Modeling the impacts of climatic change and variability on the reliability, resilience, and vulnerability of a water resource system

H. J. Fowler, C. G. Kilsby, and P. E. O'Connell

Water Resource Systems Research Laboratory, School of Civil Engineering and Geosciences, University of Newcastle upon Tyne, Newcastle upon Tyne, UK

Received 16 October 2002; revised 24 March 2003; accepted 20 May 2003; published 28 August 2003.

[1] During the last decade, there have been increasing concerns over water resource drought in northern England, brought about by the 1995 Yorkshire drought with an estimated 5-month rainfall return period of 200 years. The impacts of climatic change and variability on water resource reliability, resilience, and vulnerability in this region are examined by modeling changes to weather type frequency, mean rainfall statistics, and potential evapotranspiration. Results indicate future improvements in water resource reliability due to increased winter rainfall but reductions in resource resilience and an increased vulnerability to drought. Severe droughts comparable to that of 1995 show only a slight increase in frequency by 2080. However, there are significant increases in both the magnitude and duration of severe water resource drought, as a consequence of summer rainfall reductions and increased climatic variability. This research provides a basis for the future planning and management of the Yorkshire water resource system. *INDEX TERMS:* 1620 Global Change: Climate dynamics (3309); 1812 Hydrology: Drought; 1854 Hydrology: Precipitation (3354); 1869 Hydrology: Stochastic processes; 1884 Hydrology: Water supply; *KEYWORDS:* water resources, drought, stochastic rainfall model, climate change, North Atlantic Oscillation, UK

Citation: Fowler, H. J., C. G. Kilsby, and P. E. O'Connell, Modeling the impacts of climatic change and variability on the reliability, resilience, and vulnerability of a water resource system, *Water Resour. Res.*, *39*(8), 1222, doi:10.1029/2002WR001778, 2003.

1. Introduction

[2] Water resource systems in the UK are very sensitive to climatic variations. During the late 1980s and 1990s, there were numerous water resource drought events [*Bryant et al.*, 1994; *Marsh and Turton*, 1996], exacerbated by an enhanced hydrologic seasonality. This combination of wetter winters and drier summers continued into the mid-1990s, culminating in the serious water resource drought of 1995 which affected mainly the north of England and in particular the Yorkshire region. Current climatic trends in northern England [*Fowler and Kilsby*, 2002a] and future projected climate change in the UK in general [*Hulme and Jenkins*, 1998; *Hulme et al.*, 2002] suggest that winters will become wetter and summers drier on average. The UKCIP98 scenarios [*Hulme and Jenkins*, 1998] indicate summer reductions and winter increases as high as 50 and 30%, respectively, by the 2080s. The new UKCIP02 scenarios [*Hulme et al.*, 2002] suggest even larger summer reductions, extending as far north as Scotland. These changes will have serious implications for water resource system management in the 21st century.

[3] The exacerbation of seasonal rainfall contrasts in a changing climate may have profound effects on water resource systems in already vulnerable areas, such as Yorkshire. In much of the north of England, short-term summer drought can have an extremely detrimental effect on water supplies [*Marsh*, 1996]. The geology of many areas results in little, if any, groundwater storage potential, with a resulting reliance upon surface water resources. These resources can be depleted rapidly during a dry period, initiating a water resource "drought" during which restrictions might have to be applied. The projected climate changes may therefore impact water supplies in northern and western regions such as Yorkshire more dramatically than in southern regions of the UK which have more groundwater resources. Establishing the likely effect of such climate changes upon the reliability, resilience and vulnerability (RRV) [*Hashimoto et al.*, 1982a, 1982b] of water resource systems has become a priority for their successful future management [e.g., *Department of the Environment and the Welsh Office*, 1996; *Walker*, 1998].

[4] The 1995–1996 drought, with an estimated 5-month rainfall return period from April to August 1995 of more than 200 years [*Marsh*, 1996], caused severe water stress in the Yorkshire region [*Marsh and Turton*, 1996], necessitating the emergency measure of bringing water in by road tanker from outside the region. In Yorkshire, annual rainfall varies from just 600 mm in the eastern lowlands (Vale of York), to over 2000 mm at high western sites (Pennines) and the main sources of rainfall are weather systems from the westerly quadrant, bringing 70–80% of average annual rainfall. Single-season reservoir resources and river abstractions in the western Pennine region and some groundwater resources in the east of the region are used to supply a population of 4.5 million and around 140,000 businesses (see Figure 1). During the 1995–1996 drought, a water deficit in the west of the water resource region was exacer-

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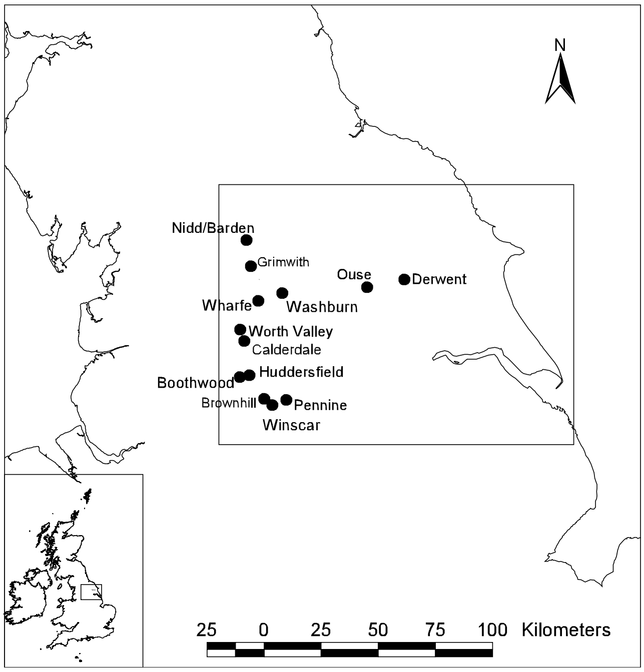

Figure 1. The Yorkshire region, UK, showing location of hydrometric data used to calibrate modeled river and reservoir resources within the Yorkshire water resource zone (square).

bated by an unusually high number of easterly weather systems during the summer and autumn months of 1995, followed by a highly anticyclonic winter through to 1996 [*Fowler and Kilsby*, 2002b]. This caused a severe water resource drought, and highlighted Yorkshire as a region that might be particularly vulnerable to climatic change.

