# Integrative approach to regional water schemes in South Africa

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

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**Abstract**: This article explores the use of a System Dynamics model as a boundary object in a case study regarding decision-making on water scarcity in South Africa. The model integrates expertise from the hydrological and ecological sciences with socio-economic information for a specific area, the Mossel Bay region. The model proved to be adaptable to multiple stakeholders, robust enough to maintain identity across stakeholders, and succeeded in allowing different stakeholders to work together without necessarily requiring consensus. This study supported communication between the stakeholders and enhanced the democratization of the decision-making processes by improving deliberation[1] on contentious issues. Further applications of boundary spanning activities using system dynamics modeling in other cases is recommended.

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

## 1. Introduction

South African water institutions have undergone major changes after the democratic elections in 1994 and the new National Water Act in 1998. The main pillars of the South African National Water Act of 1998 are sustainability, efficiency and equity. The water law strives to maintain a balance between utilizing and protecting the water resources. However, the current process for establishing rationing schemes is unable to deal with the increased competition over the scarce resource (Hughes & Mallory, 2009) and governmental authorities are struggling with this challenge. Influential hydrologists such as Hughes and Mallory (2009) recognize that relying on technical knowledge alone is not sufficient to address this challenge. They urge that social and economic scientists step in and help to understand and address the complex South African water system (van Waas, 2015). This paper represents a response by system dynamic modelers to this call. Seeking to work at the interface between decision-making and society, a system dynamics model is developed and used to cross both disciplinary boundaries and the policy-science interface.

The Mossel Bay region in the Western Cape province in South Africa (Figure 1) is struggling with the challenge of decision making on allocation of water during a period of scarcity. The region is mostly dependent on freshwater from river a runoff that is stored in four dams (the Wolwedans,

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[1] Besides being a representative democracy South Africa aspires to be a deliberative democracy in which deliberation is central to decision-making (Cohen, 1989). The use of a system dynamics model as a boundary object seeks to enable the deliberation.

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.

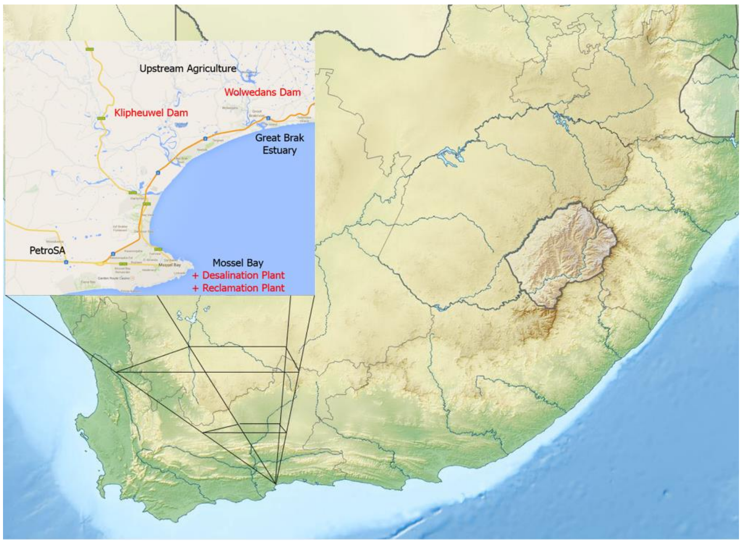

**Figure 1: Mossel Bay region in perspective to South-Africa**

During dry spells the storage provided by the dams fails to supply the full water requirement of all users and rationing is required. In recent years, multiple droughts occurred that required rationing of water (Makana, 2013; Mokhema, 2013; Mossel Bay Advertiser, 2009; Mossel Bay Municipality, 2011; PE Herald, 2011; Steyn, 2013). In Mossel Bay the regional water scheme[2] forms a contentious issue. The municipality disagrees with the trade-offs that have been made and desires a more consultative process (Mossel Bay Municipality, 2012).

In this paper, we employ the idea that system dynamics modeling can support conversations between actors (Ackermann, Anderson, Eden, & Richardson, 2010; Beall, Fiedler, Boll, & Cosens, 2011; Stave, 2003), and that system dynamics modeling facilitates policy analysis processes (Mayer, Daalen, & Bots, 2004). These attributes are combined in this research on whether a system dynamics model can successfully be used as a boundary object. A boundary object allows different people or groups to work together without requiring consensus or the same level of expertise. By using a system dynamics model in a boundary spanning manner across different disciplines and into the domain of civil society, the deliberative process is enabled. Our interest is to establish the extent to which a system dynamics model can be used to facilitate both content and process in managing a contended resource within a complex socio-ecological system.

First, the theoretical concept of using a model as a boundary object is elucidated and the chosen case study together with the methods used in this paper are presented (section 2). This is followed by a description and specification of the System Dynamics model (section 3). Then we explain how the model was used (section 4), and evaluate its use as a boundary object (section 5) before concluding the paper (section 6).

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[2] The Regional Water Scheme is the arrangement in which the rationing is determined. It contains operating rules that determine rationing based on the current water level in the dams.

## 2. Models as Boundary Objects

### 2.1. Boundary objects

Boundary objects are constructs that can enable communication and collaboration between heterogeneous groups of experts, (local) stakeholders and scientists, even in non-consensus groups.

*A scale model of a skyscraper is an example of a boundary object, because each individual will recognize it as a skyscraper, albeit from their own perspective: an architect recognizes its aesthetic aspects, an engineer focuses on construction aspects and a local community member sees it bringing shade to their backyard.*

Boundary object is a term coined by Star and Griesemer (1989) in working with heterogeneous groups of stakeholders. Three main attributes of boundary objects are: interpretive flexibility; material/organizational structure of different types of boundary objects, and the question of scale/granularity (Star, 2010). As such, *"boundary objects are a sort of arrangement that allow different groups to work together without consensus"* (Star, 2010, p. 602). Benefits of using boundary objects in heterogeneous stakeholder groups aim at collaboration and the enhancement of the sensibility to other stakeholders through the generalization of findings (Star & Griesemer, 1989; Star, 2010).

Accordingly as a boundary object, a model would need to: (i) be adaptable to multiple stakeholders, (ii) be robust enough to maintain identity across stakeholders, and (iii) succeed in allowing different stakeholders to work together without consensus (Star & Griesemer, 1989; Star, 2010). These are the three requirements for evaluating the functioning of a model as a boundary object.

### 2.2. A system dynamics model as a boundary object

The strategic nature of the water scarcity decision making problem of Mossel Bay, the long time horizon and the limited availability of (technical) data on the regional water scheme argue for a system dynamics approach. Moreover, the problem situation requires the cooperation of experts from different fields and a deliberative process with citizens from all ranks and classes. This argues for a boundary object. Accordingly, the approach of building a system dynamics model for use as a boundary object in Mossel Bay was chosen.

The modeling was undertaken in South Africa by means of an engaged process with experts from different fields, and stakeholders from the Mossel Bay region. The modeling process is depicted in its simplest form in Figure 2. The role of the System Dynamics modeler was to translate the knowledge held by the experts and stakeholders into a single, connected model and to create an implementation in Vensim (version 6.3). The knowledge and information of the experts and stakeholders was accessed through a series of interviews. These interviews were conducted with individuals, not in a group modelling process. The choice for individual interviews was made from a practical and methodological viewpoint. First, experts were located at great geographical distance from each other and second, they did not agree to meet and collaborate. Third, separate interviews also allowed more time for exploration of the individual mental models of the experts and stakeholders. An overview of the different experts and stakeholders consulted in the modeling process is provided in Appendix A.

