Water resource vulnerability: simulation and optimisation models

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Approaches to adaptation to a changing climate in water resource planning have relied on both simulation and optimisation models. Simulation models project the impacts of climate change on water system performance, while optimisation models show the optimal system performance under climate change conditions. This study uses two water resource models to analyse a water resource system in Sussex (south-east England) under climatic and socio-economic uncertainty. Overall, the simulation and optimisation models show structural model uncertainty. The simulation model highlights potential vulnerability in current operational practice, while the optimisation model shows that the current system could be vulnerable to climate change and demand growth even under the best-case scenario. The integrated scenarios in this study combine both climate scenarios from four different climate products over the periods of 2020s, 2030s and 2050s and socio-economic scenarios represented by different demand profiles. The results show that water demand quickly becomes a controlling factor once it increases by more than 35% from the 2007 baseline level. Both models demonstrate a gradual increasing risk of supply deficit in the 2020s and the 2030s. Water deficit risks vary widely in the 2050s and are highly dependent on the socio-economic scenarios.

1. Introduction

Under the pressure of population growth and climate change impacts, water resource vulnerability has manifested across scales and locations (Alcamo and Henrichs, 2002; Gan, 2000; Jain *et al*., 2002; Oki and Kanae, 2006). At the global scale, Vörösmarty *et al*. (2000) have used the water balance model to show a significant increase of vulnerability to water scarcity by the 2020s. Similarly, Arnell (1999) showed an increasing vulnerability of global water resources from the 2020s to the 2030s. However, his analysis for the 2050s also highlighted that different versions of the same model produce inconsistent projections of whether water stress would reduce or increase (Arnell, 1999). On a local scale, Fowler *et al*. (2003) showed that water resources in Yorkshire, England, would likely be vulnerable to severe drought events by the 2080s, while Lopez *et al*. (2009) demonstrated high vulnerability of water resources in south-west England by using 246 simulations from a larger perturbed physics ensemble of one climate model.

As such, adaptation to a changing climate has become a pressing need for planning of water resources. Traditionally, water planners and managers often utilise simulation and optimisation models to explore system performance under multiple options and select the best possible option (Loucks and Van Beek, 2005). In adaptation studies, simulation and optimisation models have been used in applications, as done by Kasprzyk *et al*. (2013) and Matrosov *et al*. (2013a, 2013b). Simulation models generate system
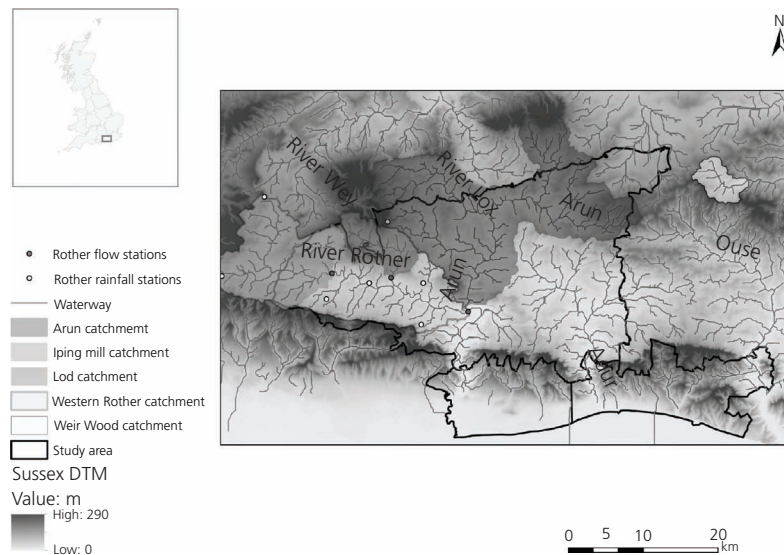
performance under a set of conditions, while optimisation models seek to find operation that gives rise to the best available system performance under such conditions. The former approach offers a comparative analysis of available options, while the latter provides a speedy assessment of the best available option according to the decision-makers' criteria.

This paper focuses on the potential implications of modelling choices on the assessment of vulnerability in a water resource system. In particular, this study questions whether such choices may highlight different vulnerabilities of the water resources system and, therefore, lead to different emphases of adaptation decisions. The study uses a case study in Sussex, south-east England, as an example. Section 2 describes the methodology used in the vulnerability assessment, including the incorporation of the uncertainty factors and the water resource models. Section 3 presents the results and a discussion of the results. Section 4 then summarises the key vulnerabilities of the Sussex water resource system to uncertainty.

2. Methodology

2.1 The study area

The study area is in Sussex in south-east England (Figure 1), a region under great pressure to adapt to population growth and climate change. These two elements have become two major new challenges for the area, with 15% of its water resource zones

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Figure 1. Map of the study area. Data courtesy of the Ordinance Survey, Centre for Ecology and Hydrology, Wallingford, and British Geological Survey 2012

seriously water stressed (Cave, 2009). Climate change, a deep uncertainty in planning, is also a big driver of changes in the water supplies (Arnell and Charlton, 2009).

