International Environmental Modelling and Software Society (iEMSs)
2012 International Congress on Environmental Modelling and Software
Managing Resources of a Limited Planet, Sixth Biennial Meeting, Leipzig, Germany
R. Seppelt, A.A. Voinov, S. Lange, D. Bankamp (Eds.)
http://www.iemss.org/society/index.php/iemss-2012-proceedings

Uncertainty Analysis of an Integrated Water System in Southern England: Exploring Physical and Socio-economic Uncertainties

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Abstract: Climate change risk assessment of water resources is fraught with uncertainty. Such uncertainty is not only the accumulation of individual uncertainty components, but also the results of intricate interactions amongst the physical environment and the socio-economic system. There is often a mismatch of model representation of these two systems: while uncertainty of physical factors has often been described using quantitative methods, socio-economic factors have largely been qualitative. In our drought assessment case study, we evaluate uncertainty in the physical factors and demand responses in the context of climate change. In particular, we focus on structural uncertainty of the supply component and data uncertainty of the demand component. To explore structural uncertainty, a model of fine scale that has nodes representing real supply and demand sources was used as a reference model; another model at the water resource zone scale was used as an emulator to reflect information loss if a coarser spatial resolution is used. The input data are the UK Climate Projections 2009, 1989-2011 historic demand and 1961-1990 historic climate data. The main model output of interest is failure of supply. We found that uncertainty from the hydrological model contributes a high uncertainty margins to the final model results; in this case study it is more influential than uncertainty from either projected climate change or demand growth.

Keywords*: demand; climate change; uncertainty analysis; water resources*

1 INTRODUCTION

Climate change is exerting pressure on the water sector to adapt. Adaptation is currently mainly driven by the changes in the hydrological cycle, in particular the redistribution of water availability in space and time. Yet, water supply is only one part of the equation. As demand is essentially people, plants and animals taking water to maintain their sustenance, it is also likely to be under the influence of climate change. Supply and demand changes are, however, mis-matched in their scale of manifestation. While hydrological shifts are exhibited at the catchment scale, demand changes are the result of collective individual decisions, many of which can be rational, irrational or habitual. Therefore, adaptation decisions should integrate these multi-scale and dynamic factors to form an effective action plan [Becu et al. 2003]

This paper presents a case study that analyses both demand and supply (and its uncertainties) at the same water resource zone level. It analyses historic data and future projections to investigate uncertainty components, and how they are projected to change in the next 40 years. In particular, the paper aims to:

i) Explore structural uncertainty inherent in the hydrological component

ii) Explore the historic responses of demand to weather changes

iii) Investigate how uncertainty from different components manifest in the integration stage, where demand and supply are matched to indicate system performance under projected changes

2 METHODOLOGY

2.1. Uncertainty integration

The study integrates uncertainty in a cascade process, to explore the explosion of uncertainty usually associated with integrated models [Dessai and Van der Sluijs, 2007]. It also bears similarities to the current approach adopted by water companies in England (Figure 1). In this study, the hydrological model CATCHMOD (Wilby et al., 1994) and a VB.NET lumped water resource model are chosen to simulate flows and the state of the water system respectively

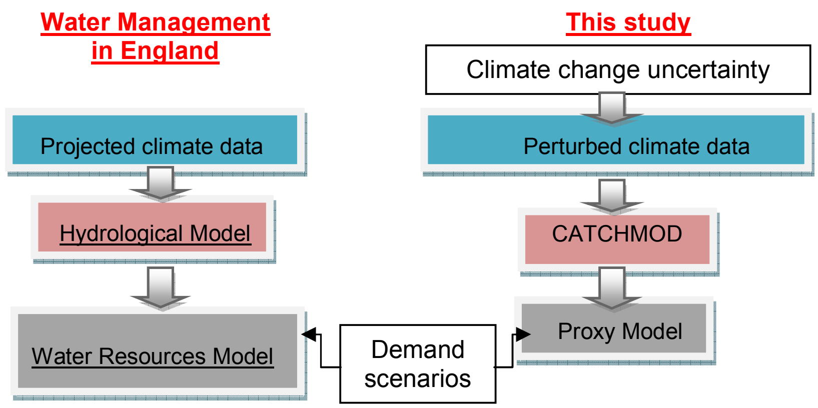

Figure 1 A comparative view of modelling process in existing water management plans and this study: The latter follows the structure of the former, but includes multiple sets of climate change impacts and uses a lumped regional water resources model as a proxy.

