# A System Dynamics Model Used as a Boundary Object in an Integrative Approach to Regional Water Schemes in South Africa

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**Abstract**: System Dynamics modeling is traditionally used in a rational, advising style or, more recently in the consensus oriented Group Model Building fashion. This article explores the use of a System Dynamics model as a Boundary Object. This entails that the model should be adaptable to multiple stakeholders, robust enough to maintain identity across stakeholders, and succeed in allowing different stakeholders to work together without consensus. The model was built in an engaged approach over many different interviews and modeling session, using the case of the decision-making process to a Regional Water Scheme in South Africa. The study found the System Dynamics model that was built to be functioning as a Boundary Object amongst different groups of experts, supporting communication and the deliberative process. Further exploration of the model as Boundary Object with more stakeholders and other cases is required.

**Key words**: System Dynamics, Boundary Objects, Coastal/Estuarine Negotiation, Policy Analysis, Water Management

## 1. Introduction

System Dynamics modeling is often used to advice policymakers, for example by providing model insights on varied issues such as flu outbreak, housebreaking and burglary or rare earth materials. The focus is on quantitative modeling of the dynamic behavior in the system and experimenting with policy options and scenarios. These are examples in which the System Dynamics modeling serves research and analyzing or design and recommending activities in Policy Analysis (Mayer, Daalen, & Bots, 2004). Group Model building uses System Dynamics modeling in groups to structure problems and gain learning and consensus by elicitation and integration of mental models (Presentation Rouwette, 2013). In that case the modelling is used in mediating or clarifying Policy Analysis activities (Mayer et al., 2004). Not often however, System Dynamics is used in democratizing Policy Analysis activities (Mayer et al., 2004).

This article describes the experience of the use of a System Dynamics model in democratizing Policy Analysis activities. And share understanding and insights gained on this type of use. In the democratizing activities the model was used as a Boundary Object to function over the boundaries of different stakeholders. This paper will describe the development of a model for use as a Boundary Object and the experience and tests of the model as a Boundary Object. The specific case that is used to perform this study in is located in South Africa and deals with water allocation in periods of water scarcity due to dry spells.

First the theoretical concepts of a model as a Boundary Object will be elucidated by reviewing theories of Boundary Objects and applying that to a model being a used a Boundary Object (section

2). Then the chosen case problem together with the methods that are used in this article is presented (section 3). This will be followed by a description and specification of the System Dynamics model together (section 4). Then we will go into how the model was used as a Boundary Object, what it contributed in the Policy Analysis activities and how well the model succeeded at this (section 5). Finally discussion takes place and conclusions are drawn (section 6).

## 2. Models as Boundary Objects

Boundary Objects have been coined by Star and Griesemer (1989) in working with heterogeneous groups of stakeholders. Boundary Objects help mostly in the communication amongst groups and are recognized in general by the stakeholders, but allow the different stakeholders to adapt or have an own view on it as well.

An example of a Boundary Object is a scale model of a skyscraper that is going to be build. Persons looking at this will recognize some common features of the skyscraper, however an architect will see usability aspects, an engineer sees construction aspects and a member of the local community sees it bringing shade to their backyard.

In their article Star and Griesemer present an example of how a group of stakeholders (at the Museum of Vertebrate Zoology at the University of California, Berkeley) coped with the phenomena of working with heterogeneous groups using Boundary Object (Leigh Star & Griesemer, 1989). The Boundary Object helped in generalizing findings, so they were sensible to other groups.

The initial definition of Boundary Object is as follows: *"Boundary Objects are both adaptable to multiple viewpoints and robust enough to maintain identity across them"* (Leigh Star & Griesemer, 1989, p. 387)

More recently Star (2010) reviewed her initial contribution of the Boundary Object with an article named *This is Not a Boundary Object: Reflections on the Origin of a Concept*. In this article she reiterates what is and is not a Boundary Object. She addresses three attributes: interpretive flexibility; material/organizational structure of different types of boundary objects and the question of scale/granularity (Star, 2010). In her view:

*"Boundary Objects are a sort of arrangement that allow different groups to work together without consensus"* (Star, 2010, p. 602).

The authors also provide a visual representation of how they view a boundary object (Figure 1). It has a many-to-many structure and the several viewings (passage points) are used by different kinds of stakeholders (allies). The Boundary Objects at the top of the structure has *"... different meanings in different social worlds but their structure is common enough to more than one world to make them recognizable, a means of translation"* (Leigh Star & Griesemer, 1989, p. 393). Relating to the skyscraper example: the boundary object is the scale of the building, the allies are the architect, engineer and local community member and the passage points are their views on the building (or a blueprint, an artistic sketch etc.)

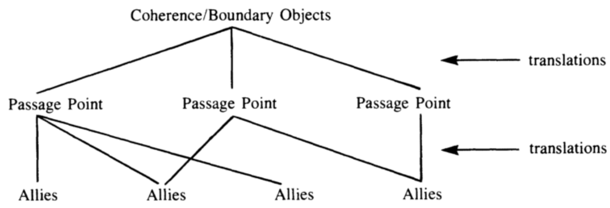


**Figure 1: The structure that Leigh Star and Griesemer propose (1989, p. 390)**

In this article a System Dynamics model is used as a Boundary Object. Therefore the Boundary Object theory should be made applicable for modeling. For this, an example of a model for water management will be used. Aspects of this model are identified similarly across different groups: graphs on the occurrence of floods or the water price over time are recognized in a similar manner across all stakeholders. This can be regarded as the Boundary Object maintaining its identity across multiple viewpoints. Looking into a model different stakeholders might focus on different aspects. A hydrologist would see infrastructural issues with capacities of pipelines, dams and reclamation works. A farmer would see seasonal patterns in the water availability to compare that with his irrigation scheme. Municipality representatives would be interested in pricing of water. These example illustrate the model being adapted to multiple viewpoints.

In this article a System Dynamics model used as a Boundary Object will be evaluated on how well the model was able to perform Boundary Object functions. From literature on Boundary Objects we identified three functions/characteristics. The model should be: adaptable to multiple stakeholders, robust enough to maintain identity across stakeholders, and succeed in allowing different stakeholders to work together without consensus.

## 3. Method choices

In this section the case that is adapted for using the System Dynamics model as a Boundary Object is presented together with the modeling approach.

The case that will be used for building the System Dynamics model as a Boundary Object will be that of determining the Regional Water Scheme for the Mossel Bay region in the Western Cape province in South Africa (Figure 2). The region of Mossel Bay is mostly dependent on freshwater in the form of river runoff that is stored in four dams (the Wolwedans, Klipheuwel, Ernest-Robertson and Hartbeeskuil Dam). The main users of water are the Mossel Bay town (~60.000 inhabitants), the ecosystem of Great Brak estuary, the agricultural sector and a large gas-to-liquids plant operated by South Africa’s national oil company: PetroSA.

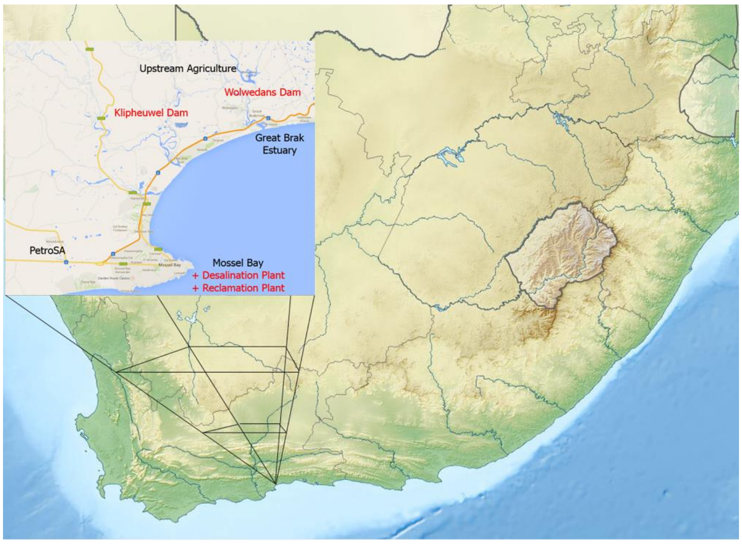


**Figure 2: Wolwedans dam in perspective to South-Africa**

During dry spells the storage provided by the dams fails to provide the full water requirement of all users and rationing is required. In recent years multiple droughts have occurred in which rationing was required (Makana, 2013; Mokhema, 2013; Mossel Bay Advertiser, 2009; Mossel Bay Municipality, 2011; PE Herald, 2011; Steyn, 2013). In the Mossel Bay Regional Water Scheme is agreed which user is supplied from what source and when rationing should be applied to what user. This would normally function well, however consultants in the field of determining these water schemes bring problems to forth. In their article hydrologists Hugh and Mallory address issues in determining Regional Water Schemes -and the operating rules embedded in them (Hughes & Mallory, 2009). Their argument is that the scarcity will increase in the coming years due to a combination of population growth, economic development and an increased variability in rainwater. Hugh and Mallory currently see inadequacies in the process for determining the Regional Water Scheme for dealing with the increased competition. They explicitly ask social and economic sciences to step in where their technical knowledge is insufficient for understanding the water system as a whole.

This issue is identified in the process for decision-making (Figure 3). A study into the Regional Water Scheme is performed, producing a proposed Regional Water Scheme which will become operational when it is ratified by the minister of Water Affairs. The problem that Hughes and Mallory indicate is in the communication between the consultant that performs the study, the diverse expert groups and the stakeholders.