The area is divided into three subareas: North Sussex, Worthing and Brighton. North Sussex is drained by the tributaries of the Rother (often called the Western Rother to distinguish from the River Rother in East Sussex), the Adur and the Arun. Among these rivers, the Rother and the Arun constitute important water resources for North Sussex. Meanwhile, water resources in Worthing and Brighton mainly rely on groundwater. Geologically, the whole study area overlays the Chalk and the Greensand aquifers, which produce moderate to high groundwater yield. The water supply of the area relies on the Rother, the Arun and various groundwater boreholes in the Worthing and Brighton areas. The water resources of the area are managed by Southern Water Services Ltd, a private company of Greensand Investments Limited. This water company originates from Southern Water Authority, a pre-1989 public water authority, and still retains various management practices and facilities of its predecessor.

2.2 The scenarios
Scenarios, as descriptions of potential future conditions, can help inform decision-making under uncertainty. Uncertainty can stem from either socio-economic and biophysical factors or often from both (Parson *et al.*, 2007; Weaver *et al.*, 2013). Scenarios can therefore be categorised into main uncertainty or influencing factors, such as climate scenarios and socio-economic scenarios (Downing *et al.*, 2003). The integrated scenarios in this study combine both types, including climate scenarios from four different climate products over the periods of 2020s, 2030s and 2050s and socio-economic scenarios represented by different demand profiles.

2.2.1 Climate and streamflow scenarios
In this study, climate scenarios from four climate products are used (Table 1). As the table illustrates, two climate products are altered observations using projected change factors and the other two are modelled data of the future periods. The chosen emission scenario is the Medium Emission Scenario. The CATCHment MODel (Catchmod) used in this study is a water balance model that has been used by the UK Environment Agency (EA) for various catchments. The model uses six key parameters, which are explained in detail by Wilby and Harris (2006). In essence, the model divides the study area into various contributing zones. Model parameters are the area of the zones, direct percolation (the fraction of precipitation infiltrating pass the soil horizon, potential drying constant), gradient of the drying curve, linear storage constant and non-linear storage constant. This study uses the Catchmod set of parameters used in the water company's 2009 Water Resource Plan. The chosen climate projections for the study area are based on the results of the Hadley Centre Regional Climate Model HadRM3 (hereby termed the RCM). Other climate projections used in the study include 10 000 Change Factors of the 2009 UK Climate Projections (UKCP09), the 11 Spatially Coherent Projections (SCPs) of UKCP09 and the Future Flows (FF) downscaled data from the 11 HadRM3 runs. They are all valid sources of climate information and have been applied in various impact and adaptation studies (Bell *et al.*, 2012; Wade *et al.*, 2013). The UKCP09 10 000 Change Factors are based on a complex methodology that includes the 11 HadRM3 simulations, many simulations of the Hadley Centre global climate model (GCM), other GCMs and a Bayesian emulator (Murphy *et al.*, 2010). The UKCP09 product adopts a probabilistic approach to represent climate change projections; this approach encapsulates a larger range of results than in previous climate scenarios and

Product name	Acronym	No. of members	References	Source	Period	Climate scenario	Spatial resolution	Temporal resolution	Grid squares used	Method	Uncertainty sampled
Hadley Centre Regional Climate Model HadRM3 PPE	RCM	11	Murphy et al. (2010)	The UK Met Office Hadley Centre	1950–2099	Historical and medium (SRES A1B) emissions scenario	25 km grid	Daily	3	Dynamic downscaling of a GCM with simplified ocean model	Regional atmospheric and land processes; different GCM boundary conditions
Spatially Coherent Projections of UKCP09	SCP	11	Sexton et al. (2010)	Similar to UKCP09	Time slices of 2020s–2080s	4 SRES scenarios	25 km grid	Absolute daily values/monthly change factors	3	Linear scaling of the RCM data based on the changes in global temperature from the GCM results	Global temperature changes from emission scenario, carbon cycle, sulfur cycle and ocean physics
FF Project – Statistically Downscaled HadRM3	FF	11	Prudhomme et al. (2012)	The Centre for Ecology and Hydrology	1950–2069	Historical and medium (SRES A1B) emission scenario	1 km grid	Daily	29	Statistically downscaled RCM data based on historical 1 km gridded data	Same as RCM's, bias corrected to a local spatial scale
UK Climate Projections 2009 (Land Projections)	UKCP09	10 000	Murphy et al. (2010)	The UK Met Office, UK Climate Impacts Programme, British Atmospheric Data Centre, University of East Anglia, Newcastle University	Time slices of 2020s–2080s	4 SRES scenarios	25 km grid	Absolute/monthly change factor to be applied on the historical 1961–1990 baseline	1	Bayesian statistical framework drawing from ensembles of Met Office climate models and other GCMs	Structural uncertainty using alternative climate models; emission scenarios; the carbon cycle, sulfur cycle and ocean physics

