Water and Environment Journal, 2012, Volume 26, Issue 3, pages 361–370

Evaluating the effects of climate change on the water resources for the city of Birmingham, UK.

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Keywords

Elan valley, Hydrologically Effective Rainfall, Modelling, Reservoir, UKCP09, Water Supply, Weather Generator, Adaptation.

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Abstract

Climate change is expected to affect precipitation patterns and may therefore impact upon water resource availability. The city of Birmingham in central England receives its public water supply from a catchment in the Elan valley, mid Wales. Baseline and future climate projections generated from a stochastic weather generator within the United Kingdom Climate Projections 2009 and a daily soil water balance model (WaSim) were used to determine the potential impacts of climate change on Hydrologically Effective Rainfall (HER). Annual HER is likely to decrease from baseline conditions (> 90% likelihood that HER will be reduced), with more frequent and persistent very dry spells and increasing seasonality. It is concluded that climate change will put additional stress on water resources for the city of Birmingham so that, coupled with expected increases in demand, adaptation measures to increase supply and / or reduce demand are likely to be needed.

Introduction

The evidence to suggest that global climate is changing is unequivocal with findings from the Intergovernmental Panel on Climate Change (IPCC) attributing >90% confidence that this is due to anthropogenic greenhouse gas emissions (IPCC, 2007). Global temperatures have risen by nearly 0.8^{o}C since the late 19th century, and projections suggest that global temperature increases of between 1.1-6.4^{o}C are likely by 2100, dependent on greenhouse gas emissions (IPCC, 2007). Climate patterns are shifting with increasing frequency of intense rainfall projected across much of the UK, whilst summers have been generally getting warmer and drier (Fowler & Ekstrom, 2009; Osborn & Hulme, 2002). Such changes have the potential to reduce water resources, putting additional stress on the environment and impacting on the quality and quantity of supplies available for society (Bates et al. 2008). Reservoirs will be impacted in terms of operation and their capacity may need to be increased to ensure sufficient water supplies are available to meet demand during deficit periods (Jones, 1999). The scale of this potential impact is already being felt across the UK with droughts in June 2010 leading to hose pipe bans affecting 6.5 million customers in the North East of England (CEH, 2010).

The city of Birmingham in central England is the UK's second largest city, with a population in excess of 1 million. Birmingham receives all of its potable water needs from the Elan valley reservoirs, with around 320Ml/d of water supplied in a normal demand year (STW, 2010). The effect of climate change on this important catchment is uncertain and there is therefore concern over the future reliability of water supplies for Birmingham. This case study aims to assess the potential effects of climate change on Hydrologically Effective Rainfall (HER) in the Elan valley under a range of emissions scenarios and time steps using the UKCP09 stochastic weather generator. HER represents the precipitation-derived water that is able to flow to the reservoir through surface water and groundwater pathways. Water companies need to respond to the challenges of climate change and measures to adapt to climate change are discussed in light of the findings of this study. Although this study focuses on a particular UK catchment, the methodological insights will have wider significance.

Study Area

The Elan valley catchment, with an area of 184km^2 and an elevation of around 400-550m above sea level, is located between -3^{o}44'24''E_52^{o}20'24''N and -3^{o}34'12''E_52^{o}13'48''N in mid Wales, UK (***Figure 1***). The Elan valley reservoirs were built between 1893 and 1904 for the Corporation of Birmingham in order to provide adequate water supplies to its rapidly increasing workforce (CPAT, 2010a). An aqueduct was built to transport the water by gravity along the 73 miles to Frankley water treatment works near Birmingham where it is still processed today. A severe drought occurred in 1937 which led to the construction of the Claerwen reservoir which opened in 1952, increasing the capacity of the Elan valley reservoirs to around 100 billion litres (Marsh & Hannaford, 2008). The catchment is underlain by Silurian and Ordovician sedimentary rocks with blanket basin peat in the uplands and Palaeozoic slate, mudstone and siltstone throughout the remainder (Rudeforth et al. 1984). The catchment mainly consists of natural grassland (***Figure 1)***. It rains on average 235 days of the year contributing to an average annual rainfall of 1841mm (Marsh & Hannaford 2008).

[Figure 1 about here]

Methodology

In order to assess the effects of climate change upon water resources in the Elan valley, a stochastic weather generator was first used to generate multiple realisations of daily time series of precipitation and potential evapotranspiration for baseline and future climate scenarios. Secondly, a soil water balance model (WaSim - Hess & Counsell, 2000) was used to simulate daily hydrologically effective rainfall for the reservoirs' catchment for the baseline and each of these future scenarios.

Climate change scenarios

The United Kingdom Climate Projections 2009 or UKCP09 (Jenkins et al., 2009) were developed on behalf of the United Kingdom Climate Impacts Programme (UKCIP). A multi model ensemble from 12 different climate models combined with a perturbed physics ensemble using the HadSM3 Global Climate Model (GCM) in a Bayesian statistical framework was used to generate probabilistic climate projections at a 25km scale resolution (Murphy et al. 2009). The climate scenarios use a low, medium and high emissions scenario corresponding with IPCC emission scenarios B1, A1B and A1F1 respectively (Nakicenovic & Swart, 2000). Baseline and seven future overlapping 30 year time slices are available – the 2020's (2010-2039), 2030's (2020-2049), 2040's (2030-2059), 2050's (2040-2069), 2060's (2050-2079), 2070's (2060-2089) and 2080's (2070-2099).