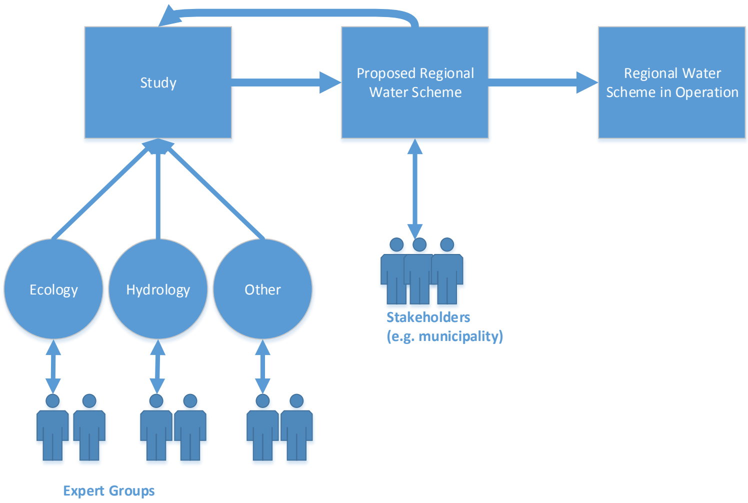


**Figure 3: Current process for determining a Regional Water Scheme**

This case fits the requirements to make use of a Boundary Object in communication or collaboration between the heterogeneous groups of experts, stakeholders and the consultant that performs the study. System Dynamics can be applied to this problem, since the question is strategic of nature and we are looking at a longer time horizon. The problem or system that will be modeled exhibits complex dynamic behavior that can be represented by feedback loops and stocks and flows with certain delays.

The modeling process will be approached by means of an engaged process with experts on the problem. The modeling will be based on interviews with one or more experts from the different groups that are sought to be combined by the model. Appendix A provides and table with an oversight of the different stakeholders and experts that have been involved in the modeling process.

Vensim is the simulator that is going to be used, because of its capabilities with System Dynamics and its accessibility. Vensim PLE can be freely downloaded for academic or evaluation purposes (http://vensim.com/download/).

## 4. A Model for Determining Regional Water Schemes in South Africa

### 4.1. Conceptual description of the model

The System Dynamics models was constructed in South Africa by means of an engaged process with experts on the different sub-models. The role of the System Dynamics modeler was to translate the knowledge that is held by the experts into a single, connected model. The sub-models that have been created are connected as is shown in Figure 4.

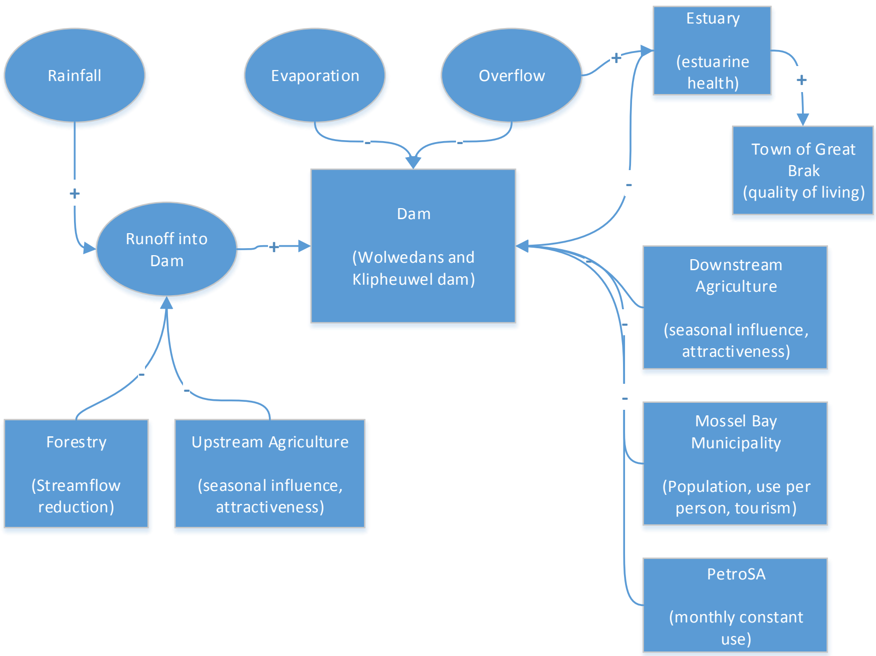


**Figure 4: Connected Sub-Models in Dam Operation Model**

## 4.2. Detailed Model Specification

The dam operation model specified for the Wolwedans Dam has multiple subsections. The seven most important subsections will be specified in detail: the Wolwedans dam subsection, the Great Brak estuary subsection, the Mossel Bay municipality subsection, the local Great Brak community subsection, the PetroSA subsection and the upstream agricultural subsection. Sections that are left out of this specification, but are found in the System Dynamics model are the Klipheuwel dam subsection and the downstream agriculture subsection. These are adaptions of the Wolwedans dam and upstream agricultural subsections and follow a structure so similar that it would be mostly a repetition of previously introduced specifications.

### The Wolwedans dam subsection

The volume of freshwater in the Wolwedans dam ($x_1$) is influenced by the runoff into the dam from the Great Brak river ($x_{11}$), the rainfall directly onto the surface of the Wolwedans Dam ($x_{12}$), evaporation from the Wolwedans Dam ($x_{13}$), overflow of the Wolwedans Dam ($x_{14}$) and extraction of water from the Wolwedans dam ($x_{15}$) for different uses downstream. This results in the following equation:

$$\frac{d}{dt}x_1 = x_{11} + x_{12} - x_{13} - x_{14} - x_{15}$$

The runoff into the dam from the Great Brak river ($x_{11}$) uses a time dependent runoff function ($runoffWDf(t)$) and is affected by the upstream use of water for agriculture ($use_{agriculture\ upstream}$) and the streamflow reduction by plants and trees ($streamfl_{forrest}$). The streamflow reduction is calculated by making a simplified streamflow reduction per square kilometer of forest and calibrating this to the data used in the RWS study (Mallory, Ballim, & Forster, 2013). The rainfall directly onto the surface of the Wolwedans Dam ($x_{12}$) is determined by a time dependent rain function $\left(rainWDf(t)\right)$which is based on hydrological data (Appendix B). The evaporation of water from the dam ($x_{13}$) is determined by a time dependent evaporation function $evapWDf(t)$. The overflow of the dam ($x_{14}$) occurs when the current volume of water in the dam ($x_1$) exceeds the capacity of the Wolwedans dam ($cap_{WD}$) and more water comes in than the sum of water extracted for use ($x_{15}$) out and evaporates ($x_{13}$) at that moment in time. The extraction of water from the Wolwedans dam ($x_{15}$) is the sum of use by the estuary ($use_{estuary}$), water used by the Mossel Bay municipality($use_{mosselbay}$), water used by PetroSA ($use_{petrosa}$) and water used by downstream irrigation ($use_{agriculture\ downstream}$).

$$x_{11} = runoffWDf(t) - use_{agriculture\ upstream} - (Surface_{forrest} * sfr_{forrest})$$
$$x_{12} = rainWDf(t)$$
$$x_{13} = evapWDf(t)$$
$$x_{14} = max(x_{11} - (x_{13} + x_{14})\ if\ x_1 > cap_{WD}\ and\ 0\ otherwise$$
$$x_{15} = use_{estuary} + use_{mosselbay} + use_{petrosa} + use_{agriculture\ downstream}$$

**The Mossel Bay municipality subsection**

The population of the Mossel Bay municipality ($x_2$) changes by the amount of births in Mossel Bay ($x_{21}$), the deaths in Mossel Bay ($x_{22}$) and the net amount of people migrating to Mossel Bay ($x_{23}$). The equation for the population of Mossel Bay would then be:

$$\frac{d}{dt} x_2 = x_{21} + x_{23} - x_{22}$$

The amount of births ($x_{21}$) and deaths ($x_{22}$) are calculated by multiplying the population of Mossel Bay ($x_2$) with the birth rate ($br_{mb}$) and the death rate ($dr_{mb}$) of Mossel Bay. The amount of people migrating to and from Mossel Bay has been put in a single net migration that is calculated by multiplying the population of Mossel Bay with a net migration rate ($mr_{mb}$).

$$x_{21} = x_2 * br_{mb}$$
$$x_{22} = x_2 * dr_{mb}$$
$$x_{23} = x_2 * mr_{mb}$$

The total number of tourists residing in Mossel Bay($x_3$) changes by the arriving of tourists in Mossel Bay ($x_{31}$) and tourists leaving Mossel Bay ($x_{32}$).

$$\frac{d}{dt} x_3 = x_{31} - x_{32}$$

The arrival of tourists in Mossel Bay ($x_{31}$) is calculated by multiplying an average number of tourists ($at_{mb}$) with a seasonally oscillating function ($touristf(t)$). The departure of tourists is dependent on the average staying time for tourists ($astt$) and the number of tourists that are currently in Mossel Bay ($x_3$).

$$x_{31} = at_{mn} * touristf(t)$$
$$x_{32} = \frac{x_3}{astt}$$

The domestic demand coming from the Mossel Bay municipality ($demand_{mb}$) is then calculated by multiplying the amount of people in Mossel Bay with a demand for water per person per month ($dpp$).

$$demand_{mb} = (x_2 + x_3) * dpp$$

**The Great Brak estuary subsection**

The Great Brak estuary subsection is based around the estuary with an indicator that represents the estuarine health ($x_4$). The health can either increase ($x_{41}$) at a certain pace, or deteriorate at a certain pace ($x_{42}$). This estuarine health is an abstract number in the case of this model. It has a range between zero and two, zero representing a dead estuary, two representing a very healthy estuary and one representing the estuary in its present state.

