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1. INTRODUCTION

1.1. MOTIVATION

It is well known that many people around the world are suffering from water scarcity, totalling around 700 million people from 43 countries [1]. A region is defined as being water stressed when the annual water supply is less than 1,700m^3 per person, water scarce when it drops below 1,000m^3 per person and in absolute scarcity when the figure drops below 500m^3 [1]. By 2025, two-thirds of the world's population are expected to be living under water stressed conditions and 1.8 billion people living in areas with absolute water scarcity [1].

The 2011 WWF report, "Big Cities, Big Water, Big Challenges", defines the main threats to urban water as water scarcity, decreasing water quality and pollution, water overuse and urban vulnerability to climate change [2].

Water scarcity is faced when the demand for water exceeds the supply, and could be due to man-made or natural causes [2]. Natural causes include the location of the city and the quantity of water available; whereas man-made causes include over-abstraction of water resources to the point where they cannot recharge sufficiently, overuse, and infrastructure development in upstream areas, reducing the amount of water available downstream [2]. Furthermore, the population and population density of many cities around the world are increasing due to population growth and rural to urban migration. Often cities cannot cope with the increasing water demand, resulting in a lack of infrastructure to supply water, or old and inefficient infrastructure leading to higher leakage rates. Decreasing water quality and pollution of water resources and rivers is a major threat and can result from agriculture and industry to name a few [2]. This reduces the availability of clean water and can also lead to disease and fatalities. Water overuse occurs when excess groundwater is extracted from aquifers, which can lead to land subsidence, as seen in Mexico City, and salt-water intrusion in coastal areas, further reducing the supply of freshwater [2]. The environmental pressures on groundwater resources are having an impact on their quality and quantity and is expected to continue until 2025 unless policy changes are made [3]. Climate change exacerbates these threats [4], further contributing to the vulnerability of the water supply.

These threats present difficulties for urban areas in terms of managing their water supply and population. In the UK, many areas are in a state of stress and will face deficits in the future. Affinity Water, for example, supplies water to three regions in the South East of the UK: a Central region, a South East region, and an East region [5]. These regions are divided into 8 Water Resource Zones (WRZs), all of which have been designated as "serious water stress areas"[5]. The planning period is a 25-year period from 2015 to 2040 [5]. At the beginning of this planning period, there is a water supply deficit in 5 of the WRZs and it is expected to increase to 7 zones by 2040 [5]. The Environment Agency (EA) has classed the majority of the Affinity supply area's groundwater zones as "Major Aquifer Intermediate" in terms of its vulnerability [6]. Therefore, the EA has ordered the water company to reduce groundwater abstractions by 70Ml per day in the central region, in what the EA calls "sustainability reductions", representing almost 6% of Affinity's resources [5]. This 70Ml per day represents the planned reductions, however, there are also possible future reductions of 215Ml per day [5] that Affinity will have to accept at some point in the future by adapting their supply sources. Furthermore, there are sustainability reductions for the abstraction of water from rivers [5]. These sustainability reductions, together with the effects of climate change, are reducing the supply of water, causing Affinity to have to adapt and become more reliant on alternative water sources, or reduce the demand for water. The residential water consumption per person per day is expected to decrease throughout the planning period due to the introduction of metering for most households, and the promotion of water conservation initiatives [5]. Although Affinity is predicting the residential water consumption per person per day to reduce during the planning period, the increase in population is resulting in an overall increase in demand for water [5]. Figure 1.1 below shows the expected supply demand gap for the whole company, where DO is the Deployable Output representing how much water can be reliably abstracted from a source, WAFU is the Water Available for Use, SR is the Sustainability Reductions, DI is the Distribution Input and THR is the Total Headroom [5].

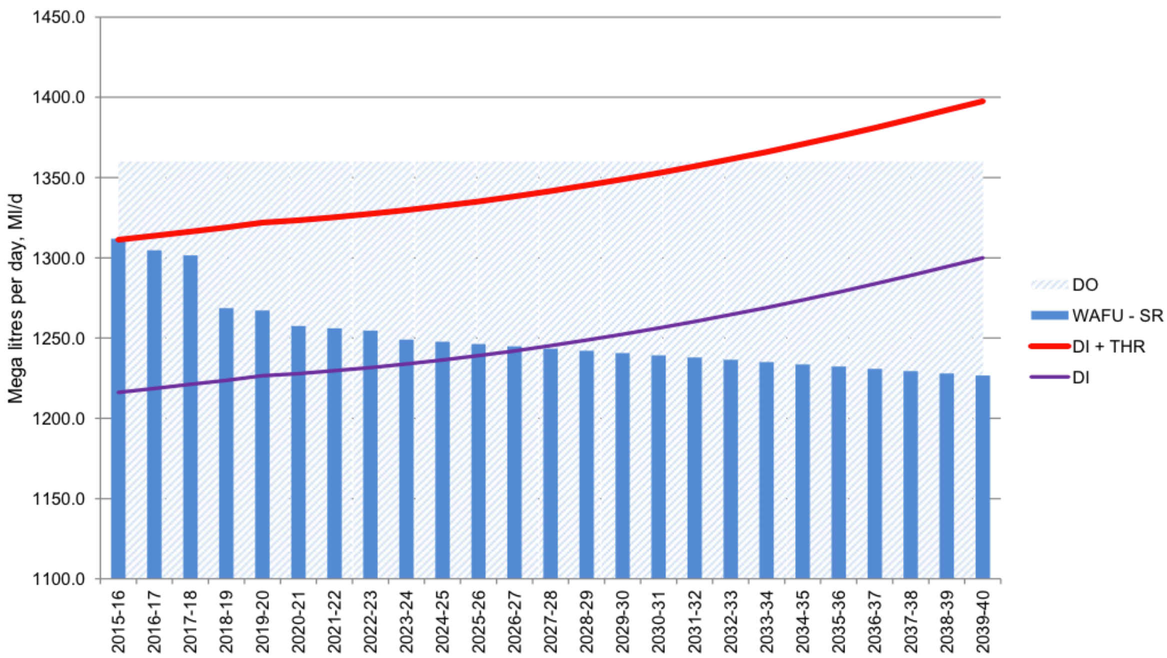


Figure 1.1: Supply/Demand Balance for a Dry Year Critical Period (DYCP) [5]

Therefore, it is important for water companies to be able to control the demand for water to ensure that supply is able to meet demand, and to enable water resources to replenish sufficiently.

Water companies in the UK are able to restrict the demand of water using four main methods, listed below in order of increasing restriction capability.

Method	**Description**	**Use by Affinity Water [5]**	**Frequency Targets set by Affinity Water [5]**
Hosepipe Bans	This restricts the use of hosepipes and sprinklers by the water company [7].	They were used in 1991, 2006 and 2012.	1 in 10 years
Drought Permit	These are granted by the EA, enabling the water company to take water from other water sources and/or change the restrictions on existing abstractions to "maintain an adequate supply of water" [7], [8].	They were used in 1991.	1 in 40 years
Drought Order	These are granted by the Secretary of State for the Environment, Food and Rural Affairs in England, and by the Welsh Assembly General in Wales [7]. It allows the water company to "restrict the non-essential use of water" [7].	N/A	1 in 40 years
Emergency Drought Order	These are granted by the Secretary of State for the Environment, Food and Rural Affairs in England, and by the Welsh Assembly General in Wales [7]. These are implemented in serious droughts and allows water companies to limit the use of water, and normally involves the use of a standpipe or water tanker to supply water to the public [7].	N/A	1 in 118 years

The majority of the public supports the use of hosepipe bans, however, some feel that water companies have imposed water restrictions too late in the UK before, feeling that it was "too little too late" [9]. Furthermore, water companies can be hesitant to impose restrictions as it has been considered in the past as a sign of failure [9]. Therefore, it is important for water companies to understand the impact that a restriction has to be able to plan for the future and know when to implement a restriction in order for it to have the desired effect.

Affinity Water announced plans last year to postpone the implementation of hosepipe bans for economically vulnerable non-household consumers [5]. Additionally, Affinity Water considers emergency drought orders only to be acceptable in the case of a civil emergency [5]. Although these measures are likely to be popular with the public, Affinity Water must be prepared to implement restriction measures, should they be required in order to maintain an adequate water supply.

The imminent water supply deficit creates a need for water resource management to support the planning of water resources and ensure that supply is able to meet demand in the future [10]. This is particularly important in areas of rapid urbanisation where the hydrologic landscape is altered by changes in land-use, and where population growth and economic growth causes a rise in water demand, possibly leading to a supply deficit [10].

1.2. OBJECTIVE

This project will develop a model that can be applied to cities in the UK by using a model from the literature review as a base to build upon. The model will be created with the water company as the client as they are the policy-maker that can restrict water demand based on the water supply situation. Water companies need to plan 25 years into the future and therefore, need to know the predicted population and hence, the predicted demand, and whether or not the current supply is sufficient to meet the expected demand. In the event of an expected deficit, the water company needs to quantify this deficit so that the correct amount of investment is allocated to provide a sufficient supply in the future. Neill Brauders, from Mott MacDonald, confirmed that the water company is a suitable client for the model in an email conversation [11].

2. LITERATURE REVIEW

2.1. WATER RESOURCE MANAGEMENT TOOLS

There are many water resource management tools that exist, however, they do not consider the consequences of consumer choices updating land and water use behaviours [10]. Water management involves the optimisation of decisions in response to changes in demand and supply [12].

Simonovic (2000) recognised and discussed two paradigm shifts that changed the approach towards water resource modelling [13]. Firstly, the complexity paradigm states that the water problem will become increasingly complex in future, whereas the tools used to model water management will become less complex [13]. Secondly, the uncertainty paradigm is due to hydrologic variability and a lack of knowledge [13].

Many models have been developed to simulate components necessary to study the water resource system. The Soil and Water Assessment Tool (SWAT), described by Arnold et al. (1998), was developed to help policy-makers understand the influence of management on water supplies and pollution in large river basins and watersheds [14]. Jacobs et al. (2004) developed an end-use model that simulates residential water demand and return flow including indoor, outdoor, hot and cold water demand [15], [16]. Blokker et al. (2010) similarly developed a water demand end-use model for small time and spatial scales using statistical information, such as census data, to simulate water demand patterns [17]. However, the model is a descriptive rather than a predictive model [17]. Grabow et al. (2007) developed a spreadsheet-based model that predicts water quality and quantity [18]. The advantage of this model was the use of a spreadsheet that enabled the involvement of those with limited modelling experience [18]. Mitchell et al. (2001) created the Aquacycle water balance model, that calculates daily flows and water demands in the system, and applied it to the Woden Valley urban catchment in Canberra, Australia [19]. Wu et al. (2010) developed a feasible new method of predicting land-use, evapotranspiration changes and streamflow by integrating the SEBAL, CGCM1 and Markov Model with remote sensing [20].

2.2. AGENT-BASED MODELS

Agent-based models (ABMs) have been widely used for many years to simulate interactions between stakeholders and to "better understand the complexity of water uses and water users" [21]. Their use has been particularly popular in natural resource management where complex systems are involved [22]. They have been used to predict the interaction of stakeholders with water availability, where individuals react to changes in consumption patterns [10]. Many ABMs have been developed in recent years. The ABM, DAWN, was developed to predict the interaction between water pricing and water demand, enabling different policy-making scenarios to be evaluated [23]. The SINUSE Model looks particularly at the water table and its interaction with its users whilst taking the social behaviour of the farmers into account [24]. The SINUSE model was applied to the complex Kairouan water table, proving that local and non-economic behaviours have a significant effect on the system dynamics and therefore, must be considered [24]. The SHADOC model is an ABM that concentrates on irrigated systems, and was applied to the Senegal River Valley [25]. The model simulates water demands and behaviours of farmers, simulating irrigation management [25]. Becu et al. (2003) built on the SHADOC model to form the CATCHSCAPE model, that simulates the catchment features and individual decisions made by the farmers [26]. The hydrological system is modelled using biophysical modules, resource management processes are used to describe the social dynamics, and different levels of control are used to describe water management [26]. The model allows the simulation to vary depending on whether the focus is on the economy, landscape or water management [26]. The FIRMA model used ABMs to combine physical, hydrological, economic and social characteristics of water resource management in order to provide a tool to aid water resource planning [27]. FIRMA uses many ABMs to represent customers, suppliers and the government, and has been applied to five regions in Europe [27]. Furthermore, the EOS model was developed by considering the Fraser River watershed and its problems [28]. The model was created in order to determine the best intervention strategy to lead to effective co-operation between stakeholders [28]. The modified EOS model shows that the agents must co-operate to reduce waste and over-consumption, however, the scenario is not realistic and very basic [28]. Espinasse et al. (2005) modelled and simulated the hydraulic management of the Camargue ecosystem using an ABM to integrate the natural and decision-making processes [29]. In 2009, the ABM technique was applied to "domestic water management in emergent metropolitan areas", in particular the area of Valladolid in Spain [30]. The model was able to demonstrate the interaction between urban dynamics and socio-geographic factors with water demand [30]. Shea (2013), used agent-based modelling to create a dynamic model that addresses the issues of water management in megacities [31]. The ABM was used to investigate the "behaviour of megacities individually and under the influence of regional management" [31].