2.2. Study Area

North Sussex (southern England) is the study site for the case study. Climatic changes may impact both groundwater and surface water sources, but we only consider surface water in this study. Surface water flows are simulated by CATCHMOD and subsequently serve as an input into the water resource model, while other changes in groundwater stores and licences are not explored. The two major surface sources of the region are an impounding reservoir called *Weirwood Reservoir and R646,* a main surface water source that provides water to the whole region.

2.3. Scenario Inputs

Climate Scenarios: 1000 sets of Change Factors under the Medium Emission Scenario are Latin-Hypercube sampled from the 10,000 sets of the UK Climate Projections 2009 [Murphy et al. 2010]. The factors reflect monthly changes of local precipitation and temperature, which via the UKWIR Delta Change Method [Conlan et al. 2006] can translate historic climate data into future weather states of the 2020s, 2030s, and 2050s under the Medium Emission Scenario.

Demand Scenarios: demand projections are based both on historic data analysis and projections provided by the water company and the EA. In their Water Management Plan, Southern Water extrapolates average and peak demand from 2009-2034, thus covering the 2020s and 2030s periods [Southern Water, 2009]. Meanwhile, the Environment Agency projects demand shifts for the 2050s under four scenarios, termed Sustainable Behaviour, Innovation, Local Resilience and Market Forces. Each of these scenarios reflects a different mode of governance and consumption [Environment Agency, 2008]. In essence, the projected change is as follows:

- **Innovation (I)**: Total Demand reduces by 4%. The responsibility to find adaptation strategies lies with the government and scientist; demand reduction is due to sustainability-led governance and technological innovation.
- **Market Forces (MF)**: Total Demand increases by 35%. Water demand is driven by the market trend, focusing on cost optimisation and growth.
- **Local Resilience (LR)**: Total Demand increases by 8%. People realise the need for demand reduction and take actions towards it. Their efforts, however, is moderate due to the low priority of demand saving and the lack of incentives from the government.
- **Sustainable Behaviour (SB)**: Total Demand declines by 15% due to pro-active demand reduction from individuals.

3 RESULTS AND DISCUSSIONS

3.1. Demand Analysis

This section analyses how demand responses to various factors such as seasonality, temperature, rainfall and day of the week. The analysis is based on historic regional water demand data. This historic demand is constructed from the historic water supply output (Distribution Input, or DI) and recorded leakage (Figure 2).

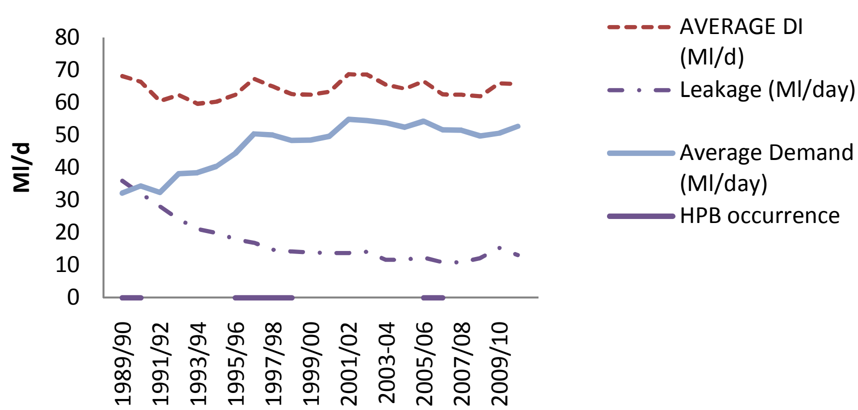

Figure 2. 1989-2011 historic Distribution Inputs, Leakage and Demand (Ml/day). Bouts of Hosepipe ban (HPB) occurrences are also shown.

As water transmission loss does not contribute to demand, water loss due to leakage is subtracted from the supply output. Figure 2 demonstrates that over the year more and more of supply output can actually reach the demand nodes instead of being lost on the pipe. Yet, demand also rises, most likely due to population growth, and leads to a relatively stable amount of water needed from supply sources. During periods of Hosepipe bans, demand remains relatively high and the effect observed is insignificant. Hosepipe bans' effects, however, may have contributed to keeping water demand similar to normal demand years. Demand also varies according to months, with summer period such as June, July and August having higher demand than other months (Figure 3). Demand appears to be stable over the whole week and is not affected by the likely higher usage over the weekend.