$$\frac{d}{dt} x_4 = x_{41} - x_{42}$$

The increase and decrease are both dependent upon the fraction of water that is supplied ($x_{43}$) and the current level of health ($x_4$). The fraction of water supplied ($x_{43}$) equals the water that is supplied ($averagesupplied_{estuary}$) as a running average over twelve months divided by the water that is required to retain health ($x_{44}$). The amount of water that is required is calculated with a function that is dependent on the current health of the ecosystem ($waterrequiredf(x_4)$). The effect of supplying enough water is larger if the estuary is further away from its maximum health ($health_{max}$). And the increase effect is spread over several months by the delay in health increase ($delay_{healthincrease}$). Analogously, for the decrease of health, supplying less water than required will make the health decrease more strongly and if the health comes closer to zero, the decrease will become less. This effect occurs over some time, the delay in health decrease ($delay_{healthdecrease}$).

$$x_{41} = \max(0, \frac{x_{43} * (health_{max} - x_4)}{delay_{healthincrease}})$$
$$x_{42} = \max(0, \frac{(1 - x_{43}) * x_4}{delay_{healthdecrease}})$$
$$x_{43} = \frac{averagesupplied_{estuary}}{x_{44}}$$
$$x_{44} = waterrequiredf(x_4)$$

**The local Great Brak community subsection**

The quality of living conditions for the people in Great Brak ($LQ_{gb}$) is included as an index in the model.

$$LQ_{gb} = \frac{x_5 + (1 - x_6) + \frac{x_4}{2}}{3}$$

The living qualities are determined by the attractiveness of Great Brak to tourists ($x_5$), the effect that a flood has on the area ($x_6$) and the health of the estuary ($x_4$). The attractiveness to tourists ($x_5$) is modeled as a stock which restores ($x_{51}$) to a certain level after it has been decreased by the effects of a low water quality ($x_{52}$) or a flood ($x_{53}$). A flood also has a direct effect on the quality of living conditions ($x_6$) this effect goes up after a flood occurred ($x_{61}$) and slowly dies out if time passes after a flood ($x_{62}$). The check to whether a flood occurs is based on the amount of water that is spilling over the dam. This is a simplification, since in reality it would depend on the water level in the estuary. There is a strong connection to the spillover and the water level of the estuary, however tide and timely breaching also play a role.

$$\frac{d}{dt} x_5 = x_{51} - x_{52} - x_{53}$$
$$\frac{d}{dt} x_6 = x_{61} - x_{62}$$
$$x_{51} = \frac{1 - x_5}{delay_{ragb}}$$
$$x_{52} = x_5 * (1 - effect_{wqt}f(x_4))$$

$$x_{53} = x_5 \; if \; 'flood = yes' \; and \; 0 \; otherwise$$
$$x_{61} = \max(0, 1 - x_6 + x_{62}) \; if \; 'flood = yes' \; and \; 0 \; otherwise$$
$$x_{62} = \frac{x_6}{duration_{flood}}$$
$$flood = yes \; if \; x_{14} > flood_{overflow}$$

**The PetroSA subsection**

The PetroSA subsection is modeled relatively simple, since the processes in the plant have not been modeled, but a constant operation, requiring a constant monthly amount of water is assumed ($demand_{petrosa}$). This demand can be met or not resulting in a certain utilization of the PetroSA plant ($x_7$). This is a running average of the fraction that the plant is in use ($operating_{petrosa}$) over a year. How much the plant is in use at a certain moment is a function of the amount of water that is supplied to the plant ($operating_{petrosa}f(x_7)$). PetroSA also uses 1.000 $\frac{m^3}{day}$ from Reverse Osmosis plant that runs on Mossel Bay effluent.

**The upstream agriculture subsection**

Agriculture is practices both upstream as well as downstream of the Wolwedans dam, however mostly upstream. It therefore is difficult to ration in practice, since it abstracts water before it is inside the dam. There is also some agriculture downstream which is included in the model. Only the upstream agriculture is specified in this thesis, since the structure is very similar.

Central in the agricultural subsection is the total area of land in use ($x_8$). This changes when new land is taken in use ($x_{81}$) or land is reduced for other uses ($x_{82}$).

$$\frac{d}{dt}x_8 = x_{81} - x_{82}$$

New land is taken in use for agriculture when there is an attractiveness for agriculture ($x_9$) and there is area available for the construction ($ta_{argi}$). A certain period is taken into account for the construction and abolishment of agricultural land ($delay_{agri}$).

$$x_{81} = \max(0, \frac{(x_9 - 1)(ta_{au} - x_8)}{delay_{agri}})$$
$$x_{82} = \max(0, \frac{(1 - x_9)(x_8)}{delay_{agri}})$$

The monthly demand that the agriculture has ($demand_{au}$) is determined by an average for water consumption of the crops that are grown ($consumption_{crops}$), together with a seasonal factor for irrigation ($irrigationf(t)$) multiplied by the amount of land on which agriculture is practiced ($x_8$). The attractiveness of agriculture upstream ($x_9$) can rise ($x_{91}$) or fall ($x_{92}$) due mostly by the amount of water that is supplied compared to the desired amount of water ($x_{91}$). The attractiveness has a ceiling ($maxattr_{au}$) and a tipping point ($tippingpointattr_{au}$) at which level of rationing it becomes unattractive for farmers to have more agricultural land. The fraction that is supplied to farmers ($fractionsupplied_{au}$) is calculated over the period of the last twelve months. The model uses the following formulas for this:

$$demand_{au} = x_8 * consumption_{crops} * irrigationf(t)$$
$$\frac{d}{dt}x_9 = x_{91} - x_{92}$$

$$x_{91} = \max(0, ((fractionsupplied_{au} - tippingpointattr_{au}) * (maxattr_{au} - x_9))$$

$$x_{92} = \max(0, ((tippingpointattr_{au} - fractionsupplied_{au}) * maxattr_{au})$$

$$fractionsupplied_{au} = \frac{\int_{t-12}^{t} demand_{au}}{\int_{t-12}^{t} use_{au}}$$

## 4.3. Variables and Uncertainties

The model variables are described, uncertainty ranges are provided and units for the variable are provided in the table below.

| Model variable | Description | Range | Units |
|---|---|---|---|
| Reduction of runoff by upstream trees etc. ($Streamfl_{forrest}$) | The amount of runoff that is reduced by forestry. Methods are available to assess this, currently the value is backwards engineered form a more extensive study (Mallory et al., 2013, pp. 4–3). | 7500 - 9500 | $\frac{m^3}{month}$ |
| Rain on Wolwedans dam ($rainWDf(t)$) | Currently not in model (see Appendix B). | - | $\frac{m^3}{month}$ |
| Evaporation from Wolwedans dam ($evapWDf(t)$) | Currently not in model (see Appendix B). In reality this should be a function of the water surface as well, however this has been kept out of the current model. | - | $\frac{m^3}{month}$ |
| Runoff into Wolwedans dam ($runoffWDf(t)$) | The runoff into the Wolwedans dam is just downstream from the quaternary catchment area K20A. The time dependent function that is used is based on simulated runoff for the period 1920 to 2010. The unit for this is m³ per unit of time (see Appendix B for more on the table functions). | 0,01-27,22 | $\frac{m^3}{month}$ |
| Capacity of the Wolwedans dam ($cap_{WD}$) | The amount of million cubic meters of water can be contained in the dam at maximum capacity. This is found in (Mallory et al., 2013, pp. 3–2) and is relatively certain. | 25,5 | $m^3$ |
| The population of the Mossel Bay municipality ($x_2$) | Information taken from the Census (Census, 2011) | 89430 | $person$ |
| Birth rate of Mossel Bay ($br_{mb}$) | *Had difficulty finding accurate values, see migration for approach in this model.* | - | $\frac{person}{person * month}$ |
| Death rate of Mossel Bay ($dr_{mb}$) | *Had difficulty finding accurate values, see migration for approach in this model.* | - | $\frac{person}{person * month}$ |
| Net migration rate Mossel Bay ($mr_{mb}$) | Since little data was found on birth, death and migration rates the growth over ten years has been used to calculate a net growth rate for the three combined (Census, 2001 & 2011). | 0,00187 | $\frac{person}{person * month}$ |
| The average staying time for tourists ($astt$) | An estimate for the average time that tourists stay on their holiday in the area. No data was found on this, so an estimate is used. | 0,10 - 1 | $month$ |
| The average amount of tourists in Mossel Bay region ($at_{mn}$) | The average amount of tourists that are staying. This value is multiplied by the seasonal impact function to get to how many tourists would normally arrive. No data was found on this, so an estimate is used. | 15.000-25.000 | $person$ |
| Average demand for water per person per month ($dpp$). | The average water demand per person in the Mossel Bay region. The basic reserve component is 25 liters per person per day (0,75 cubic meters per person per month) (DWA, 2013). The UN states 50 liter per person per day is required (1,5 cubic meters per person per month) and Germany uses 122 liter per person per day (3,6 cubic meters per person per month) (Institute Water for Africa, 2014). | 0,75 – 3,5 | $\frac{m^3}{person * month}$ |
| The surface of the forest area upstream of the Wolwedans Dam ($Surface_{forrest}$) | It is found that this is 28,8 square kilometer (Mallory et al., 2013, pp. 4–3). | 28,8 | $km^2$ |
| A streamflow reduction per square kilometer constant ($sfr_{forrest}$) | This is deducted from a deeper study into this (Mallory et al., 2013, pp. 4–3). That study used the 2006 streamflow reduction curves generated by ACRU (Smithers & Schulze, 1995). | 8622 | $\frac{m^3}{km^2 * month}$ |
| The estuarine health ($x_4$) | This in an arbitrary indicator for estuarine health. This should be validated with the ecologists so that is captures the main behavior that the estuary would exhibit given the water supplied. There should always be a translation step by experts to make sense of this value. | 0-2 | Dimensionless |
| The maximum health the estuary can have ($health_{max}$) | The maximum value for the indicator for estuarine health. | 2 | Dimensionless |
| The time over which an increase in health is spread ($delay_{healthincrease}$) | The time the estuary needs to recover its health from being without water for a certain period. This value needs to be calibrated using experts and data on the estuary. | 48 - 250 | $month$ |