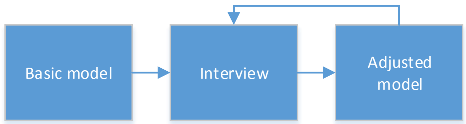


**Figure 2: Simplified modeling process**

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

The crux of the water scarcity problems in the Mossel Bay region was found to revolve around the operation of the largest storage dam in the area, the Wolwedans Dam. During this research the Dynamic Water Allocation Model (D-WAM) has been created and specified for the Wolwedans Dam. The multiple subsections are connected as shown in Figure 3. The six most important subsections of D-WAM are specified in detail: (i) the Wolwedans dam subsection, (ii) the Mossel Bay municipality subsection, (iii) the downstream Great Brak estuary subsection, (iv) the local Great Brak community subsection, (v) the PetroSA subsection, and (vi) the upstream agricultural subsection.

Two additional sub-sections, the Klipheuwel dam subsection and the downstream agriculture subsection, are adaptations of the Wolwedans dam and upstream agricultural subsections. Because their structure is so similar to the aforementioned subsections, they are not described separately. Other substructures such as forestry, evaporation and overflow are relatively small and described in Appendix B. Appendix B contains a list of the D-WAM variables together with the uncertainty space over which they can be simulated and references to the data sources used.

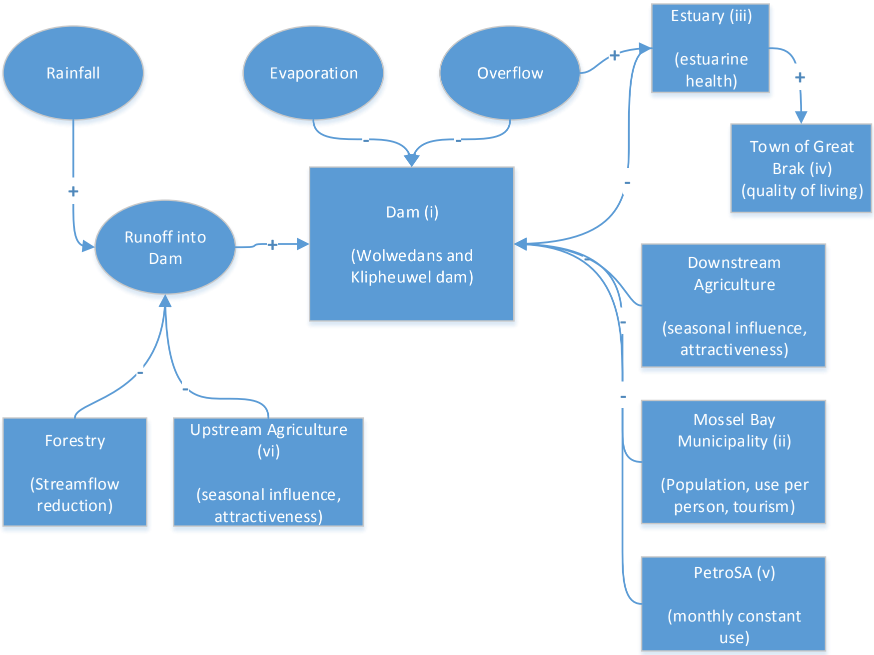


**Figure 3: Connected Sub-Models in Dam Operation Model**

### 3.1 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 (see 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 ($use_{agriculture\ downstream}$).

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

### 3.2 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 ($mr_{mb}$).

$$\begin{aligned}
x_{21} &= x_2 * br_{mb} \\
x_{22} &= x_2 * dr_{mb} \\
x_{23} &= x_2 * mr_{mb}
\end{aligned}$$

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 ($x_3$).

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

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 ($dpp$).

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

### 3.3 The downstream 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 biologically degraded '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 ($delay_{healthdecrease}$).

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

### 3.4 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.

$$\frac{d}{dt}x_5 = x_{51} - x_{52} - x_{53}$$
$$\frac{d}{dt}x_6 = x_{61} - x_{62}$$
$$x_{51} = \frac{1 - x_5}{delay_{ragb}}$$
$$x_{52} = x_5 * (1 - effect_{wqt}f(x_4))$$
$$x_{53} = x_5\ if\ 'flood = yes'\ and\ 0\ otherwise$$
$$x_{61} = \max\,(0, 1 - x_6 + x_{62})\ if\ 'flood = yes'\ and\ 0\ otherwise$$
$$x_{62} = \frac{x_6}{duration_{flood}}$$
$$flood = yes\ if\ x_{14} > flood_{overflow}$$

### 3.5 The PetroSA subsection

The PetroSA subsection is modeled relatively simple. The processes in the plant have not been modeled, but a constant operation is assumed, requiring a constant monthly amount of water ($demand_{petrosa}$). 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 $\frac{m^3}{day}$ of the Reverse Osmosis plant that runs on Mossel Bay effluent.

### 3.6 The upstream agriculture subsection

Agriculture is practiced both upstream as well as downstream of the Wolwedans dam, however mostly upstream. It therefore is difficult to ration in practice, since it extracts 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 article, 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 ($ta_{au}$). 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 ($fractionsupplied_{au}$). 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:

$$demand_{au} = x_8 * consumption_{crops} * irrigationf(t)$$

$$\frac{d}{dt}x_9 = x_{91} - x_{92}$$

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

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

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

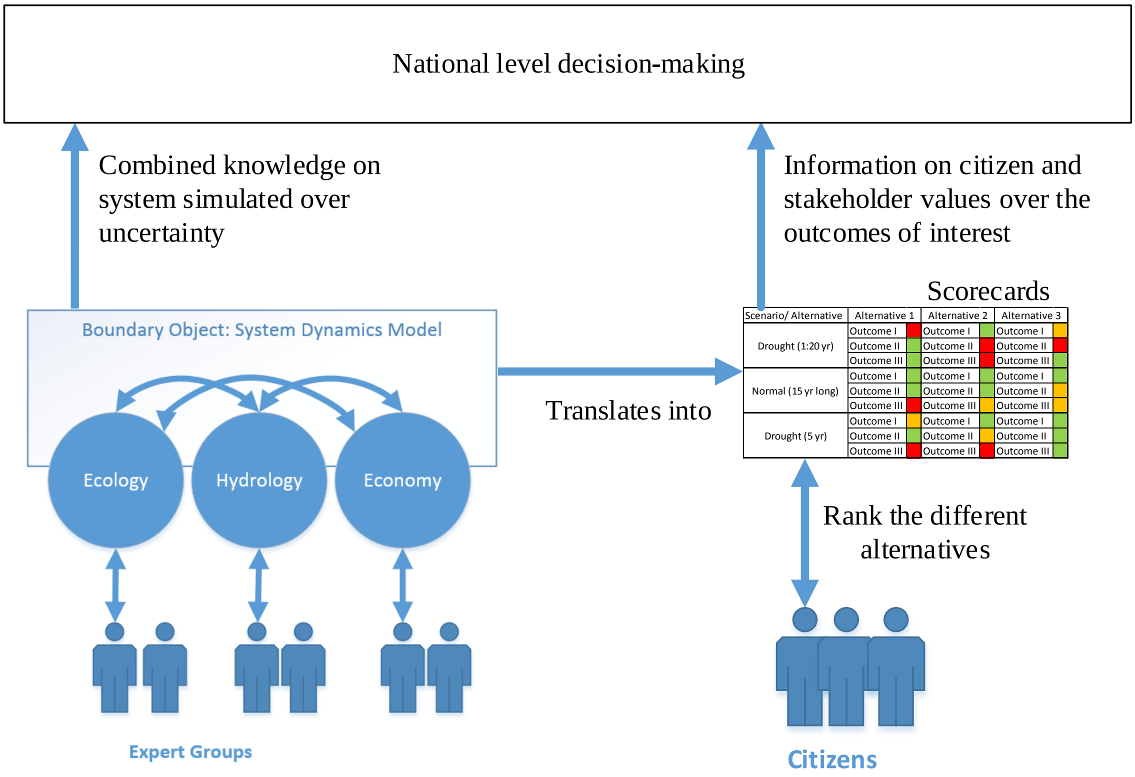
This model as a set of differential equations has been instantiated and simulated in Vensim. Appendix C shows how functions have been implemented as table functions in Vensim, appendix D shows screenshots of the different sub-models in Vensim, appendix E shows behavior of runs in graphs and finally appendix F depicts a small test to verify the Euler integration for this modeling instance.