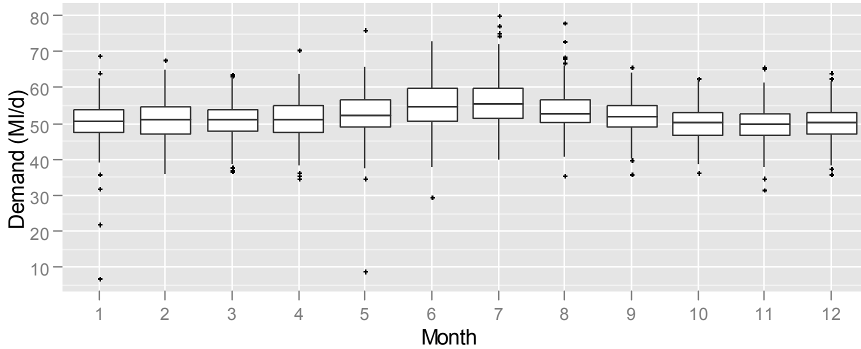

Figure 3. Boxplot of North Sussex daily demand according to months for the period 1989-2011, bank holidays are excluded

When analysed in conjunction with maximum, minimum daily temperature, and rainfall record from the adjacent Shoreham weather station, North Sussex demand show little responses on a monthly scale. As Shoreham weather data is only available from 1998, the 1998-2011 demand is used for this part of analysis. The effect of maximum temperature, however, is observed when the data is divided into groups of water demand when daily max temperature is larger than 25, within the range of 10-25, within the range of 5-10 and lower than 5 Celsius degree (Figure 4). The effect, however, is confounded by seasonality, as all data within the group of high temperature (≥25^{0}C) occurs within the peak summer period (April to October). Thus, demand is not linked to changes in temperature and rainfall in the climate scenarios in the subsequent analysis. Furthermore, as leakage and water demand are not represented separately in the water resource model, the chosen demand profile amalgamates both and is selected to be Distribution Input of the 1995 calendar year. It should be noted that 1995 is a drought year and therefore likely to have higher-than-average demand.The choice of particular historic year for annual supply profile, however, is not likely to affect the final results, as DI data demonstrates a relatively similar fluctuation across the years.

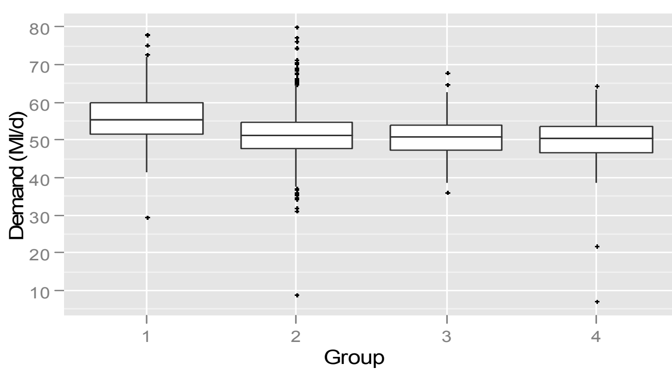

Figure 4. Boxplots of North Sussex 1998-2011 water demand according to temperature groups:from left to right, >25, between 10-25, between 5-10 and under 5 Celsius degree.

3.2. Supply Analysis

Three alternative parameterisations of the hydrological CATCHMOD model are chosen to present structural uncertainty in the hydrological component (Table 1). These models have similar performance over the calibration period of 1994-2004, and therefore are considered comparatively reliable to project flows of the catchments.

Table 1. The sets of parameters used and their associating goodness-of-fit criteria (note: RMSE stands for Root Mean Squared Error). The grey shading indicates the best performing model according to the criteria of that row.