SRES, The Intergovernmental Panel on Climate Change's Special Report on Emission Scenarios

Table 1. The four climate products used in the study

enables the quantification of uncertainty. Yet these projections have received criticism for the lack of interannual variability and spatial correlation among the grids (Chun *et al.*, 2013). By contrast, the 11 runs of the HadRM3 are spatially coherent and include temporal variability but lack the probabilistic ranges of UKCP09. Furthermore, the RCM runs might require bias correction before being used for hydrological models. Based on the original RCM data and historical gridded rainfall data, the FF project had bias correction and further downscaled the RCM data. These two sets of outputs thus also have different spatial resolutions, with the UKCP09 grids being 25 km × 25 km and the FF grids being 1 km × 1 km. The streamflow scenarios were generated from the hydrological model Catchmod (Wilby, 2005) using rainfall and potential evapotranspiration (PET), the latter being calculated using the temperature-based Oudin equation (Oudin *et al.*, 2005).

2.2.2 Socio-economic scenarios

The focus of this study and the models used is on domestic water supply and therefore does not include industrial water use. Household water demand projections in the 2020s and the 2030s were based on Southern Water's projections from their 2009 Water Resource Management Plan. In this plan, Southern Water extrapolates the average and peak demands for the period 2009–2034, thus covering part of the 2020s and 2030s periods (Southern Water, 2009). The average dry year demands in 2024 and 2034 were selected to act as a representative demand for the 2020s and the 2030s, particularly during dry periods. The daily pattern of the demand profile was based on the estimated 1995 water demand and linearly scaled to produce the 2020s, 2030s and four 2050s demand profiles. The projected annual demand in 2007–2034, which covers the 2020s and 2030s periods, was prepared by Southern Water based on assumptions on population growth, household number, metering proportion, metering effect and per capita consumption. At the time of the study, projections from the water company for the 2050s were not available. Therefore, the figures used figures were from the 2050s Foresight Water Scenarios, which project changes in total water demand based on factors such as per capita consumption, population and household.

For the 2050s, this study used the EA 2050 scenarios (EA, 2008). The 2007 annual water demand was used to produce the four 2050s demand profiles under the corresponding socio-economic scenarios described by the EA scenarios, which use a 2006/2007 baseline. While the 2020s and 2030s Southern Water's projections are based on extrapolated water demand, the Foresight Scenarios by the EA (Berkhout and Hertin, 2002; SPRU, 2002) provide a more general assessment of societal trend in the future, including water demand. These scenarios describe alternative socio-economic states of future society based on a spectrum of consumers' and policymakers' choices. They reflect the potential varying degrees of sustainability awareness in governance – that is, sustainability against short-term socio-economic concerns. The scenarios were named Sustainable Behaviour, Innovation, Local Resilience and Market Forces. Each of these scenarios reflects a

different mode of governance and consumption (EA, 2008). In essence, the projected changes are as follows.

- *Innovation*: The total demand reduces by 4%, the water per capita consumption (pcc) is 125 (l/d)/capita and the population grows by 35%. The responsibility to find adaptation strategies lies with the government and scientists; demand reduction is due to sustainability-led governance and technological innovation.
- *Market Forces*: The total demand increases by 35%, the pcc is 165 (l/d)/capita and the population grows by 45%. Water demand is driven by the market trend, focusing on cost optimisation and growth.
- *Local Resilience*: The total demand increases by 8%, the pcc is 140 (l/d)/capita and the population grows by 25%. People realise the need for demand reduction and take actions towards it. Their efforts, however, are moderate due to the low priority of demand saving and the lack of incentives from the government.
- *Sustainable Behaviour*: The total demand declines by 15% due to proactive demand reduction from individuals; the pcc is 110 (l/d)/capita, and the population grows by 20%.

2.3 Water resources models of the current Sussex area

The Sussex area has been modelled by a simulation model (Wade, 2005) and an optimisation model (Atkins, 2009). These models are designed for different purposes. The former model was used to study the deployable output of the area given changes in flows of the Rother River and domestic water demand. The latter was used for the recent water resources management plan to analyse the area's water shortage and appraise planning options. They have both been used for water resources planning in the area. Given the different structures of these models, the study uses these models to explore whether model choices may highlight different vulnerabilities of the water resources system. Such differences, arising from using different model structures to characterise the study area, are classified as structural uncertainty (Beven, 2009). The study preserves the details of each model, such that the optimisation model has more details of the Sussex water delivery network than the simulation model does. This study uses three models to demonstrate model structural uncertainty on vulnerability analysis as follows.