## 4. The use of the model as a boundary object

The use of the D-WAM model in boundary spanning is depicted in Figure 4 (next page). The diagram shows that via model simulations the experts received feedback on how their sub-system influences, and is influenced by, the other sub-systems. This provoked some interesting discussions, particularly on the level of detail that needs to be included in such a boundary spanning model. For instance, initially the ecologists wished to include a great deal of detail on the response of the downstream estuary to different water allocations. Only by receiving feedback from D-WAM simulations did they come to understand that the present level of detail of the model enables a different discussion than is currently held. The new discussion focused at national level decision making on the regional water schemes. So, the system dynamics model worked as a boundary object to select and focus the discussion. This experience represents one of many examples of the experts who gained new, interdisciplinary insights by engaging with the model.

The translation of model outcomes into scorecards provides the means by which citizens can interact with the D-WAM model. The scorecards present the outcomes of interest on a colored scale. These outcomes represent the effects of different combinations of dynamic allocation alternatives and different run-off scenarios (including different water scarcity situations). The citizens can then rank the combinations according to their own preferences. Using the simplified scorecards enables citizens that are uncomfortable with quantitative models to participate in deliberations on water allocations. This may apply to many citizens that are affected by the Mossel Bay regional water scheme. By facilitating inclusive model-based decision making, the D-WAM boundary spanning process potentially addresses the concern of the Mossel Bay municipality for more deliberation.

Further, there are two types of information flowing out of this process into national level decision-making on regional water schemes. These include (i) interdisciplinary knowledge on the system that is gained from the modeling process; this could be information on the effects of the operating rules on the resilience of the ecosystem, and (ii) information on the values of citizens contained in the trade-offs they make regarding water allocations. It should be stressed that this last step is very meaningful given the South African ambition to be a *participatory* democracy.



| Scenario/ Alternative | Alternative 1 | | Alternative 2 | | Alternative 3 | |
|---|---|---|---|---|---|---|
| Drought (1:20 yr) | Outcome I | 🟥 | Outcome I | 🟩 | Outcome I | 🟧 |
| | Outcome II | 🟩 | Outcome II | 🟥 | Outcome II | 🟥 |
| | Outcome III | 🟩 | Outcome III | 🟥 | Outcome III | 🟩 |
| Normal (15 yr long) | Outcome I | 🟩 | Outcome I | 🟩 | Outcome I | 🟩 |
| | Outcome II | 🟩 | Outcome II | 🟩 | Outcome II | 🟧 |
| | Outcome III | 🟥 | Outcome III | 🟧 | Outcome III | 🟧 |
| Drought (5 yr) | Outcome I | 🟧 | Outcome I | 🟩 | Outcome I | 🟩 |
| | Outcome II | 🟩 | Outcome II | 🟧 | Outcome II | 🟩 |
| | Outcome III | 🟥 | Outcome III | 🟥 | Outcome III | 🟩 |

**Figure 4: Use of the Model as a Boundary Object in the Context of the Existing Process**

## 5. Evaluating the use of the model as a boundary object

To recap, a boundary object exhibits the following three attributes: (i) it is adaptable to multiple stakeholders, (ii) it is robust enough to maintain identity across stakeholders, and (iii) it succeeds in allowing different stakeholders to work together without consensus. The questions that now need answering are: “Did the D-WAM model function as a boundary object?” and “How well did it function as a boundary object?”

D-WAM modeling sessions with different experts took place at different geographic locations, at their convenience. This means that the experts and stakeholder were not constrained in expressing their views by the presence of others, nor did they have to agree with each other. Instead, the systems modeler travelled rather than the experts and stakeholders. By designing the consultation in this way the process of model building and interaction succeeded in allowing stakeholders to work together without forcing consensus (satisfying the third criterion above). During the sessions two-way exchanges of knowledge occurred. This meant that the modeler gained knowledge on the required structure and behavior of the sub-model to which the expert(s) were contributing. At the same time, the experts gained knowledge on the appropriate level of detail required for connection between the sub-models. The experts expressed that they learned by having to make their knowledge of dynamic interactions explicit, as the following example illustrates.

*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 with the modeler and the experts learned more about the connections of the estuary – their sub-system of interest – to tourism, of particular interest to the Mossel Bay municipality.*

When interacting with the model, different stakeholders can focus on different aspects: e.g., a hydrologist may see infrastructural issues such as the capacities of pipelines, dams and reclamation works, while a farmer may see seasonal patterns in the water availability that affect his irrigation scheme. Finally municipal representatives may be interested in water pricing for households. These examples underline the adaptability of the system dynamics model to multiple viewpoints (satisfying the first criterion).

The model also maintains its identity across multiple viewpoints (the second criterion). Some aspects of the D-WAM model are recognized universally by all the different experts and stakeholders: e.g., *flood occurrences* or *variations in the water price over time*. This can be regarded as the model maintain identity across stakeholders, despite its adaptability to multiple uses.

In summary, the Dynamic-Water Allocation Model proved to be:

- Adaptable to multiple stakeholders, in the sense that it allowed for experts and stakeholders to contribute to the model, at their own convenience and level of understanding, and gain a diversity of insights from the model.
- Robust enough to maintain identity across stakeholders, since the model is simulated in an integrated fashion allowing interactions between the different sub-models.
- Successful in allowing different stakeholders to work together without consensus. The lack of consensus on model parameters was dealt with by specifying uncertainty ranges for the parameters. This allowed the process to continue, while the participants can agree to disagree and yet keep working with the model.

This means that the D-WAM model functioned as a boundary object within this research endeavor and can act to facilitate further deliberation in the decision-making on water allocation. However, a more extensive use of the D-WAM within the Mossel Bay region would require interaction with a broader representation of stakeholders and citizen groups, rather than the experts consulted in this development and initial application phase.

Our further interest is to establish the extent to which system dynamics modelling can facilitate the integration of specialist knowledge into decision making processes in the management of contended resources within complex socio-ecological systems. By conceptualizing and using a system dynamics model as a boundary object it can serve as a catalyst for interactions that involve individual stakeholders at multiple levels from decision makers to specialists to local citizens. This integrates both the content and the processes within resource management, but needs to be validated further in practice.