[5] This paper examines the effect of both natural variability and climate change on the Yorkshire water resource system using RRV analysis [*Hashimoto et al.*, 1982a, 1982b]. Natural variability in the climate system is examined using the North Atlantic Oscillation (NAO) index, the difference between normalised sea level pressure over the Azores and Iceland. The usual index is given by the December to March average of this pressure difference [e.g., *Jones et al.*, 1997]. Shifts in the NAO affect temperature and rainfall in northern Europe by way of changes in synoptic weather patterns, particularly the frequency and magnitude of surface westerlies [*Hurrell*, 1995]. These shifts were found to significantly affect rainfall patterns in northern England [*Fowler and Kilsby*, 2002a], particularly in western Yorkshire where most supply reservoirs are located. Climate change impacts are examined using the UKCIP98 medium-high 2021–2050 and 2051–2080 climate change scenarios [*Hulme and Jenkins*, 1998], although the more recent UKCIP02 scenarios [*Hulme et al.*, 2002] are now available. Because of larger simulated summer reductions in the UKCIP02 scenarios it is likely that the impact of climate change on drought severity examined here would be even greater in these new scenarios.

[6] This analysis represents the state of the art in the assessment of climate change impacts on both hydrological regimes and water resource systems. Although there have been many studies on the effects of climate change on hydrological regimes, few have considered the implications for water resources, and there has been little use of RRV analysis. Where RRV analysis has been used [*Lane et al.*, 1999; *Vogel et al.*, 1999; *Maier et al.*, 2001; *Kay*, 2000], studies have concentrated on modeling simple systems such as individual storage reservoirs [e.g., *Vogel et al.*, 1999] and have simply perturbed the means of annual or monthly historical data by a change "factor" representing climate impacts [e.g., *Hewett et al.*, 1993; *Wardlaw et al.*, 1996; *Vogel et al.*, 1999]. Here, an integrated methodology is presented for modeling the impacts of both natural climatic variability and climate change on a complex water resource system using RRV analysis. Changes to daily weather type frequency, sequencing and rainfall variability are modeled synthetically by the use of a stochastic weather-conditioned daily rainfall generator [*Fowler et al.*, 2000, H. J. Fowler, et al., A weather-type conditioned multi-site stochastic rainfall model for the generation of scenarios of climatic variability and change, submitted to *Journal of Hydrology*, 2003 (hereinafter referred to as Fowler et al., submitted manuscript, 2003)] and a separation is made between single "source" and system "supply" reliability by the inclusion of system supply constraints such as pipe sizes within the water resource system model. This provides an insight into the relative importance of natural climate variability and climate change in controlling water resource system performance. This distinction is important as increased climatic variability may have a larger impact upon water resource system performance than changes to mean climate. This integrated methodology provides both a robust approach to the modeling of climate impacts on complex water resource systems and a framework for their future management.

2. Indicators for Water Resources Assessment

[7] The use of indices of reliability, resilience and vulnerability (RRV) for classifying and evaluating water resource system performance was first suggested by *Hashimoto et al.* [1982a, 1982b]. More recently, the *ASCE Task Committee on Sustainability Criteria* [1998] have recommended that these indicators are combined into an aggregated indicator of sustainability but this gives little indication of the relative system performance for each indicator. Therefore here the original *Hashimoto et al.* [1982a, 1982b] indicators are used to examine the performance of the Yorkshire water resource system for each scenario, evaluating the outputs of the water resource system with reference to the imposed demands. A distinction is made between the analysis of sources and the ability to meet "demands", which is additionally constrained by the capacity of both pipe links and treatment works within the system.

[8] Firstly, a criterion, C, is defined for each water supply source, where an unsatisfactory value is one where the source is unable to provide a prespecified yield, using either reservoir control rules or river abstraction limits (see Figure 2 for an example). The time series of simulated daily values of either river flows or reservoir levels, X_t, are then evaluated to some future time, T. Each water supply source will have its own range of satisfactory, S, and unsatisfactory, U, values defined by the criterion, C [*Hashimoto et al.*, 1982a, 1982b]:

$$\text{If} \quad X_t \geq C \quad \text{then} \quad X_t \in S \quad \text{and} \quad Z_t = 1$$
$$\text{else} \quad X_t \in U \quad \text{and} \quad Z_t = 0 \qquad (1)$$

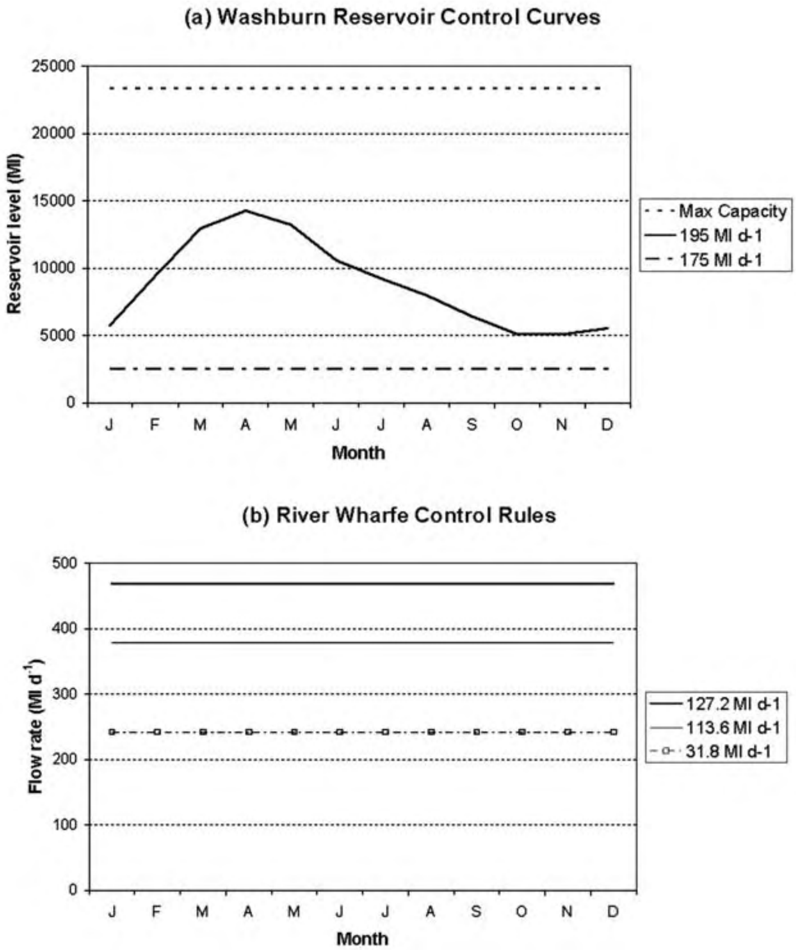

Figure 2. Example control rules for reservoir and river source abstractions in megaliters (or thousand cubic meters) per day: (a) Washburn reservoir group and (b) River Wharfe; allowable abstraction rate above given level for given month.