R646	Model 1	Model 2	Model 3
R^2	0.826	0.862	0.865
Nash-Sutcliffe Efficiency	0.798	0.800	0.733
RMSE	1.690	1.705	1.943
Weirwood	**Model 1**	**Model 2**	**Model 3**
R^2	0.728	0.707	0.735
Nash-Sutcliffe Efficiency	0.697	0.704	0.695
RMSE	0.241	0.281	0.241

Yet, they show significant variations within the baseline (1961-1990) and other timeslices. Figure 5 displays the simulated flow of the driest week (from now on termed the 7-day low flow) in the 1961-1990 basecase (without climate change perturbation) and 1000 climate scenarios (2020s, 2030s, and 2050s). The basecases consist of a single value (as there is no profile variation of demand or climate inputs). In other timeslices, the max, average and min 7-day low flow projected by each model is shown. As can be seen, climate uncertainty expands into the future, yet, even at the baseline level, structural uncertainty of the hydrological model dominates.

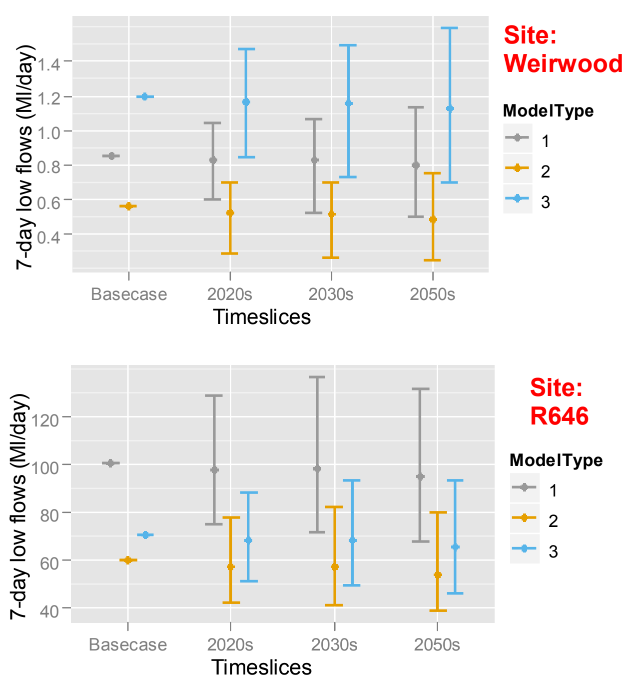

Figure 5. Max, average and minimum of 7-day low-flow projections (Ml/day), simulated for Weirwood and R646

3.3. Water Resources Analysis

This section demonstrates the integrated uncertainty when climatic, hydrological and demand uncertainty is acting alone or in conjunction (Figure 6). In the basecase, there is no water system failure for 1961-1990 weather under 1995 demand profile over all alternative hydrological parameterisation (which projects different supply availability). In this study, a system is considered to fail if it has a supply deficit of 0.01 Ml/day; this definition should be used solely for the purpose of the study and may not be what water companies use in practice. The daily 1995 supply profile is used for the basecase; it is then scaled up or down to represent the demand profiles in 2020s and 2030s based on the ratio between Southern Water's projected annual average demand and 1995 annual average demand.

$$\%\ \text{change} = (\text{Projected annual demand})/(1995\ \text{annual demand}) \qquad (1)$$

From 1981-2005, southern England experienced an increase of 15% in water demand [Environmental Agency 2009]. This is equivalent to an growth rate of 0.06% per year; based on this rate, demand in 2050s would be 28% higher than 2008 demand. Meanwhile, based on the same 2008 baseline, the EA predicts an increase of 5% for 2020s and 15% less to 35% increase for 2050s. A 2050s basecase is subsequently chosen assuming an increase of 25% compare to the 2008 baseline and is then scaled according to the EA's four demand profiles. As such, assuming that Southern Water's 2020s demand also reflects a 5% increase from 2008, the value for 2050s was constructed by deducing the 2008 value and then scaled up by 25%, the median growth rate of EA's 2050s bounds. This 2050s baseline is then further scaled according to the EA's four case scenarios (refer to Section 2.3).

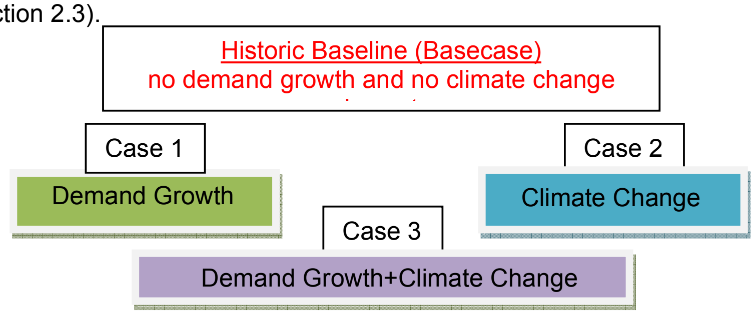

Figure 6. Description of scenarios: system failures due to demand growth, due to climate change impacts or due to both.