## 6. Concluding Remarks

Boundary objects and System Dynamics rarely coincide in the scientific literature, and there is little research on the use of a System Dynamics model as a boundary object. Traditionally System Dynamics has been used in a rational, advisory style and more recently in a consensus-seeking Group Model Building style. The experience from this study reveals that a System Dynamics model can be useful in eliciting experts' knowledge and stakeholders' perspectives. The model can act to allow communication across disciplinary boundaries and can span the science-policy divide. In our opinion using a System Dynamics model as a boundary object can help in democratizing and improving decision-making processes in controversial policy areas. We recommend that in-depth applications are performed to test whether the promise identified in this study holds true both in a broader application within our case study and in other situations.

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

An extra character was added in the name field to prevent showing in search engines.

| Date | Name | Field | Purpose | Type of interaction |
|---|---|---|---|---|
| 13-4-2014 | R M$eissner | International Relations | Networking | Collegial Talk |
| 13-4-2014 | N F$unke | Public Policy | Networking | Collegial Talk |
| 13-4-2014 | E M$oyo | Anthropology | Networking | Collegial Talk |
| 13-4-2014 | M Cl$aassen | Ecology | Networking | Collegial Talk |
| 21-4-2014 | K Nor$tje | Anthropology | Networking | Collegial Talk |
| 13-4-2014 | W Masa$ngane | Student | Networking | Collegial Talk |
| 22-4-2014 | S Mallo$ry | Hydrology | Networking | Interview |
| 28-4-2014 | E Eli$ot | Anthropology | Gaining insight | Excursion |
| 1-5-2014 | S Mal$lory | Hydrology | Networking | Interview |
| 5-5-2014 | S Mallo$ry | Hydrology | Gaining insight | Interview |
| 8-4-2014 | P Besnar$d |  | Networking | Workshop Session |
| 8-4-2014 | L Gov$ender |  | Networking | Workshop Session |
| 8-4-2014 | D Ilc$es |  | Networking | Workshop Session |
| 8-4-2014 | L Oell$erman |  | Networking | Workshop Session |
| 8-4-2014 | A Pi$ke | Water Law | Networking | Workshop Session |
| 8-4-2014 | V Re$ddy |  | Networking | Workshop Session |
| 8-4-2014 | S Rug$gunan |  | Networking | Workshop Session |
| 8-4-2014 | M K$han |  | Networking | Workshop Session |
| 8-4-2014 | I Sk$oryk |  | Networking | Workshop Session |
| 8-4-2014 | G van der $Meu |  | Networking | Workshop Session |
| 8-4-2014 | V Zu$lu |  | Networking | Workshop Session |
| 8-4-2014 | B Zwa$ne |  | Networking | Workshop Session |
| 8-4-2014 | M Mb$ele |  | Networking | Workshop Session |
| 8-4-2014 | S Si$ngh |  | Networking | Workshop Session |
| 8-4-2014 | S A$li |  | Networking | Workshop Session |
| 9-5-2014 | L Ce$lliers | Ecology | Gaining insight | Introduction Meeting |
| 25-5-2014 | K Har$ris | Ecology | Gaining insight | Brunch |
| 25-5-2014 | N Kra$nz | Water Stewardship Germany | Gaining insight | Brunch |
| 29-5-2014 | S Mall$ory | Hydrology | Gaining insight | Interview |
| 2-6-2014 | H Thom$pson | Water Law | Gaining insight | Interview |
| 7-6-2014 | R Meis$sner | International Relations | Gaining insight | Excursion |
| 13-6-2014 | N Fou$rie | Government | Gaining insight and Validation | Interview / excursion |
| 19-6-2014 | H Ven$ter | Citizen of Great Brak river | Gaining insight | Interview |
| 19-6-2014 | D de W$et | Citizen of Great Brak river | Gaining insight | Interview |
| 23-6-2014 | S Mallo$ry | Hydrology | Modeling | Interview |
| 24-6-2014 | P de Vill$ier | Coastal science & management | Gaining insight | Interview |
| 24-6-2014 | P Huizin$ga | Coastal engineering | Gaining insight | Interview |
| 25-6-2014 | S Taljaa$rd | Water Quality: Estuary and Marine | Gaining insight | Interview |
| 25-6-2014 | L van Nie$kerk | Ecology | Gaining insight | Interview |
| 27-6-2014 | B Clar$k | Ecology | Gaining insight | Interview |

| | | | | |
|---|---|---|---|---|
| 27-6-2014 | E Weid$emann | Government | Gaining insight | Interview |
| 30-6-2014 | P Huizin$ga | Coastal engineering | Modeling | Modeling Session |
| 30-6-2014 | S Talja$ard | Water Quality: Estuary and Marine | Modeling | Modeling Session |
| 30-6-2014 | L van N$iekerk | Ecologist | Modeling | Modeling Session |
| 30-6-2014 | A Ther$on | Coastal engineering | Validation | Presentation & Discussion |
| 30-6-2014 | B Gwe$ba | | Validation | Presentation & Discussion |
| 30-6-2014 | C Mbo$lambi | | Validation | Presentation & Discussion |
| 30-6-2014 | H Mp$e | | Validation | Presentation & Discussion |
| 30-6-2014 | C Raut$enbach | Hydrodynamic modelling | Validation | Presentation & Discussion |
| 30-6-2014 | R van B$allegooyen | | Validation | Presentation & Discussion |
| 30-6-2014 | M Carsten$s | | Validation | Presentation & Discussion |
| 30-6-2014 | J Cunni$ngham | | Validation | Presentation & Discussion |
| 30-6-2014 | S Taljaa$rd | | Validation | Presentation & Discussion |
| 30-6-2014 | L van N$iekerk | | Validation | Presentation & Discussion |
| 2-7-2014 | E Mer$tz | Ecology | Gaining insight | Interview |
| 3-7-2014 | A Eitn$er | Government | Gaining insight | Interview |
| 3-7-2014 | D Nai$doo | Government | Gaining insight | Interview |
| 8-7-2014 | R Me$issner | International Relations | Validation | Presentation & Discussion |
| 8-7-2014 | N Fun$ke | Public Policy | Validation | Presentation & Discussion |
| 8-7-2014 | El Mo$yo | Anthropology | Validation | Presentation & Discussion |
| 8-7-2014 | M Cla$assen | Ecology | Validation | Presentation & Discussion |
| 8-7-2014 | K Nort$tje | Anthropology | Validation | Presentation & Discussion |
| 8-7-2014 | W Mas$angane | Student | Validation | Presentation & Discussion |
| 16-7-2014 | L Dunc$ker | Anthropology | Validation | Presentation & Discussion |
| 16-7-2014 | Z Nku$na | Researcher-HIE | Validation | Presentation & Discussion |
| 16-7-2014 | E Mam$akwa | Candidate Researcher | Validation | Presentation & Discussion |
| 16-7-2014 | M Mat$ji | Manager | Validation | Presentation & Discussion |
| 16-7-2014 | B Map$osa | Researcher Wash & Public Health | Validation | Presentation & Discussion |
| 16-7-2014 | E Ngori$ma | Researcher Water Quality | Validation | Presentation & Discussion |
| 16-7-2014 | P Pa$ge | Researcher Numerical modeler | Validation | Presentation & Discussion |

# Appendix B 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. In reality this should be a function of the water surface as well, however this has been kept out of the current model. South Africa does have rainfall data for the dams available. (see appendix C) | - | $\frac{m^3}{month}$ |
| Evaporation from Wolwedans dam ($evapWDf(t)$) | Currently not in model. In reality this should be a function of the water surface as well, however this has been kept out of the current model. South Africa does have evaporation models for the dams available. (see appendix C) | - | $\frac{m^3}{month}$ |
| 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 $m^3$ per unit of time (see 0 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 ($at_{mb}$) | 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 |

## Appendix C Table functions in System Dynamics Model

In 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. In Figure 5 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. In the current model therefore is assumed that rainfall and evaporation cancel each other out. This is true over the span of a year, however can make a difference on a monthly timespan.