A weather generator (Jones et al. 2009) provides finer spatial (5km resolution) and temporal (daily or hourly time step) detail. The WG uses two stochastic models in series to generate internally consistent daily weather variables, the first generating rainfall data and the second generating other weather variables such as temperature, humidity and Potential evapotranspiration (ETp) from this primary variable using inter variable mathematical / statistical relationships (Kilsby et al. 2007). ETp is calculated using the FAO modified Penman Monteith method (Doorenbos & Pruitt, 1977).

The weather generator was applied to a group of 5km x 5km grids representing the Elan catchment, as it does not allow for spatio-temporal correlation. One hundred randomly generated runs provided equally probable and statistically credible representations of weather variables for baseline conditions and for each combination of emissions scenarios and timeslice. Watts et al. (2004) states that there is similar variability across 100 weather generator runs as there are with 1000 runs.

WaSim soil water balance model

Model description

WaSim is a one dimensional daily soil water balance model that simulates inputs (Precipitation), outputs (actual evapo-transpiration, surface runoff, potential recharge and drainage) and changes in soil water storage in response to weather (Hess & Counsell, 2000). WaSim was chosen due to its flexibility, data availability and demonstrated value as a research tool in hydrological studies (eg. Fasinmirin et al. 2008; Holman et al. 2009; Hess et al. 2010).

The soil is divided into up to 5 compartments (***Figure 2***). Water moves from upper compartments to lower compartments when the soil layer exceeds field capacity and any water draining out of the lowest layer of a freely drained soil is taken as potential recharge. For seasonally waterlogged soils, drain flow occurs when the water table is above the height of the ditches or drain and is a function of the mid drain water table height (after Youngs et al., 1989). Surface runoff comprises the infiltration-excess runoff (estimated using the widely recognised SCS curve number method of Conservation Engineering Division, 1986) and runoff due to saturated soil. Any precipitation that does not run off is assumed to infiltrate.

Actual evapotranspiration is taken as the area-weighted average of soil evaporation (estimated using the method of Ritchie, 1972) and plant transpiration. Plant transpiration is assumed to occur at a rate proportional to the reference evapotranspiration (Allen et al. 1998) depending on the plant type and soil water content, but does not take into account the effect of raised atmospheric CO_2 concentrations (Gedney et al. 2006). It occurs at the potential rate whilst the root zone soil water content is between field capacity (here defined as the soil water content at a suction of 5 kPa) and the limit of easily available water (at 200 kPa), and under restricted water supply decreases linearly to zero at permanent wilting point (1500 kPa) (Brisson, 1998). For soil water contents above field capacity, it decreases linearly to zero when the root zone soil water content reaches saturation (0 kPa).

Hydrologically Effective Rainfall (HER) is taken as the sum of potential recharge and runoff in freely draining soils and of drainage and runoff in slowly permeable, seasonally waterlogged soils.

[Figure 2 about here]

WaSim model set-up

WaSim requires data on the soil, land cover, drainage and weather. The dominant soils in the catchment (from Rudeforth at al. 1984) are blanket peat (Crowdy series - 39% of the catchment), seasonally waterlogged clay loam soils over impermeable rocks (Hafren series- 39%) and freely draining clay loams (Manod series- 18%) with the remaining 4% of the catchment consisting of the reservoirs. These are within Soil Hydrological Groups D (Crowdy) and C (Hafren and Manod), and are assumed to be in Fair soil condition (Conservation Engineering Division, 1986). Volumetric water contents at suctions of 0, 5, 200 and 1500 kPa and hydraulic conductivity are given in ***Table 1***.

Permanent grass was represented with a crop coefficient (representing the ratio of crop potential evapotranspiration to reference potential evapotranspiration) of 1 and a rooting depth of 0.5 m.

For each of these 21 climate scenarios (3 emissions scenarios for each of the 7 different time slices) WaSim was run for each combination of soils (3) and weather files (100). The HER outputs for each soil type were then area-weighted, with the reservoir effective rainfall calculated as precipitation minus evaporation, taken as 1.2 times ETp (Penman, 1950).

Results

Weather Variables

Average annual rainfall (AAR) in the catchment derived using the UKCP09 weather generator is projected to increase from baseline (1876mm) over the 7 time periods for low, medium and high emission, with the 2080's under high emissions having a median AAR across the 100 runs of 2024mm (rising to 2209mm for the 75th percentile). Although there is little variability between median AAR across the scenarios and timeslices, the range of results in excess of 2000mm indicates considerable variability between the 100 runs as shown in ***Figure 3***. Annual potential evapotranspiration (ETp) shows increasing variability and significant increases within the scenarios with, for example, the minimum annual average ETp of 461mm within the 100 runs in the 2050's low scenario being greater than the median value of 448mm for the baseline.

[Figure 3 about here]

Average monthly temperatures changes are similar throughout the year with temperatures being cumulatively higher under each of the time periods. There is little change in winter (DJF) ETp, but progressive increases with time and emissions scenario in summer (JJA) ETp and lesser increases in spring (MAM) and autumn (SON) (***Figure 4***). There is a clear trend of increasing seasonality in precipitation, with increases in the winter and reductions during the summer months. The 25th percentile monthly precipitation for the medium emissions scenario in the 2080's shows December and August to have an increase of 35mm (+16%) and a decrease of 49mm (-45%), respectively, in comparison to the baseline.