| | | | |
|---|---|---|---|
| The time over which a decrease in health is spread ($delay_{healthdecrease}$) | The time the estuary will take to decrease in health when being supplied less than is required. This value needs to be calibrated using experts and data on the estuary. | 5 - 40 | $month$ |
| Recovery time of tourist opinion on flood ($delay_{ragb}$) | The time that the effects of a low water quality or flood diminishes for tourists. This is an estimate that should be validated. | 12 - 60 | $month$ |
| Duration of effect flooding ($duration_{flood}$) | The duration a flood has a negative effect on a community. This is an estimate that should be validated. | 12 | $month$ |
| Variable for flood in estuary ($flood_{overflow}$) | A flood occurs if the water level in the estuary rises. The water level is dependent on the amount of water in the estuary. In goes: overflow, water served, rainfall and (some) runoff and out goes water into the sea. In this case the variable is only measured using a certain overflow of the dam. It provides a reasonable estimation for floods. | 750.000 | $\frac{m^3}{month}$ |
| The demand of the PetroSA GTL plant ($demand_{petrosa}$) | PetroSA has an allocation of 5,6 million m3/annum from the Wolwedans Dam. This is being used fully in recent years (Mallory et al., 2013, pp. 4–2) | 460.000 | $\frac{m^3}{month}$ |
| The total amount of land available for agriculture upstream ($ta_{au}$) | Estimate – no reliable data available to me at this time. The area, consumption per square kilometer have been reversed engineered from the consumption figures. | 100.000 | $km^2$ |
| Total area of agricultural land upstream ($x_8$) | Estimate – no reliable data available to me at this time. The area, consumption per square kilometer have been reversed engineered from the consumption figures. | 10000 | $km^2$ |
| Delay to construct or abolish agricultural land ($delay_{agri}$) | Delay for farmers to respond to a change in the situation of water management. This is an estimate that needs validation. | 36-60 | $month$ |
| The average consumption of water for crops ($consumption_{crops}$) | Estimate – no reliable data available to me at this time. The area, consumption per square kilometer have been reversed engineered from the consumption figures. | 5 | $\frac{m^3}{km^2 * month}$ |
| $tippingpointattr_{au}$ | The point in which farmers really start to get appalled by the water shortages. This is an estimate that needs validation. | 0,7 - 0,9 | Dimensionless |
| $maxattr_{au}$ | The maximum value for the indicator for attractiveness of agriculture upstream. | 2 | Dimensionless |

## 5. Using the model as a Boundary Object

Figure 5 shows an example of how the model could be used as a Boundary Object to facilitate the information between the groups in the existing decision-making process. The diagram shows the interactions between the groups of experts by directly working with the model, or more specifically with the sub-model that fits their expertise. The model is represented as part of the larger study into the Regional Water Scheme that is used to translate and integrate the knowledge from the different experts groups. The interaction between the stakeholders, the study and the expert groups goes via the Boundary Object with a translation in between.

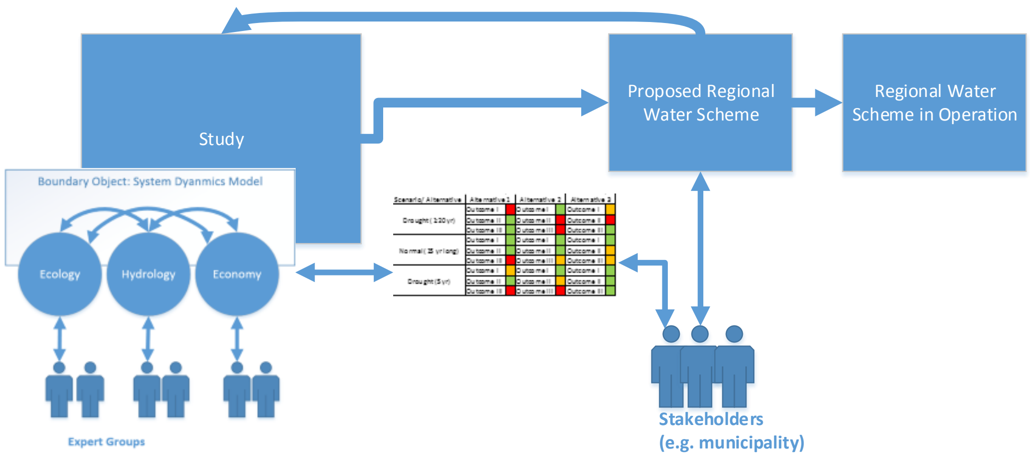


**Figure 5: Use of the Model as a Boundary Object in the Context of the Existing Process**

This translation is in the form of a scorecard, a color-coded and simplified representation of the model outcomes. Different policy alternatives are shown over different model input scenarios. Using scorecards is suggested to enable participation of stakeholders, or citizens that are unable to work with quantitative System Dynamics models. This is the case for a large share of the citizens that are affected by the Regional Water Scheme. The use of scorecards are be better explained if looking at them in the structure of Star and Griesemer (Figure 6).

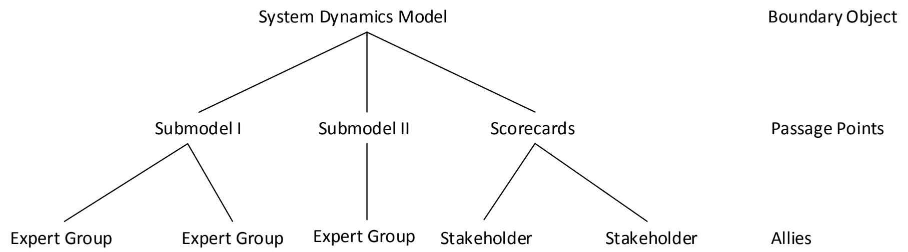


**Figure 6: Model as Boundary Object in the Structure of Star and Griesemer**

The question that needs answering now it did it function as a Boundary Object and how well did it function as a Boundary Object. We can answer these questions only for parts of the interactions with the Boundary Object, since in the current process the interactions with stakeholders by means of scorecards did not take place yet.

However the modeling process with the different expert groups was performed and validated. The modeling sessions took place decentralized at the convenience of the different groups. During these sessions two-way traffic of knowledge occurred. In this case meaning that the modeler gained knowledge on the sub-model that the expert(s) were contributing to, while at the same time the expert groups gained insights on the connections of their sub-models to other sub-models. An example being: a modeling session with an ecologist, water specialist and hydrologist on the 30th of July (Appendix A). During this session insights on the functioning of the estuary were shared by the experts towards the modeler and the experts learned more about the connections of their system of interest –the estuary– to the rest of the water system, namely tourism, floods and the Mossel Bay municipality. In this case the model was used as a Boundary Object, rather than a means to model and advice, or seek for consensus. This was confirmed during presentations and discussions. It allowed the expert groups to contribute their knowledge into the Boundary Object and gain understanding from the Boundary Object at their own convenience.

The System Dynamics model that has been created showed to be:

- Adaptable to multiple stakeholders, in the sense that it allowed for expert groups or stakeholders to contribute to the model in their own group, at their own convenience and level of understanding.
- Robust enough to maintain identity across stakeholders, since the model is simulated in an integrated fashion allowing interactions between the different sub-models.
- Succeeding in allowing different stakeholders to work together without consensus, since the non-consensus that was identified was dealt with by specifying it as the uncertainty space. This allowed the stakeholders to keep working together, agree to disagree and separate the non-consensus from the progress of the process at hand.

This means that the model as created functioned as a Boundary Object and showed to be promising for improving the decision-making process. However the Boundary Object has not been used in a decision-making process yet and the translation via scorecards to other stakeholders has not been tested yet. Therefore it remains promising and more application is required to test whether these promises hold.

## 6. Discussion and Conclusions

Literature on Boundary Objects and System Dynamics did not coincide. Little to no literature was found on using a System Dynamics model as a Boundary Object. Traditionally System Dynamics has been used in a rational, advising style and more recently in a consensus seeking Group Model Building style. Using a System Dynamics model as a Boundary Object can be seen as an application that is not oriented at just advising a client, or reaching consensus on different views, but is an application that allows different views to work together and communicate.

To stress the distinction from other modeling approaches the analogy of the scale model of the skyscraper can be used again. In that case it is clear that it is not built to advise with, nor to achieve consensus on the scale model. The scale model is meant for different groups to be allowed to communicate on the building. For one group technical aspects will come to mind. For the other group esthetical aspects will come to mind. The scale model does not have the intention for the different users to reach consensus on its construction, or its esthetics. It merely serves as a Boundary Object to facilitate communication across groups.

The experience from this study shows that a System Dynamics model can be used in this manner. In the case study it promoted the deliberative process in decision-making on a Regional Water Scheme in South Africa. It is suggested to try and use System Dynamics models as Boundary Objects more often.