[9] Another indicator is defined, W_t, which indicates a transition from an unsatisfactory to a satisfactory state [*Hashimoto et al.*, 1982a, 1982b]:

$$W_t = \begin{cases} 1, & \text{if} \quad X_t \in U \quad \text{and} \quad X_{t+1} \in S \\ 0, & \text{otherwise} \end{cases} \tag{2}$$

[10] If the periods of unsatisfactory X_t are then defined as $J_1, J_2, \ldots, J_N$ then reliability, resilience and vulnerability indices can be defined [*Hashimoto et al.*, 1982a, 1982b]:

Reliability $$C_R = \frac{\sum_{t=1}^{T} Z_t}{T} \tag{3}$$

Resilience $$C_{RS} = \frac{\sum_{t=1}^{T} W_t}{T - \sum_{t=1}^{T} Z_t} \tag{4}$$

Vulnerability $$C_V = max\left\{ \sum_{t \in J_i} C - X_t, \quad i = 1, \ldots, N \right\} \tag{5}$$

[11] These measures are used to examine the reliability, resilience and vulnerability of the water sources within the Yorkshire water resource system for the baseline and future climate change scenarios. Reliability, C_R, measures the frequency of source failures. Resilience, C_{RS}, gives an indication of the speed of recovery of the source from a failure and vulnerability, C_V, is a measure of the extent of failure. Failure is defined as when the source is unable to provide a prespecified yield.

[12] The performance of the water resource system, including pipe capacity and treatment work size restrictions, is also evaluated with reference to the imposed demands. A conjunctive use element [*Wood et al.*, 1997; *Lettenmaier et al.*, 1999] is defined, as although the reliability, resilience and vulnerability of water sources within a system can be determined on an individual basis, shortages in supply may only occur when concurrent shortfalls occur at more than one source. In this case, reliability measures the frequency of failure to supply any demand. Resilience measures the speed of recovery of the system from any failure, and vulnerability is defined as (1) the maximum duration of system failure in days and (2) the cumulative maximum extent of system failure in

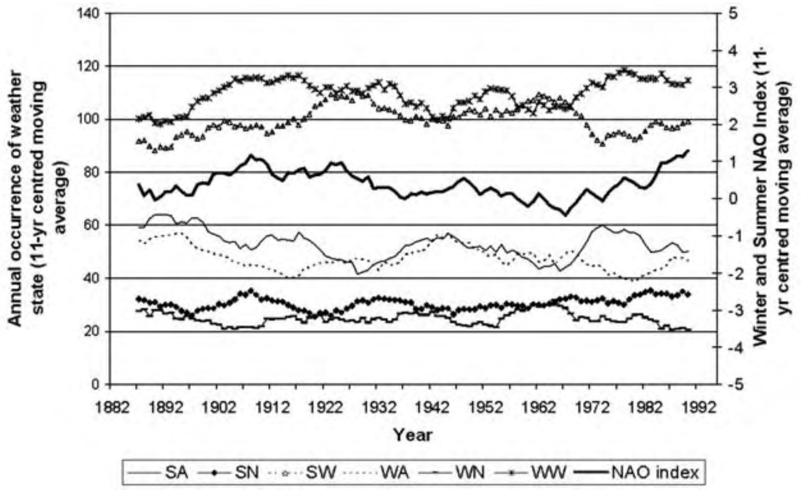

Figure 3. Eleven-year centered moving averages of the North Atlantic Oscillation (NAO) index and six weather "states" or groupings. Weather states are grouped according to source direction, rainfall amount and season, therefore giving WA, WN, and WW (winter anticyclonic, northerly, and westerly) and SA, SN, and SW (summer anticyclonic, northerly, and westerly).

ML. Here, a failure is defined as the inability of the system to meet the imposed demands.

3. Climate Variability and Change Scenarios

3.1. Natural Climate Variability

[13] Natural variability in the climate system is examined using the North Atlantic Oscillation (NAO) index. The usual index is given by the December to March average of this pressure difference [e.g., *Jones et al.*, 1997]. It has been shown by *Fowler and Kilsby* [2002a], that rainfall is affected by the phase of the NAO, where a high-phase NAO is defined as positive and a low-phase NAO is defined as negative. This is a result of both changes in weather state frequencies and their associated rainfall properties.

[14] Figure 3 shows the 11-year centered moving average of the NAO and weather states for the period 1882–1996. A clear correlation can be observed between the NAO and the frequency of weather states, especially the summer and winter anticyclonic (SA and WA) and summer and winter westerly (SW and WW) states. During a positive NAO period, such as from 1980–1990, there is an increased frequency of the WW and SA weather states, to the detriment of the SW and WA weather states. In a low NAO period, such as 1960–1970, the reverse situation occurs.

[15] Previously, *Fowler et al.* [2000] examined the differences in mean summer and winter rainfall in the west and east of the Yorkshire water resource region during high- and low-phase NAO periods (Table 1). It was found that during a high-phase NAO, there is an increase in mean winter rainfall of 2% in the west and 1% in the east. This is offset by a slight reduction of 1% in mean summer rainfall in the west, but no change is observed in the east. During a low-phase NAO the opposite effect occurs, raising mean summer rainfall by 5–6% and lowering mean winter rainfall by 2–4%. It is recognised that these changes may not be statistically significant from zero. However, these perturbations may provide a basis for simulating natural climate variability as changes in the frequency of weather state occurrence.