- *The reference model*: The reference model in this study is the water resource model used by the water company and their consultancy company. They used Aquator, a water resource software application by Oxford Scientific Software Ltd. This model was constructed by Atkins Ltd for Southern Water's Water Resource Management Plan 2009 and other planning reports.
- *The Visual Basic .Net (VB.Net) simulation model*: This model was coded in VB.Net based on an Excel-based model by Wade (2005). The model shows demand-supply interactions of North Sussex, which consists of the River Rother, Weirwood and Hardham groundwater and other groundwater

sources and transfer to and from other water companies (South East Water and Portsmouth Water). The model can use time series for groundwater sources and demand profiles. These regional demands were constructed by summing the relevant individual demand profiles of the Aquator model. Like the Aquator model, the groundwater nodes are subject to daily and annual licenses. In this study the model uses these licenses to determine available groundwater abstraction, such that water can be withdrawn from the groundwater sources until reaching the maximum amount permitted by the daily and annual licences. This model simplifies the Aquator model to the scale of water resource zones, with each zone consisting of major proxy nodes instead of individual Aquator nodes.

■ *The Generalised Algebraic Modelling Software (Gams) optimisation model*: This model was coded in Gams based on a summary note of the Aquator model. The model simplifies the Aquator model but retains more details than the simulation model. The optimisation model additionally includes the Worthing and Brighton areas, but the deficits of each region are still separated and therefore can be compared to those of the simulation model. Compared to the simulation model, the optimisation model has more detailed modelling of the water

flows, including the transfer capacity in each link. Each scenario requires three model runs. For each scenario, the model first minimises total deficits in environmental flows; it then minimises the supply deficits while maintaining environmental deficit at that minimum level. Finally, the model minimises the operational cost of pumping and delivering water supply. This cost was based on model specification of the Aquator model, with slight alteration to reflect the supplying priority of the source nodes. Compared to the simulation model, the optimisation model has a more detailed network configuration. In this model and the Aquator model, the Weirwood reservoir can supply only for part of the network instead of the whole Sussex demand as in the simulation model.

Table 2 presents the main differences of the three models. The reference Aquator model is the most complex model but with the longest running time. On the other hand, the simulation model and the optimisation model have a shorter running time due to their simplified network version and simpler visual interface compared to the reference model. The reference has a detailed network structure, with transfer constraints on many links, particularly in the Worthing and Brighton areas. Meanwhile, the optimisation model

	Reference model	Simulation model	Optimisation model
Software description	■ Commercial software used by water companies and other consultancy companies in water resource planning ■ Has a GUI	■ VB.Net program coded by Lan Hoang based on Wade (2005) ■ Has a simple GUI, very little visualisation	■ Gams program coded by the lead author based on the Aquator Sussex model ■ Can be used for other model network by changing the input files ■ No GUI, linked to a Python visualisation tool
Timescale	Daily	Daily	Weekly
Spatial scale	Includes North Sussex, Worthing and Brighton	Includes North Sussex, Worthing and Brighton	Includes North Sussex, Worthing and Brighton
Spatial resolution	Individual supply and demand nodes within each region	Regional demands	Simplified nodes from Aquator network
Calculation mode	Optimisation/simulation	Simulation	Optimisation
Annual groundwater licenses	Yes – individual nodes	Yes – regional nodes	Yes – regional nodes but finer scale than those of the simulation model
Reservoir control curve	Yes – partially implemented	No	Yes – can be partially or fully implemented
Demand profile	Modified 1995 regional demand profile downscaled to the node level	Modified 1995 regional demand profile at the water resource zone level	Modified 1995 regional demand profile at the sub-water resource zone level
Running time	~30 min per run	~15 s per run	~2 min per run

GUI, guided user interface

Table 2. Comparison of the three water resource models

and the simulation model implement transfer constraints at the regional level – for example the link between North Sussex and Worthing. Additionally, the optimisation retains more details of North Sussex and Brighton than the simulation model. Yet the optimisation model runs on a weekly time step, while the reference model and the simulation model use a daily time step. Model uncertainty due to different model structures and algorithms was analysed using a 1888–2005 reference input data. The input data for the future climate contain the full set (11 members) RCM, FF and SCP and a sampled set of UKCP09 data (100 for the optimisation model and 1000 for the simulation model) for each of the time periods 2020s, 2030s and 2050s. Socio-economic scenarios in the model consist of one universal scenario for the 2020s and 2030s and four EA scenarios for the 2050s, as described in Section 2.2.2. The vulnerability of the study area to droughts was subsequently analysed through the simulation and the optimisation models using climate and socio-economic scenarios.