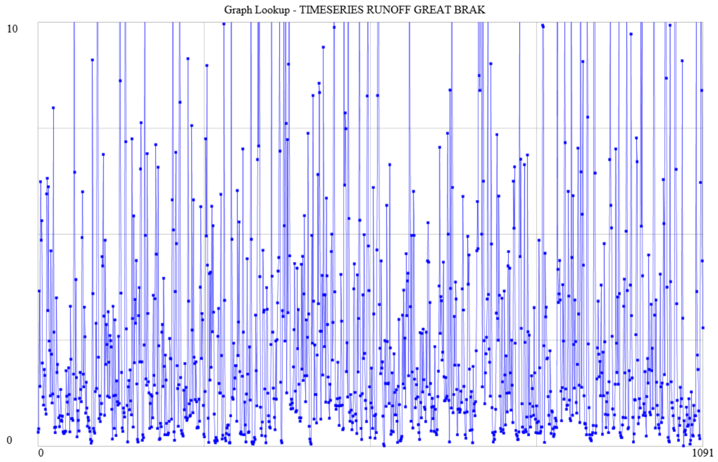

**Figure 5: Table function runoff into Wolwedans dam**

$touristf(t)$: 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 statistical study on tourism in South Africa (Lehohla, 2013, p. 13). In Figure 6 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.

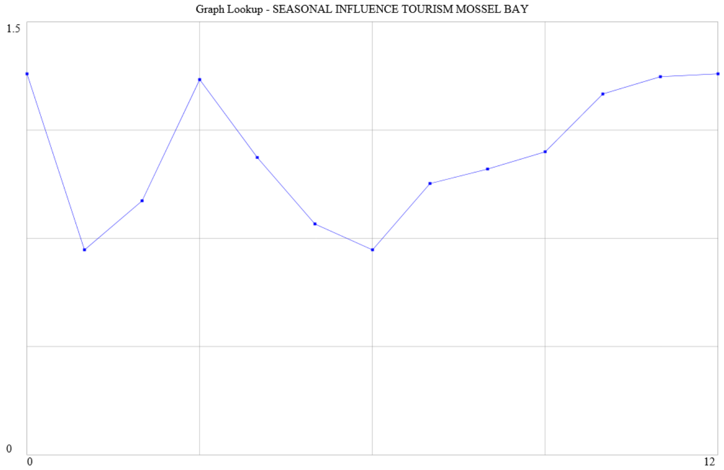

**Figure 6: Table function for tourists over time**

$waterrequiredf(x_4)$: 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 on 30-06-2014 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 7 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.

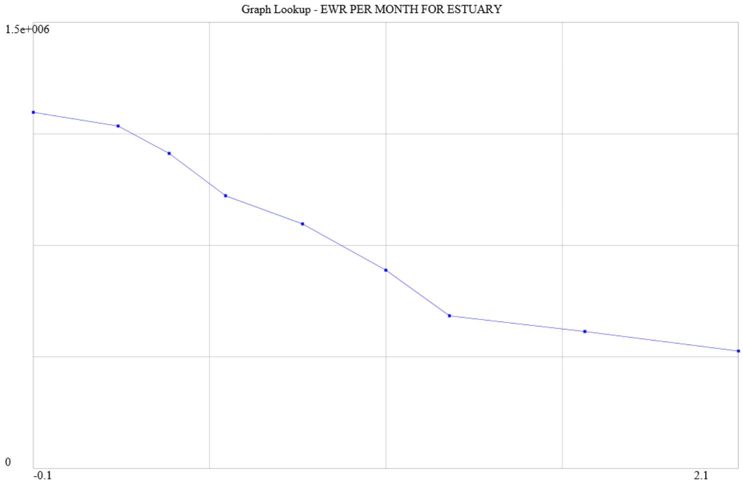

**Figure 7: Table function for water required for estuary over estuarine health**

$effect_{wqt}f(x_4)$: 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 8 the table function is presented in a graph.

**Figure 8: 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 9 the table function is presented in a graph.

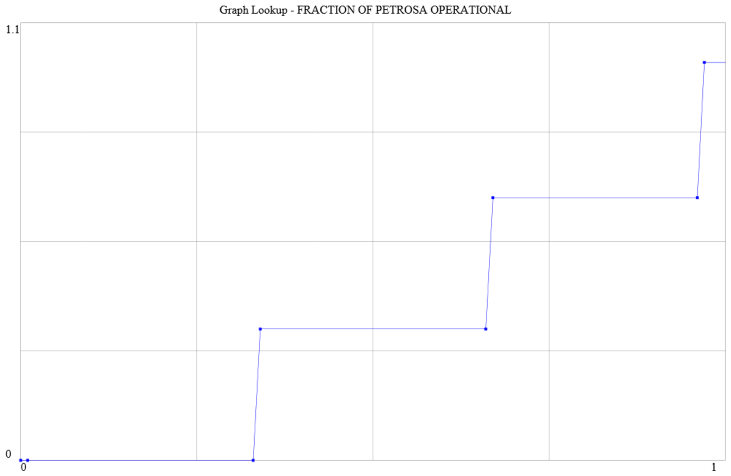

**Figure 9: Table function for the level of operating at PetroSA depending on the fraction of demand for water supplied.**

$irrigationf(t)$: 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.