3.2. UKCIP98 Climate Change Scenarios 2021–2050 and 2051–2080

[16] The UKCIP98 climate change scenarios [*Hulme and Jenkins*, 1998] were constructed using the HadCM2 GCM output for the use of the climate impacts community in the UK. These scenarios are based upon the HadCM2 experiments that use a 1% rise per annum in greenhouse gas concentrations over the next century and future projected changes appear similar to observed trends across the UK, particularly in rainfall [*Fowler and Kilsby*, 2002a]. Four scenarios are presented: low, medium-low, medium-high and high. In this analysis, the medium-high climate change scenario for the periods 2021–2050 and 2051–2080 is considered, as estimates of the changes in within month rainfall variability are available for this scenario in addition to the estimates of mean monthly change. A separation of the effects of natural variability from those of climate change was examined. For certain seasons and periods, rainfall changes in the intra-ensemble range were found to be larger than the ensemble mean change [*Hulme and Jenkins*, 1998]. This suggests that a high proportion of

Table 1. Changes to Winter and Summer Mean Rainfall Resulting From a High- or Low-Phase NAO When Compared to the Baseline Scenario of 1961–1990

		High-Phase NAO, Percent Change From Baseline	Low-Phase NAO, Percent Change From Baseline
East	Summer	+0.0	+5.0
East	Winter	+1.0	−2.0
West	Summer	−1.0	+6.0
West	Winter	+2.0	−4.0

Table 2. UKCIP98 Medium-High Climate Change Scenario for the Periods 2021–2050 and 2051–2080: Rainfall and PE Change

	2021–2050			2051–2080		
Season	Rainfall Change, %	Rainfall Variance Change, %	PE Change, %	Rainfall Change, %	Rainfall Variance Change, %	PE Change, %
Summer	−5	+10	+6	−9	+10	+8
Winter	+9	+5	0	+16	+15	+10
Annual	+3 to +5	–	+6	+4 to +10	–	+10

the seasonal mean rainfall changes in the medium-high scenario are due to natural climate variability rather than anthropogenically induced climate change [*Hulme and Jenkins*, 1998]. This particular GCM scenario must, however, be considered just one possible future scenario among many other possible scenarios.

[17] The projected changes to rainfall amount, rainfall variability and potential evapotranspiration (PE) for summer and winter, defined as April to September and October to March respectively, are shown in Table 2. It can be observed that the major changes are summer rainfall reductions and winter rainfall increases, with increasing PE throughout the year. However, changes may also occur in the monthly distribution of PE [*Hulme and Jenkins*, 1998]. The largest increases occur in late summer and early autumn, with a relative decrease in spring PE. The relative projected change to the monthly PE distribution from the ‘‘baseline’’ of 1961–1990, as a percentage of annual PE, is shown in Table 3.

[18] Seasonal changes in airflow characteristics under the UKCIP98 medium-high scenario are also applied using the parameters of the high-phase NAO, as the changes to airflow characteristics [*Hulme and Jenkins*, 1998] are found to be very similar. Their analysis suggests a reduction of northerly and easterly flow in autumn, decreased westerly and north-westerly flows and increased anticyclonicity in summer, and decreased anticyclonicity in winter and spring. This suggests that any increase in winter rainfall will come from an increase in westerly flows combined with an increase in mean daily rainfall on a westerly day. In summer months, the reduction in rainfall may be an outcome of an increase in anticyclonic conditions combined with a reduction in westerly mean daily rainfall.

4. Modeling Approach and Results

[19] In the following sections, simulations are performed that explore the behavior of the Yorkshire water resource system under scenarios of climatic variability and change using the indices described previously. Water resource system behavior is examined for (1) a control climate using observed data from the period 1961–1990 in a baseline scenario, (2) climate variability using the examples of the high- and low-phase NAO, and (3) a future climate scenario for the periods 2021–2050 and 2051–2080. However, first a description is given of the Yorkshire water resource system, and the modeling procedures followed in simulating rainfall, PE and stream flow inputs. This is followed by an analysis of the results of the water resource system simulations, based on the indices of reliability, resilience and vulnerability.

4.1. Yorkshire Water Resource System (YWRS) Model

[20] The Yorkshire water resource system covers an area of some 15,000 km^2, supplying a population of 4.5 million people, located in eleven main demand zones: Skipton, Bradford, Calder, Harrogate, Malton, Leeds, Wakefield, Selby, Doncaster, Hull and Sheffield. In the YWRS model (Figure 4), the Hull and Selby demands are not modelled. Hull is assumed to be adequately supplied by the River Hull and the Hull and Wolds boreholes and Selby is assumed to be adequately supplied by the Selby boreholes, which also generate an excess inflow of 5 ML d^{-1} to the system. Total demand is at a maximum in July, at 1237 ML d^{-1} but does not presently fluctuate substantially throughout the year. Water sources are split geographically, with most reservoir and river sources located in the wetter west of the region and groundwater sources to the east.

[21] Within the YWRS model, the reservoir sources are aggregated into 10 groups, as each grouping is managed as an integrated resource. These reservoirs are operated using standard control rules (see Figure 2 for an example). Water abstractions are also taken from four rivers within the region. The rivers Wharfe and Ouse are located in the west of the region and have ‘‘flashy’’ flow regimes whereas the rivers Derwent and Hull overlie limestone to the east of the region and have more stable flow regimes. An example of controls on river abstractions is also shown in Figure 2. The six groundwater sources are not modeled in this study. These provide a very small input to the water supply distribution system and are treated as constant input sources within the YWRS model. Constraints on pipe-size linkages and water treatment work sizes in the water supply distribution system are also modeled as shown in Figure 4.

[22] Under current climate conditions, failures in supply are generally a result of low flows which allow little or no abstraction from the rivers Wharfe and Ouse. These low flow events also cause the rapid depletion of certain reservoir sources, mainly the Pennine and Washburn groups, which then provide the solitary supply for the large urban demands of Sheffield and Leeds respectively. Pipe

Table 3. Monthly Disaggregation Factors Applied to Future Annual PE Scenarios, 2021–2050 and 2051–2080, and Comparison With Baseline PE Monthly Disaggregation Factors

Month	Percentage of Annual Total PE 1961–1990	Percentage of Annual Total PE 2021–2050 and 2051–2080	Percentage Change
January	2.0	1.9	−5.0
February	2.9	2.6	−10.3
March	6.1	4.9	−19.7
April	9.4	7.4	−21.3
May	14.4	10.7	−25.7
June	15.9	14.1	−11.3
July	17.0	17.4	+2.4
August	14.3	17.7	+23.8
September	8.9	13.1	+47.2
October	4.9	5.9	+20.4
November	2.5	2.6	+4.0
December	1.7	1.7	0.0