2.3. Cellular-Automaton Models

Cellular-automaton models have been used to model decisions that drive land-use changes [10]. Ducrot et al. (2004) developed a model that used cellular automata and agent-based modelling to model water catchments and the connections between urbanisation, hydrological processes and land-use changes [22]. However, it required further development [22]. Marshall et al. (2008) investigated the impact that changes in land cover have on the hydrology of the watershed by modelling the watershed, and by using cellular automation and Markov Chain analysis to simulate land cover change [32]. Similarly Choi et al. (2008) used a cellular automaton model with an hydrological model to predict streamflow in the river basin in response to urban growth, and applied it to the Kishwaukee River Basin in the USA [33]. However, Poelmans et al. (2010) investigated the application of coupled cellular automaton and hydrological models and concluded that the "importance of using accurate projections of the spatial pattern of urban expansion increases systematically at local scale levels" [34]. McColl et al. (2007) utilised an alternative land-use change model, *What If,* together with the hydrological model, HEC-HMS, to develop a methodology to improve land-use policy strategies at the watershed scale in order to minimise run off [35].

2.4. Complex Adaptive System Models

However, many of the models discussed above do not consider stakeholder decisions that can influence the system. A complex adaptive system (CAS) is an approach that combines various sub-systems, such as social, economic and physical systems, which "change and interact with one another" whilst being influenced by external factors [36]. A CAS is an open system in that it interacts with the environment and external factors, but it is adaptive because it can adapt to the changing environment [36]. The CAS approach has been applied to urbanised deltas in a paper that argues that the approach is useful and "relevant for planners as well as scientists" [36]. The CAS Model presented by Giacomoni et al. (2013), described in more detail in section 2.5., uses both cellular automaton models and ABMs with hydrologic models, to simulate the behaviours of consumers and policy-makers, and model the interactions between population growth, land-use change, the hydrologic cycle and water use, and was applied to the city of Arlington, Texas in the USA [10]. Furthermore, adaptive policies are included to represent the interaction of feedback loops regarding water use, land-use, population and the hydrologic cycle [10]. It has been stated that the relationship between human and natural systems cannot be accurately studied separately due to the presence of feedback loops [37]. Furthermore, Sullivan (2011) outlines the importance of Integrated Water Resources Management, where a better understanding of the complexities surrounding the management of water is needed to be able to allocate water efficiently [4]. Hellström et al. (2000) created a framework that analyses the sustainable urban water management system that takes these multi-dimensional complexities into account, such as social, cultural, economic, environmental and technical criteria [38]. However, the complexities included in modelling tools creates management challenges, which was investigated by Garrick et al. (2008) whilst considering the Colorado River Basin [12].

2.5. Giacomoni et al. (2013)

2.5.1. Background

The CAS framework, set out in the paper by Giacomoni, Kanta, & Zechman in 2013, tackles the "complexity of environmental and social interactions" with the water supply network, by developing a dynamic model for water resource management, that provides information regarding the effect of feedbacks on the sustainability of the urban water supply [10]. From this point forward, the model outlined in the paper by Giacomoni et al. (2013), will be called the "Giacomoni Model". Giacomoni et al. (2013) define a CAS as a "complex network of agents that are constantly adapting to their environment" [10]. The framework integrates changes in population growth, land-use, consumer behaviour, decision making, hydrology and infrastructure to review the sustainability of the urban water system [10]. The Giacomoni Model is complex as it utilises many different types of model components including system dynamics, cellular automata, ABMs and hydrologic models [10].

The Giacomoni Model was developed by considering a set of dynamic feedback loops that characterise the urban water supply network, shown in figure 2.1 [10]. The loop on the left represents the relationship between water availability, water use and water conservation [10]. This loop balances, as shown by the negative sign in the centre of the loop, because as water usage increases, water availability decreases and hence, consumers implement water efficient practices which then reduces water usage [10]. The loop in the centre represents the relationship between land use, population and water use [10]. This loop shows that as urban areas grow, the demand for water increases due to the increased population, and hence water availability decreases [10]. This causes policy-makers to place restrictions on the expansion of the urban area, stabilising the demand for water and hence, produces a balancing loop [10]. The loop on the right, however, can be balancing or reinforcing. This loop represents the relationship between changes in land-use and the hydrologic cycle, showing that as the urban area grows, the amount of impervious surface area increases, which in turn increases the surface runoff [10]. The increase in surface runoff increases water availability but it can also reduce the amount of water that infilrates into the ground and replenishes groundwater aquifers, hence reducing the "natural yield of the watershed" [10]. Land-use restrictions can then be implemented by the policy-maker to reduce the amount of new impervious areas [10]. This loop can be balancing or reinforcing depending on the increase in surface runoff compared to the reduction in groundwater flow [10].

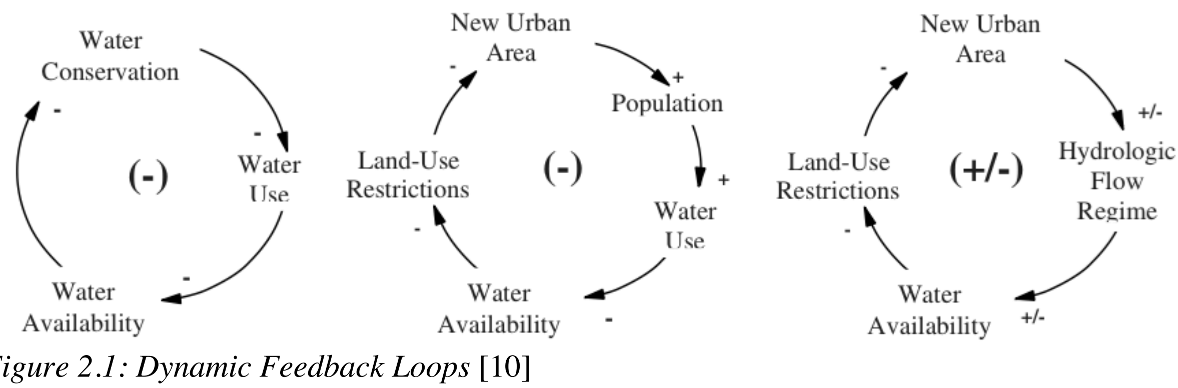


Figure 2.1: Dynamic Feedback Loops [10]

2.5.2. LIMITATIONS OF THE GIACOMONI MODEL

The complex model requires many inputs such as land-cover information, population characteristics, housing information and household, commercial, industrial and agricultural water demands [10]. This makes the model problematic to implement for data-scarce regions [10]. In many ways the model is also too complex, involving many calibration parameters and variables requiring a vast amount of data in order to run the model. In many cases, the data required for some of the model components is not even available for developed countries, such as the distance to main roads and minor roads, required for the Land-Use Change Model component.

Additionally, the Giacomoni Model only considers water supplied from a reservoir, and does not consider water supplied from an aquifer or a river. This limits the model's applicability to most cities, and does not give a full picture of the sustainability of the water resource situation to a city since it does not model other possible water sources.

3. DATA & METHODOLOGY

3.1. OBJECTIVE

The literature review identified a gap in the models that are currently available. There is a requirement for a model that is sufficiently complex to model a water resource system, but simple enough to easily apply to a city. Furthermore, Simonovic (2000) recognised the need for simpler models that will need to be applied with a lack of information [13].

This project will develop a Simplified Adaptive Systems (SAS) model that can be used in the UK by using a model from the literature review as a base. The Giacomoni Model was selected as the base model because it was successful, complex and also had a clear use case. The model however, did have several weaknesses, such as having complex model components and not including all possible sources of water, preventing the application of the model to most cities.

The objective of the project is to adapt and simplify the Giacomoni Model so that it can be applied to a city in the UK. The model will be written and implemented using MATLAB. It will then be applied to Arlington, in order to compare the two models, and then applied to a city in the UK. In this case, Luton was chosen as the use case due to the research conducted into Affinity's water supply, and the future restrictions on the water supply that will be imposed, creating a need for an accurate predictive model.

3.2. STRUCTURE OF THE GIACOMONI MODEL

The dynamic feedback loops, shown in figure 2.1, are combined to form the Giacomoni Model. The schematic of the Giacomoni Model demonstrates how these loops are linked and is shown below in figure 3.1. In this model, the states of each agent, and the system, are updated at each time step [10].

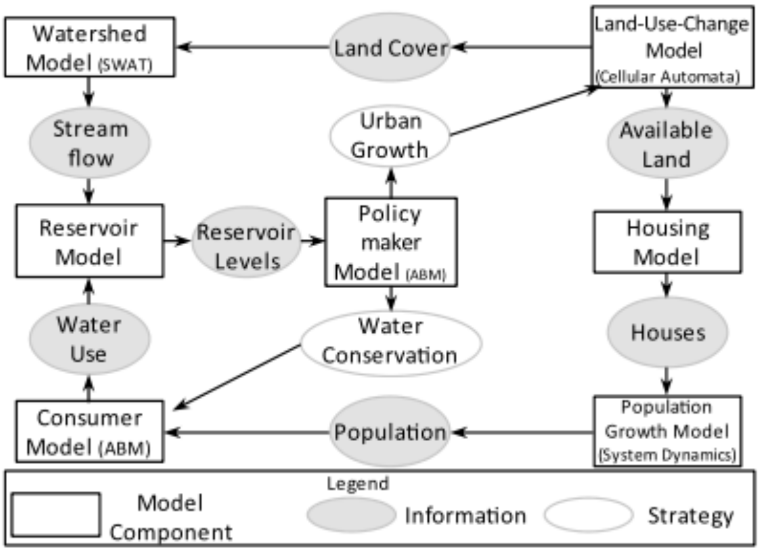


Figure 3.1: Giacomoni Model structure [10]

The Policy-Maker Model and Consumer Model are both ABMs, representing individual actors in the system [10]. The Land-Use-Change Model is a cellular automaton system where the landscape is represented as a grid, where each cell is updated at each time step [10]. The Land-Use-Change Model simulates the change in land-use from rural to urban use, producing land cover information which serves as an input to the watershed model [10]. The Giacomoni Model uses the Soil and Water Assessment Tool (SWAT) as the hydrologic model, calculating the streamflow which forms the input to the Reservoir Model [10]. Meanwhile, the Land-Use-Change Model also calculates the available land for urbanisation which is then used in the Population Growth Model, which creates new agents [10]. The total water demand at each time step is calculated in the Consumer Model, which forms the withdrawals from the reservoir, and thus, the Reservoir Model is able to calculate changes in reservoir level [10]. The Policy-Maker Model is an ABM which represents the policy-maker, taking information about current water availability, in terms of the reservoir level, to make decisions about urban growth and water conservation policies [10]. These policies form inputs to the Land-Use-Change Model and Consumer Model [10].

As can be seen in figure 3.1, the Giacomoni Model includes many individual model components that are complex in their nature, with many parameters that can be used for calibration. The Giacomoni Model is also complex due to the interactions between the agents and the environment, which leads to a complex and unpredictable state of the system which then impacts agent behaviour through the feedback system [10]. Furthermore, the model is adaptive due to the integration of adaptive consumers and an adaptive policy-maker [10]. The Policy-Maker Model component represents public officials restricting water use and land-use change based on current water availability [10]. The consumers are also adaptive since they are able to make land and water use decisions [10].

The Giacomoni Model was implemented using AnyLogic, a modelling environment specifically designed for dynamic models [10].

3.3. Development of the SAS Model

The Giacomoni Model only takes into account water supplied by a reservoir. In reality, water may be abstracted from a river, aquifer or reservoir in order to supply water to the public. The proportion of water supplied from different sources depends on the location of the city and hence, varies between cities. Therefore, it was evident that rivers and aquifers also need to be included in the SAS model. In order to confirm that rivers and aquifers are of equal importance in the UK, the water supply to a selection of UK cities was investigated. The list of cities was compiled using the 2011 census data for city populations greater than 200,000 [39]–[41]. However, the urban area population definition was used for London instead of the city population definition. Due to the layout of London, the 'city' has a very small population but the 'urban area' has a very large population. If the city population definition were to be used, London would not have featured in this list, which did not seem sensible.

This resulted in a list of 27 cities, however only 11 cities were used as these did not require assumptions to be made about the percentage of water obtained from each source. This was considered to be more reliable since the inclusion of the other cities proved that the results were sensitive to these assumptions. The final set of data used is shown in the table below.