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## Appendix A List of interactions with stakeholders concerned with RWS decision-making

| Date | First Name | Last Name | Field | Purpose | Type of interaction |
|---|---|---|---|---|---|
| 13-4-2014 | Richard | Meissner | International Relations | Networking | Collegial Talk |
| 13-4-2014 | Nikki | Funke | Public Policy | Networking | Collegial Talk |
| 13-4-2014 | Elliot | Moyo | Antropologist | Networking | Collegial Talk |
| 13-4-2014 | Marius | Claassen | Ecologist | Networking | Collegial Talk |
| 21-4-2014 | Karen | Nortje | Antropologist | Networking | Collegial Talk |
| 13-4-2014 | Winile | Masangane | Student | Networking | Collegial Talk |
| 22-4-2014 | Stephen | Mallory | Hydrologist | Networking | Interview |
| 28-4-2014 | Eliot | Eliot | Antropologist | Gaining insight | Excursion |
| 1-5-2014 | Stephen | Mallory | Hydrologist | Networking | Interview |
| 5-5-2014 | Stephen | Mallory | Hydrologist | Gaining insight | Interview |
| 8-4-2014 | Peter | Besnard | | Networking | Workshop Session |
| 8-4-2014 | Leon | Govender | | Networking | Workshop Session |
| 8-4-2014 | Dimov | Ilces | | Networking | Workshop Session |
| 8-4-2014 | Larry | Oellerman | | Networking | Workshop Session |
| 8-4-2014 | Andrew | Pike | Water Law | Networking | Workshop Session |
| 8-4-2014 | Vijay | Reddy | | Networking | Workshop Session |
| 8-4-2014 | Shaun | Ruggunan | | Networking | Workshop Session |
| 8-4-2014 | Mariam | Khan | | Networking | Workshop Session |
| 8-4-2014 | Ivan | Skoryk | | Networking | Workshop Session |
| 8-4-2014 | Gavin | van der Meu | | Networking | Workshop Session |
| 8-4-2014 | Vincent | Zulu | | Networking | Workshop Session |
| 8-4-2014 | Brideggete | Zwane | | Networking | Workshop Session |
| 8-4-2014 | Monoli | Mbele | | Networking | Workshop Session |
| 8-4-2014 | Suren | Singh | | Networking | Workshop Session |
| 8-4-2014 | S. | Ali | | Networking | Workshop Session |
| 9-5-2014 | Louis | Celliers | Ecologist | Gaining insight | Introduction Meeting |
| 22-5-2014 | | | System Engineering | Networking | INCOSE South Africa |
| 25-5-2014 | Kyle | Harris | Ecologist | Gaining insight | Brunch |
| 25-5-2014 | Nicole | Kranz | Water Stewardship Advisor Germany | Gaining insight | Brunch |
| 29-5-2014 | Stephen | Mallory | Hydrologist | Gaining insight | Interview |
| 2-6-2014 | Hubert | Thompson | Water Law | Gaining insight | Interview |
| 7-6-2014 | Richard | Meissner | International Relations | Gaining insight | Excursion |
| 13-6-2014 | Nick | Fourie | Government | Gaining insight and Validation | Interview / excursion |
| 19-6-2014 | Hildrene | Venter | Citizen | Gaining insight | Interview |
| 19-6-2014 | Denise | de Wet | Citizen | Gaining insight | Interview |
| 20-6-2014 | | | Wolwedans Dam visit | Gaining insight | Excursion |
| 23-6-2014 | Stephen | Mallory | Hydrologist | Modeling | Interview |
| 24-6-2014 | Pierre | de Villier | | Gaining insight | Interview |
| 24-6-2014 | Piet | Huizinga | | Gaining insight | Interview |
| 25-6-2014 | Susan | Taljaard | Water Quality | Gaining insight | Interview |
| 25-6-2014 | Lara | van Niekerk | Ecologist | Gaining insight | Interview |
| 27-6-2014 | Barry | Clark | Ecologist | Gaining insight | Interview |

| | | | | | |
|---|---|---|---|---|---|
| 27-6-2014 | Erwin | Weidemann | Government | Gaining insight | Interview |
| 30-6-2014 | Piet | Huizinga | | Modeling | Modeling Session |
| 30-6-2014 | Susan | Taljaard | Water Quality | Modeling | Modeling Session |
| 30-6-2014 | Lara | van Niekerk | Ecologist | Modeling | Modeling Session |
| 30-6-2014 | Andre | Theron | | Validation | Presentation & Discussion |
| 30-6-2014 | Bafana | Gweba | | Validation | Presentation & Discussion |
| 30-6-2014 | Cikizwa | Mbolambi | | Validation | Presentation & Discussion |
| 30-6-2014 | Hellen | Mpe | | Validation | Presentation & Discussion |
| 30-6-2014 | Christo | Rautenbach | | Validation | Presentation & Discussion |
| 30-6-2014 | Roy | van Ballegooyen | | Validation | Presentation & Discussion |
| 30-6-2014 | Marileen | Carstens | | Validation | Presentation & Discussion |
| 30-6-2014 | Janine | Cunningham | | Validation | Presentation & Discussion |
| 30-6-2014 | Susan | Taljaard | | Validation | Presentation & Discussion |
| 30-6-2014 | Lara | van Niekerk | | Validation | Presentation & Discussion |
| 2-7-2014 | Edith | Mertz | Ecologist | Gaining insight | Interview |
| 3-7-2014 | Altus | Eitner | Government | Gaining insight | Interview |
| 3-7-2014 | Dick | Naidoo | Government | Gaining insight | Interview |
| 8-7-2014 | Richard | Meissner | International Relations | Validation | Presentation & Discussion |
| 8-7-2014 | Nikki Funke | Funke | Public Policy | Validation | Presentation & Discussion |
| 8-7-2014 | Elliot | Moyo | Antropologist | Validation | Presentation & Discussion |
| 8-7-2014 | Marius | Claassen | Ecologist | Validation | Presentation & Discussion |
| 8-7-2014 | Karen | Nortje | Antropologist | Validation | Presentation & Discussion |
| 8-7-2014 | Winile | Masangane | Student | Validation | Presentation & Discussion |
| 16-7-2014 | Louiza | Duncker | Antropologist | Validation | Presentation & Discussion |
| 16-7-2014 | Zama | Nkuna | Researcher-HIE | Validation | Presentation & Discussion |
| 16-7-2014 | Ednah | Mamakwa | Candidate Researcher | Validation | Presentation & Discussion |
| 16-7-2014 | Maselanganye | Matji | Manager | Validation | Presentation & Discussion |
| 16-7-2014 | Bongi | Maposa | Researcher Wash & Public Health | Validation | Presentation & Discussion |
| 16-7-2014 | Esther | Ngorima | Researcher Water Quality | Validation | Presentation & Discussion |
| 16-7-2014 | Philip | Page | Researcher Numerical modeller | Validation | Presentation & Discussion |

## Appendix B Table functions in System Dynamics Model

This appendix the table functions that have been used in the System Dynamics model will be briefly introduced.

$runoffWDf(t)$: Table function to determine the runoff into the Wolwedans dam. This function is based on (simulated) hydrological data over a period from 1920 to 2010 (see appendix A). In Figure 7 the table function is presented as a graph. For $rainWDf(t)$ & $evapWDf(t)$ similar graphs will be used as input. However these are presently not yet made available.

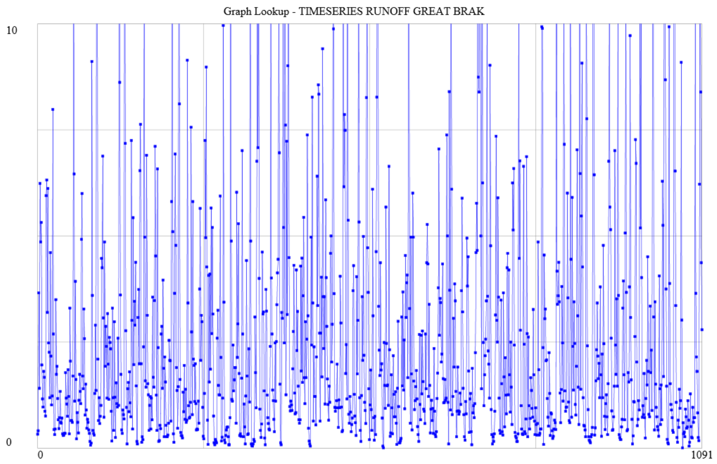


**Figure 7: Table function runoff into Wolwedans dam**

$touristf(t)$: Table function to determine the number of tourists over time. This function is added to account for the different seasons of the year regarding the number of tourists that reside in Mossel Bay. Since a large share of the water is used by tourists this is added. The function is based on a study by Soer (2005) on tourism in South Africa. In Figure 8 the table function is presented as a graph. The x-axis (time) has a maximum of 12 in which each number represents a month from January to December.

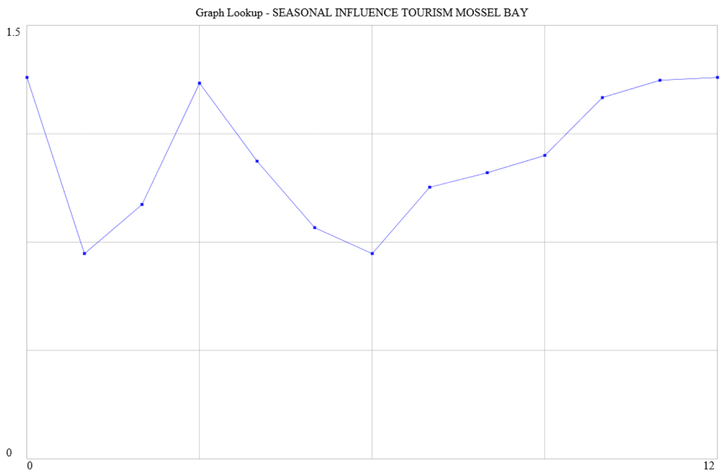


**Figure 8: Table function for tourists over time**

$waterrequiredf(x_4)$: Table function for the water required for the estuary based on the current level of health of the estuary. This is based on the expert session that was held at Stellenbosch together with personal correspondence with Jill Slinger. This function might be debatable and could be a good candidate for testing multiple table functions against each other. In Figure 9 the table function is presented in a graph. At normal health (a value of 1 on the x-axis) the requirement will be set at 800.000 cubic meters per annum. At low health this will increase to 1.100.0000 cubic meters per annum and at high health 600.000 cubic meters per annum. The assumption hereby is that a healthy estuary is less ‘thirsty’ than an unhealthy estuary is.