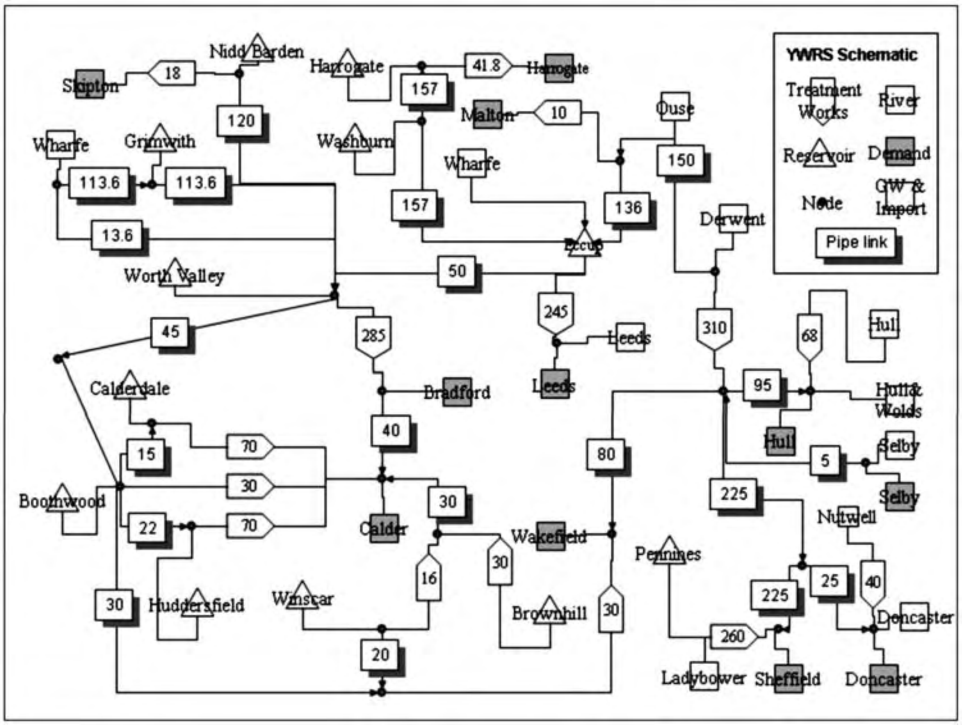

Figure 4. A schematic of the Yorkshire water resource system (YWRS) model. River abstractions, reservoir abstractions, groundwater abstractions, and imports and demands are modeled. The model also includes pipe capacity and water treatment work size restrictions upon the supply of water within the system. Pipe capacities and treatment work capacities are given in megaliters (or thousand cubic meters) per day.

capacity restrictions within the system can exacerbate these supply deficits (see Figure 4).

4.2. Rainfall Modeling

[23] *Fowler et al.* [2000] developed single-site stochastic rainfall models for the Yorkshire water resource region. This methodology coupled a semi-Markov based weather generator to the Neyman Scott Rectangular Pulses (NSRP) stochastic rainfall model [see *Cowpertwait et al.*, 1996a, 1996b] and was conditioned on historical daily rainfall data. Using the climatology of the region, the Lamb weather types [*Lamb*, 1972; *Jenkinson and Collinson*, 1977] were grouped into three clusters or weather "states": "anticyclonics", "northerlies" and "westerlies", using the same grouping for each subregion (site). These were then split seasonally (October–April, May–September) giving the winter-anticyclonic (WA), winter-northerly (WN), winter-westerly (WW), summer-anticyclonic (SA), summer-northerly (SN) and summer-westerly (SW) weather states. The weather generator was then calibrated using Lamb's daily weather-type data from 1961 to 1990 and the NSRP model fitted using rainfall data for each weather state.

[24] The above modeling approach was extended to multiple sites by Fowler et al. (submitted manuscript, 2003), combining Monte-Carlo simulation and sampling techniques to preserve monthly historical rainfall cross-correlations between two subregional NSRP rainfall models. The combined semi-Markov weather generator and NSRP model reproduces key aspects of the historic rainfall regime down to an hourly time step and allows the impact of variability in the frequency or persistence of weather types and changes in rainfall properties to be investigated. More details can be obtained from *Fowler et al.* [2000, submitted manuscript, 2003].

[25] For the modeling of the Yorkshire water resource system, the combined model was fitted for each weather state for each of the western and eastern subregions using observed rainfall data for a baseline period from 1961–1990. For each climate variability or change scenario the models were refitted using the new rainfall statistics for that scenario (see Tables 1 and 2) and a 1000 year synthetic rainfall series was generated.

4.3. Potential Evapotranspiration (PE) Modeling

[26] Historical PE data was derived using the 1961–1990 monthly terrestrial climatology of *New et al.* [1999, 2000]. The FAO (UN Food and Agriculture Organization) recommended combination formula for reference evapotranspiration [*Doorenbos et al.*, 1984] was used to translate these climate variables into a monthly time series of PE.

[27] The relationship between the PE cell data and rainfall in Yorkshire was then examined using regression analysis. For the modeling exercise, five 0.5° by 0.5° cells cover the water resource region, with four cells in the west of the region and one in the east. In this wet region of the UK, the accuracy of PE estimation is not critical for the storage based components of the resource scheme considered, with annual PE ranging from about 530 to 630 mm. However, there is a natural correlation between high summer PE and summer rainfall deficit but little variation in winter PE, with

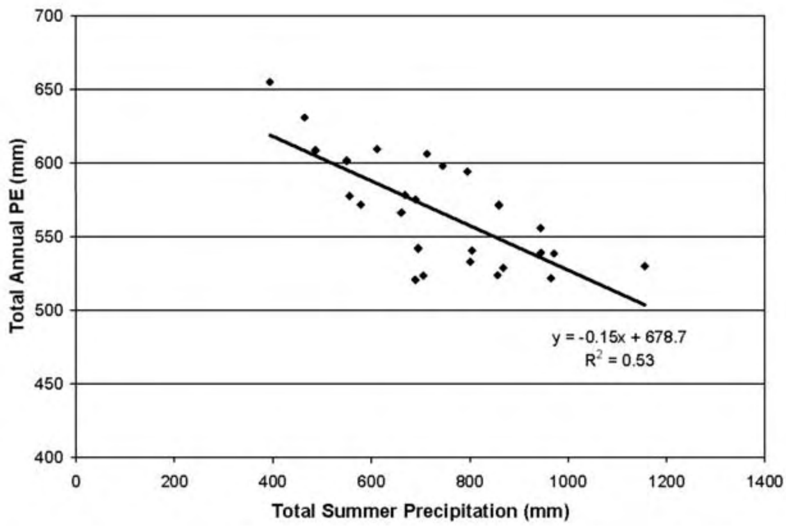

Figure 5. The relationship between summer precipitation and annual PE for the Wharfe catchment.

values ranging from 100 to 140 mm per year. Because of the interdependence of summer rainfall and summer PE, strong linear regression relationships were found between summer rainfall and annual PE over the period 1961–1990. An example of the relationship between summer rainfall and annual PE for the Wharfe catchment is shown in Figure 5 and the correlation coefficient (R^2) value in each case exceeds 0.53. These equations were applied to the synthetically generated rainfall series to produce annual PE series. These were then disaggregated into monthly values using a sinusoidal relationship based on average historical proportions from 1961–1990 (see Table 3).