[Figure 4 about here]

Hydrologically Effective Rainfall

Baseline

The baseline (1961-90) estimate of average annual HER in the catchment by WaSim is 1328mm/year. This is higher than the average annual HER of 1071mm (1971-2000) given by the UK Meteorological Office Rainfall and Evaporation Calculation System

(MORECS, v2.0; Hough & Jones, 1997) for the surrounding 40 km x 40 km grid square, and by an estimate of average annual HER of 1255 mm derived from monthly naturalised river flow (1935-1977) for the Gauging Station 55006 below the Caban Coch Reservoir (Marsh & Hannaford, 2008). It is considered that the WaSim estimate is acceptable, given the (1) different time periods over which the three values have been calculated, (2) input data averaging over the much larger MORECS grid square (1600 km^2 in comparison to the 184 km^2 for the gauging station/catchment) which results in it having a lower average altitude, a different soil type and average annual rainfall in excess of 200mm lower than that of the hydrological catchment and (3) the inherent uncertainties in estimating the naturalised flows within a long-term impounded catchment.

Future annual HER

As a generalisation, the WaSim results show that there is a slight flattening and broadening of the distribution of annual HER with increasing emissions and with time, indicating increasing likelihood of very dry and very wet years. The effect of this on the uncertainty of a given annual HER range can be investigated within a single emissions scenario (i.e. across the seven timeslices) or at a single timeslice (i.e. across the three emissions scenarios). For example, the "certain" likelihood of a given annual HER occurring within the Medium emissions scenario represents the lowest likelihood of that annual HER occurring across the 100 simulations within any of the seven timeslices; whilst the 100^{th} percentile likelihood represents the highest likelihood of that annual HER occurring across the 100 simulations within any of the seven timeslices. **Figure 5** shows the likelihood of a given annual HER range within a single (Medium) emissions scenario across all of the timeslices, and also across all of the emissions scenarios (Low, Medium and High) within a single timeslice (2070-99). Across the emissions scenario, the uncertainty in the likelihood of a given range of annual HER (as given by the range about the median likelihood) are up to 20% of the median likelihood around the centre of the annual HER distribution, but become greater and can exceed 50% within the outer parts of the distribution

[Figure 5 about here]

Future monthly and seasonal HER

The changes in average monthly HER for the medium emissions scenario (***Figure 6)*** show a similar pattern to that observed for precipitation (***Figure 4***) but with greatest reductions occurring one to two months later than precipitation due to the need to replenish larger soil moisture deficits arising from the increased evapotranspiration. Average monthly HER for summer (JJA) and winter (DJF) for the 2020's, 2050's and 2080's for the low emissions scenario are shown in ***Figure 7***. Average monthly summer HER under each of the time series shows a less than 10% chance of being above baseline HER. In winter the probability of HER being above baseline HER in the 2020's is 50%, with the 2050's suggesting it is very likely to be above baseline HER (92%) and the 2080's suggesting it is almost certain (100%).

[Figure 6 about here]

[Figure 7 about here]

Frequency of Droughts

Although information on annual and monthly changes in HER is of value, a major concern of water resource planners is the frequency and persistence of droughts. 'Very Wet', 'Wet', 'Normal', 'Dry' and 'Very Dry' years have been classified according to percentile ranges of baseline annual HER. A future Very Dry year will have annual HER in the bottom 5^{th} percentile of the baseline period; a Dry year will have annual HER between the 5^{th}-20^{th} percentiles of the baseline; a Normal between the 25^{th}-75^{th}; a Wet year between the 75^{th}-95^{th} and a Very Wet year between the 95^{th} to Maximum annual HER . The distribution of the different HER years within each of 100 equally probable runs under the Medium emissions scenarios in the 2020's and 2050's is shown in ***Figure 8***, ordered by increasing frequency of Very Dry years. The number of Very Dry years varies significantly within the different runs for both timeslices, from between 10 years to 0.

From the 3000 modelled years for each emissions-timeslice combination, the probability of Very Wet years does not change significantly but the probability of Very Dry years increases with time and emissions by up to around 7% (***Table 2***).

[Figure 8 about here]

A one year drought will be buffered by the reservoir storage but persistent or repetitive years of drought will increase stress on the environment and may affect the resilience of water supplies. To provide a preliminary assessment of the effect of the increasing frequency of droughts on reservoir storage, a simple monthly reservoir water balance of inflows (as given by the monthly HER) and outflows (taken as the combined sum of river compensation flows of 1.5 m^3/s [CEH, 2011] and transfer volumes of 340 Ml/d, representing the average transferred to Birmingham in a drier summer [Severn Trent Water Ltd, 2008]) was conducted, allowing for a maximum storage capacity of 99,107 Ml and a dead water level of 6% full (Severn Trent Water Ltd, 2010). From the 100 simulations for each emissions-timeslice combination, the number of consecutive years in which simulated reservoir storage fell below 35%, which represents the lowest monthly Drought Warning trigger level, was identified. ***Figure 9*** shows the results for each of the 30 years timeslices for the Medium emissions scenario compared to 100 baseline simulations. Although the reservoir water levels are simulated to re-fill each winter, indicating that the drought length is less than the 18-month critical period of the reservoirs, there is a general trend of increasing frequency and length of consecutive years in which summer reservoir storage reaches concerning levels.

[Figure 9 about here]

Discussion

This study has highlighted the variability in possible future climate conditions and shown that although Average Annual Rainfall (AAR) is likely to increase, annual Hydrologically Effective Rainfall (HER) is likely to decrease, resulting in reduced water availability. The impacts of climate change appear more sensitive to the time period than the emissions scenario with the 2080's showing greater variability in weather variables than the 2020's (***Figure 4***). The seasonal effects of climate change upon HER are significant and there is a very low probability (6%) that HER will be above baseline conditions in summer months (JJA) of the 2080's for the low emissions scenario but a certain probability (100%) that HER will be above baseline conditions in winter months (DJF) as shown in ***Figure 7***. This preliminary study suggests that changes in seasonal distribution of HER coupled with increased frequency of very dry years may threaten the reliability and resilience of water supplies, necessitating water supply companies to respond to ensure the reliability of water supplies to their customers.

