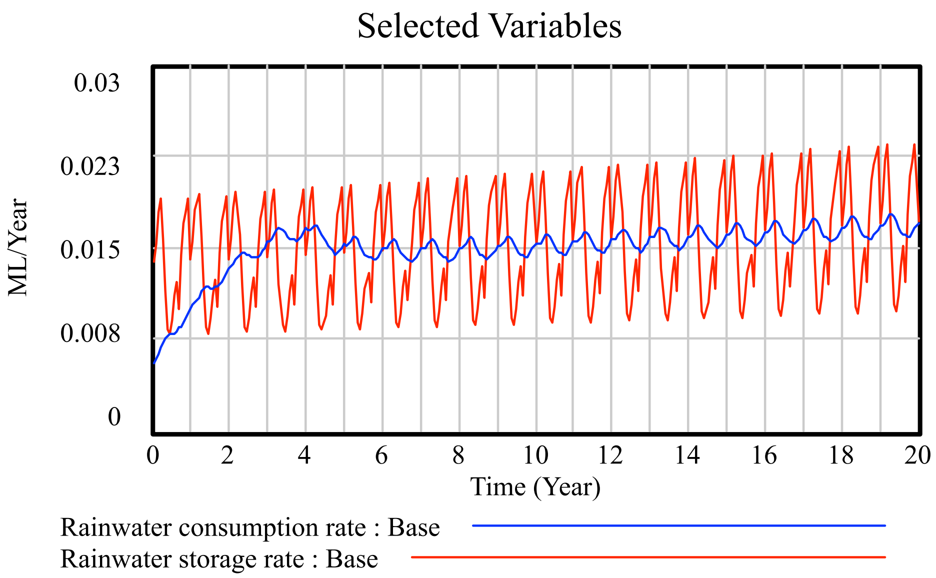

Figure 12: Base - rainwater storage against consumption rate

The next model output displayed here is the 'Water security index'. As introduced in Section 4.9, this index is computed as the 'Total water supply' over the 'total household demand'. The results displayed in Figure 13 below, indicate that the water security index never attains a value greater than 2, as per the requirement of the Department of Water Affairs, and indeed declines steadily over the simulation. In short, the simulation confirms that the growing demand for water is acting to exacerbate the problems of water service delivery of the Sundays River Valley Municipality.

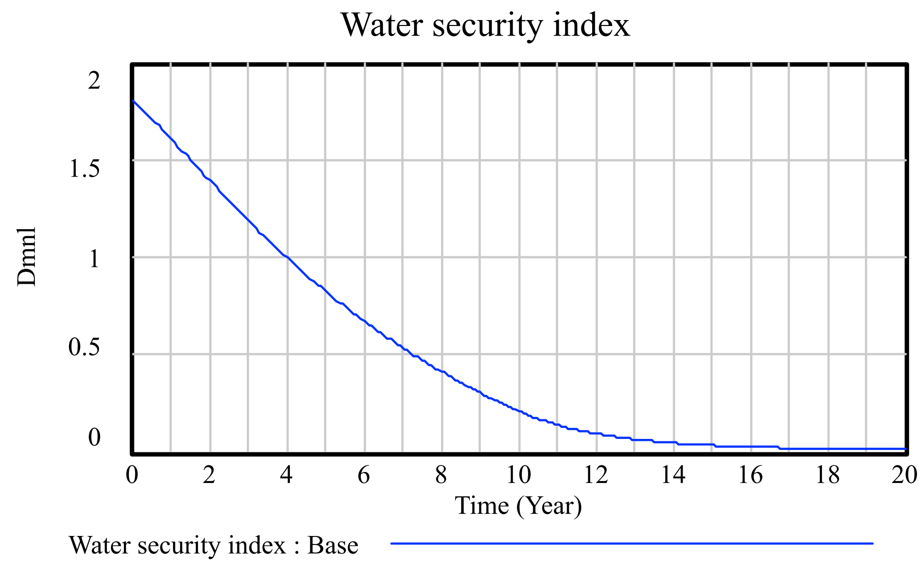

Figure 13: Base - water security index

One of the options available to the municipality is to implement a programme of reducing the consumption of potable water by connected households. The assumption behind such a 'household water conservation policy' is that the municipality could implement a programme to detect and repair household-level wastage of potable water. Preliminary results from this policy are displayed in figures 13 and 14 below. Figure 14 compares the baseline simulation with a 10% reduction in average water use per connected household (AWCH), using the potable water consumption rate (r_{pwc}) and the total household demand (*THD*).