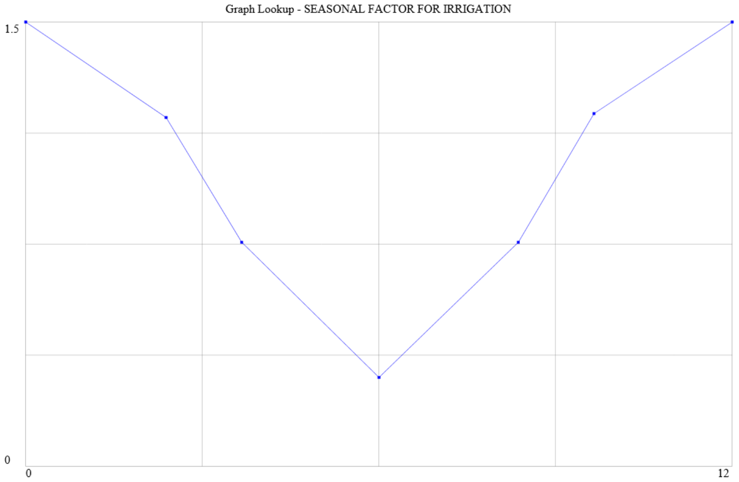

**Figure 10: Table function for the seasonal influence on irrigation water requirements**

## Appendix D Sub-models in Vensim

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

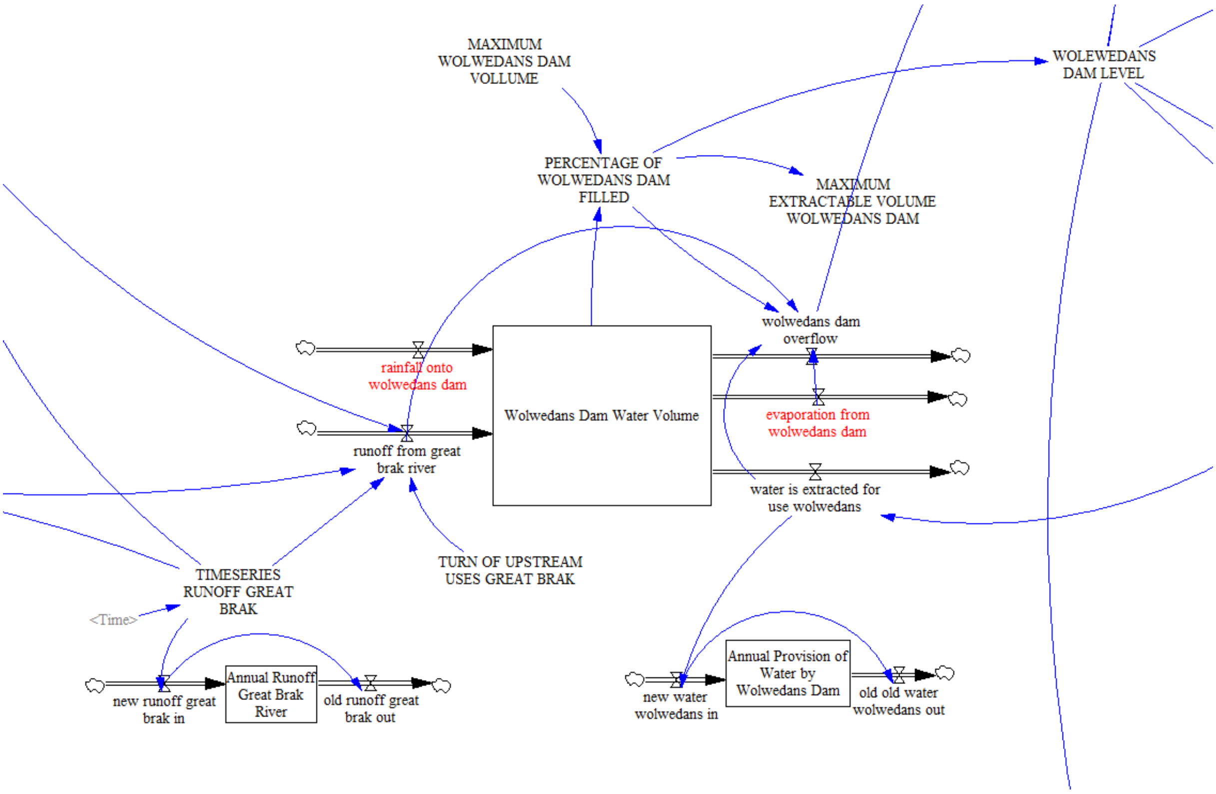

Figure 11: Wolwedans Dam Sub-Model

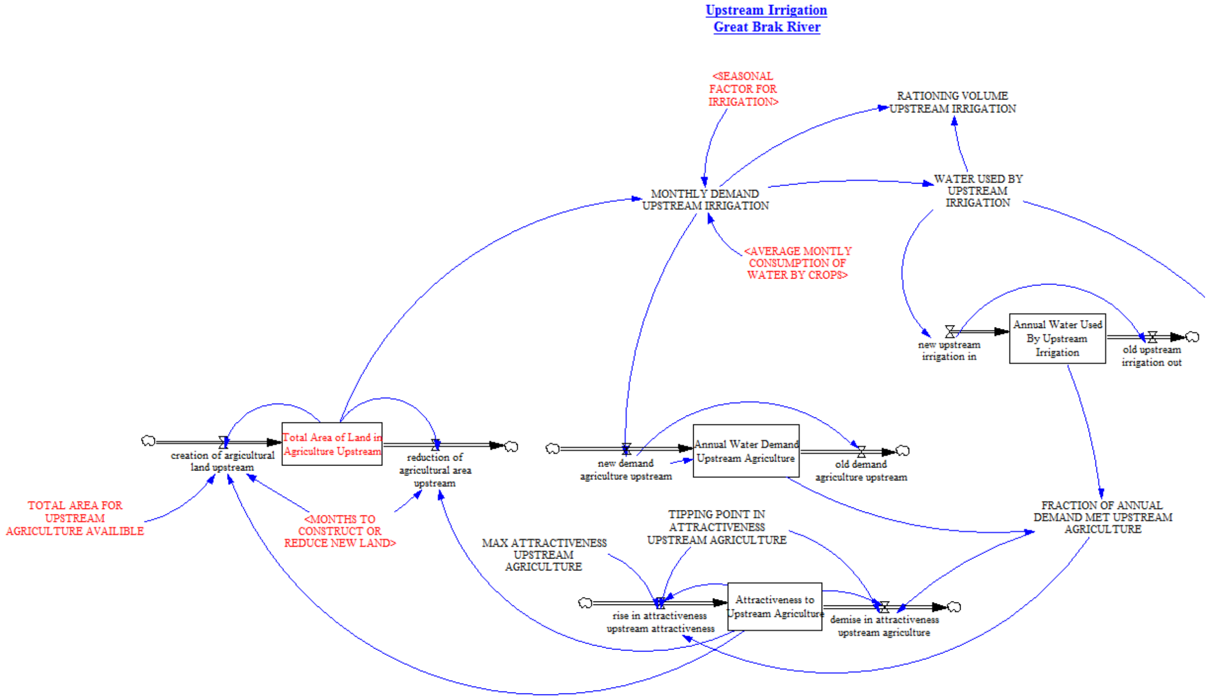

Figure 12: Upstream Agriculture Sub-Model

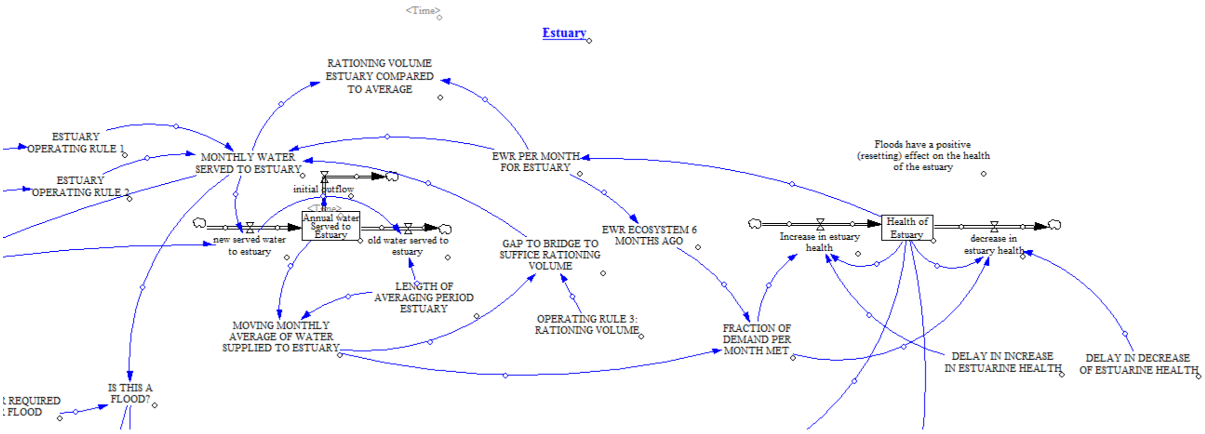

**Figure 13: Great Break Estuary Sub-Model**

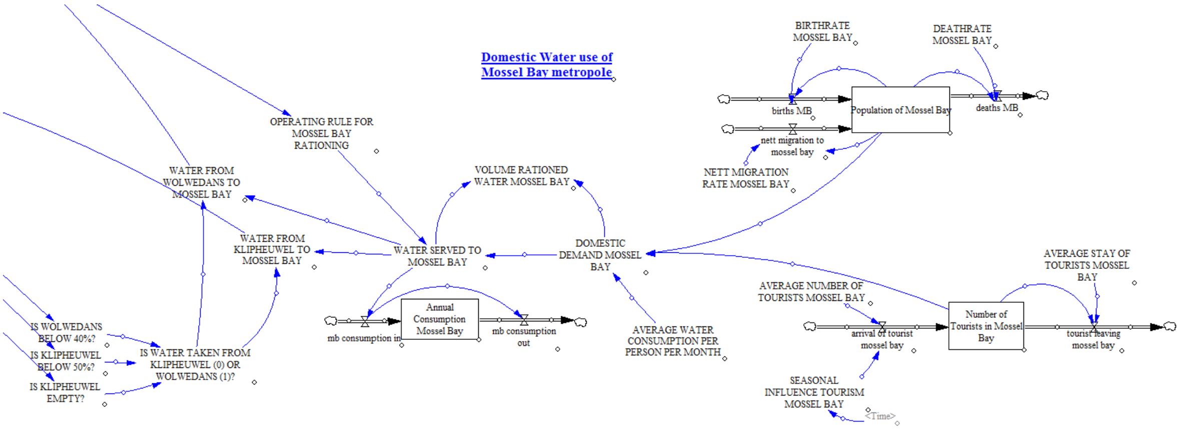