City	Supplier	Percentage Surface Water Used	Percentage Reservoir Used	Percentage Groundwater Used	References
Bradford	Yorkshire Water	25%	50%	25%	[42], [43]
Brighton and Hove	Southern Water	0%	0%	100%	[44], [45]
Greater London Urban Area	Thames Water	65%	0%	35%	[46], [47]
Kingston upon Hull	Yorkshire Water	25%	50%	25%	[43], [48]
Leeds	Yorkshire Water	25%	50%	25%	[43], [49]
Liverpool	United Utilities	25%	67%	8%	[50], [51]
Luton	Affinity Water	30%	10%	60%	[5], [52]
Manchester	United Utilities	25%	67%	8%	[50], [51]
Reading	Thames Water	65%	0%	35%	[46], [47]
Sheffield	Yorkshire Water	25%	50%	25%	[43], [53]
Southampton	Southern Water	63%	0%	37%	[44], [45]
Mean		33.9%	31.2%	34.9%	
Standard Deviation		21.0%	28.8%	25.8%	

Using this data, the normal distributions for the percentage of surface water, reservoir and groundwater used were calculated and plotted, as shown in figures 3.2, 3.3 and 3.4 respectively.

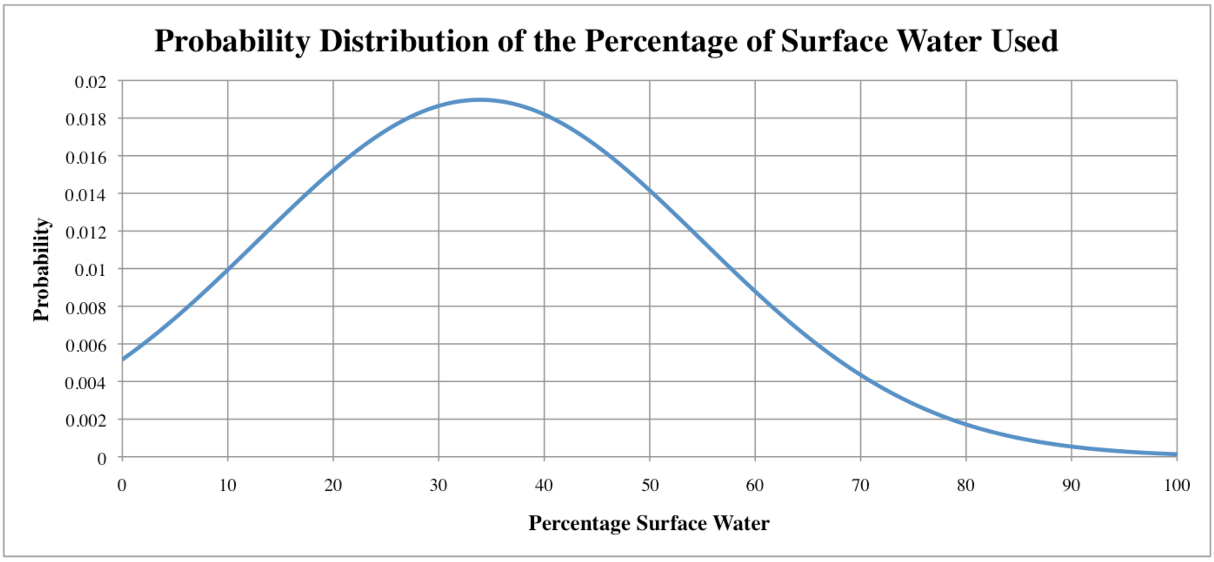


Figure 3.2: Probability Distribution of the Percentage of Surface Water Used

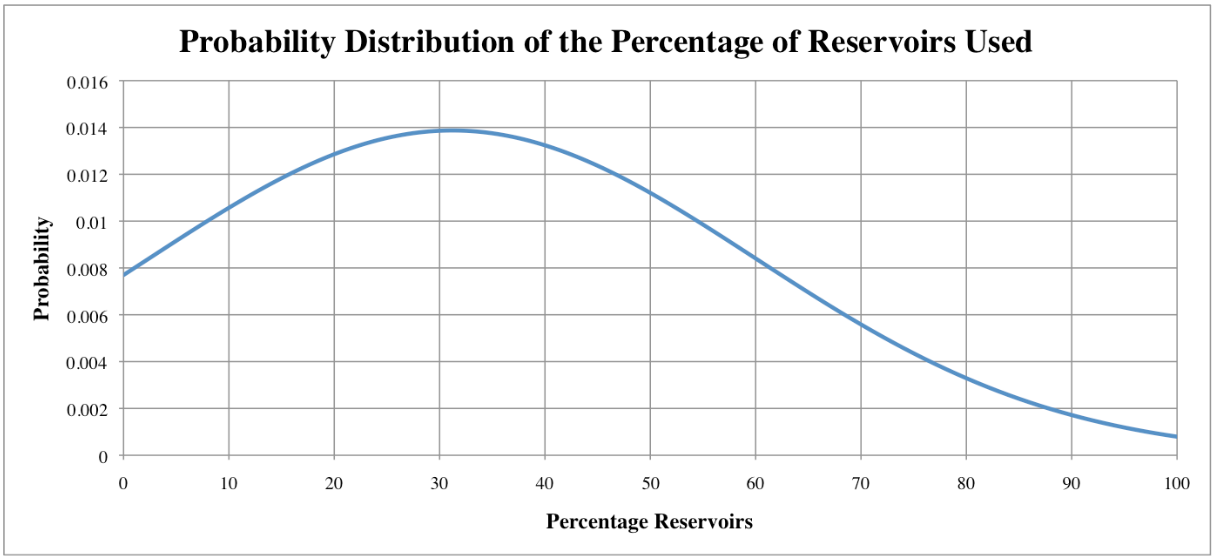


Figure 3.3: Probability Distribution of the Percentage of Reservoirs Used

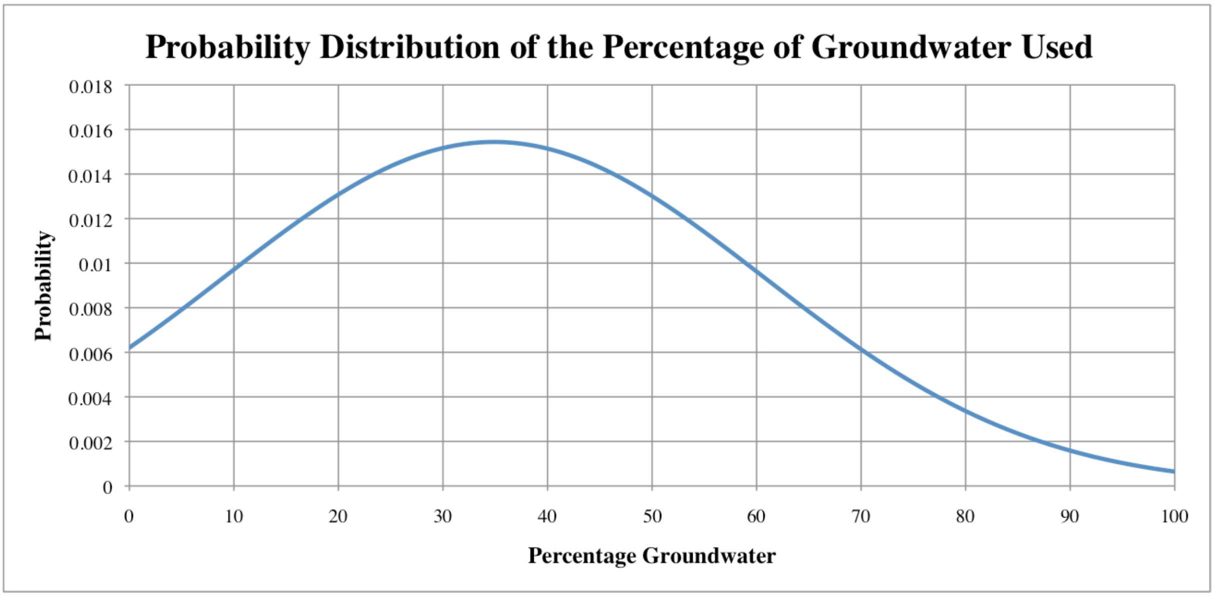


Figure 3.4: Probability Distribution of the Percentage of Groundwater Used

The figures above confirmed that the use of rivers and aquifers needed to be included in the SAS model as they formed an equally important role in the supply of water to urban areas in the UK. This resulted in the introduction of the River and Aquifer Model components in the SAS model, as can be seen in figure 3.5.

One of the main changes to the Giacomoni Model is the removal of the policy-maker's influence over urban growth. In the UK, the policy-maker is the water company as they are the body that is able to restrict water supply and demand. However, they are unable to restrict urban growth, and therefore, this output from the Policy-Maker Model component has been removed. In the USA, the policy-maker is likely to be the Government since water is publicly supplied and therefore, the policy-maker is able to restrict both water demand and urban growth simultaneously. Another change to the Giacomoni Model is the removal of the Housing Model as that was regarded as an added complication that was unnecessary. The final model schematic for the SAS model is shown in figure 3.5.

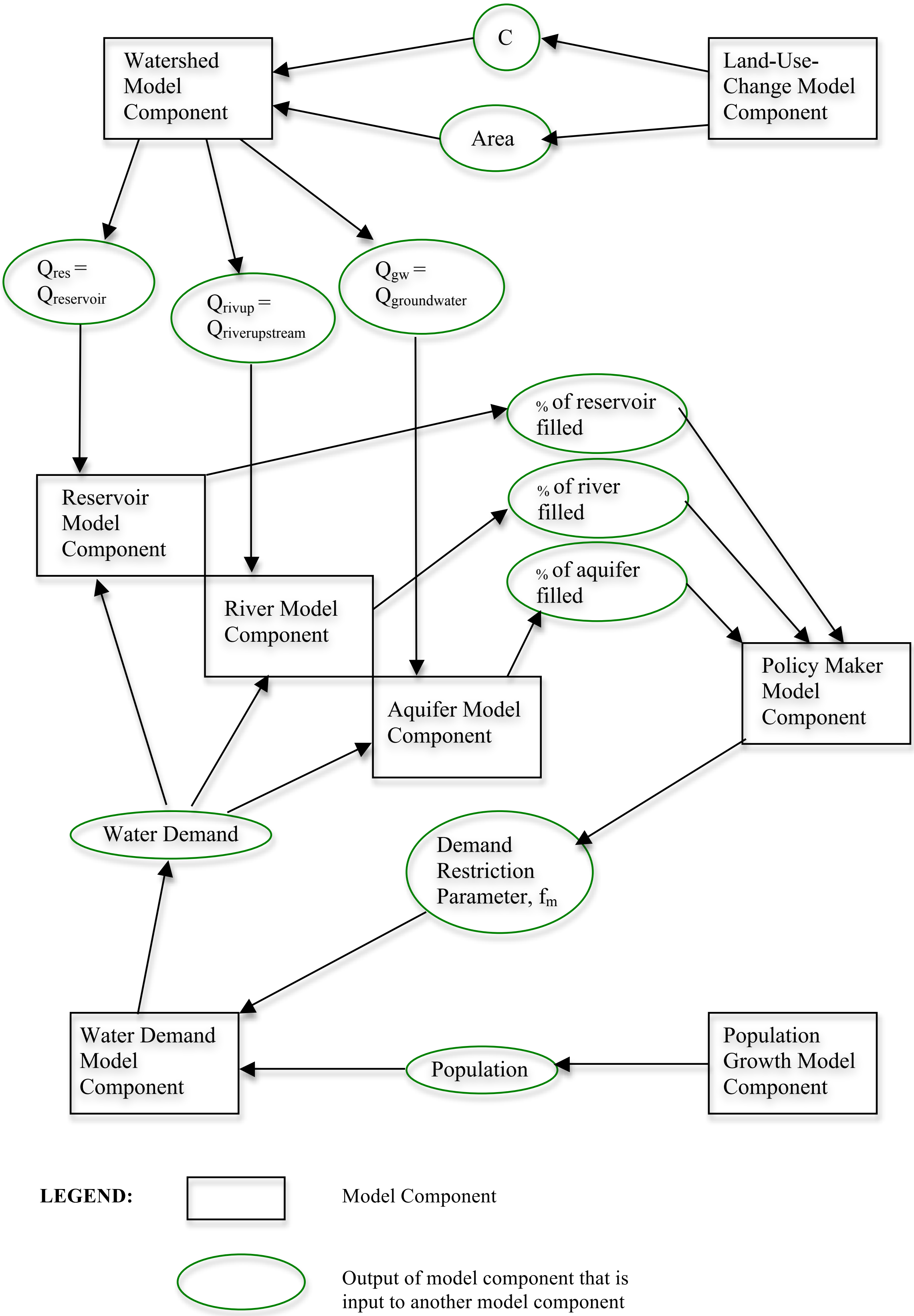


Figure 3.5: Schematic of the SAS Model

3.4. SAS Model's Population Growth Model

For the Population Growth Model, a model similar to that used in the Giacomoni Model was employed. The model used is a simple model that uses data readily available from census information. The population growth was modelled as follows, taken from the Giacomoni Model [10]:

$$\frac{dP}{dt} = B + I - D - E$$

where P is the population, dP/dt is the rate of growth of population, B is the rate of births, D is the rate of deaths, I is the rate of immigration and E is the rate of emigration. The Giacomoni Model expanded this equation further, using the fertility rate, average lifespan and housing attractiveness multiplier [10]. It was thought however, that this was overcomplicating what could be a simple model. Furthermore, many of the parameters used in the Giacomoni Model are not readily available from census data in the UK; whereas the parameters used in the Population Growth Model for the SAS Model are readily available for all cities in the UK, and is therefore easily applicable to any UK city.