Supply

Historical droughts such as in 1937 and 1976 led water companies in the UK to review their storage capacity, and new schemes were constructed enabling them to supply water during the 1995/96 drought (Subak, 2000). Management procedures have also been introduced to ensure reliability of water resources, such as Drought Plans which trigger responses such as hosepipe bans or the implementation of drought permits to vary levels of abstraction.

The critical drought period from which the Elan valley reservoirs would go from full to empty without spilling is 18 months (STW, 2009), which enables current demands to be sustained whilst maintaining target levels of headroom. It is likely that the reservoirs' capacity will be able to buffer the pressures from climate change throughout the current 25 year water planning cycle, given the findings of this study and the estimated reduction in Severn Trent Water's (STW) deployable output by around 6.5 % by 2025 due to climate change (Crookall & Bradford, 2000). However, the

longer term shifts in monthly ETp and precipitation (***Figure 4***) are expected to result in the increased frequency of very dry years by around 7% (***Table 2***) and increasing seasonality of reservoir inflows as suggested by the HER results(***Figure 6***). The preliminary reservoir water storage results presented suggest that there will be increasing frequency of low summer reservoir levels as a result of the increasing seasonality of inflows, although further detailed reservoir simulation modelling is needed to assess their ability to meet demands beyond the current 25 year water planning cycle.

Alternative reservoir operating policies may provide operational and cost effective ways of mitigating reservoir system performance losses but are unlikely to work in isolation. Increasing the Elan reservoir storage capacity (Sheriff et al. 1996; EA, 2006) would counteract the anticipated increased hydrological variability, as additional surplus winter HER can be captured rather than allowed to spill.

Demand

Downing et al. (2003) suggest that the direct impact of climate change on domestic water demand is expected to be insignificant by 2020. However, the effects of changes in demographics, technology and human behaviour may have significant effects on future water demand in Birmingham. Environment Agency (2001) indicate that future domestic demand in England & Wales may change by -28 and +33% between 1997 and 2025 depending on the scenario assumptions. The population of Birmingham is also expected to rise from 1,028,700 in 2009 to 1,170,000 by 2028 (BCC, 2010). The effect of the additional population will aim to be offset by the UK water strategy to reduce household consumption from 150l/p/d to 130l/p/d (EA, 2009).

Given the important climate and socio-economic uncertainties in the water resource and water demand projections and the significant economic costs involved in adaptation, the response of water companies to climate change (Arnell & Delaney, 2006) will best be addressed through integration into a wider risk based framework

(eg. Willows & Connell, 2003; Lindley et al. 2006) to develop suitable adaptation strategies based on win-win or low regret options. The combination of the effects of climate change on the reliability of the water resources and the potential for significant increases in water demand from the growing population centre supports a twin track approach of reducing demand and increasing supply as the best way to maintain supplies whilst improving resilience (EA, 2009; STW, 2010). Given the capacity limit of the aqueduct that transports the water supplies from the Elan valley to Birmingham of 345Ml/d, increasing supply may need to be delivered locally through (1) increased abstraction of groundwater from the Permo-Triassic sandstone aquifer underlying Birmingham, which would require additional treatment due to contamination but will help combat rising urban groundwater levels; (2) reducing leakage from around 525Ml/d (2006/07) to the target economic level of leakage of 453Ml/d by 2015 in the wider Severn Trent region (OFWAT, 2010); (3) further network integration to allow increased transfers of water around the water distribution network.

Conclusions

1. This study suggests that water resources in the Elan valley will be impacted by future climate change. The changes in seasonal distribution of HER are significant and increasing with time, with summers showing very high (>90%) confidence that HER will be reduced from baseline levels, with winters generally above baseline. The number of very dry years is simulated to increase by around 7% from baseline leading to increasing frequency of low simulated reservoir storage levels.

2. The direct impacts of climate change on domestic water demand are expected to be much less than the effects due to changes in technology and human behaviour and the increasing population of Birmingham. The climatic changes are likely to alter the frequency of droughts and reduce the reliability of public water supply unless supplies are increased and / or demand reduced. Increasing the Elan reservoir storage capacity would counteract the anticipated increased hydrological variability, but would be

costly, involve long lead times and potentially (if future demand increases) be constrained by the limits of the aqueduct that transports the water supplies from the Elan valley to Birmingham.

3. The twin track approach of increasing supply and reducing demand appears the best way to maintain supplies whilst improving resilience due to the anticipated increased demands and limited capacity of current infrastructure. This could be achieved through i) Increased groundwater abstraction ii) Reductions in leakage and iii) Increased water transfers.

Acknowledgements

The authors acknowledge the support and advice provided by Richard Rees (Birmingham City Council), William Groves (Environment Agency) and Marcus O'Kane (Severn Trent Water). The views expressed in this paper are those of the authors and do not necessarily represent those of Birmingham City Council, the Environment Agency or Severn Trent Water. MORECS data were provided by John Fullwood of the Met Office, Naturalised river flow and precipitation data was provided by the National River Flow Archive and the Land Cover Map 2000 data from the Centre for Ecology and Hydrology.