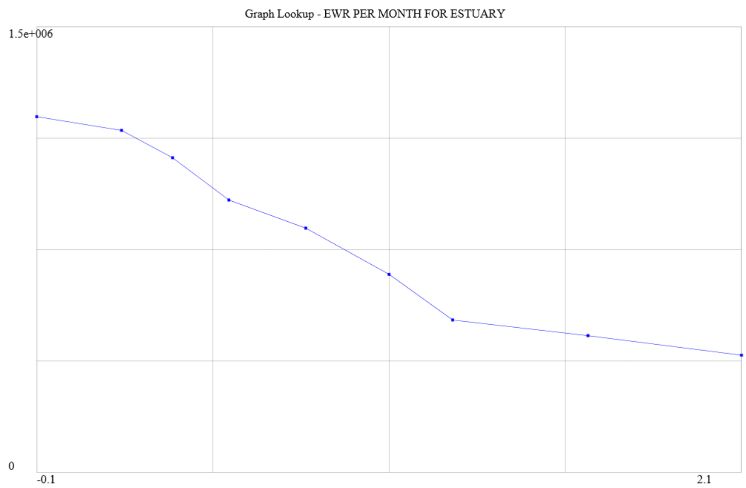


**Figure 9: Table function for water required for estuary over estuarine health**

$effect_{wqt}f(x_4)$: Table function for the effect that a low water quality in the estuary has on the attractiveness to tourists. The effect only occurs when the estuarine health gets below 1 and will especially start having an effect if it gets below 0,5. In Figure 10 the table function is presented in a graph.

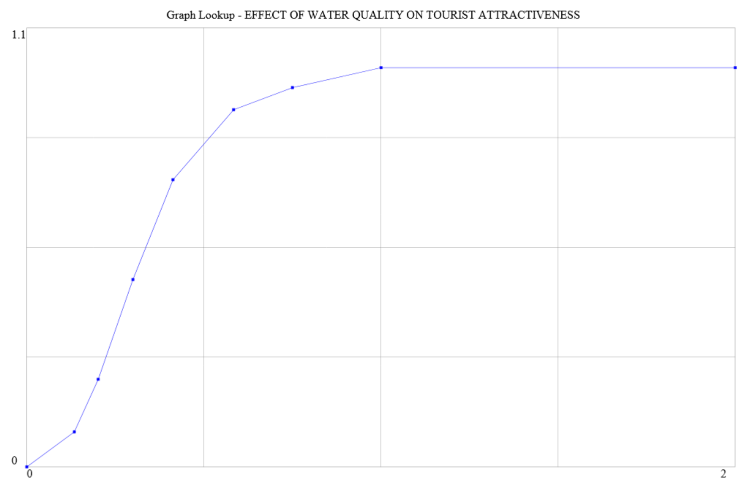


**Figure 10: Table function for the effect of water quality on the attractiveness for tourists**

$operating_{petrosa}f(x_7)$: Table function to determine the level of operation at PetroSA depending on the fraction of its demand that is being met. Since PetroSA operates three units that can be switched on or off the operating level will have three levels as well. In Figure 11 the table function is presented in a graph.

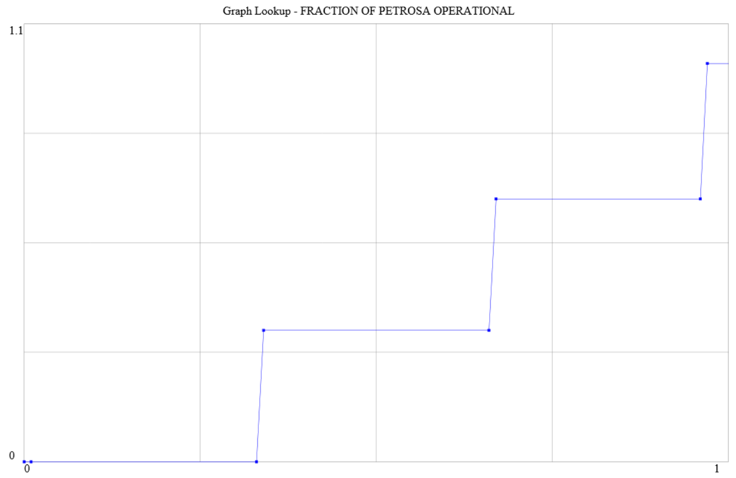


**Figure 11: Table function for the level of operating at PetroSA depending on the fraction of demand for water supplied.**

$irrigationf(t)$: Table function to account for the seasonal variation in the demand for irrigation for agriculture. At this moment this is just an estimate that should be further evaluated and validated by experts from the region.

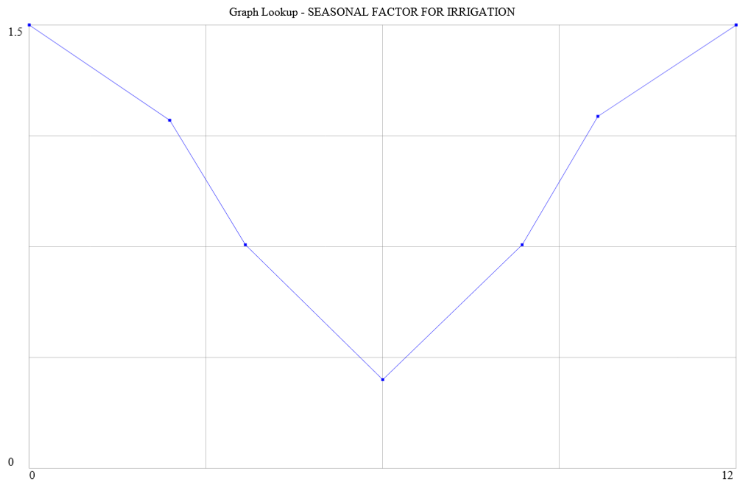


**Figure 12: Table function for the seasonal influence on irrigation water requirements**

## Appendix C Sub-models in Vensim

The following images show the structure of the model as implemented in Vensim.