3.5. SAS Model's Land-Use-Change Model

The Land-Use Change Model used by the SAS Model was different to the one used by the Giacomoni Model. The Giacomoni Model's Land-Use-Change Model calculated the "likelihood that an undeveloped cell within a grid will change its state to urban land use" [10]. It computed this likelihood based on the number of developed neighbours, distance to main roads, distance to minor roads and the distance to central areas [10]. It is difficult to find information on these parameters in the UK and therefore, it was decided that the Land-Use-Change Model for the SAS Model would be completely different. The SAS Model's Land-Use-Change Model instead takes the initial area of the watershed, A, and initial coefficient of runoff, C, at the beginning of the simulation period and increases C with each monthly time step by the constant d, keeping the area of the watershed constant with time. This is shown below.

$$C_t = C_{t-1} \times d \qquad \text{(where } d > 1\text{)}$$

This is a very simple model but far easier to implement than the Giacomoni Model's version. It is believed that the coefficient of runoff, C, will increase with time due to the conversion of rural land to urban land, increasing the area of impervious ground surface.

3.6. SAS MODEL'S WATER DEMAND MODEL

The Giacomoni Model's Water Demand Model considers only residential consumers and simulates both indoor and outdoor demand [10]. However, industrial demand plays a major part in the demand for water in cities in the UK and therefore, it was believed that the total water demand should be calculated in the SAS Model as well as the residential demand. The Giacomoni Model used a complicated formula taking into account the lawn area, crop factor and effective rainfall for each household [10]. This was not possible to replicate for the SAS Model since that amount of detailed information is not available for every city. Therefore, it could not be used to create an easily applicable model, which was the aim for the SAS Model.

Instead, the Water Demand Model for the SAS Model computes the water demand using the initial water consumption per capita, multiplied by the demand restriction parameter, f_m, which is determined using the Policy-Maker Model. This model allows flexibility in the value of the water consumption that will be used. By keeping the value of water consumption constant throughout the time period, the worst-case demand will be calculated, as it is likely that the water consumption will decrease with time as consumers use more efficient technologies, and become more aware of the water that they are consuming. If there is an estimate of the amount by which the water consumption will reduce, this could also be tested by the model, demonstrating its flexibility.

The formula used for the Water Demand Model for the SAS Model is as follows:

$$Demand_t = Water\ Comsumption\ per\ capita_t \times Population_t \times f_{m_{t-1}} \times number\ of\ days\ in\ the\ month$$

$$Total\ Water\ Demand = Demand + Industrial\ Demand$$

where the *number of days in the month* is an average value of 30.42, used to simplify the coding. The *Total Water Demand* is then used as an input for the Aquifer, River and Reservoir Models, since a percentage of the *Total Water Demand* forms the abstraction from these sources, depending on the city in question and which water sources are used.

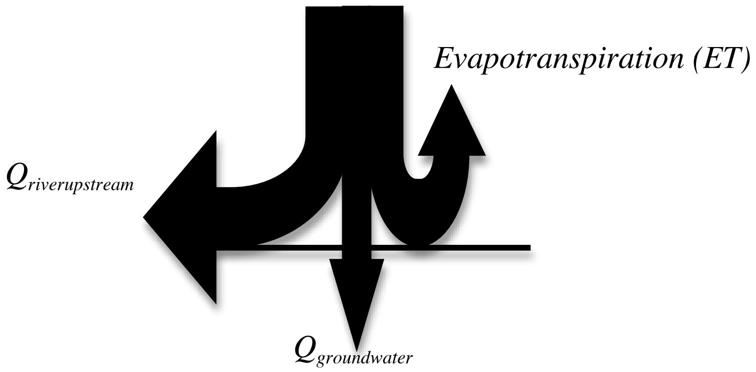
3.7. SAS MODEL'S WATERSHED MODEL

The Giacomoni Model uses the SWAT Model as their watershed model, which is a hydrologic model that simulates "watershed land-management practices" [10]. However, it requires complex input information and therefore, it was not possible to use the SWAT Model in the SAS Model as it is too complicated and requires information that is not available.

Therefore, a new model needed to be developed. The simplest model that could be used to calculate the streamflow from the watershed was the Rational Method.

The coefficient of runoff, C, and the area of the watershed, A, is obtained from the Land-Use-Change Model. Rainfall intensity values are obtained from either climate predictions, if those are to be tested, or, similarly to the Giacomoni Model, different annual climate scenarios can be used, and repeated every year. By repeating the same rainfall scenario over the simulation period, it reduces the "influence of the high variability of climatic inputs" and focuses the analysis "on the interactions among system components" [10]. However, this is flexible and can be changed depending on the user, and what they want to test.

Several different streamflows needed to be calculated in this model in order to form inputs to the Reservoir, Aquifer and River models. The diagram below illustrates the proportion of rainfall that runs off, evaporates and infiltrates.



where

$Q_{riverupstream} = C \times i \times A$ (C is the coefficient of runoff, i is the rainfall intensity)

$ET = a \times i \times A$ (a is the proportion of incident rainfall that evaporates)

$Q_{groundwater} = (i \times A) - Q_{riverupstream} - ET$

The method used to calculate the components above is a simple water balance equation where the incident rainfall is divided between run off, infiltration and evapotranspiration. With the respective proportions of each depending on the region in question, determining the values of parameters C and a.

Using these values, the flow going into the reservoir is calculated as follows, where the flow is assumed to be a percentage of $Q_{riverupstream}$, represented by the constant c.

$$Q_{reservoir} = c \times Q_{riverupstream} \qquad \text{(where } 0 < c < 1\text{)}$$

One of the limitations of the Watershed Model is that it assumes the aquifer catchment area is the same as the river catchment area. In reality, this may not be the case, however, in the scope of this project, it is not realistic to model an aquifer in any other way.

A major limitation of the Watershed Model is that the Rational Method is used, which is typically used for small watersheds. This was considered to be acceptable since watershed areas in the USA are generally much larger and therefore, the rational method is more suitable to the UK than the USA.

3.8. SAS MODEL'S AQUIFER MODEL

The function of the Aquifer Model is to compute the groundwater level at each monthly time step, taking into account inflows and outflows from the system. The groundwater level is calculated using the formula below:

$$GroundwaterVolume_{t} = GroundwaterVolume_{t-1} + Q_{groundwater_t} - GroundwaterAbstraction_{t}$$

where $GroundwaterAbstraction = TotalWaterDemand \times G$

where G is the percentage of the *Total Water Demand* supplied by the aquifer, which varies amongst cities in the UK.

Using the values of *GroundwaterVolume* at each time step, the percentage of the aquifer filled is calculated at each time step, as shown below, where the *MaxGroundwaterVolume* depends on the Aquifer in question.

$$PercentageGroundwaterFilled = \frac{GroundwaterVolume}{MaxGroundwaterVolume}$$

3.9. SAS MODEL'S RIVER MODEL

The function of the River Model is similar to the Aquifer Model in that it calculates the River Volume at each monthly time step, taking into account the inflows and outflows from the river. The river level is calculated using the formula below:

$$RiverVolume_t = RiverVolume_{t-1} + Q_{riverupstream_t} - RiverAbstraction_t - Q_{reservoir_t}$$

where $RiverAbstraction = TotalWaterDemand \times R$

where R is the percentage of the *Total Water Demand* supplied by the river, which varies amongst cities in the UK.

Using the values of *RiverVolume* at each time step, the percentage of the river filled is calculated at each time step, as shown below, where the *MaxRiverVolume* depends on the River in question.

$$PercentageRiverFilled = \frac{RiverVolume}{MaxRiverVolume}$$

3.10. SAS Model's Reservoir Model

The function of the Reservoir Model is similar to the Aquifer Model in that it calculates the reservoir volume at each time step. It is similar to the Reservoir Model in the Giacomoni Model in that it calculates the storage and level in monthly time steps by considering the inflows and outflows to the system. The inflows include the streamflow, $Q_{reservoir}$, and imports from other water basins, and the outflows include abstraction for residential and industrial demand, and exports to other water basins. This is similar to the Giacomoni Model, however, the SAS Reservoir Model does not include inflows from direct rainfall or outflows from evaporation or spills [10]. The reservoir level for the SAS Model is calculated using the formula below:

$$ReservoirVolume_t = ReservoirVolume_{t-1} + Q_{reservoir_t} + Imports_t - ReservoirAbstraction_t - Exports_t$$

where $ReservoirAbstraction = TotalWaterDemand \times S$

where *S* is the percentage of the *Total Water Demand* supplied by the reservoir, which varies amongst cities in the UK.

Using the values of *ReservoirVolume* at each time step, the percentage of the reservoir filled is calculated at each time step, as shown below

$$PercentageReservoirFilled = \frac{ReservoirVolume}{MaxReservoirVolume}$$

where the *MaxReservoirVolume* depends on the Reservoir in question. If the reservoir in question is subject to sedimentation, the *MaxReservoirVolume* could be re-modelled to reduce with time in order to represent this.

3.11. SAS Model's Policy-Maker Model

The Policy-Maker Model for the Giacomoni Model determines the "level of water restrictions and the allowable rate of land-use conversion" using the level of water in the reservoir [10]. The SAS Policy-Maker Model is similar to that used in the Giacomoni Model, however, the values for the demand restriction parameter, f_m, are different in order to correspond to the different restrictions the water companies can use in the UK. Furthermore, the SAS Policy-Maker Model differs to the Giacomoni Policy-Maker Model in that it is able to take into account the reservoir, river or aquifer level. Depending on the city to be modelled and the water sources used, different sources can be monitored in order to determine whether the area is in a drought. Therefore, the SAS Model includes three different types of Policy-Maker Model, enabling the user to choose whether the river level, aquifer level or reservoir level determines the demand restriction parameter, f_m.

The Policy-Maker Model uses an 'if' loop to calculate the demand restriction parameter for each time step, which is then implemented in the Water Demand Model in the next time step. This was considered to be acceptable due to time lags in the system, which prevents the demand restriction parameter being based on current reservoir, river or aquifer levels.

The 'if' loop used in the Policy-Maker Model is shown below, where the Percentage is the Percentage River, Reservoir or Groundwater Filled depending on which source is used to determine when to impose restrictions.

$Percentage$:

$90\% - 100\%$	$\Rightarrow f_m = 1$	(optimum)
$75\% - 90\%$	$\Rightarrow f_m = 0.7$	(hosepipe ban)
$60\% - 75\%$	$\Rightarrow f_m = 0.5$	(drought permit)
$45\% - 60\%$	$\Rightarrow f_m = 0.3$	(drought order)
$0\% - 45\%$	$\Rightarrow f_m = 0.2$	(emergency drought order)

3.12. Implementation of the SAS Model

MATLAB was used to write and run the model. In order for the 'if' loops to work correctly, a mixture of functions and loops within the master script were used. This ensured that the values for each parameter were updated at every time step and that the Policy-Maker Model component was correctly implemented in the model.

3.13. Giacomoni Model's Application to Arlington, Texas

In the paper by Giacomoni et al. (2013), the Giacomoni Model was applied to the city of Arlington, Texas, in the USA, to simulate part of the water supply [10]. The city has an area of 255km^2 with a population of approximately 390,000 with 55% of the residential water demand supplied by Lake Arlington [10]. The Village Creek Watershed supplies Lake Arlington with water and drains 370km^2 of mostly agricultural land, where 6.7% of the watershed area is within the city boundary [10]. By 2060, the population is expected to increase to 472,000 as the area of the city increases, converting rural to urban land [10]. A map showing the city of Arlington, the watershed area and the modelling area is shown below in figure 3.6.

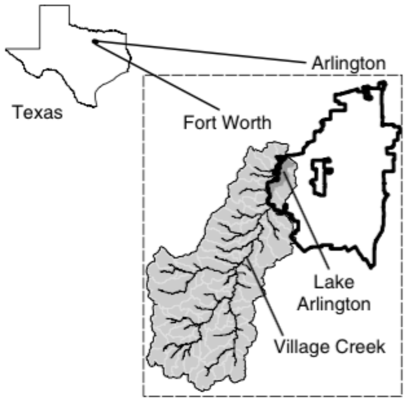


Figure 3.6: Map of Arlington (dark line), The Village Creek Watershed (shaded area) and the modelling area (dashed rectangular area) [10]

Three different rainfall scenarios, Mid-1, Mid-2 and Mid-3, were used, as shown in figure 3.7 [10]. These scenarios were repeated over the simulation period of 50 years in order to reduce the "influence of the high variability of climatic inputs" [10]. For each of the climatic scenarios, two simulation models were produced; a 'Giacomoni Model', where the policy-maker does not implement any water conservation or land-use restriction policies, and a 'Giacomoni Policy Model', where the policy-maker implements adaptive policies [10].

