HOW DO CLIMATE AND LAND USE CHANGES AFFECT THE WATER CYCLE?
MODELLING STUDY INCLUDING FUTURE DROUGHT EVENTS PREDICTION USING RELIABLE DROUGHT INDICES[†]

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ABSTRACT

To investigate the impacts of climate and land use changes on the hydrology, the Don Catchment in Yorkshire, UK, has been selected. A physically based distributed catchment-scale (DiCaSM) model has been applied. The model simulates the surface runoff, groundwater recharge and drought indicators such as soil moisture deficit *SMD*, wetness index *WI* and Reconnaissance drought index RDI. The model goodness of fit using the Nash-Sutcliffe Efficiency factor was > 91% for the calibration period (2011-2012) and 83% for the validation period (1966-2012). Under different climate change scenarios, the greatest decrease in streamflow and groundwater recharge was projected under medium and high emission scenarios. Climate change scenarios projected an increase in evapotranspiration and soil moisture deficit, especially in the latter half of the current century.

Increasing the woodland area had the most significant impact by reducing the stream flow by 17% and groundwater recharge by 22%. Urbanization could lead to increase in stream flow and groundwater recharge. The climate change impact on the streamflow and the groundwater recharge was more significant than the land use change. Drought indices *SMD*, *WI*, and *RDI* projected increase in the severity and frequency of the drought events under future climatic change especially under high emission scenarios.

[†] Comment les changements climatiques et d'utilisation des terres affectent-ils le cycle de l'eau? Étude de modélisation comprenant la prévision des futurs événements de sécheresse à l'aide d'indices de sécheresse fiables

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KEY WORDS: climate change; land use change; DiCaSM Hydrological model; Don Catchment; reconnaissance drought index (RDI); soil moisture deficit (SMD).

RĖSUMĖ

Pour étudier les impacts des changements climatiques et de l'utilisation des terres sur l'hydrologie, le bassin versant du Don dans le Yorkshire, au Royaume-Uni, a été sélectionné. Un modèle à l'échelle du bassin versant distribué physiquement (DiCaSM) a été appliqué. Le modèle simule le ruissellement de surface, la recharge des eaux souterraines et les indicateurs de sécheresse tels que le déficit d'humidité du sol SMD, l'indice d'humidité WI et l'indice de reconnaissance de la sécheresse RDI. La qualité de l'ajustement du modèle à l'aide du facteur d'efficacité de Nash-Sutcliffe était > 91% pour la période d'étalonnage (2011-2012) et 83% pour la période de validation (1966-2012). Dans différents scénarios de changement climatique, la plus forte diminution du débit et de la recharge des eaux souterraines a été projetée dans des scénarios d'émissions moyennes et élevées. Les scénarios de changement climatique prévoyaient une augmentation de l'évapotranspiration et du déficit hydrique du sol, en particulier dans la seconde moitié du siècle en cours.

L'augmentation de la superficie boisée a eu l'impact le plus important en réduisant le débit du ruisseau de 17% et la recharge des eaux souterraines de 22%. L'urbanisation pourrait entraîner une augmentation du débit des cours d'eau et de la recharge des eaux souterraines. L'impact du changement climatique sur le débit et la recharge des eaux souterraines était plus important que le changement d'affectation des terres. Indices de sécheresse SMD, WI et RDI devraient augmenter la gravité et la fréquence des épisodes de sécheresse dans le cadre des changements climatiques futurs, en particulier dans les scénarios d'émissions élevées.

MOTS CLÉS: changement climatique; changement d'affectation des terres; Modèle hydrologique DiCaSM; Don Catchment; indice de reconnaissance de la sécheresse (RDI); déficit hydrique du sol (SMD).

INTRODUCTION

Changes in the land surface hydrology are attributed to the collective effects of the changes in the climate, changes in vegetation, and the soil (Wang *et al*., 2018). Therefore, it is important to understand the impact of climate and land use changes on the water cycle and water resources availability. The water cycle includes input, mainly rainfall, and output such as evapotranspiration, runoff to streams, ground water recharge and change in water storage. In the UK, the land surface has changed slightly due to human interventions that mainly resulted in changes in land use for food production, energy, housing and recreation. The recent land use changes are probably happening faster than at any other time in the human history, due to increase in demand for the natural resources, rapid changes in urbanisation, an increase in water demands for domestic and agricultural use. This is very significant for the UK where two-thirds of the land area is grassland. Approximately 14% of the UK is urban land which has significantly increased (by 300,000 ha) since 1998 (Rounsevell and Reay, 2009). The other key land use changes are the agricultural land use practices which are driven by the farmers' decisions, which are economically driven by the availability of investment and subsidies (Shiferaw *et al*., 2009).