**Figure 14: Municipality of Mossel Bay Sub-Model**

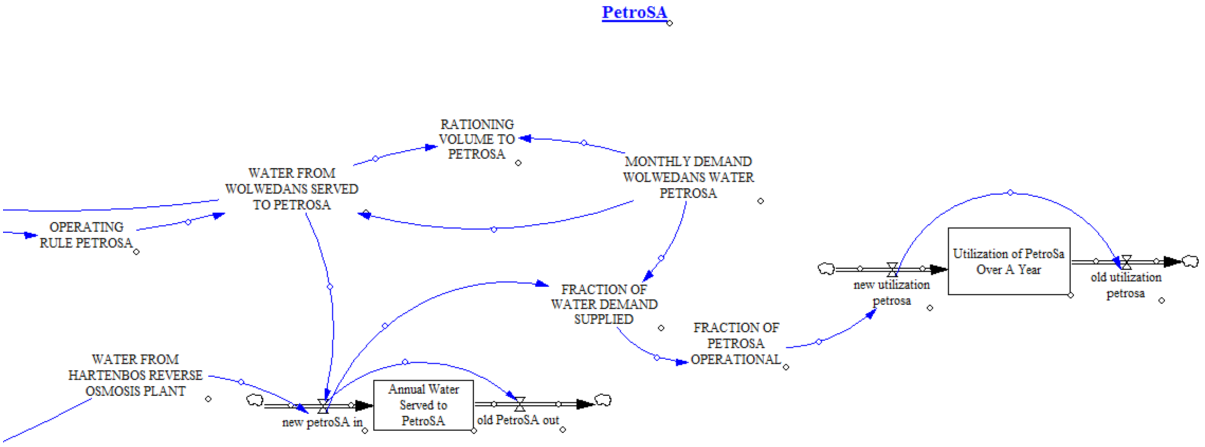

**Figure 15: PetroSA Sub-Model**

## Appendix E 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.

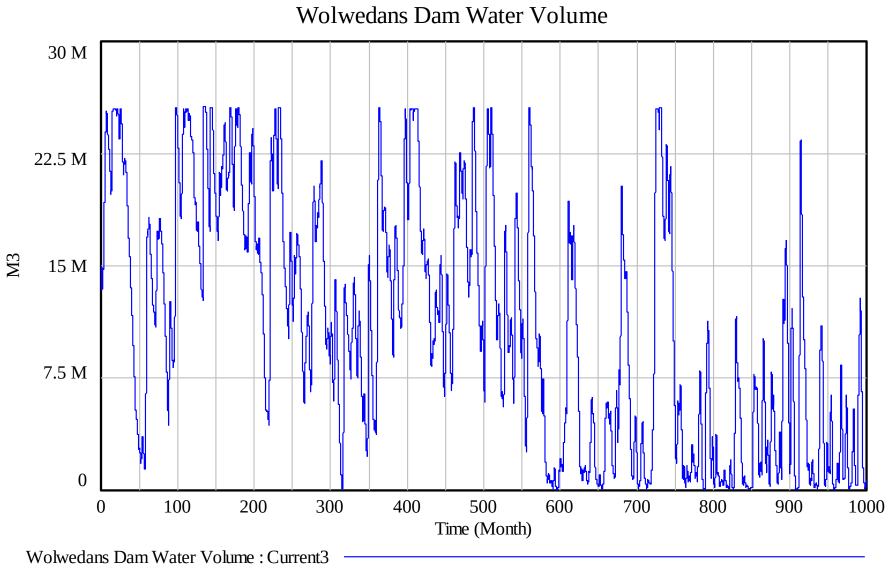

**Figure 16: Graph of a Single Run for the Wolwedans Dam Water Volume**

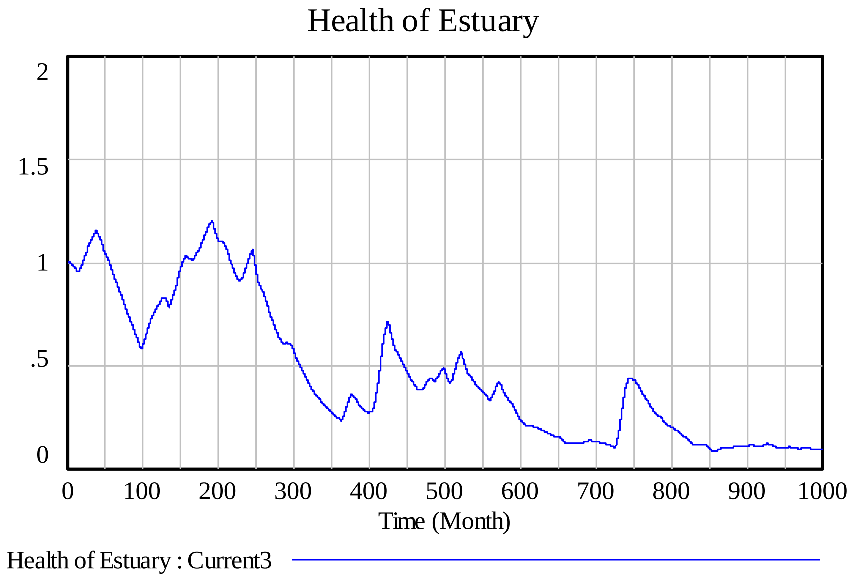

**Figure 17: Graph of a Single Run for the Great Brak Estuary Health**

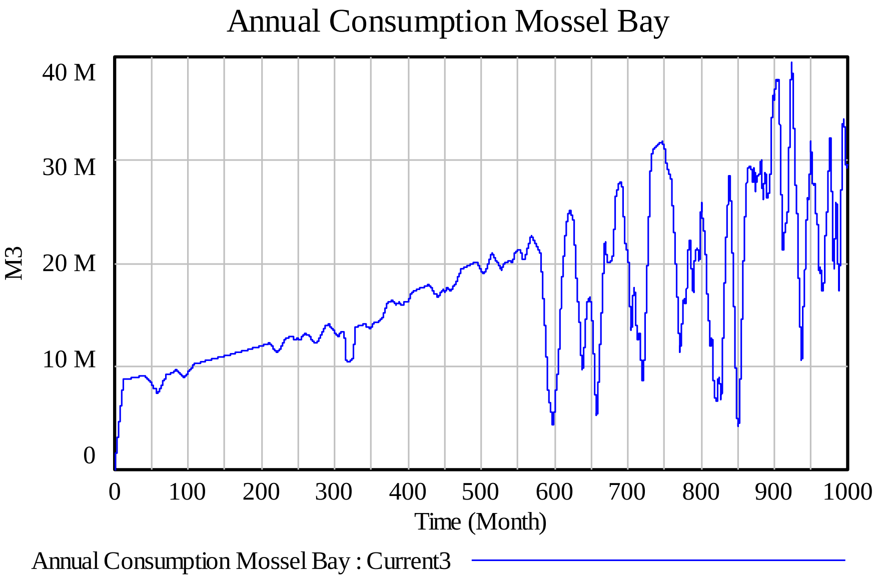