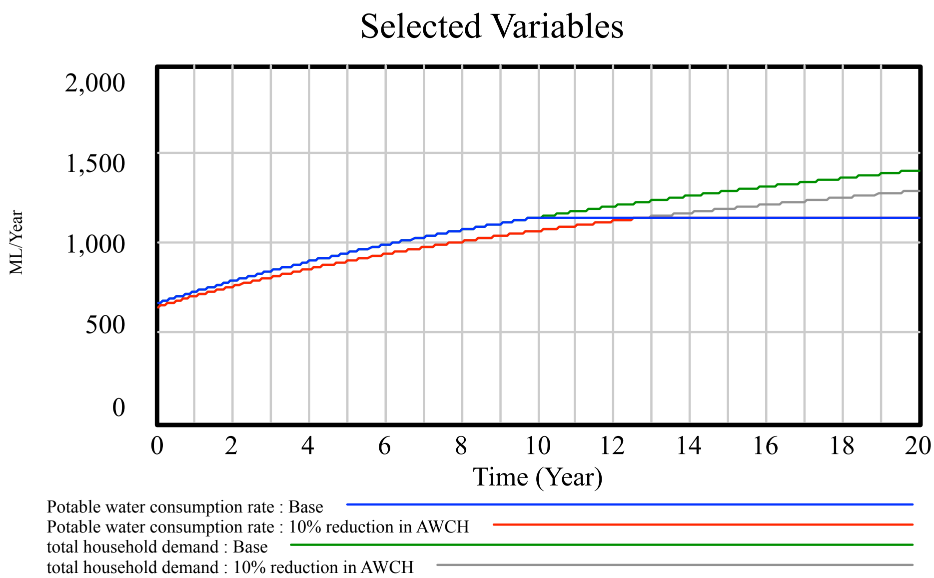

Figure 14: Potable water consumption rate + total household demand – comparison of base and 10% reduction simulation runs.

The results demonstrate that a 10% reduction allows the municipality to meet household water demand for a full two years longer than in the baseline run (with demand only exceeding available supply after Year 12 of the simulation period). However, the 10%

reduction only marginally increases the overall water security of the municipality (see Figure 15), as it fails to provide an adequate buffer in the event of a system failure or unexpected spike in demand.

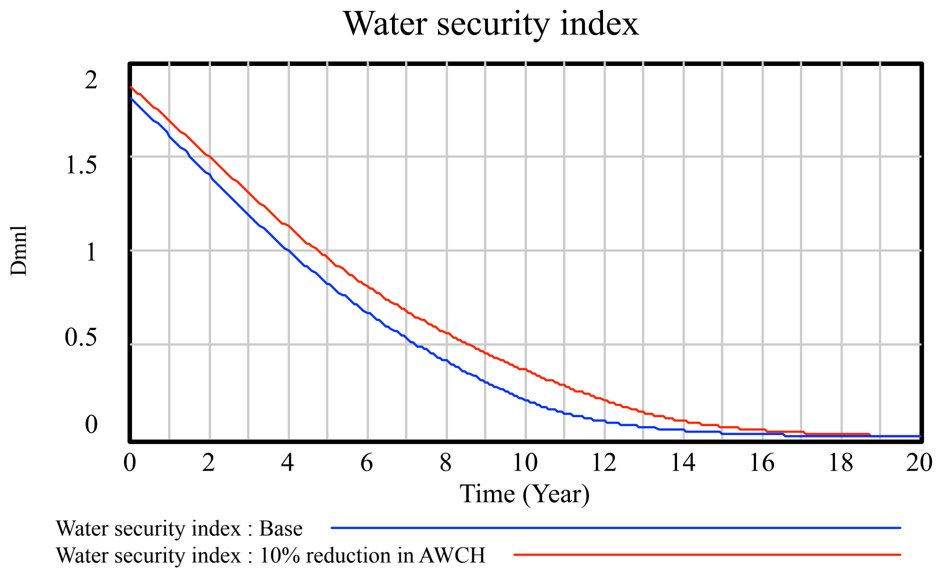

Figure 15: Water security index – comparison of base and 10% reduction simulation run

6. Conclusion

In this paper, the development of the 'Kirkwood water demand system dynamics model' (*K-DEM*) was outlined, in order to assess how the Sundays River Valley Municipality (SRVM) can reconcile its available water supply with the growing demand for potable water in Kirkwood. The key dynamics that were modelled included the impacts of households progressively receiving full water and sanitation services; the use of rainwater harvesting as an alternative form of water supply; and the possible effect of a household-level water conservation / water demand management (WC/WDM) programme. A key insight derived from the modeling approach is that whilst the municipality is perhaps unable to constrain the rate of connection, the municipality can effectively counter the impacts of rapid expansion by investing in WC/WDM measures, with possible policies including programmes to address bulk water losses and household-level water conservation. The next step in the application of the *K-DEM* model to the water management issues facing the municipality is an extensive scenario and policy analysis.

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