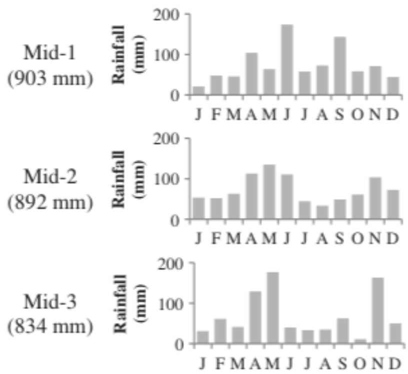


Figure 3.7: Rainfall scenarios [10]

The results of the Giacomoni Model and Giacomoni Policy Model are shown in figure 3.8. Figure 3.9 shows the implementation of the water conservation stages for the different climate scenarios.

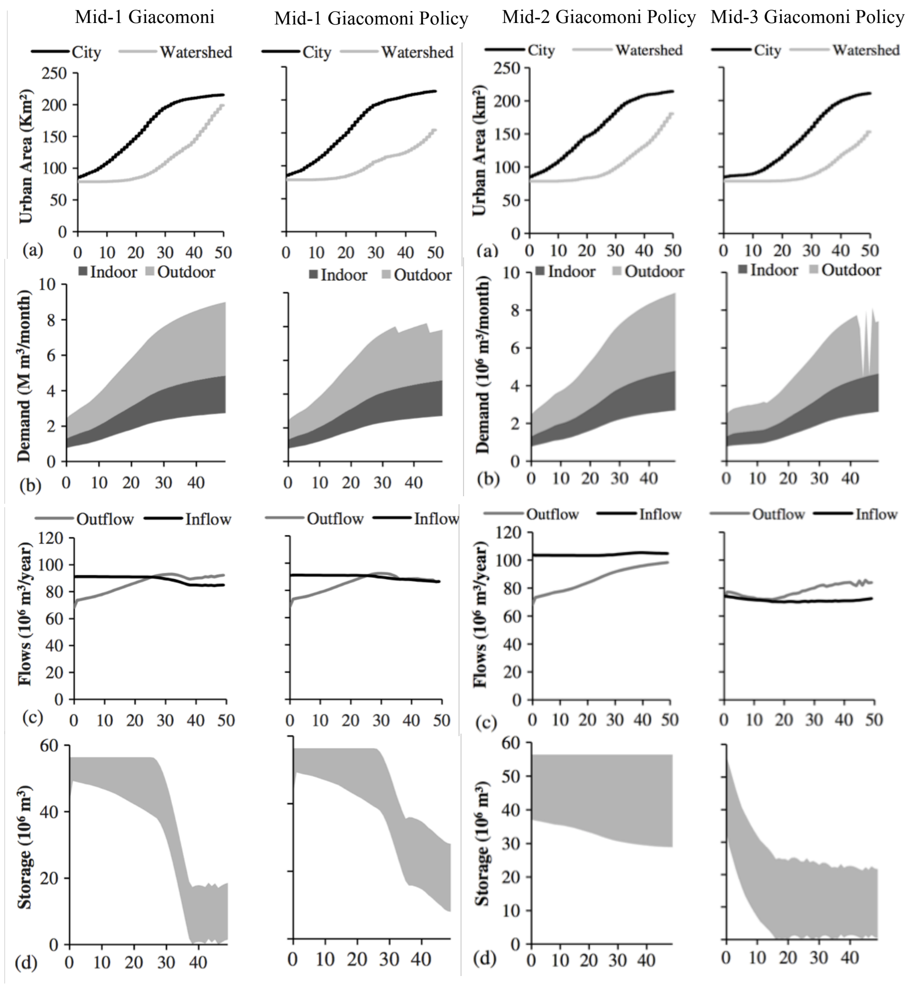


Figure 3.8: Mid-1 Giacomoni, Mid-1 Giacomoni Policy, Mid-2 Giacomoni Policy and Mid-3 Giacomoni Policy Results [10]

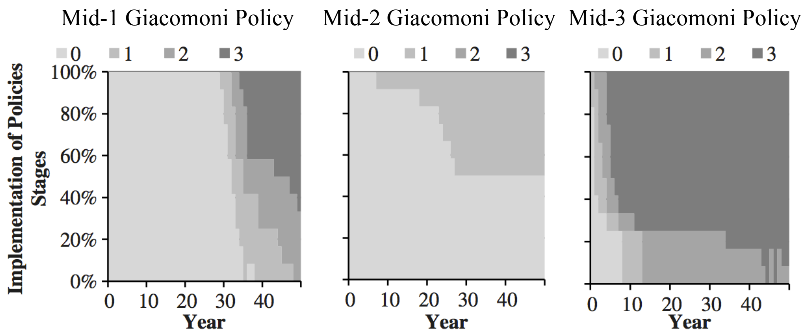


Figure 3.9: Implementation of water conservation strategy stages for Mid-1, Mid-2 and Mid-3 Giacomoni Policy scenarios [10]

Figure 3.9 demonstrates that as the amount of rainfall received by a watershed decreases, the extent to which the adaptive policies need to be implemented increases. This is shown by the Mid-3 climate scenario representing the lowest level of rainfall, causing adaptive policies to be implemented almost immediately [10]. Moreover, figure 3.9 shows that as the variation in monthly rainfall increases, the extent to which the adaptive policies need to be implemented increases. The Mid-2 scenario has more uniform rainfall throughout the year and results in a policy strategy implementation that only uses stages 0 and 1. However, the Mid-3 climate scenario has much more varied rainfall, resulting in lower reservoir storage, causing stage 3 of the policy conservation strategy to be employed for the majority of the simulation period. Furthermore, by comparing Mid-1 Giacomoni and Mid-1 Giacomoni Policy results, it shows that the implementation of conservation policies has the intended effect of increasing the reservoir storage and reducing water demand, by implementing higher stages of water conservation policies as the reservoir volume decreases, balancing the inflows and outflows of the system [10]. This demonstrates that the inclusion of adaptive policies allows the system to behave in terms of the feedback loops, restoring "balance to the water resource system" [10].

3.14. SAS Model Validation – Application to Arlington, Texas

The SAS Model was applied to Arlington as a preliminary means to test the methodology, similar to the Giacomoni Model. The aim of this was to model the water system of Arlington using, as far as possible, the same conditions, assumptions, and values used in the Giacomoni Model. This enabled the Giacomoni and SAS Models to be compared on a like-for-like basis. However, this proved to be difficult due to a lack of information presented in the Giacomoni et al. (2013) paper.

The simulation period used was 2010 to 2060 in order to match the simulation period used in the Giacomoni Model.

3.14.1. Population Growth Model for Arlington

The Giacomoni paper predicts that the population of Arlington will increase to 472,000 by 2060 from 390,000 [10]. Therefore, this scenario was used during the test.

3.14.2. Land-Use Change Model for Arlington

The watershed area is reported in the paper to be equal to 370km^2 and is "primarily agricultural land" [10]. This remained constant throughout the simulation period. The coefficient of runoff, C, was estimated to be 0.3 [54] initially, increasing steadily at a rate, d, of 1.0005, representing the increasing proportion of urban area. If the model were to be used for a real case study, the coefficient of runoff would be calculated for a certain time step using maps and information about the land use. The value of d would then be found by calibrating the model with actual data. In the case of Arlington, the simulation period is 2010-2060 and therefore, the calibration period would ideally be 2000-2010, or any period with available data. Once the model has been calibrated and the value of *d* has been found, the model can then be used to project forward and predict future land-use.

3.14.3. Water Demand Model for Arlington

In order to be able to compare the results from the Giacomoni and SAS Model, the residential and total demand have been separated so that it is possible to plot the residential demand in order to compare the results with those given in figure 3.8.

The water consumption per capita per day in Arlington was not disclosed. Therefore, the initial consumption was estimated using the results in figure 3.8. The residential demand was estimated to start at approximately 2.5Mm^3/month, and by using the initial population of 390,000 [10], the water consumption per person per day was calculated to be equal to 6.41m^3/month/person.

The industrial demand was also not disclosed, however this was initially estimated to be approximately 3,500m^3/month.

3.14.4. Watershed Model for Arlington

The Giacomoni Model repeats the same rainfall every year for the whole simulation period, with total rainfall values similar to that received in the area, as shown in figure 3.7. The SAS Model used the Mid-1 scenario to enable the models to be compared.

It was assumed that the streamflow to the reservoir was equal to the streamflow from the watershed, and therefore, the parameter *c* was set equal to one.

3.14.5. Reservoir Model for Arlington

The Giacomoni Model paper reports that the total capacity of the reservoir is 49.6Mm^3 [10]. The abstraction from the reservoir was calculated using the fact that the reservoir provides 55% of the city's total water supply [10]. Arlington also imports and exports water constantly throughout the simulation period, however, these values were not disclosed [10]. It was initially estimated that the amount of water imported was equal to 800,000m^3/month, and the amount of water exported was equal to 1,500m^3/month. The initial storage was also estimated to be equal to 30.5Mm^3, using figure 3.8 [10].

3.14.6. Policy-Maker Model for Arlington

The Reservoir Policy-Maker Model was used for Arlington since rivers and aquifers have not been modelled in this case, in order to match the Giacomoni Model as far as possible. However, due to the influence of the restriction parameter, f_m, on the water demand, the values of f_m used are different to those used in the Giacomoni Model. Furthermore, the stages used are different to those set out in section 3.2.8. so that they follow those used in the Giacomoni Model more closely.

The values used are shown below.

$$\begin{array}{ll} \textit{Percentage}: & \\ 75\% - 100\% & => f_m = 1 \\ 60\% - 75\% & => f_m = 0.7 \\ 45\% - 60\% & => f_m = 0.5 \\ 0\% - 45\% & => f_m = 0.3 \end{array}$$

3.14.7. Results

In order to be able to easily compare the results of the Giacomoni and SAS Model applications to Arlington, the graphs were produced to be as similar as possible to those in figure 3.8. However, figure 3.8 includes a graph showing the change in urban area within the city and the watershed. This graph will not be included since the policy-maker in the SAS Model is not able to control land-use change, and therefore, the rate at which the urban area increases is represented by the coefficient of runoff, C, which increases proportionally with time.

Figure 3.8 includes the inflows and outflows from the reservoir, which have been defined for the SAS Model as follows:

$$Inflow = Q_{reservoir} + Imports$$
$$Outflow = ReservoirAbstraction + exports$$

The Giacomoni Model results, given in figure 3.8, are unclear due to the way they have been plotted. However, for the sake of comparison, it will be assumed that the values to be compared are an average of the shaded regions. This was considered to be acceptable since the maximum capacity of the reservoir was disclosed to be 49.6Mm^3, and the shaded region extends beyond this value.

Figure 3.10 shows the results for the initial run of the model, with the input data presented in sections 3.14.1 to 3.14.6.

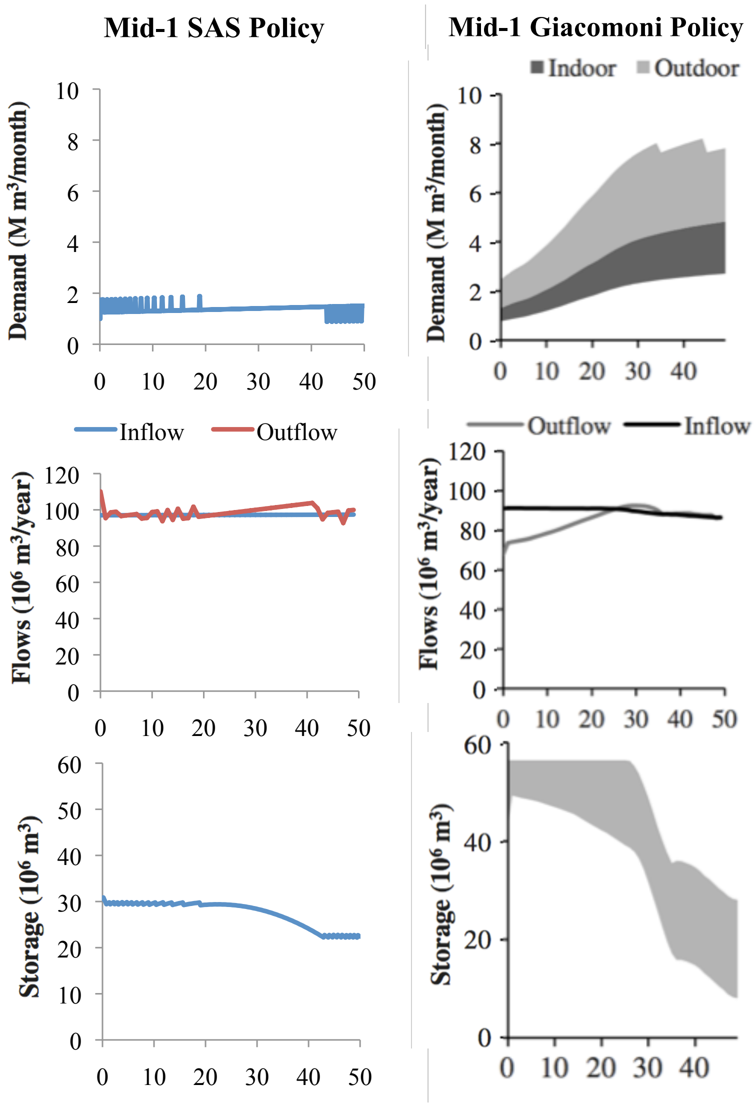


Figure 3.10: Mid-1 SAS Policy results (left) compared to Mid-1 Giacomoni Policy results [10] *(right) for residential demand, inflows and outflows, and reservoir storage*

As can be seen in figure 3.10, the results obtained from the SAS Model are not the same as those obtained from the Giacomoni Model. This prompted a series of changes to the input data in an effort to calibrate the model to get the results as similar to the Giacomoni Model results as possible.