**Figure 18: Graph of a Single Run for the Consumption by the Mossel Bay Municipality**

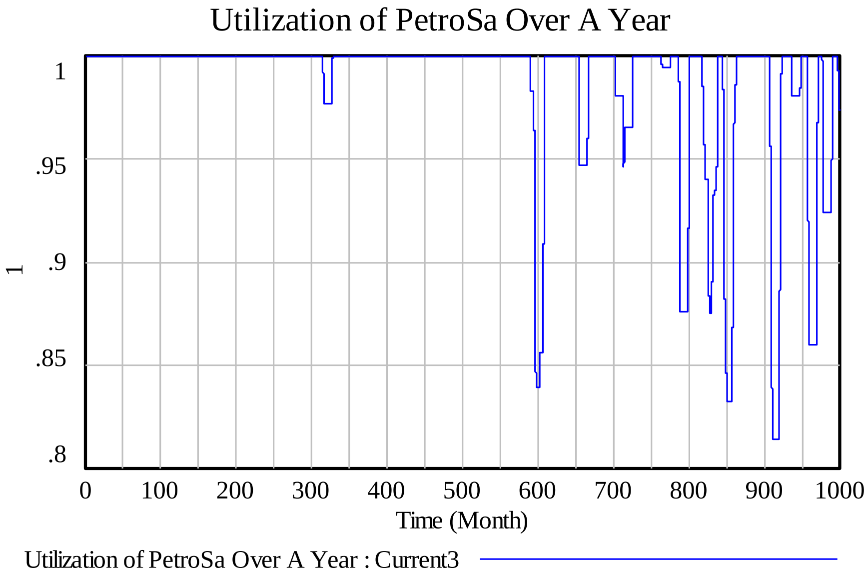

**Figure 19: Graph of a Single Run for the Utilization of PetroSA over a year**

## Appendix F 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 20 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.

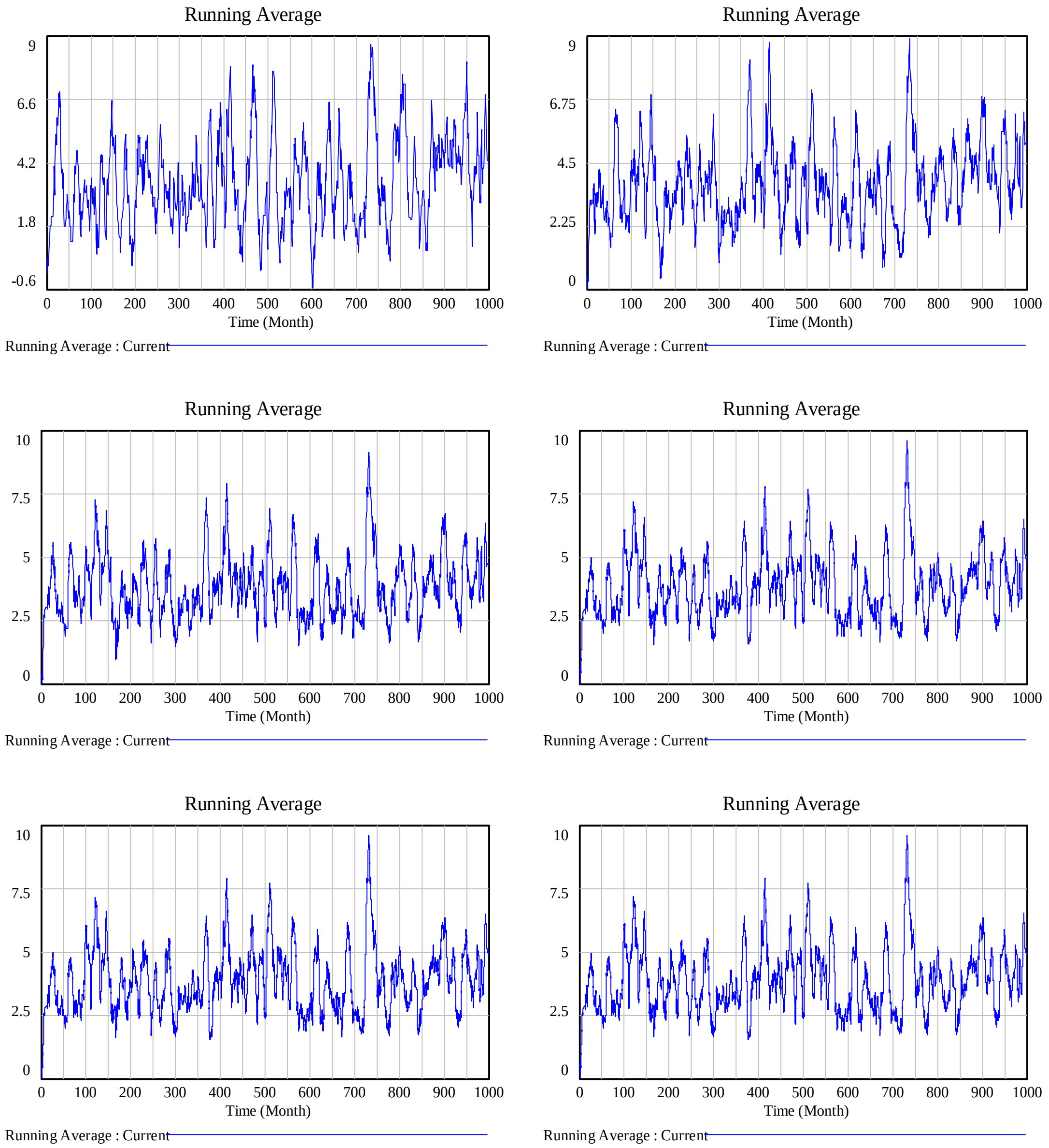

**Figure 20: Tests with different time steps**

*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.*