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Figure captions

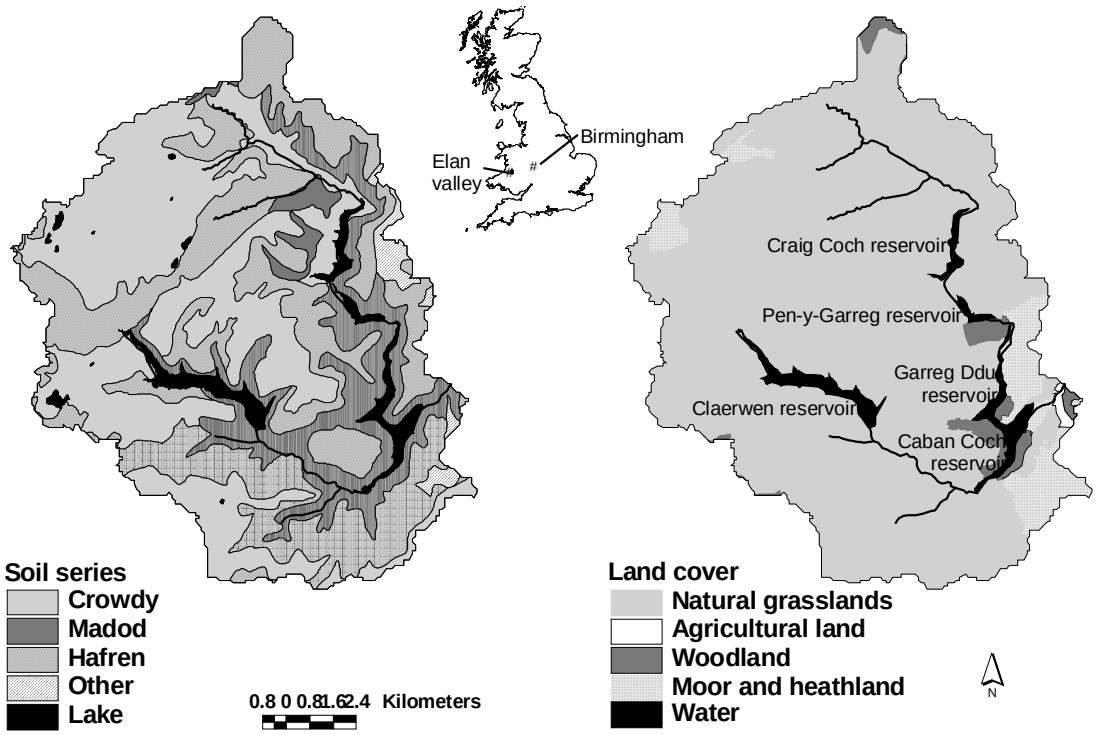


Figure 1 The Elan valley catchment and reservoirs.

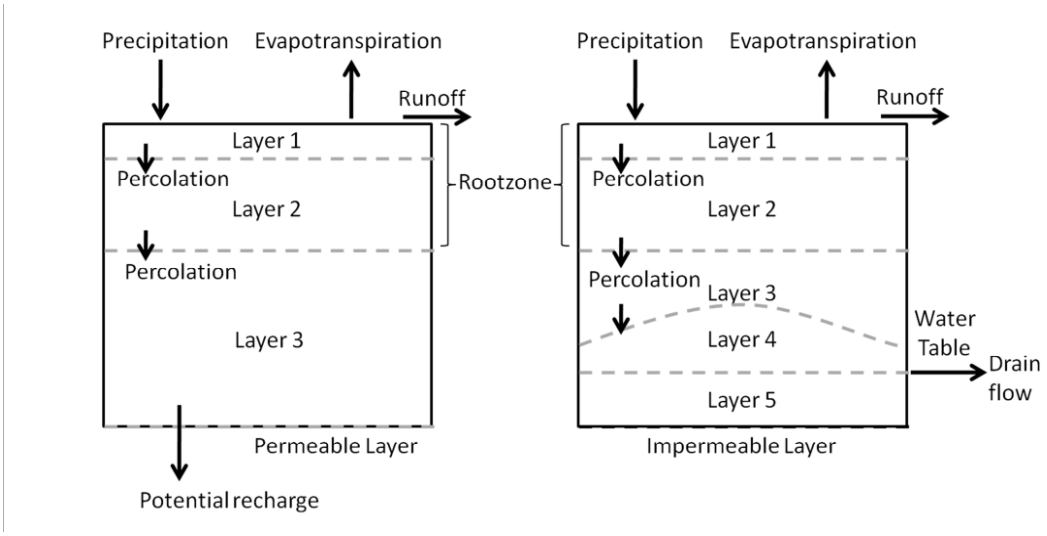


Figure 2 Schematic of the WaSim soil water balance model for (left) freely draining and (right) low permeability soils (modified from Hess and Counsell, 2000)