The result of the calibration process is shown in figure 3.11.

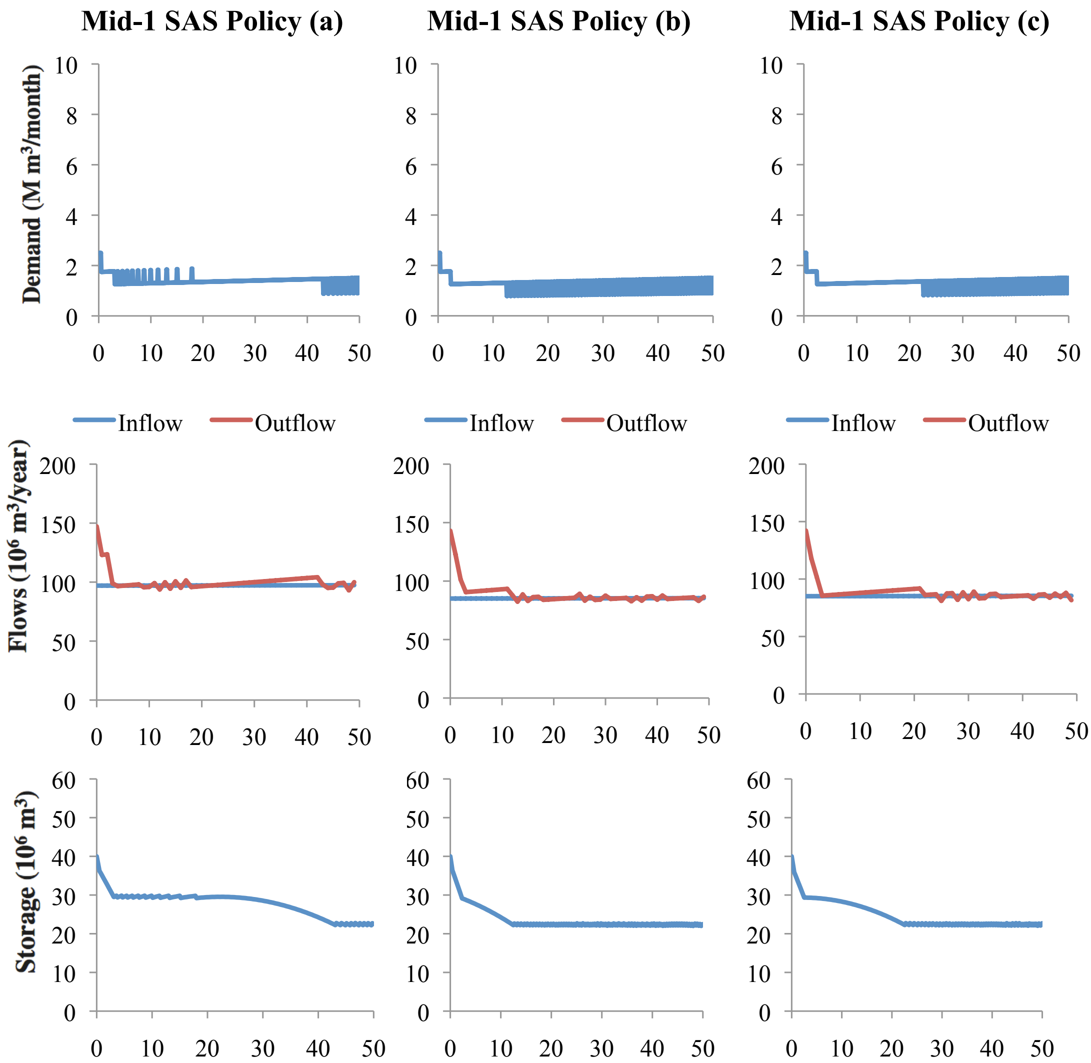


Figure 3.11: SAS Model results after calibration stages (a), (b) and (c) for residential demand, inflows and outflows, and reservoir storage

Figure 3.10 shows that the initial volume of the reservoir is far lower than the Giacomoni Model predicts. Therefore, calibration stage (a) involved increasing the initial volume of the reservoir to 40Mm^3. As can be seen in figure 3.11(a), this causes the initial demand to increase due to a higher initial value of f_m, resulting in a higher initial outflow value. However, after approximately 3 years, the demand, flows and reservoir storage return to the values predicted in figure 3.10. This is likely to be due to the structure of the model and the stabilising function of the Policy-Maker Model.

The flow values given in figure 3.10 are slightly higher than those obtained from the Giacomoni Model and therefore, calibration stage (b) involved reducing the imports and exports to 700,500m^3 and 1,000m^3 respectively, in addition to the changes made in calibration stage (a). Figure 3.11(b) shows the result of this calibration stage and shows that the inflow values are reduced and the outflow values are slightly reduced, although the initial demand remains high due to the increased initial volume from stage (a). Additionally, the storage has now reduced to the final value in a much shorter period of time. However, calibration stage (c) increases this period by approximately 10 years after reducing the extra demand from industry to 1,000m^3, in addition to the changes made in calibration stages (a) and (b). This does not affect the demand graph since it shows the residential demand only. However, this change barely affects the outflow from the reservoir since the value of extra demand is small in comparison to the residential demand.

As can be seen in figures 3.10 and 3.11, the SAS Model does not yield the same results as the Giacomoni Model. This is likely to be due to the lack of information required and the difference in structure between the two models in terms of the Policy-Maker Model components. The policy-maker in the US is able to influence both land-use change and water demand whereas the policy-maker in the UK is able to influence only water demand. In order to demonstrate the influence of the Giacomoni Model's policy-maker, the SAS Model's Policy-Maker Model component was removed, and calibrated in order to compare the Mid-1 SAS results with the Mid-1 Giacomoni Results, without the influence of the policy-maker. In order to calibrate the results, it was noted that the initial volume of the reservoir shown in figure 3.11 was too low and hence, the initial volume was increased to the maximum capacity of 49.6Mm^3. Furthermore, since the outflow from the reservoir was still too high at the end of calibration stage (c), the amount of exports and extra demand from industry was reduced to zero. However, the reduction in outflows was not sufficient and therefore, the percentage of demand supplied by the reservoir, S, was reduced to 50%, and the water consumption was reduced to 3.19m^3/month/person in order to reduce the outflow quantity further. The demand predicted by the Giacomoni Model increases at a higher rate than the SAS Model predicts in figure 3.11 and therefore, the Population Growth Model component was changed to predict that the population grows to 650,000 in 2060 instead of the initial prediction of 470,000. Lastly, the quantity of imports was increased to 750,000m^3 in order to increase the initial inflow. The results after calibration are shown in figure 3.12.

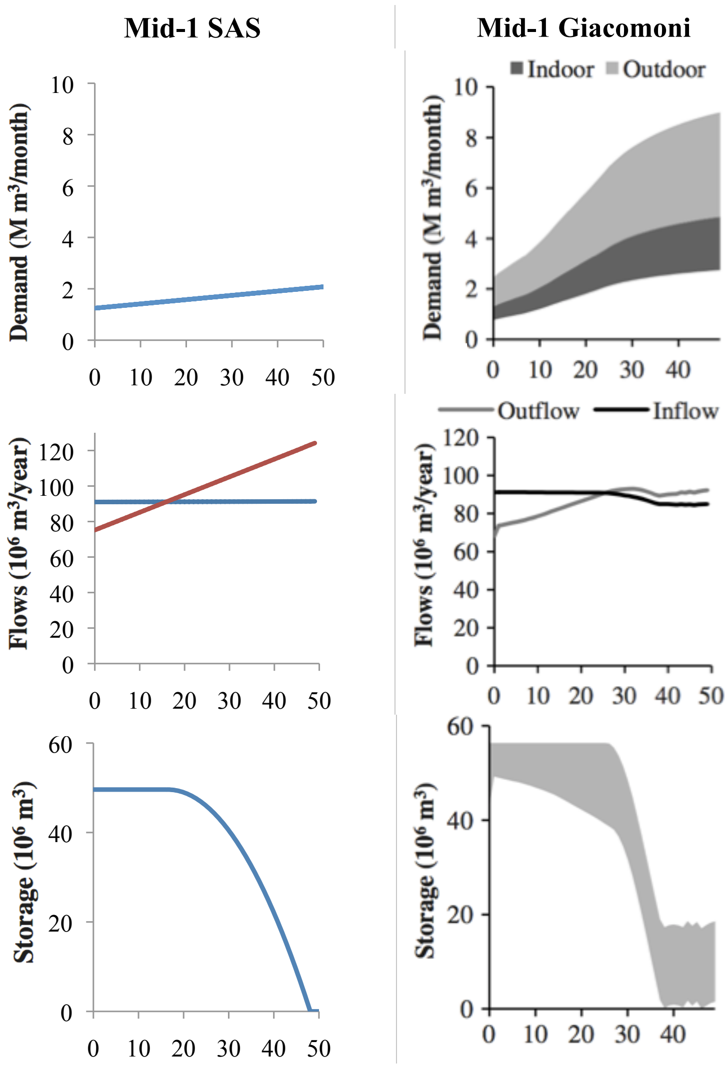


Figure 3.12: Mid-1 SAS results (left) and Mid-1 Giacomoni results [10] *(right)*

The results shown in figure 3.12 show a much stronger correlation between the results found from the SAS Model and the Giacomoni Model. The initial demand is approximately correct and it grows at a rate that is consistent with the indoor demand found by the Giacomoni Model. Furthermore, the flow into the reservoir and the flow out of the reservoir start at approximately the same values. The main difference however, is that the outflow continues to rise after it exceeds the inflow value, and the rate at which it increases is higher due to the increased rate at which the population grows. Hence, the point at which the inflow and outflow crosses occurs earlier than the Giacomoni Model predicts, due to the higher rate at which the outflow increases. The reservoir storage predicted by the SAS Model, however, is very similar to that predicted by the Giacomoni Model. Both start at the maximum capacity, continue for approximately 20 years and then fall to zero. The main difference between the model's predictions is that the Giacomoni Model predicts that the storage starts to fall much later and reduces quicker than the SAS Model predicts.

However, the similarity between the results found by the two models shows that the underlying structure and components of the SAS Model is sufficient to model and predict the expected demand, inflows and outflows, and reservoir storage. Therefore, the Policy-Maker Model component was added to this calibrated model in order to assess the influence of the policy-maker. The results are shown in figure 3.13.

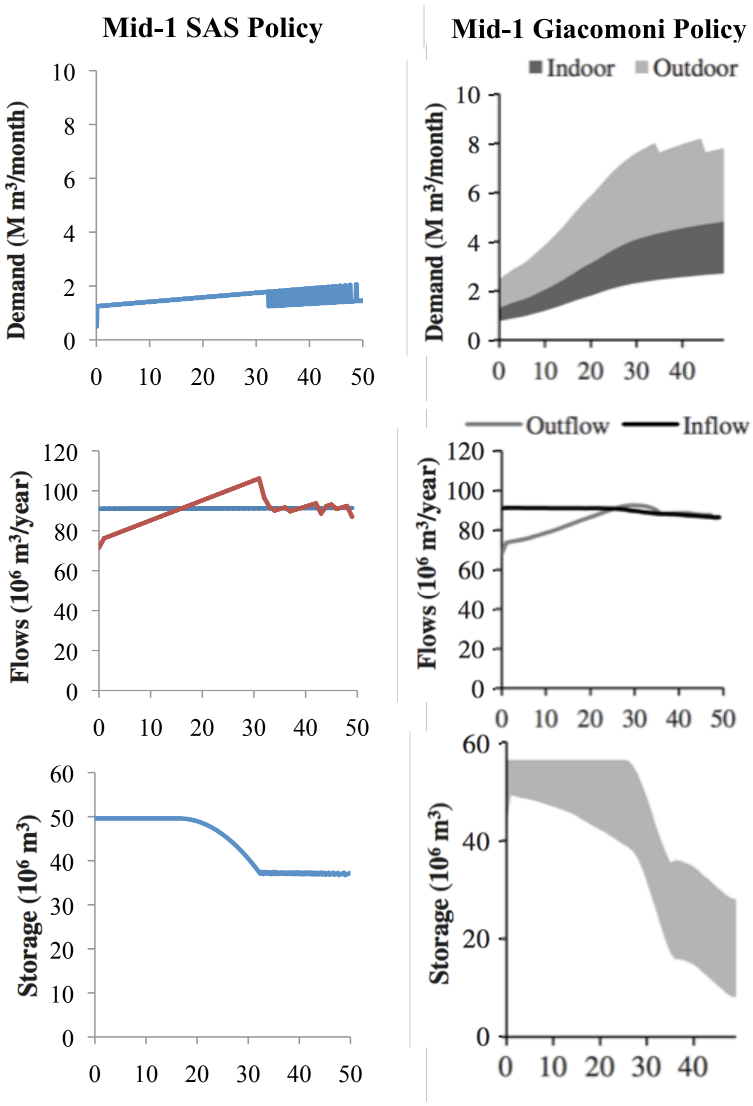


Figure 3.13: Mid-1 SAS Policy results (left) with Mid-1 Giacomoni Policy results [10] *(right)*

Figure 3.13 demonstrates that the introduction of the policy-maker results in a higher reservoir volume being maintained since the policy-maker is able to reduce demand and hence, outflows from the reservoir. However, the addition of the Policy-Maker Model component has resulted in more significant differences between the two models than found in figure 3.12. Therefore, it can be concluded that the reason for the differences in results in figures 3.10 and 3.12 is the Policy-Maker Model component. A policy-maker in the US is able to restrict land-use change as well as water demand. An investigation into the effect that a US policy-maker can have is outside the scope of this project. However, this raises an interesting side issue that highlights whether public or private utilities are better equipped to manage the sustainability of water resources supplying a city.