3. Results and discussion

3.1 Model evaluation against the reference model

This section compares the performances of the three models based on the state of the Weirwood reservoir from 1888 to 2005. For less severe events, the simulation model tends to be more conservative and empties the reservoir less than the reference model. The reference model mimics hosepipe bans, which reduce water demand every time the Rother flows are below the 90th percentile of the Rother curve (the mean daily flows during the 1961–1990 period), and therefore reduces demand pressure on Weirwood. The Weirwood reservoir also follows a control curve, which shows the minimum storage before the reservoir can release water. An example of a control curve is shown in Figure 2. If the control curve is applied when the Rother flows are higher than the recession curve, the Weirwood time series of the optimisation model become close to those of the reference model,

in particular during the 1921/1922 drought (Figure 3). The optimisation model still exhibits a slight tendency to not take the full inflows, due to its optimisation mode, which aims to reduce the total duration of water deficits within the whole period.

The simulation model appears to perform reasonably well compared to the reference model if the state of Weirwood Reservoir is used as an indicator. To characterise the correlation, firstly, this study uses the Spearman coefficient, a measure of whether one variable is statistically dependent on another variable. If the absolute value of the Spearman coefficient is close to 1, the two variables are more likely to have the same sign. Secondly, the study uses the Pearson coefficient, which has the value of 1 or −1 if there is total linear dependence between two variables. In particular, the Spearman coefficient of Weirwood storage between the simulation model and the reference model is 0·89 and the Pearson coefficient is 0·84. Both models identified the 1921/1922 drought as the most serious drought event of the time series. A comparison example of the specific reservoir state is depicted in Figure 3, which compares the reference model and the optimisation model.

Overall, the three models show structural uncertainty by using different algorithms and optimisation/simulation mode. These differences can contribute to the different supply deficit in each model (Table 3). A contributing factor is the network specification of each model, as the reference model is constrained by transfer capacity and has to rely on Weirwood in certain nodes; meanwhile, the simulation model and the optimisation model have a more relaxed constraint and therefore can be less dependent on Weirwood. The application of the control curve in each model also creates a slight discrepancy. Nevertheless, the control curve was left in the optimisation model because planning was done in prescriptive mode and the control curve would help preserve reservoir storage. As such, they can highlight potential
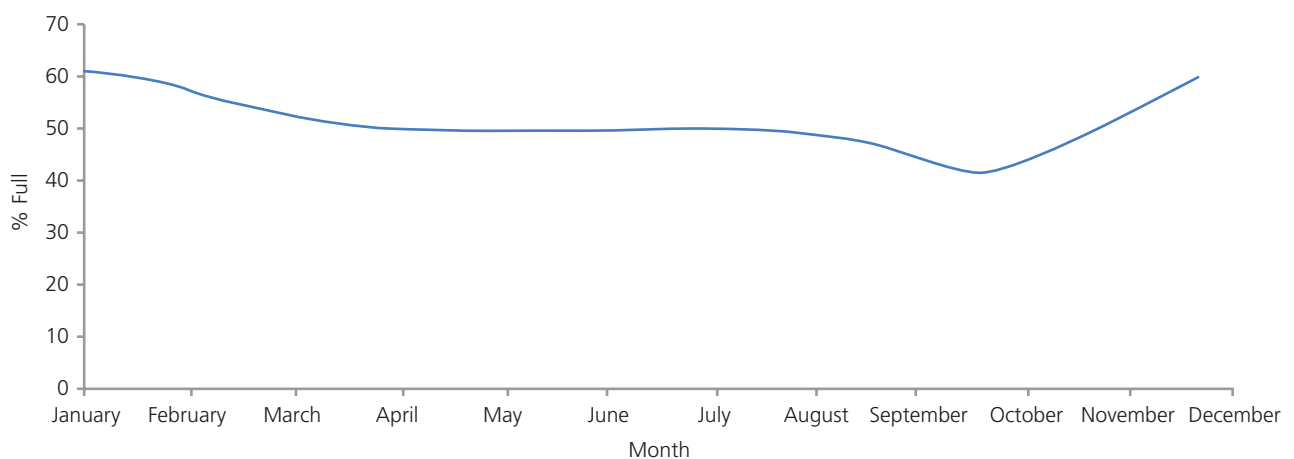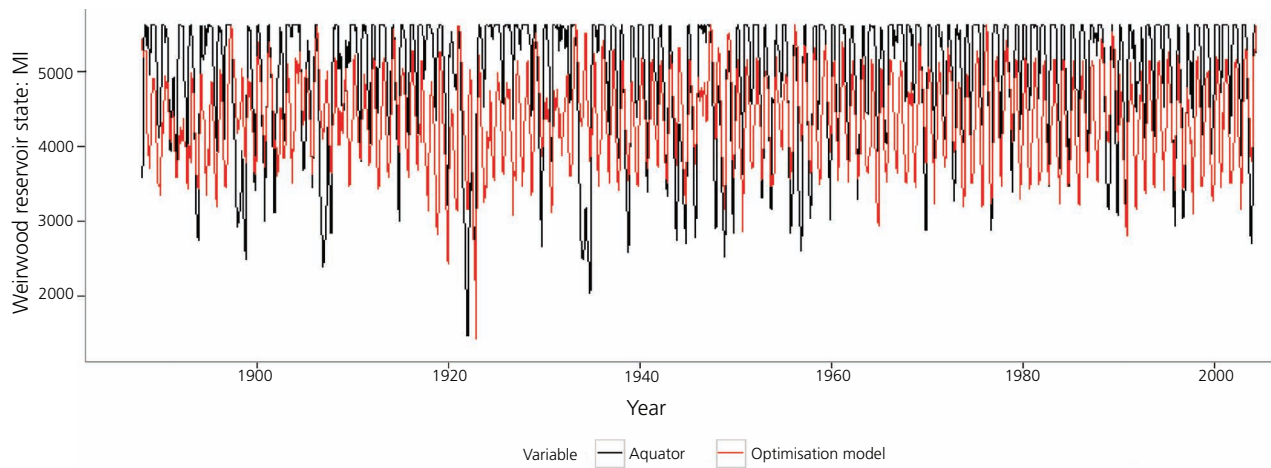
Figure 2. Example of a reservoir control curve, extracted from Drought Plan, 2008 (Southern Water, 2008)