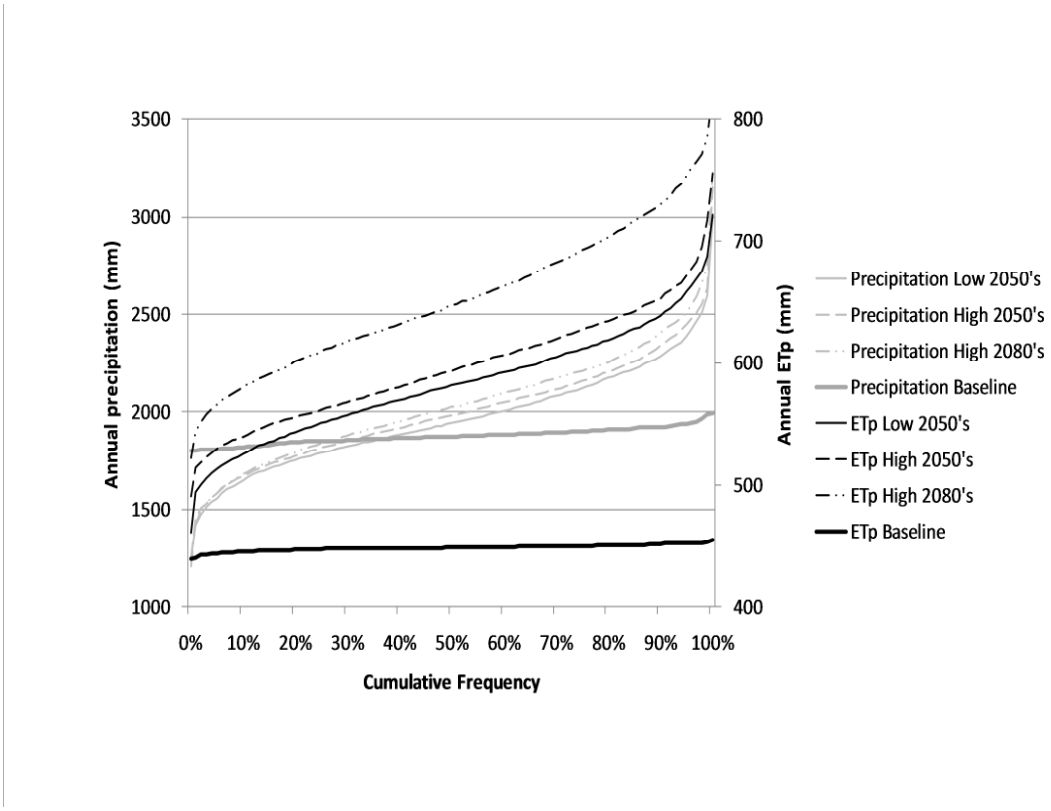


Figure 3 Cumulative frequency distribution of baseline and future Annual Average Rainfall and Evapotranspiration Potential (ETp).

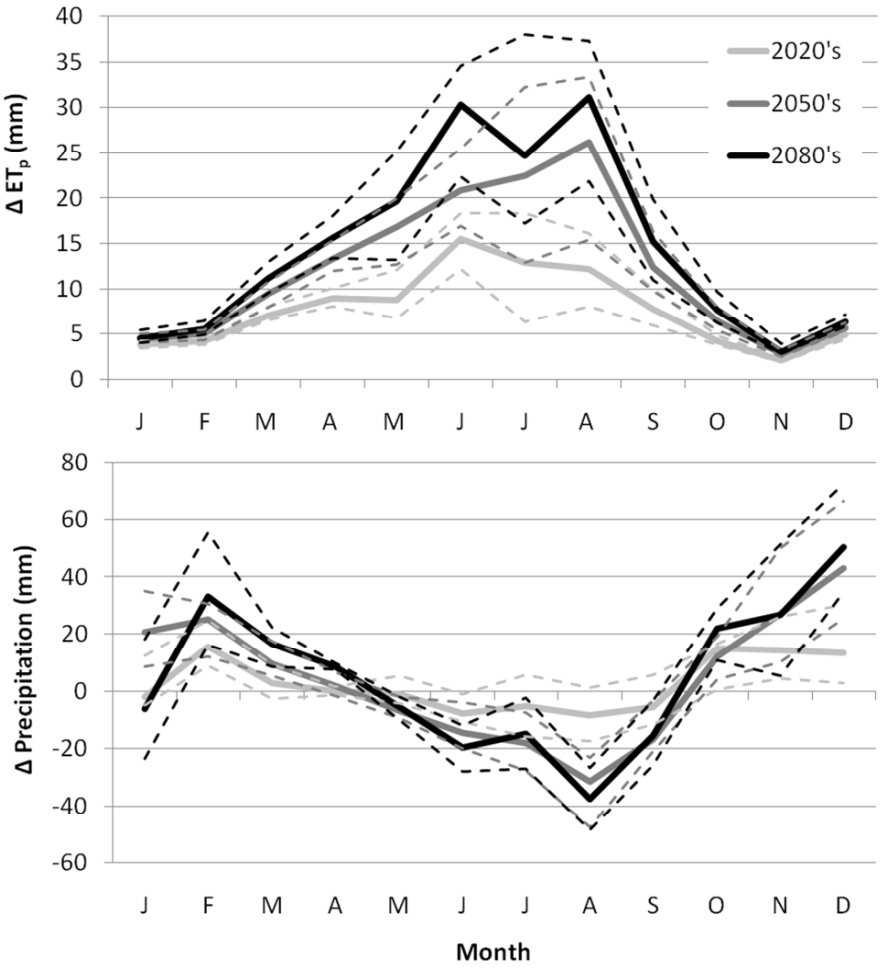


Figure 4 Long term monthly changes from baseline for (upper) Potential Evapotranspiration (ETp) and (lower) precipitation for the medium emissions scenario [median- solid line; upper and lower quartiles - dotted lines]