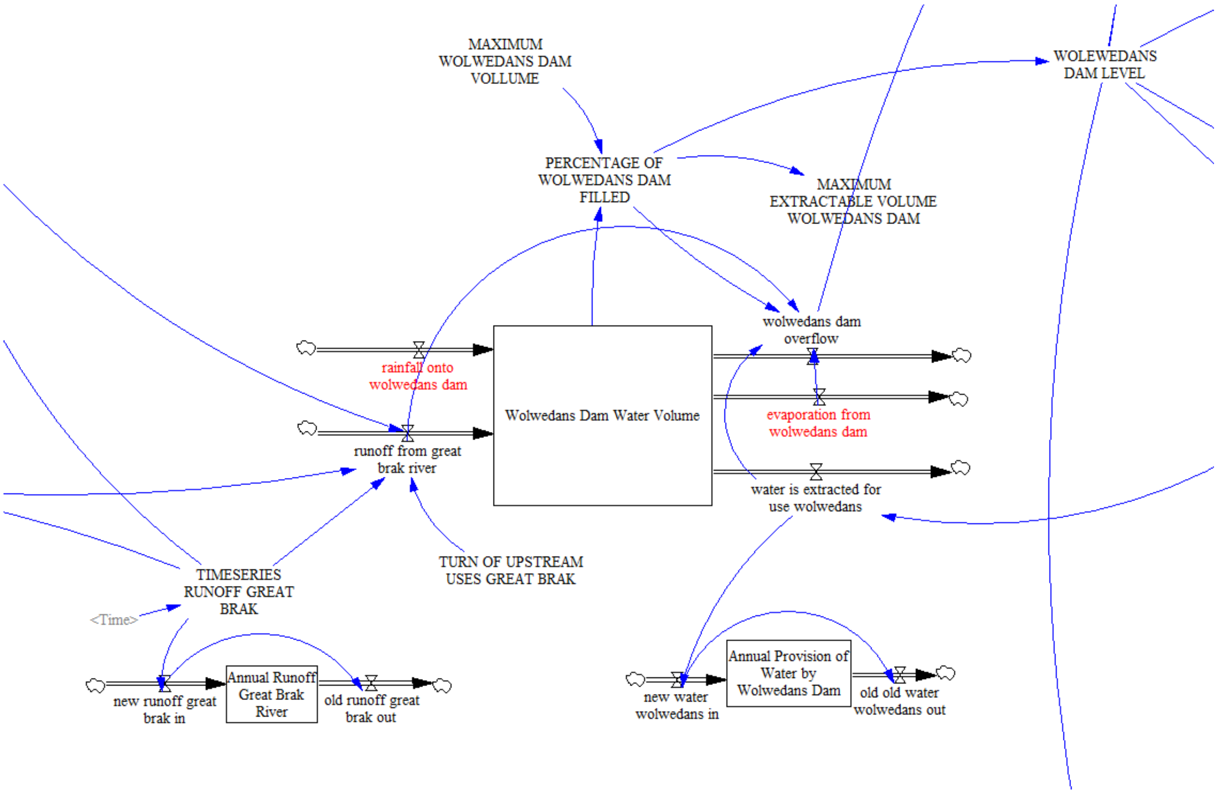


**Figure 13: Wolwedans Dam Sub-Model**

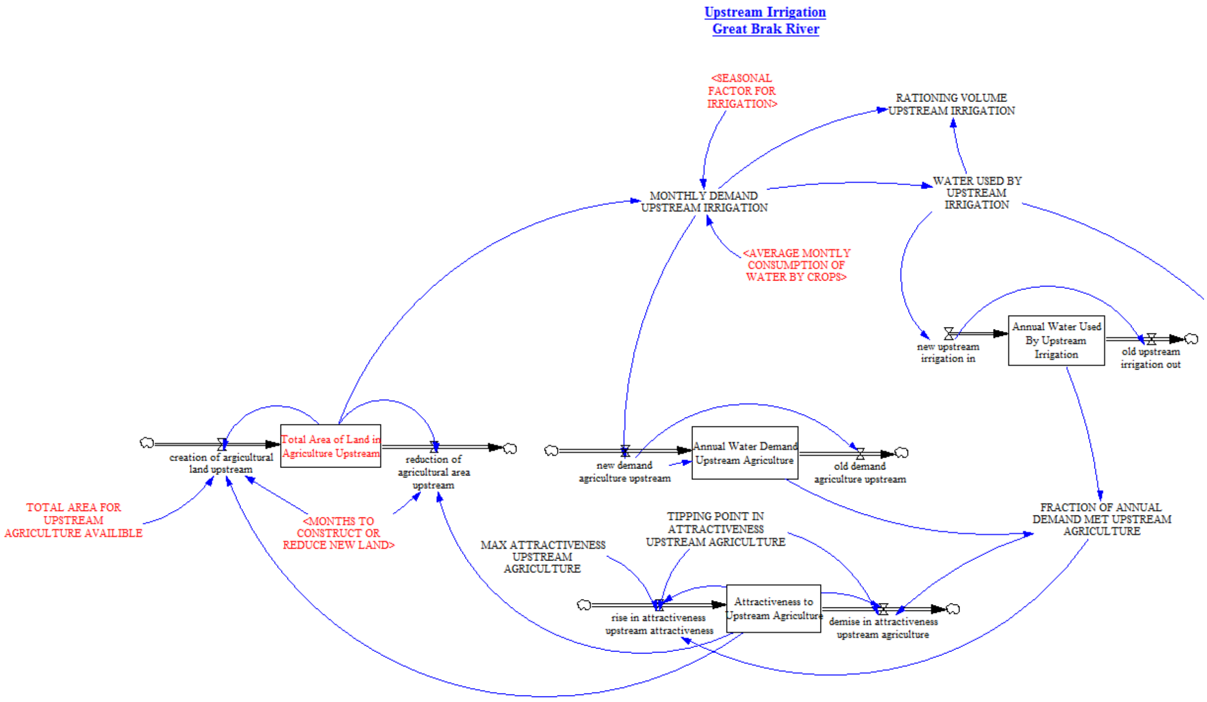


**Figure 14: Upstream Agriculture Sub-Model**

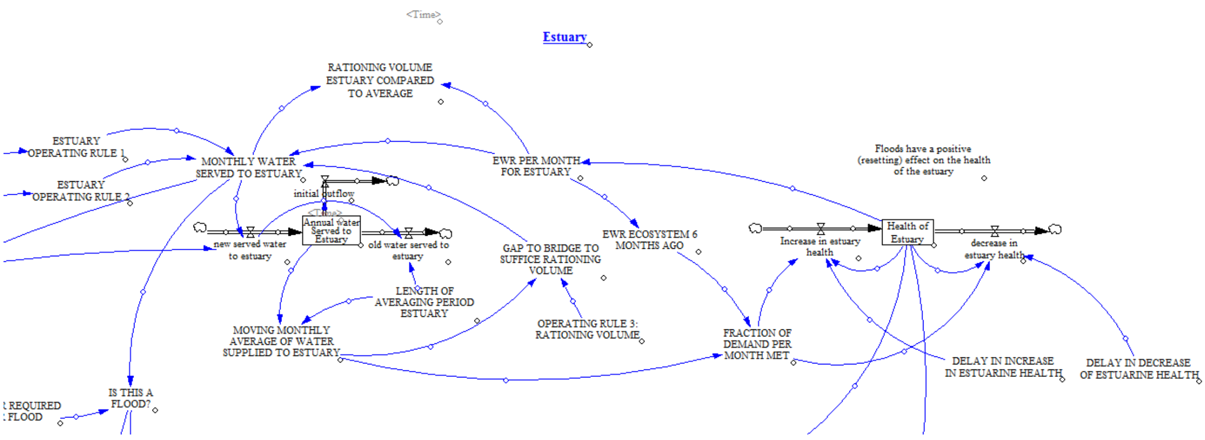


**Figure 15: Great Break Estuary Sub-Model**

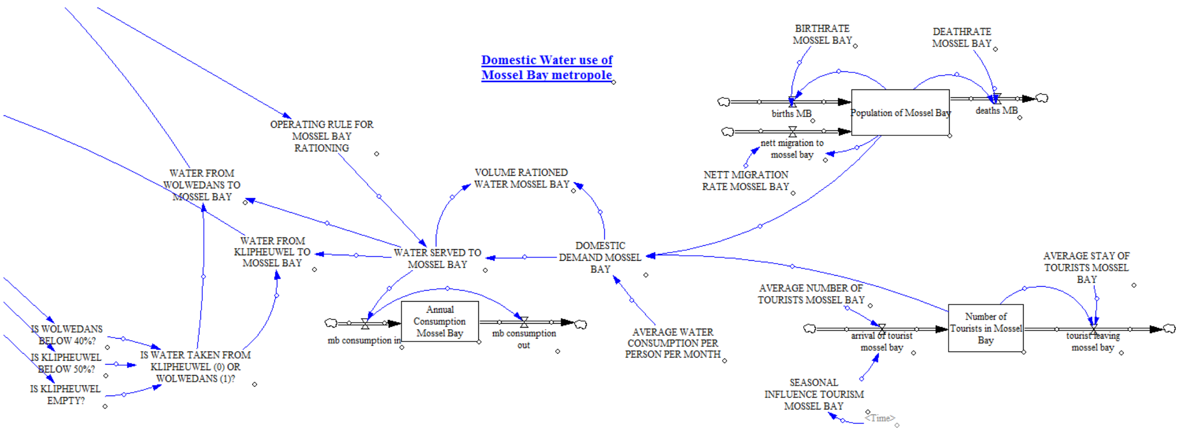


**Figure 16: Municipality of Mossel Bay Sub-Model**

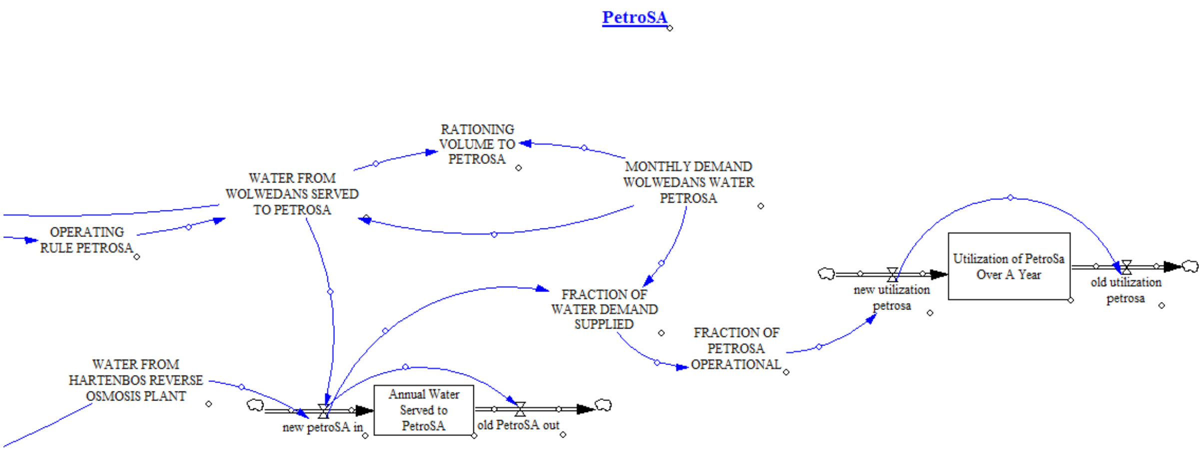


**Figure 17: PetroSA Sub-Model**

## Appendix D Preliminary Model Results

The following graphs show the preliminary model results. Since this article was mostly about the use of the model as a Boundary Object rather than the model results or validity of the model the graphs are left unexplained in this article. For more information contact the researcher.