Case1: If demand grows according to the forecast rate of the EA and Southern Water, even without climate change impacts, system failure will grow with time (Table 2). By 2050s, only with the most sustainable lifestyle, can we only revert the system back to the state it would be in 2030s.

Table 2. % of failure occurrence over a 30-year period, as projected by Model 1, 2 and 3 for each timeslices, according to forecasted demand growth

	Base Case	2020s	2030s	2050s	I	LR	UD	SB
Model 1	0.00%	0.00%	0.05%	0.28%	0.18%	1.79%	48.59%	0.05%
Model 2	0.00%	0.56%	0.59%	1.02%	0.81%	2.36%	48.20%	0.58%
Model 3	0.00%	0.45%	0.54%	0.82%	0.80%	1.80%	50.39%	0.51%

Case 2: Meanwhile, while acting on its own, climate change will likely increase the number of system failures (Table 3). However, when climate change impacts are

concerned, structural hydrological uncertainty, in essence the difference amongst model prediction becomes larger. For instance, in the timeslice 2050s of Case 1, model 1 to 3 projects 0.28%, 1.02%, and 0.82% failure occurrence (table 2). Meanwhile, with climate change effect, Model 1 forecasts very little changes in 2050s system vulnerability, while Model 2 and 3 project a mean of 0.78% and 0.40% failures over a 30-year period. Thus, both demand growth and climate change impacts are likely to increase the number of system failures; although by 2050s, failures due to demand are slightly higher than those due to climate change impacts.

Table 3. Mean percentage of failure occurrences over 30 years under the Medium Emission scenario, with 1995 water demand

	2020s	2030s	2050s
Model 1	0.00%	0.00%	0.00%
Model 2	0.57%	0.58%	0.78%
Model 3	0.28%	0.28%	0.40%

Case 3: When both demand growth and climate change impacts are combined, the number of failures grows higher than with only one of these drivers (Table 4). While the impacts are gradual in the early timeslices (2020s and 2030s), the combined effect of both climate change and demand accelerates in 2050s. Compared to corresponding categories in Table 2, the number of failures has grown from 1.5 to 2 times in 2050s and other 2050s' four case scenarios. Yet, the effect of hydrological structural uncertainty is still evident, thus highlights the importance of considering trickling uncertainty from upstream component of the uncertainty cascade.

Table 4. Mean percentage of failure occurrences over 30 years under demand growth and climate change (under the Medium Emission scenario)

	2020s	2030s	2050s	I	LR	UD	SB
Model 1	0.00%	0.04%	0.33%	0.21%	1.58%	46.86%	0.05%
Model 2	0.71%	0.80%	2.20%	1.70%	4.22%	49.49%	1.02%
Model 3	0.46%	0.53%	1.46%	1.13%	3.21%	51.23%	0.64%

4 CONCLUSIONS AND RECOMMENDATIONS

In summary, the paper has explored the uncertainty inherent in climate change scenarios, hydrological models, demand scenarios and how they propagate throughout the risk assessment. In response to the aims stated at the onset of the paper, it is found that

i) Structural uncertainty can greatly influence hydrological and water resource projections. In this case study, it is the dominant uncertainty factor and has higher effect than either projected demand growth or climate change impacts. A global sensitivity analysis is recommended in further research to fully analyse the effect of structural uncertainty on the overall results.

ii) Historic responses of demand to weather have been weak or confounded by other variables such as seasonality and scale of monitoring. It is therefore suggested that more data analysis is conducted in this component.

iii) Uncertainty from components exacerbate at the integration stage, with uncertainty from model structure, demand growth and climate change impacts enhancing variations within model results.

Overall, uncertainty is inherent in both the supply and demand side. The study shows that the system of interest will become more vulnerable in the future, and that adaptation measures need to be taken for the sustainable management of water resources in this region.

ACKNOWLEDGMENTS

The authors thank Southern Water and Atkins for data and discussion and the EPSRC (EP/6061181/1) for financial support.

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