4.4. Hydrologic Modeling

[28] A simplified version of the Arno hydrologic model [*Todini*, 1996] was used to translate the daily rainfall, areally averaged using Theissen polygons, and PE data into stream flow series that could be used as input to the YWRS model. Daily data from 1970 to 1996 were used to calibrate and validate models for inflows from the 10 reservoir and 4 river sources.

[29] Historical monthly reservoir and daily river flow data for 1970 to 1996 were taken from previous studies [*Mott MacDonald*, 1996, 1997]. Where adequate data were available, the monthly reservoir inflows were derived from reservoir operation data using a standard water balance approach, taking account of change in reservoir storage, spill, compensation or other releases, abstractions for supply, and transfers to/from other reservoir groups. However, for most reservoirs, there were insufficient data available and thus flows were generated for the whole period using a catchment model whose main parameters were based on those of a nearby catchment [*Mott MacDonald*, 1997]. Daily river flow data [*Mott MacDonald*, 1996] were generated using the HYSIM model and are based on naturalised flow series. Therefore it may reasonably be assumed that all river flow series used for calibration and validation already take account of upstream abstractions and discharges.

[30] These flow series were used for model calibration and validation on a monthly and daily time step respectively for the reservoired and river catchments. A split-sample approach was employed, with data from 1970 to 1982 used for model calibration and the remaining data used for model validation. Genetic algorithm optimization, developed by *Duan et al.* [1992], produced R^2 values in excess of 0.7 and a satisfactory water balance, defined as ±5%, for all reservoired and river catchment models (see Table 4 and Figure 6).

4.5. Results

[31] The RRV indicators are applied to the baseline 1961–1990, climatic variability and future climate scenarios. For each scenario, demand is assumed to be the same as the baseline. The same methodology is followed for each scenario.

[32] 1. A 1000 year rainfall series is generated at multiple sites using the combined semi-Markov generator and NSRP model. The parameters of the model are perturbed, relative to the baseline, according to the scenario under investigation.

Table 4. Calibration and Validation Statistics for the 14 YWRS Inflows[a]

WRPM Group	Calibration R^2	Calibration Water Balance	Validation R^2	Validation Water Balance
Washburn	0.79	1.01	0.72	0.93
Winscar	0.59	1.10	0.48	0.98
Pennine	0.83	1.00	0.81	1.09
Nidd/Barden	0.62	0.91	0.76	0.98
Grimwith	0.79	0.98	0.87	1.01
Worth Valley	0.86	1.07	0.83	1.13
Calderdale	0.93	1.00	0.93	0.96
Boothwood	0.88	0.94	0.88	0.95
Huddersfield	0.92	0.95	0.90	0.97
Brownhill	0.84	0.87	0.83	0.90
Wharfe	0.69	1.07	0.66	1.10
Ouse	0.60	1.15	0.61	1.16
Derwent	0.61	1.06	0.59	1.08

[a]R^2 refers to the Nash and Sutcliffe "efficiency" measure. The water balance statistic refers to the simulated total inflow/observed total inflow.

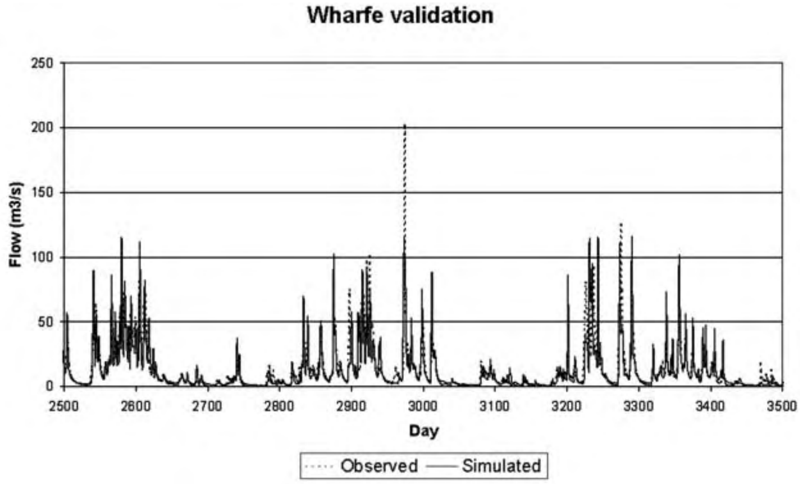

Figure 6. The River Wharfe validation sequence from day 2500 to day 3500, showing observed and simulated daily flows.

[33] 2. Regression equations relating PE to rainfall are used to produce a 1000 year monthly PE series.

[34] 3. The rainfall and PE series are used as inputs to the hydrologic models, producing 1000 year stream flow series.

[35] 4. The stream flow series are input to the YWRS model and the outputs of the model are evaluated using the indicators of reliability, resilience and vulnerability, with reference to the imposed demands.

[36] The results for water resource system performance (supply reliability) are summarized in Table 5.

4.5.1. Baseline Model: 1961–1990

[37] Under current climate conditions, supply deficits reach a maximum cumulative extent of 74,562 ML during a drought period of 165 days and are consistent with rates of failure produced using historical inflow data for the 1961–1990 period [*Mott MacDonald*, 1996]. Under the baseline scenario the reliability of individual supplies within the system is generally high, but resilience is low as a result of both small system "headroom" (the overall supply demand gap) and the vulnerability to low flows in the rivers Ouse and Wharfe. For example, in the baseline scenario, the river Wharfe does not supply any water to the system for approximately 8% of the simulation time (not shown). The baseline scenario simulation suggests that the return period of the 1995–1996 drought could be estimated at around 170 years.