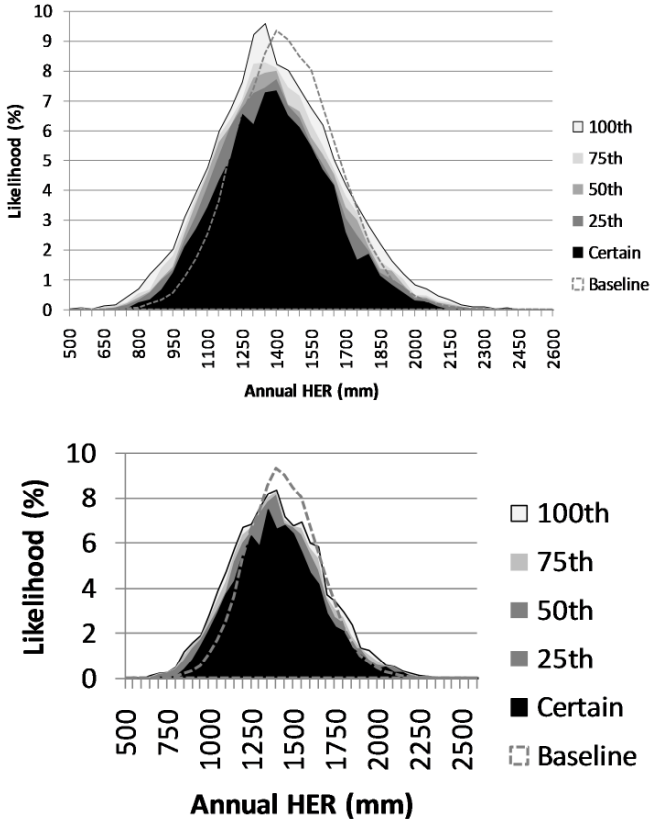


Figure 5 Uncertainty within annual HER due to (upper) time within the Medium emissions scenario and (lower) due to the range of emissions scenario within a single timeslice (2070-99).

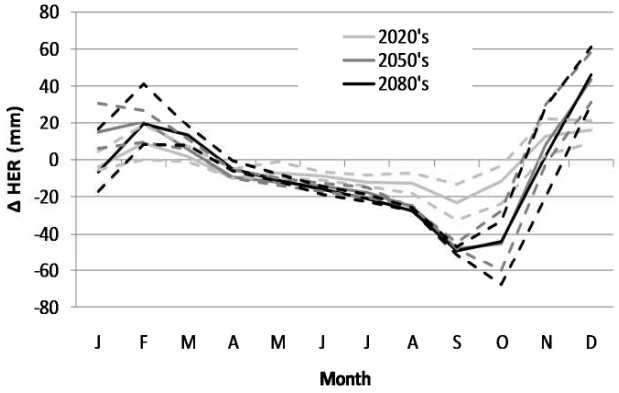


Figure 6 Long term monthly changes from baseline for Hydrologically effective Rainfall for the medium emissions scenario. [median- solid line; upper and lower quartiles - dotted lines]

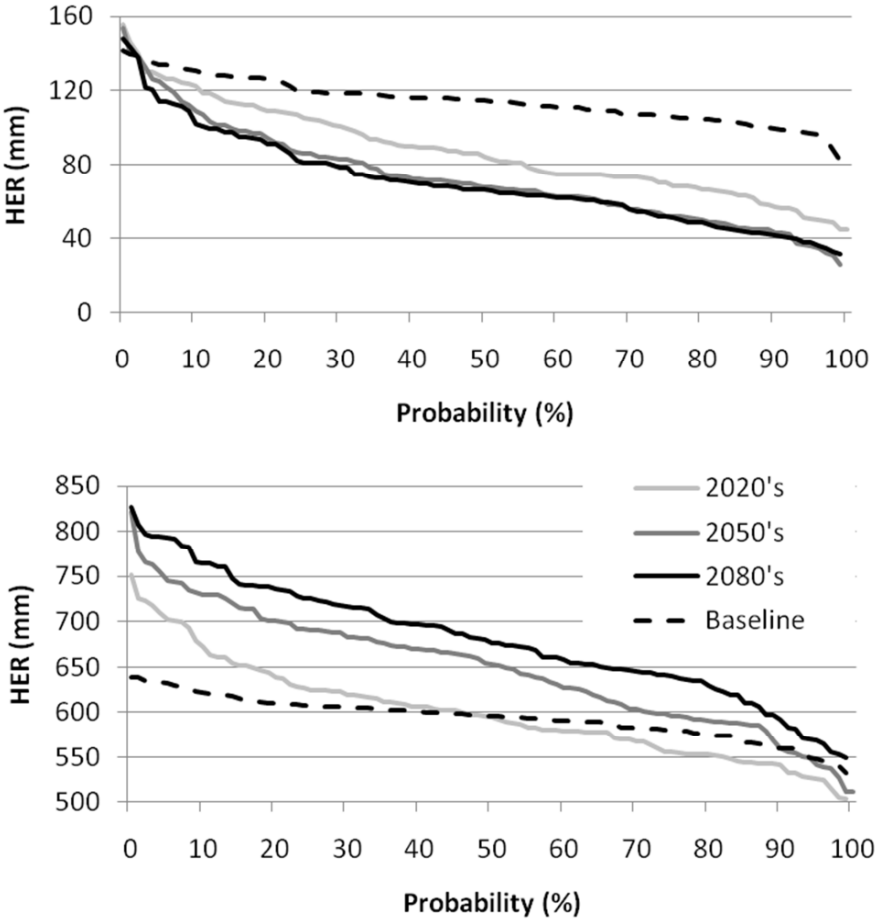


Figure 7 Average monthly Hydrologically Effective Rainfall (HER) under low emissions scenario in the 2020's, 2050's and 2080's for (upper) Summer and (lower) Winter.