Figure 3. Comparison of the reference against the optimisation model if the control curve is applied only during high flows

vulnerabilities as well as potential opportunities of efficient water allocation.

3.2 Vulnerability analysis
#### 3.2.1 Simulation model results
The simulation model confirms that the Sussex water system was sensitive to drought conditions of 1975–1976 and 1921–1922. If tested against the whole time series from 1888 to 2005, the drought period that brought the worst supply deficit was the 1921–1922 period. Otherwise, for a shorter time series of 1961 onwards, the 1975–1976 drought was the most serious drought. The results indicate that the water system was well insured against the 1976 drought type, which was probably due to the current practice of using the worst historical drought as the design event in water resource and drought planning. Yet the results also indicate that the system is not immune to deficit risks due to demand growth, specifically under the Market Forces demand scenario. If demand

jumps by 35% from the 2007 level, supply deficit will be ubiquitous in the 2050s and every single year might be at a 60% daily risk of water supply deficit if no new measures are put in place.

Among the demand scenarios in the 2050s, only the most sustainability-oriented scenario (Sustainable Behaviour) could reduce mean supply deficit to a level lower than the 2020s/2030s level (Figure 4). The results were set up to flag when a deficit occurs. When there are surplus years, such occurrences are recorded as 0 deficit. The Innovation scenario, the sustainability-led governance and individualistic consumption, meanwhile appear to be a neutral scenario compared to the 2020s and 2030s period. In the Local Resilience scenario, which is without sustainability-oriented governance, the projections show that, even if each individual exhibits environmental awareness and behaves responsibly, the water system still becomes less sustainable due to the overall demand increases. Finally, Market Forces – the most

	Simulation model	Optimisation model
Factors reducing deficits	Assumption of total system connectivity	Optimisation mode
	No reservoir control curve so can empty out reservoir to abate supply deficits	Reservoir storage and annual groundwater licenses can be optimised with regard to the inflows and demand time series
		Coarse time step
Factors increasing deficits	Simulation mode	Constraints on link capacity
	Daily time step – can be subject to severe shortage at a daily time scale	Reservoir control curve can prevent water release

Table 3. Contributing factors to the reduction and increase of supply deficit in each model
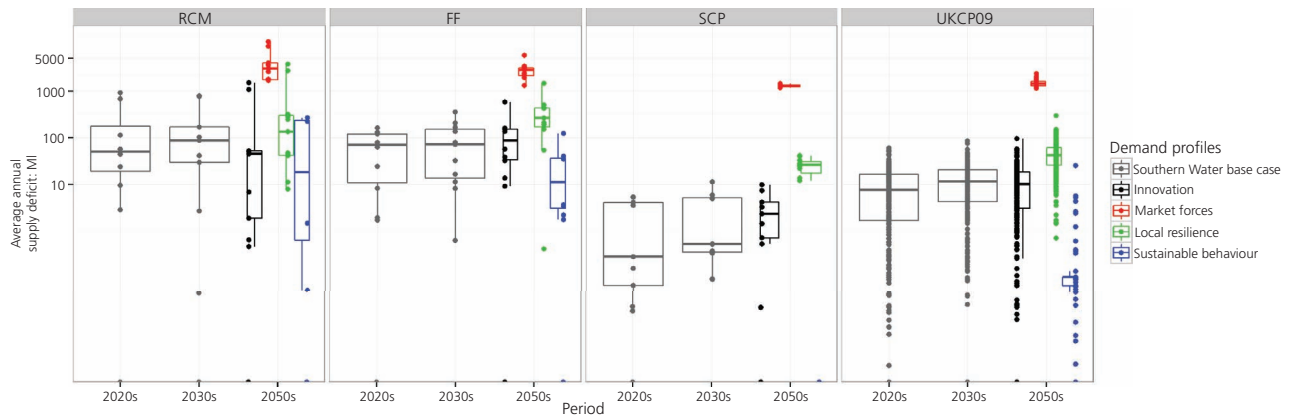
Figure 4. Average annual supply deficit (in megalitres) in North Sussex, Worthing and Brighton in the 2020s, 2030s and 2050s periods according to different climate and socio-economic scenarios using the simulation model. The dots represent the deficit in each ensemble member/scenario of each climate product. The box plots at the background are provided for reference of the median and other statistics