4.5.2. High-Phase NAO

[38] Model simulations suggest that, under a scenario of high-phase NAO, supply reliability is slightly decreased at all major demand centers compared to the baseline scenario, particularly at Calder, Wakefield and Leeds. The likelihood of the conjunctive failure of supplies is very similar to that of the baseline scenario and the reliability of reservoir sources is generally improved as a consequence of increased winter rainfall. However, during summer months, due to decreased rainfall, river source supplies are more likely to fail and minimum reservoir storage levels are lowered. Therefore, when failure does occur it is generally more severe. The longest duration of failure changes from 165 to 189 days and the total shortfall also increases to 84,115 ML. This increased vulnerability is also reflected in the likelihood of occurrence of a drought event as severe as that of 1995–1996 which, under a high-phase NAO, is reduced to a 100-year event, from an estimated 170-year event under the baseline scenario.

4.5.3. Low-Phase NAO

[39] The opposite effect is observed in the low-phase NAO scenario simulation. Supply reliability and conjunc-

Table 5. Summary of Water Resource System Performance Results as Percentage Change From the Baseline Scenario (1961–1990)[a]

Scenario	Change in Annual PE (Percent From Baseline)	Percent Change in Rainfall Amount and (Variability) From Baseline		Percent Change in Average Water Supply Reliability From Baseline	Percent Change in Total System Resilience From Baseline	Percent Change in Total System Vulnerability From Baseline		Return Period of 1995 Drought Event, years
		Winter	Summer			Duration, Days	Extent, ML	
Baseline (1961–1990)	–	–	–	–	–	–(165)	–(74562)	170
High-NAO	–	+2	−1	−0.1	−1.2	+14.5 (189)	+12.8 (84115)	100
Low-NAO	–	−3	+5	+1.3	+0.6	−9.1 (150)	−0.8 (73955)	1000
2021–2050	+6	+9 (+5)	−5 (+10)	0.0	−10.7	+18.8 (196)	+8.8 (81138)	140
2051–2080	+10	+16 (+15)	−9 (+10)	−0.3	−17.8	+34.5 (222)	+9.9 (95504)	125

[a]Absolute drought duration in days and extent in total megaliters are in parentheses for each scenario. The return period for the 1995–1996 drought event is calculated using a simple frequency approach, i.e., a drought is counted as a 1995–1996 magnitude event if the duration of water supply failure exceeds 147 days (the water supply failure duration of the system simulated during 1995–1996), and the number of 1995–1996 drought events counted during the 1000-yr simulation is simply divided by 1000 to estimate the return period.

tive failures are significantly improved when compared to the baseline scenario. Supply vulnerability is decreased in general, with the longest duration of failure being 150 days compared to 165 for the baseline scenario. The extent of the total system shortfall is also reduced by approximately 1000 ML. This increased reliability in supply is also reflected in the drought severity statistic; the return period of a drought as severe as that of 1995–1996 is approximately 1000-years under a low-phase NAO. This constitutes a major reduction in frequency upon the baseline scenario. The increased summer rainfall during a low-phase NAO event is seen to significantly reduce the risk of severe drought in Yorkshire.

4.5.4. UKCIP98 Future Climate Scenario 2021–2050

[40] Under the 2021–2050 scenario, simulations suggest that the reliability of supply to most demand centers is similar to that of the baseline scenario, and in some cases increased. However, the resilience of supplies to most major demand centers is reduced due to increases in the duration and magnitude of drought. The increased vulnerability of the system to severe drought is also shown by the increase in duration of drought and its magnitude. This is increased to 196 days, with the cumulative water supply deficit also increased by 9% to 81138 ML.

[41] Source reliability is, on the whole, improved under the 2021–2050 scenario. Reservoirs exhibit increased reliability and many show an improvement in minimum levels. However, the reliability of river sources is substantially reduced, with flow levels allowing no abstractions becoming more prevalent under the 2021–2050 scenario, particularly on the rivers Wharfe and Ouse. As the abstraction from river sources exerts such a strong control on the successful supply of water to the system, this has a significant effect and is a cause of the increased vulnerability of supplies to some demand centers. The projected return period for a drought as severe as the 1995–1996 drought has changed little from the baseline and is estimated as about 140 years. However, the severity of drought (measured using the percentage change in total system vulnerability from the baseline) will increase in both magnitude and duration when compared to historical droughts.

4.5.5. UKCIP98 Future Climate Scenario 2051–2080

[42] Under the 2051–2080 scenario, the reliability of water supplies to many of the demand centers is similar or improved when compared to that of the baseline scenario. The resilience of water supplies is in all cases reduced under the 2051–2080 scenario, however, and the vulnerability of water supplies is markedly increased at almost all demand centers. The failure of the water resource system to adequately supply demand reaches a total duration of 222 days. The magnitude of failure is also substantially greater. The total deficit is increased by 10% over the baseline scenario, but by only 2% over the 2021–2050 scenario.

[43] System reliability improves on average but there are increases in the frequency of river flow levels where no abstractions are allowed during summer. The likelihood of occurrence of flows below these levels is increased to some 9 and 1% of the simulation time for the rivers Wharfe and Ouse, respectively. The likelihood of occurrence of a 1995–96 drought event is not increased markedly under the 2051 to 2080 scenario. The return period is estimated as 125 years. However, in general, drought events are likely to be more severe than the 1995–1996 drought, in terms of both duration and magnitude due to the large increase in total system vulnerability projected for this scenario.

5. Summary of Results

[44] A summary of results obtained by this analysis can be found in Table 5. Natural climatic variability plays a large role in the frequency and magnitude of drought events within Yorkshire and elsewhere in the UK. Under a low-phase NAO scenario, summer rainfall across the UK is increased and there is reduced seasonality. This causes a significant improvement in both supply reliability and vulnerability when compared to the baseline. This results in a drought as severe as the 1995–1996 drought only being expected once every 1000 years. Higher summer rainfall under a low-phase NAO scenario significantly reduces the risk of severe drought in Yorkshire. Under a high-phase NAO scenario, however, enhanced seasonality causes reduced summer and increased winter rainfall across much of the UK. This causes a small reduction in water supply reliability at all major demand centers in Yorkshire, although the reliability of reservoir sources is generally improved due to winter rainfall increases. However, vulnerability is significantly increased, as the reduced summer rainfall lowers minimum reservoir storage level and increases the severity of failure when it occurs. This increased vulnerability is also reflected in the drought severity statistic with the return period of a drought event as severe as that of 1995–1996 being reduced from 170 years under the baseline to 100 years under a scenario of high-phase NAO.