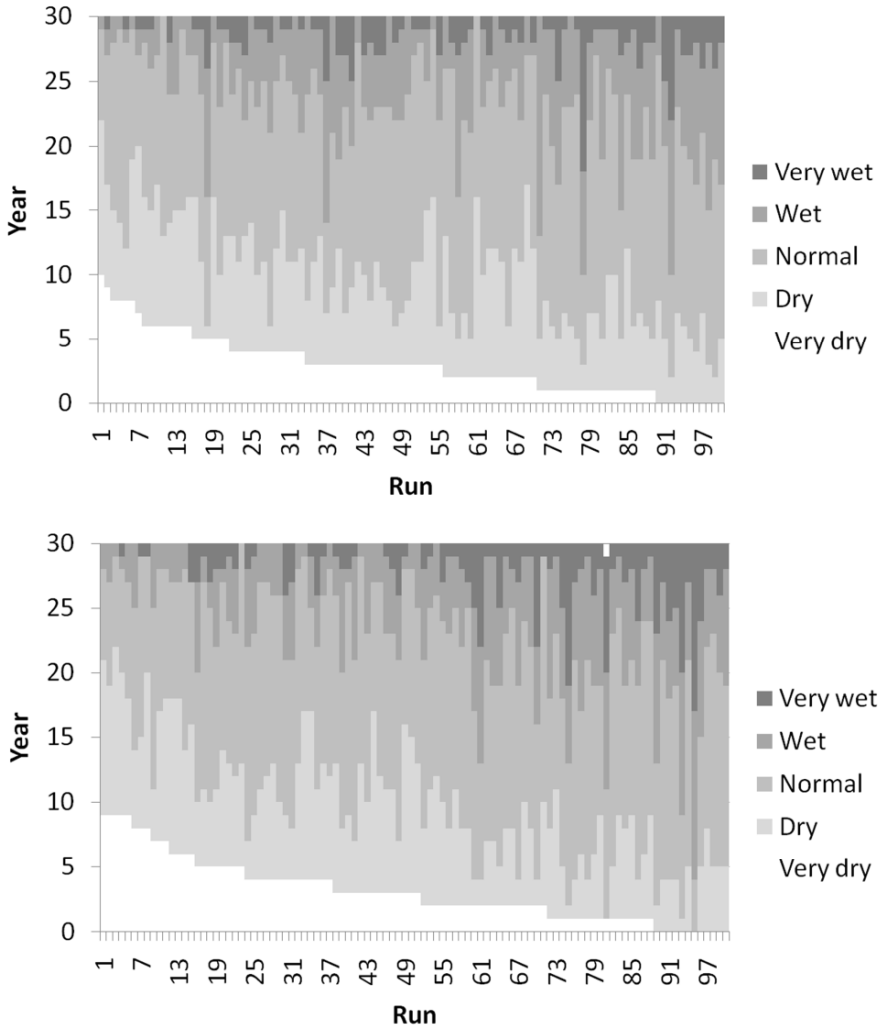


Figure 8 Frequency of very wet to very dry years in the Elan valley under medium emissions scenario for the (upper) 2020's and (lower) 2050's.

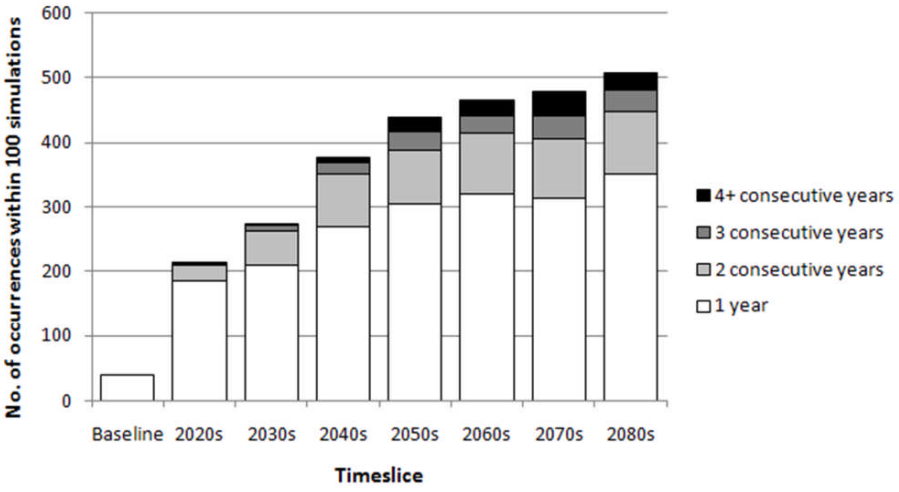


Figure 9 Number of occurrences of consecutive years in which modelled monthly reservoir

storage falls below 35% within the 100 simulations of 30 years for the Medium emissions scenario.

Table 1 Main soil input parameters to WaSim

	Soil		
	Crowdy	**Hafren**	**Manod**
Saturation (%)	88.2	50.5	58.0
Field Capacity (%)	75.0	32.0	39.6
Permanent Wilting Point (%)	28.2	12.5	18.7
Saturated hydraulic conductivity (m/d)	1.2	3.1	2.7
Curve Number (AMC II)	73	65	65

Table 2 Probability (%) of different years of differing annual HER under a range of scenarios.

	Scenario						
Annual HER	Baseline	Low 2020's	Low 2050's	Medium 2020's	Medium 2050's	High 2020's	High 2050's
Very Dry	5	11	12	10	12	11	10
Dry	20	23	24	23	25	25	23
Normal	50	45	41	44	43	44	43
Wet	20	17	16	17	14	16	16
Very Wet	5	5	6	5	6	4	7



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Evaluating the effects of climate change on the water resources for the city of Birmingham, UK

Warren, Andew J.; Holman, Ian P.

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