4. LUTON CASE STUDY

Luton was chosen as the use case for the SAS model because it was one of the few cities in which the proportion of groundwater, surface water and reservoir water used falls within one standard deviation to each side of mean. It is also of particular interest due to the sustainability reductions set out by the EA [5].

Luton is supplied by Affinity Water [52], and is located in WRZ3 [5]. The area imports water from Anglian Water's Grafham reservoir, providing 91Ml/day on average and 109Ml/day at peak times [5], [55]. After further communications with Affinity Water, it was revealed that Luton is "fed from a combination of local groundwater sources and imports from Grafham" [55]. Unfortunately, much of the information and data required to accurately run and calibrate the model was not disclosed by Affinity Water since the "information is classed as official sensitive, previously known as restricted" [56]. However, by the time the lack of information and difference in the sources used to supply Luton was revealed, it was too late to consider a different city. Nevertheless, if the model were to be used in industry, all required information would be available.

The planning period used in the Water Resources Management Plan (WRMP) is 25 years to 2040 [5]. Therefore, the simulation period that will be used when applying the model to Luton is 2010 to 2040 in order to validate and calibrate the model using 2010 to 2015 and 2015 to 2040 for predictions. Ideally, the calibration period would be larger, however, groundwater level data is only available back to 2010, given in section 4.8. [5].

4.1. Population Growth Model for Luton

The WRMP reports that the population in WRZ3 is expected to increase by 21% during the planning period [5], as shown in the table below.

	2012/13	2020	2040
WRZ3	699,253	732,431	845,584

The Population Growth Model will reflect these predictions in order to remain consistent with the WRMP. However, in order to model the population growth for Luton, ONS data was collected for Luton UA for 2012. This value was then used to calculate the predicted population in 2020 and 2040. This resulted in the values given in the table below.

Year	2012	2020	2040
Population for Luton UA	203,641 [57]	213,293	246,405

These values were used to create a trend line in Excel, selected using the R^2 value closest to 1, which was then used to find the population at each time step. This formed the population input for the SAS Model for Luton.

4.2. Land-Use Change Model for Luton

Affinity Water was unable to disclose exact information about the catchment area. However, research suggested that Luton is located in the catchment area for the Upper Lee River, which has a catchment area of 70.7km^2 [58]. A map of the catchment area is shown in figure 4.1.

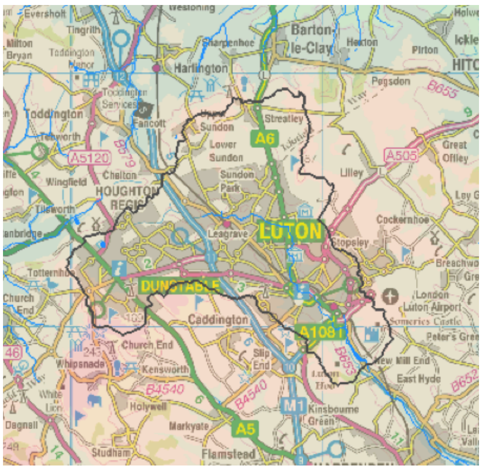


Figure 4.1: Map of the catchment area [59]

The catchment was described as being "substantially urbanised" [58], which can be seen in figure 4.1. It was estimated that approximately 70% of the catchment area is urban and the remaining 30% is suburban. Therefore, an approximate initial value of runoff coefficient, C, was calculated by finding the weighted average, using a value of 0.825 for urban land use and 0.325 for suburban land use [54], shown below.

$$C = 0.825 \times 70\% + 0.325 \times 30\% = 0.625$$

The constant, d, denotes the rate at which C increases, representing the expected urbanisation of the area. This was initially estimated to be equal to 1.0005.

4.3. Water Demand Model for Luton

The WRMP gives Per Capita Consumption (PCC) forecasts for the planning period without any intervention [5]. These values are forecasted for a Normal Year Annual Average (NYAA) using the average climate, a Dry Year Annual Average (DYAA) using a lower annual rainfall and a Dry Year Critical Period (DYCP) [5]. However, Affinity used the NYAA for the Weighted Annual Average Demand (WAAD) [5] and therefore, the NYAA will be used for this case study.

The PCC predictions for NYAA are given in the table below for WRZ3 [5].

	2012 (l/p/d)	**2014/15 (l/p/d)**	**2019/20 (l/p/d)**	**2024/25 (l/p/d)**	**2029/30 (l/p/d)**	**2034/35 (l/p/d)**	**2039/40 (l/p/d)**
WRZ3	153.71	151.98	148.61	144.69	141.75	139.61	138.11

The demand values were plotted on Excel in order to interpolate values for the other time steps, forming the water consumption input for the SAS Model.

Non-household consumption however, is expected to remain constant throughout the planning period since "non-household customers have implemented schemes to make significant reductions in water use" in recent years and therefore, there is little scope for future reductions [5]. Leakage and other minor components of demand will also be taken into account in order to calculate the total water demand, as shown below [5].

	Non-household consumption	**Leakage**	**Minor Components**
WRZ3	31.42Ml/d	36.91Ml/d	2.34Ml/d

However, these components of demand are for WRZ3 and not Luton UA. Therefore, the population for WRZ3 and Luton UA was used to scale the demand for Luton UA. This resulted in a combined demand for non-household consumption, leakage and the minor components of 20.58Ml/d.

4.4. WATERSHED MODEL FOR LUTON

Similar to the Giacomoni Model, the annual rainfall will be repeated throughout the simulation period in order to focus the analysis on the "interactions among system components" [10]. The rainfall data used will be based on the average rainfall received in Luton, shown in the table below, retrieved from the Met Office [60]. This is different to the WRMP, where Affinity used DEFRA climate predictions [5].

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rainfall (mm)	67	47.7	49.1	54.1	52	52.7	48.8	62.5	57.2	81.1	75	65.1

Communication with Affinity Water revealed that the supply of water to Luton includes water supplied from a reservoir that is owned by Anglian Water. Therefore, the reservoir will not be modelled in the Watershed Model component since the water from the reservoir is included in the imports to the region.

In order for $Q_{groundwater}$ to be calculated, the constant a is required in order to estimate the quantity of evapotranspiration. The constant a was estimated to be equal to 0.3 due to the high proportion of impervious land cover [61].

The values for $Q_{riverupstream}$ were validated by comparing them with actual streamflow data for the Upper Lee in 2013, shown in figure 4.2.

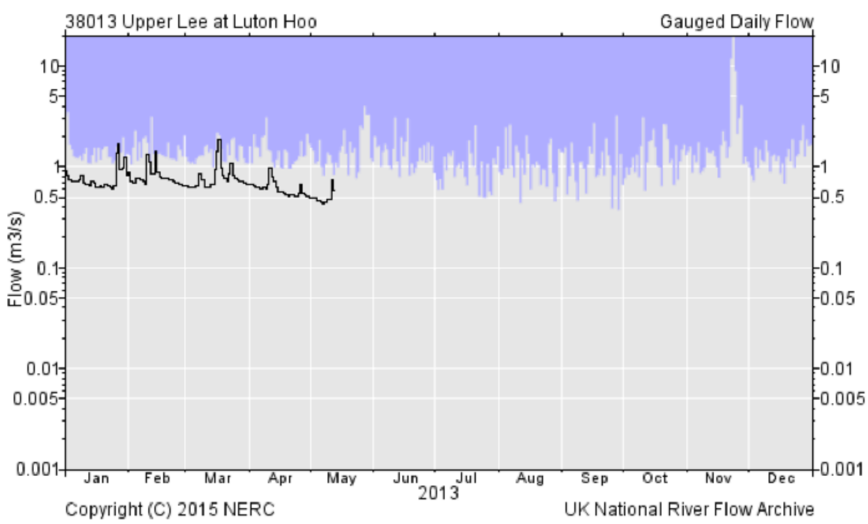


Figure 4.2: Actual streamflow data for the Upper Lee River [62]

4.5. AQUIFER MODEL FOR LUTON

The Aquifer Model component is very important for the Luton Case Study since the groundwater level is used by Affinity to determine the demand restriction parameter, f_m. Affinity has groundwater level records dating back to the 1960s [5], however, they were not able to disclose this information. Therefore, groundwater level data that dates back to 2010, given in the WRMP and shown in figure 4.3, was used for calibration purposes instead. The maximum groundwater volume was estimated to be 400Mm^3 with an area of 1.9Mm^2 and an initial volume equal to 180Mm^3.

The amount of water abstracted from the aquifer was estimated using the total demand for WRZ3 in 2011/12, and the average amount of water that is imported into WRZ3, since the remaining water must be provided by the aquifer. The demand in 2011/12 was equal to 176.89Ml/d and the average amount of water imported was equal to 91Ml/d [5]. Therefore, the percentage of water supplied by the aquifer, G, was estimated to be approximately 50%.

4.6. RIVER MODEL

The Upper Lee River is the river that runs through the city of Luton. However, the River Model component will not be used since the river level is not used by the policy-maker to determine the demand restriction parameter.

4.7. RESERVOIR MODEL FOR LUTON

As mentioned in section 4.4, Luton is not supplied from a reservoir owned by Affinity Water, and instead imports water from a reservoir owned by Anglian Water. Therefore, a reservoir will not be modelled. However, since Affinity imports and exports water to surrounding water companies [5], these will be included separately. For WRZ3, the import and export arrangements are shown in the table below [5]. These are not expected to change during the planning period since no new bulk transfers have been planned and existing transfers will remain the same [5].

Arrangement	Average Ml/d (max)	Peak Ml/d (max)
Anglian Water -> WRZ3	91	109
WRZ3 -> Cambridge Water	0.04	0.04
WRZ3 -> Anglian Water	0.14	0.14

The values in the table above give the transfers to WRZ3. However, the imports and exports to Luton are required and therefore, the values in the table above were scaled using the population of Luton UA and WRZ3 to give the values in the table below.

Arrangement	Average Ml/d (max)	Peak Ml/d (max)
Imports	26.5	31.7
Exports	0.053	0.053

Affinity Water also has the ability to transfer water between WRZs, however these will not be considered because the WRMP does not take them into account due to "limitations on pipe work, pumping stations or other infrastructure" that do not enable water to be pumped from any WRZ to any other WRZ [5].

4.8. Policy-Maker Model for Luton

Affinity Water uses the groundwater levels in "trigger observation wells" to determine when water demand restrictions should be imposed [5]. The trigger values used by Affinity in the central region are shown in figure 4.3.