[45] Both the 2021–2050 and 2051–2080 climate change scenarios show similar water supply reliability to the baseline scenario. Indeed, in some cases the overall reliability of water supply to a demand center is improved. However, the resilience of water supplies is reduced for all demand centers and the increased vulnerability of the system to severe drought events is shown by the increase in both cumulative supply deficits and duration of failure. System failure duration increases from 165 days in the baseline scenario, to 196 days for the 2021–2050 scenario, and 222 days for the 2051–2080 scenario. The cumulative system supply deficit also increases, by 9 and 10%, respectively, for the two scenarios. However, the occurrence of a 1995–1996 drought event is only slightly raised. The return period for a 1995–1996 magnitude drought event is 140 years for the 2021–2050 scenario and 125 years for the 2051–2080 scenario. The important result however, is that, in general, drought events are expected to be more extensive in both magnitude and duration than severe historical droughts when measured using percentage change in total system vulnerability.

[46] System reliability generally improves under the 2021–2050 scenario. Reservoir sources exhibit increases in reliability and many show improvements in minimum level, but under the 2051–2080 scenario this trend reverses. The major impact, however, comes from increases in the frequency of river flows during summer months at which no abstraction is allowed. This causes the reliability of river

sources to substantially reduce under both scenarios, but particularly the 2051–2080 scenario.

6. Discussion and Conclusions

[47] This study has shown that water resources in Yorkshire are likely to become increasingly vulnerable to severe drought events under future climate change. However, natural climate variability may play an equally important role in the frequency of drought events and their magnitude within Yorkshire and elsewhere in the UK. It has been shown [*Fowler and Kilsby*, 2002a] that a high-phase NAO enhances seasonality and causes a reduction in summer rainfall and increased winter rainfall across much of the UK. The opposite effects are true of the low-phase NAO. In terms of water resources, if the underlying trend from the 1970s toward a higher NAO, with associated higher winter temperatures and a steeper northwest to southeast rainfall gradient, continues then there may be serious drought concerns [*Mayes*, 1995]. If climate projections are accurate then the NAO is likely to continue its recent positive trend [*Hulme et al.*, 2002]. This will have severe implications for water resource systems in the north of the UK where there is a reliance on surface water sources.

[48] The results of this investigation into the effects of natural climatic variability and future climate change on water resources in Yorkshire therefore suggest that (1) current natural climatic variability may produce more frequent severe drought events than is estimated for the examined future climate change scenario, which also includes estimates of natural variability; (2) for the future climate scenarios (2021–2050 and 2051–2080), model results suggest an increased vulnerability to severe drought, with increases in both magnitude and duration. This is due to a combination of increases in summer PE and declining summer rainfall that will increase the likelihood of summer water shortages. (3) Although an increase in winter rainfall will improve water resource reliability on average, increased variability coupled with decreased summer rainfall may lower system resilience and mean that more severe drought will occur in regions reliant on single-season reservoirs than under current climatic conditions. (4) The largest impact on the Yorkshire water supply system comes from increased frequency of low flows in rivers during summer drought events. The reliability of river sources is substantially reduced for both the 2021–2050 and 2051–1080 scenarios, particularly in terms of the increased frequency of flow rates where no abstraction is allowed. (5) The frequency of drought is only slightly raised. The return period for a 1995–1996 magnitude drought event is lowered from 170 years to 140 years for the 2021–2050 scenario and 125 years for the 2051–2080 scenario. However, more importantly, in terms of total system vulnerability, these droughts will be more extensive in both magnitude and duration than severe historical droughts, and may develop more rapidly [*Fowler and Kilsby*, 2002b].

[49] There are some caveats to this modeling approach. Firstly, that a stationary climate process is assumed. The time series modeling approach assumes a stationary 1000 year period for each of the low- and high-phase NAO scenarios, respectively. However, the existence of the NAO could be viewed as a quasi-stationary process, where low- and high-phase NAO periods cycle in a pseudorandom manner. Secondly, there is no quantification of uncertainty in the projected changes. Uncertainty is found at each stage of the modeling process, with uncertainties in the climate change scenario being added to by uncertainties in rainfall modeling, PE modeling, hydrological modeling, and, finally, uncertainties in the estimates of the impacts of climate change. Additionally, uncertainties in the quantification of future demands on water resources, and alternative operating scenarios for the water resource system to mitigate the impacts of potential climate change have not been considered in this study.

[50] Further work in this area will concentrate both on the representation of the NAO as a quasi-stationary process and the inclusion of uncertainty estimates. Uncertainty estimates in the climate change scenarios may be derived by the use of future climate projections from different global climate models and ensemble members. It must be noted however, that there is currently no accepted methodology for estimating the uncertainty in future emissions scenarios, which may arguably attribute the largest uncertainty in the whole system. Uncertainty in estimates of the impacts of climate change and climatic variability on the reliability, resilience and vulnerability of a water resource system can however, be addressed by using an ensemble of rainfall simulations representing the same scenario.

[51] However, despite these concerns, linking the prevalence of synoptic weather patterns and rainfall to the NAO may yet provide an important predictor of future hydrological drought in Yorkshire. Strong connections have been found between winter rainfall and the NAO, particularly in western Yorkshire, where most surface water supplies are located [*Fowler and Kilsby*, 2002a]. If the NAO can be forecast with some skill using sea surface temperature or other variables then it may be possible to estimate winter reservoir recharge a few months in advance [e.g., *Wedgbrow et al.*, 2002]. This would provide an important predictor of hydrological drought and allow the forward planning and prioritization of water supplies.

[52] **Acknowledgments.** This work was undertaken as part of a Ph.D. thesis funded jointly by the Engineering and Physical Sciences Research Council and the Environment Agency. Rainfall data were supplied by Mike Stokes (Environment Agency, York, UK) and the British Atmospheric Data Centre, and Lamb Weather Type data by Phil Jones (Climate Research Unit, University of East Anglia, UK). I would like to thank John Jepps at the Environment Agency in Leeds for useful discussions and supply of model inflows.

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H. J. Fowler, C. G. Kilsby, and P. E. O'Connell, Water Resource Systems Research Laboratory, School of Civil Engineering and Geosciences, Cassie Building, University of Newcastle upon Tyne, Newcastle upon Tyne NE1 7RU, UK. (h.j.fowler@ncl.ac.uk)