extreme scenario in which both individual consumers and policy makers do not care for sustainability – poses a significantly high risk of system failures. In this socio-economic scenario, even under the mildest climate change prospect (projected by the SCP climate product), the system will experience high supply deficit. The UKCP09 climate product leads to a similar but wider range of supply deficit compared to SCP, while RCM and FF show more serious conditions that lead to high frequencies of failures.

3.2.2 Optimisation model results
Similar to the simulation model, the optimisation model shows that the different climate products and socio-economic scenarios can vary the projections of annual supply deficits by up to 10 000 Ml (Figure 5). Optimisation model results demonstrate that demand uncertainty is significant in 2050s. Aside from the Market Forces

scenario, the Local Resilience scenario poses a slightly higher deficit risk compared to the Innovation and the Sustainable Behaviour scenarios. The optimisation model further shows that smart supply allocation can potentially alleviate water supply deficit. In practice, the model results are, however, the minimum possible deficit, since such efficient supply allocation requires perfect information (prior to the decision) of the climate conditions and drought sequences.

Nevertheless, the Market Forces scenario is the failure threshold of the system, in which the system fails in all 2050s climate conditions. Moreover, in terms of environmental flows in the River Rother, except for the RCM group, the river flows may frequently fall below the current minimum environmental flows. This reflects the risks of drier river states and the reducing supply capacity of the Rother to the Sussex water supply system. Despite
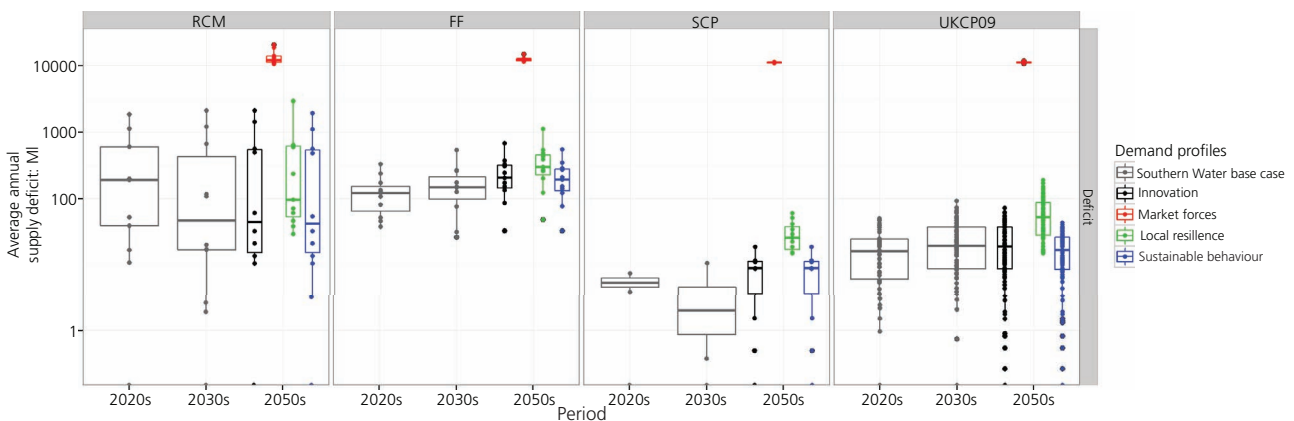
Figure 5. Average annual supply deficit (in megalitres) in North Sussex, Worthing and Brighton in the 2020s, 2030s and 2050s periods according to different climate and socio-economic scenarios using the optimisation model. The dots represent the deficit in each ensemble member/scenario of each climate product. The box plots at the background are provided for reference of the median and other statistics

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the slight variation in the cost of alternative sources, the overall cost is mostly influenced by the water demand level and remains relatively stable across the climate products.