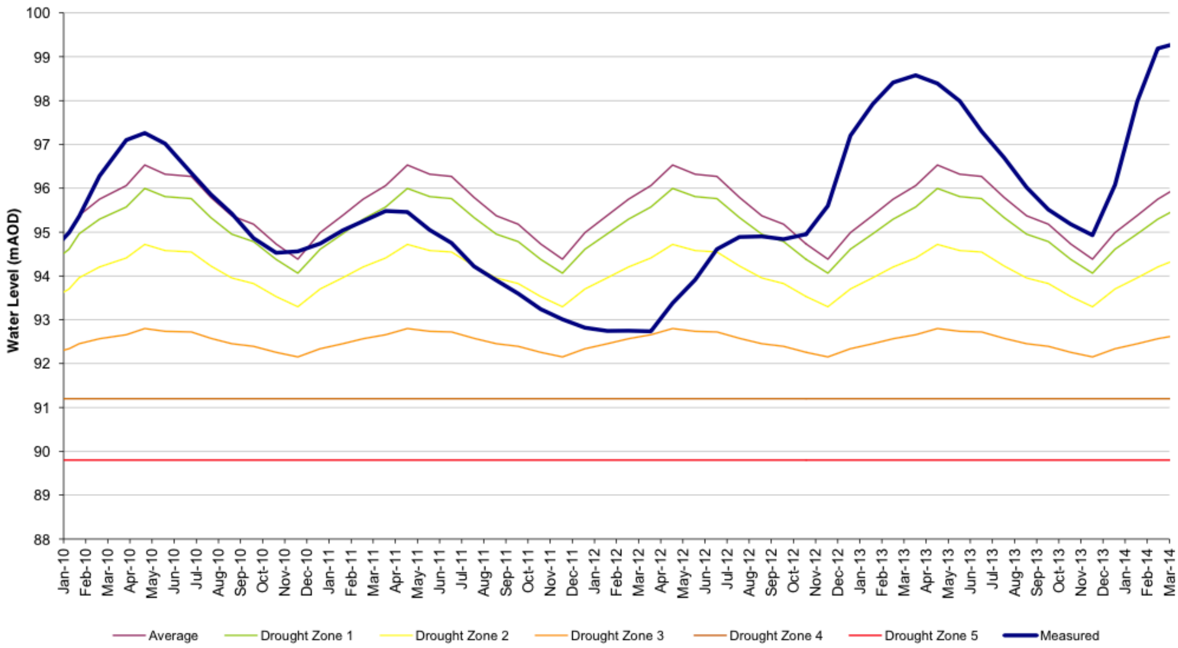


Figure 4.3: Groundwater Trigger Points and measured levels in the Central Region [5]

Therefore, the Policy-Maker Model will determine the demand restriction parameter using the groundwater level instead of using the percentage of the aquifer filled. The values used for the Policy-Maker Model component are given below.

Groundwater Level (m):

$95-100 \quad => f_m = 1$

$94-95 \quad => f_m = 0.7$

$92-94 \quad => f_m = 0.5$

$91-92 \quad => f_m = 0.3$

$90-91 \quad => f_m = 0.2$

4.9. RESULTS

The demand, groundwater level and streamflow calculated by the SAS Model using the values given in sections 4.1 to 4.8, are shown in figure 4.4.

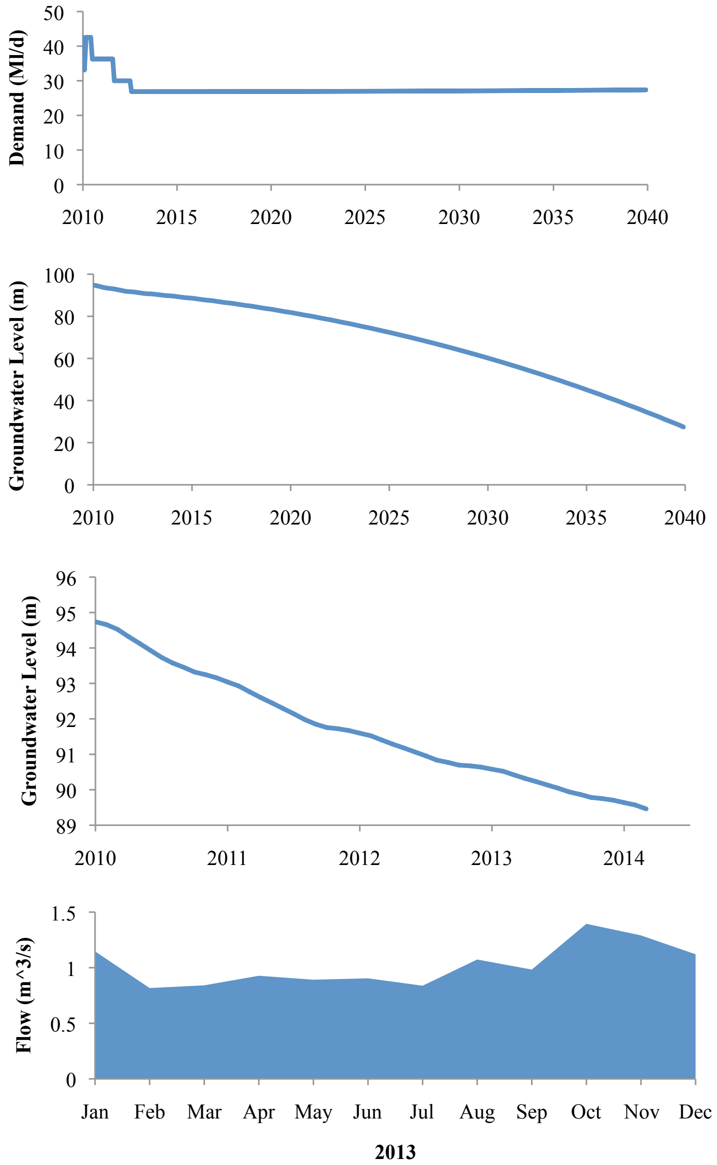


Figure 4.4: SAS Model Results for Luton before calibration

The streamflow calculated by the Watershed Model component, shown in figure 4.4 for 2013, was compared to the actual streamflow data provided by the EA, shown in figure 4.2. Both graphs give values that fluctuate between $1m^3/s$ and $1.5m^3/s$ and therefore, the streamflow calculated in the Watershed Model component is considered to be correct.

However, the groundwater levels calculated for 2010-2014, given in figure 4.4, are different to those given in figure 4.3. By comparing these two graphs it is evident that the aquifer used to supply Luton is being recharged more than the SAS Model is currently predicting. This is likely to be due to the lack of information available about the aquifer catchment. In order to account for the increase in aquifer recharge, the parameter a will be reduced from 0.3 to 0.2. This parameter determines the proportion of rainfall that evaporates and hence, by reducing this parameter, it increases $Q_{groundwater}$, representing recharge from elsewhere. The results after making this adjustment, and calibrating the initial volume, aquifer area and maximum volume to $18Mm^3$, $190{,}000m^2$ and $40Mm^3$ respectively, are shown in figure 4.5.

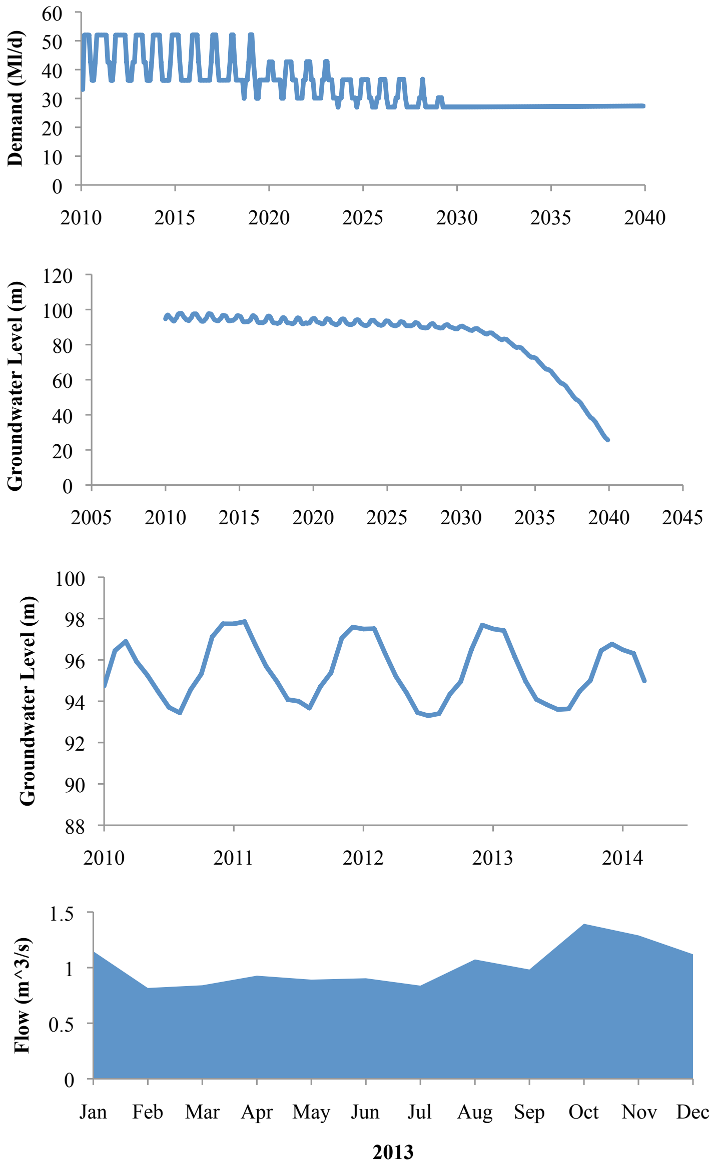


Figure 4.5: SAS Model Results for Luton after calibration

Figure 4.5 shows that the calculated streamflow is unchanged, however, the groundwater level calculated for 2010-2014 is far more consistent with the groundwater level measured by Affinity Water, shown in figure 4.3, since it fluctuates between 98m and 93m and varies seasonally. Further differences between measured and predicted groundwater levels are due to the fact that the SAS Model uses average rainfall data rather than actual rainfall data, and therefore, the levels are unlikely to match perfectly. Moreover, the lack of information available about the aquifer used means that the SAS Model has been forced to calibrate the model with the small amount of information that is publicly available. This suggests that the SAS Model is applicable to data-scarce situations, which the Giacomoni Model is not.

Figure 4.5 shows that the SAS Model predicts that the groundwater level in the aquifer that supplies Luton will begin to fall in year 2030. Additionally, the demand is predicted to fluctuate for the first 30 years as demand restriction methods are implemented as the groundwater level varies. The policy-maker implements different demand restriction methods in order to maintain the groundwater level of the aquifer. However, as the most severe demand restriction method is implemented in year 30, forcing the demand to its lowest possible level, the groundwater level falls as the abstractions continue without further recharge.

5. CONCLUSION AND FURTHER WORK

5.1. CONCLUSION

The Giacomoni Model is a complex and highly parameterised model with data requirements that make validation and calibration very difficult. The SAS Model that has been developed during this project has far simpler components with fewer parameters for calibration. The Giacomoni Model requires approximately 200 inputs, if not more, with the SWAT Model forming the majority of these inputs [63]. In comparison, the SAS Model requires a maximum of 23 inputs for both running the model and calibration. This enables the SAS Model to be applied to cities in data-scarce situations, which the Giacomoni Model is not able to do. The SAS model is still complex in that it combines many different models and systems to represent the interaction of different systems and feedback loops. However, the model components themselves are significantly simplified, enabling the model to be more easily applied to different cities around the UK since less data is needed which is not readily available in the UK. Although the information required for Luton could not be obtained from Affinity Water, the client for the model is the water company and therefore, a lack of information would not be a problem if the model were to be used in industry.

By comparing the Giacomoni Model with the new SAS Model that has been developed in this project, the benefits of the SAS Model are clear. It enables not only reservoirs to be modelled, but also rivers and aquifers, allowing the SAS Model to be applied to all cities in the UK. This allows the Policy-Maker to monitor the reservoir level, river level or groundwater level to determine the demand restriction parameter. The SAS model is therefore, much more adaptable than the Giacomoni Model which restricts its applicability to cities which only use reservoirs, if the whole water supply system is to be modelled.

The application of the SAS Model to Arlington demonstrates how easy it is to apply to a city and calibrate. The results obtained showed that the underlying SAS Model is sufficient to predict the demand, inflows and outflows of a reservoir, and reservoir storage. However, introduction of the Policy-Maker Model component drew attention to the different impact that a policy-maker in the US can make compared to a policy-maker in the UK.

The Luton case study results further demonstrate the success of the SAS Model in a data-scarce situation. The results obtained support the order from the EA to reduce the amount abstracted from aquifers, in what they have termed 'sustainability reductions'. However, the results also suggest that the trigger values and restriction methods currently used by Affinity are not sufficient to maintain the supply of water to Luton in the future.

The application of the SAS Model to both Arlington and Luton proves how flexible the model is since one or more of the reservoir, aquifer and river models can be used depending on the city being modelled, and the water sources it uses.

5.2. Further Work

Although water companies in the UK are not able to influence urban growth, the Policy-Maker Model could, in future, be adapted to include a public body as well as the water company in order to incorporate restrictions on urban growth. In the UK, in particular, urban growth could be slowed if there is a lack of water supply by preventing the construction of new housing developments in and around cities. The effect of this coordination between public and private bodies should be investigated in order to make a recommendation as to whether this would be beneficial or detrimental to the sustainability of the urban water supply.

The model should also be applied to other cities in the UK with a full set of data, and one that preferably uses all three water sources, in order to prove the effectiveness and usefulness of the SAS Model.

Further investigation could be conducted to determine the minimum level of complexity that a model must have in order to be successful. Complexities could be added to the SAS Model to determine the optimum level and investigate trade offs between data required and successful results.

Further investigations into the effect of the threshold values and demand restriction methods used by the policy-maker could be conducted to determine the optimum arrangement that will result in sustainable water resources.

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APPENDIX A: RISK RETROSPECTIVE

The risk assessment completed at the beginning of the project cited risks and hazards associated with the use of a computer. This covered the extent of the hazards encountered throughout the duration of the project. Relevant measures were taken including the use of an ergonomic workstation, sufficient lighting and regular breaks.