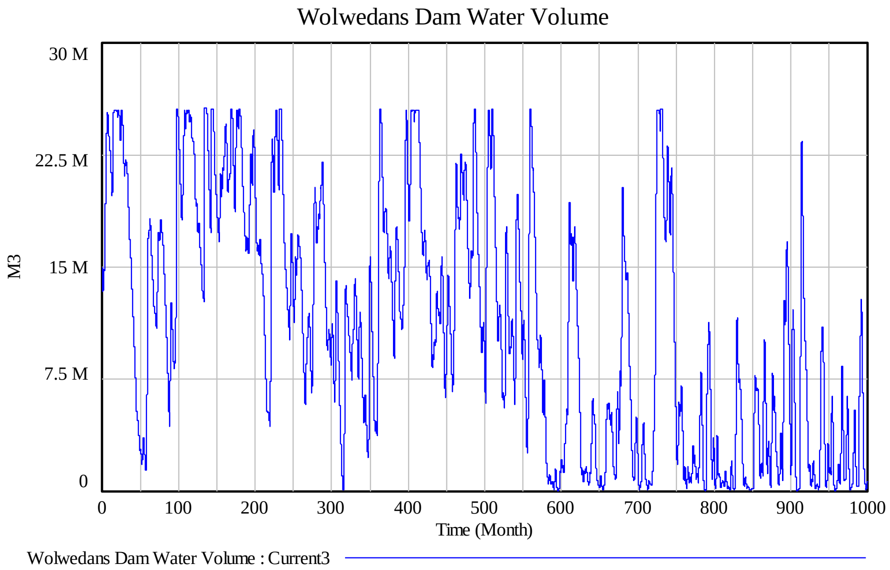


**Figure 18: Graph of a Single Run for the Wolwedans Dam Water Volume**

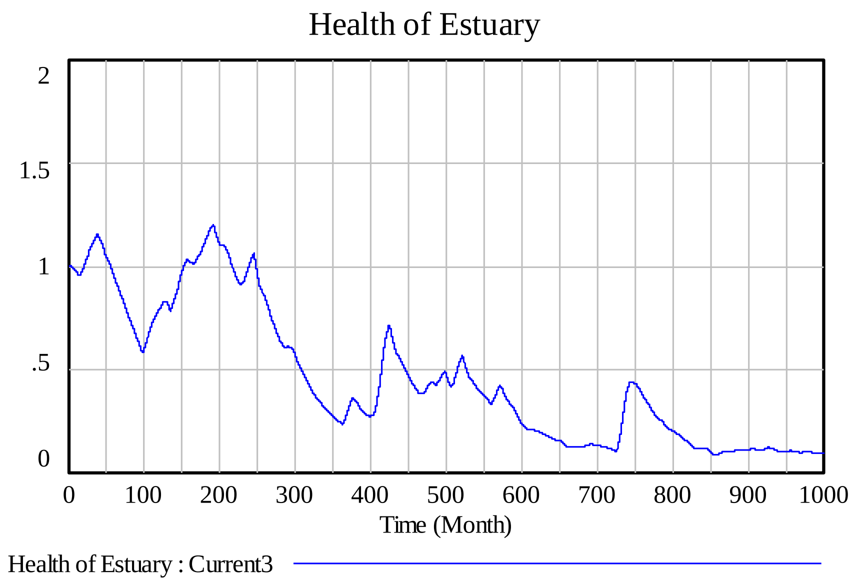


**Figure 19: Graph of a Single Run for the Great Brak Estuary Health**

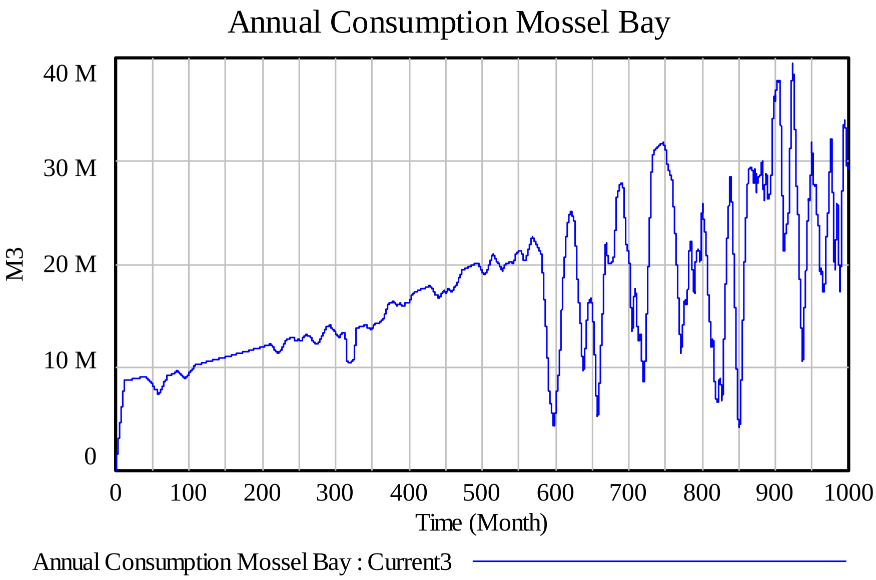


**Figure 20: Graph of a Single Run for the Consumption by the Mossel Bay Municipality**

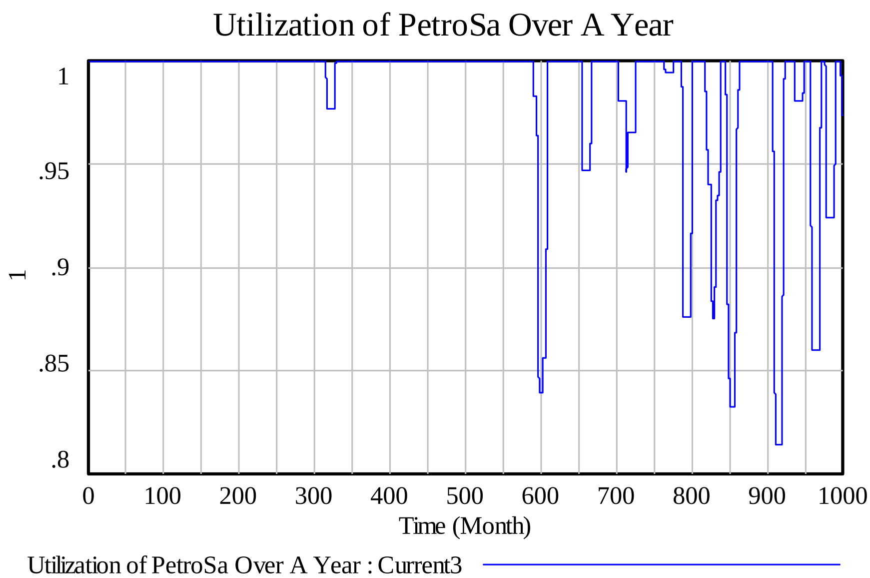


**Figure 21: Graph of a Single Run for the Utilization of PetroSA over a year**

## Appendix E Testing of integration method

A small test was performed changing the time step of the Euler integrator method for solving the differential equations. If changing the time step would cause different model behavior that would be a problem. In Figure 22 test results on a running average created in the model has been done. It did not show deviation for the time steps under 1. Therefore no clues were found that the Euler integration method is not coping with the discrete input.

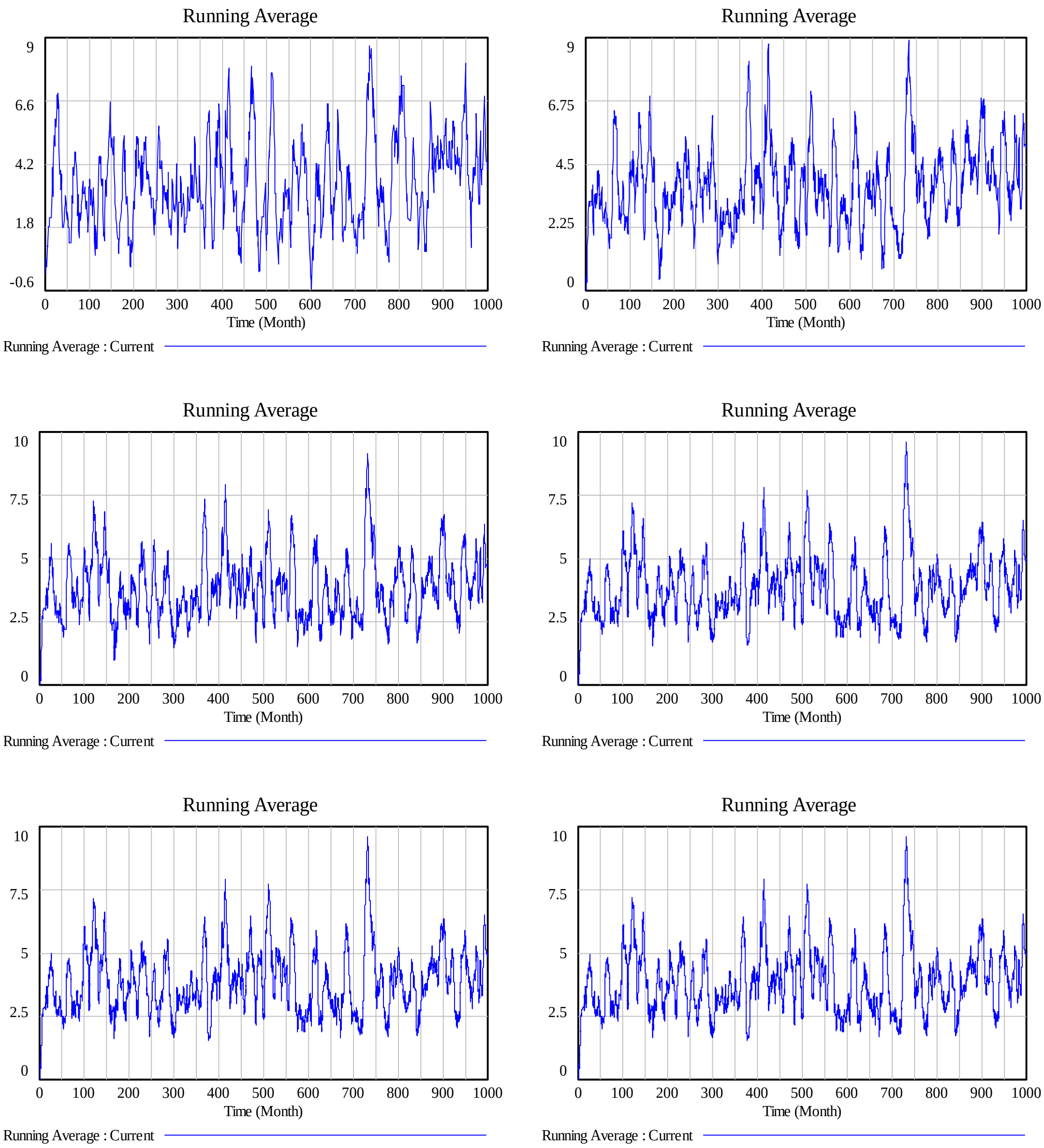


**Figure 22: Tests with different time steps**

*The time steps used from right to left, top to bottom: 1; 0,5; 0,25; 0,125; 0,0625; 0,03125; 0,015625 and 0,0078125.*