Optimisation model results further indicate potential locations of water supply deficits. Overall, within the 2020s and the 2030s, deficit occurs only in the North Sussex area. Aside from the intercompany transfer and the environmental flow deficits in Rother and Weirwood, deficit in other nodes appear to be negligible. Model results depict the heterogeneous distribution of risks on the network according to the different climate products. Overall, RCM and FF climate conditions will lead to more severe deficits, while the SCP group rarely leads to any deficit or system failures. However, in three North Sussex nodes, the risks across the climate product are similar, while in another node, the risk by RCM conditions is higher than the FF and UKCP09 conditions.

The socio-economic scenarios of the 2050s show further impacts on the study area under different demand profiles. The deficit mainly occurs in the North Sussex area, because the Worthing and Brighton areas are more reliant on groundwater, and, in this model, are less likely to be affected by changes in surface water supply from the River Rother and the River Medway (Weirwood reservoir). The Market Forces scenario, however, shows that with extreme water demand, the Brighton area might experience water deficit under all climate conditions. Network analysis further demonstrates that under such situation, the nodes with fewer accesses to alternative supplying sources are likely to fail. In the case of the Market Forces scenario, each region of the study area will also become highly localised in its supply, as there is little spare capacity to transfer water to other regions.

4. Implications of model choice and structural uncertainty in vulnerability analysis

Overall, the comparative usage of a simulation model and an optimisation model in this study shows that using one of the two might highlight different features and vulnerability of the water system. The simulation model highlights potential vulnerability if the current operational practice is applied in the future. On the other hand, the optimisation model shows the vulnerability of the current system under the best possible operation. As shown in Section 3, the current Sussex water resources zone could be more resilient to water deficit risks if certain improvements in reservoir control rule are implemented. However, ultimately, the system still needs to undergo structural changes to enhance system capacity to cope with future higher demand and climate risks.

In terms of vulnerability indicated, simulation results show specific drought types and conditions that could lead to failure. They thus emphasise that new drought types as projected in the RCM and FF climate products could be dangerous to the water system, which still performs well under variations of the historic extreme droughts. Optimisation results meanwhile identify failure risk factors that go beyond operational ones, failure risks that threaten

the most optimised systems. Therefore, their different structures help highlight whether operational practice or inherent supply/demand vulnerability are the key risks of failure. Through a conjunctive use of both a simulation and an optimisation model, the study depicts that the current system could be vulnerable to climate change and demand growth both under the current practice and under the best-case scenario. As such, using solely a simulation model or an optimisation model can orientate adaptation decisions towards improving operational practices or enhancing current infrastructure. A simulation model can demonstrate that the system is vulnerable, while an optimisation model can explore if there are any options or operational improvements that reduce system vulnerability. On the other hand, an overoptimised system can fail to consider uncertainty and therefore shows unrealistic performance that is possible only under perfect knowledge of climate and water demand changes. The study therefore shows the impact of modelling choices and model structural uncertainty on vulnerability analysis of climate change impacts.

Risk factors highlighted in the study include climate risks as projected by different climate products and socio-economic scenarios. Study results further demonstrate that water demand is quickly becoming a controlling factor once it increases by more than 35% from the 2007 water demand level. Both models show a gradual increasing risk of supply deficit in the 2020s and the 2030s. Water deficit risks vary widely in the 2050s and are highly dependent on the socio-economic scenarios of the area.

The study also illustrates the wide uncertainty within climate and socio-economic scenarios. In essence, the four different climate products of RCM, SCP, UKCP09 and FF project various levels of risks. They do not produce the same range of risks and, instead, consistently project a mild range of risks (e.g. SCP) to medium but diverse range risks (UKCP09) to a range of more severe risks (FF and RCM). Therefore, the number of scenarios being tested might not be a good indication of how wide the range of risks is. In essence, UKCP09 has a high number of scenarios but appears to project comparable or less severe risks to ensembles of fewer members such as FF and RCM.

5. Conclusion

In conclusion, the study has explored the potential implications of model choice and structural uncertainty on system vulnerability. It shows that, while both optimisation and the simulation models perform relatively well compared to the reference model of the managing water company, they indicate different risk factors. The simulation model shows that the current system is vulnerable to new drought sequences that are different to the historical ones, while the optimisation model identifies structural limitations in the supply network that are susceptible to water deficits.

Overall, while climate uncertainty is still a significant influence, water demand is quickly becoming a controlling factor once the 2007 demand level increases past the 35% threshold. Both models demonstrate a gradual increasing risk of supply deficit in the 2020s

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and the 2030s; the risks vary widely in the 2050s and are highly dependent on the socio-economic scenarios. The model shows that in order to avoid frequent supply failures in the 2050s, it is essential to maintain or lower the demand profile. The socio-economic scenarios indicate that such reservation can occur only under sustainability-led governance or socially responsible consumerism (such as the Innovation or Local Resilience scenarios). The future failure risks are mainly distributed within the North Sussex area, with the exception of the Market Forces scenario.

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