The UK and the study area (North East of England) have experienced a number of droughts, the most severe one is the one of 1976 (Marsh and Green, 1997). Annual precipitation in the region varies significantly, from 600 mm in the eastern lowlands to 2000 mm in western Pennine sites (Fowler and Kilsby, 2002). Contrary to the water supplies in the South-East region, water supplies in the North East depend on the reservoirs which fill during the winter months and are drawn down during the summer, this suggests that the water supplies in the region are more vulnerable to drought which is evident from the 1995 drought event (Fowler and Kilsby, 2002). The studied catchment, the Don, is very significant for the water supplies in the region as there are 23 reservoirs within the catchment boundary, which are recharged mainly during the winter months. Therefore, the main types of physical modification that affect the Don Catchment are the water storage and supply reservoirs, flood management structures, urbanisation and recreation including navigation (The_Don_Network, 2018).

The historic long-term record of the climate variables for the Sheffield area (part of the Don catchment area), covering the period from 1883 to 2015, suggests a significant annual warming trend (1.0 °C per century), combined with an increase in annual precipitation (69 mm per century) with no significant trend in seasonal precipitation (Cropper and Cropper, 2016). There is a general perception that the urbanisation possibly added urban heat which contributed to the long-term warming trend which resulted in extreme precipitation events. This could potentially affect the water resources availability in the future and increase the drought risk, as water supplies within the catchment significantly depend on the reservoirs. Considering the historic climate and land use changes and likely changes in the future, it is important to study of the impacts of climate and land use changes on the studied catchment. Given this catchment was subjected in the past to several drought events, this study will investigate a number of drought indices.

Although a number of studies, including Burke *et al*. (2010), Jackson *et al*. (2015), Wilby *et al*. (2015) and Spraggs *et al*. (2015), have been carried out to identify the historic droughts in the UK using the observed data, less focus has been given to study the drought risk at catchment scale under different climate and land use change scenarios and their impacts on water resources. This study aims to address this issue in more detail and will also apply a number of indicators for the historic and future climate change which could potentially be used as drought indicators to identify meteorological, agricultural and hydrological droughts. Due to the limited availability or access to the aquifers, the surface water reservoirs significantly contribute to the water supplies of the studied area. As the water available in the reservoirs is vulnerable to climate change, the reliability of water resources availability in the catchment could be at higher risk due to the climatic variability.

In this study future climate change scenarios, UKCP09, were considered. The climate predictions are based on the families of the UK Meteorological Office (the Hadley Centre) climate models, combined with climate models of the Intergovernmental Panel on Climate Change (IPCC AR4) and Coupled Model (CMIP3), while the changes in temperature are taken from three emission scenarios: low (IPCC SRES: B1), medium (IPCC SRES: A1B) and high (IPCC SRES: A1F1), which provides estimates for the over seven 30-year overlapping times. The emissions scenarios were proposed by the Intergovernmental Panel on Climate Change (IPCC) in the Special Report on Emissions Scenarios – SRES (IPCC, 2000).

The emission scenarios are based on four storylines, A1, A2, B1 and B2 and their sub-divisions. The differences among the four are associated with the expected future population growth and economy development, adoption of new clean and efficient technologies, and the governance that accounts for the health of the environment. B1 is the lowest while A2 is the highest emission scenario. B1 storyline describes a world with the same low population growth as in the A1 storyline, but with rapid changes in economic structures with the introduction of clean and resource-efficient technologies. The A2 (high emission scenario) storyline describes a world with high population growth with fragmented and slow economic growth and technological changes slower than in other storylines.

The objectives of this study are to quantify the impact of climate and land use changes on catchment water resources availability (surface and groundwater) and to develop suitable drought indicators to predict future drought events.

The findings of the study are importance for the Don catchment for managing the water abstraction, improvement in water infrastructure and planning for future drought risk under climate change.

MATERIALS AND METHODS

The study catchment

The Don Catchment (NRFA no. 27006) is in the North East of the country with a catchment area of 373 km^2 (Figure 1). The key land uses of the catchment are: woodland which covers 13% of the catchment area (mainly broadleaved trees and heather area, 50 and 40% respectively, and 10% coniferous trees), arable land, 6.1% (spring barley, 2.38%, winter barley 1.80% and other crops 1.74%), grassland, 46%, bog and marsh area, 15.6% and urban area, around 18.0% (Figure 2). The catchment contains a moderate permeability bedrock, which almost covers half of the catchment. Based on historical data, the average annual precipitation for the Don Catchment is 1085 mm and average temperature 7.8 °C for the baseline data, 1961-1990, the average annual precipitation for the studied period 1991-2012 was 1089 mm and the average temperature 8.5 °C. The Don catchment is important for drinking water as it supplies conurbations of South Yorkshire. Therefore, protecting drinking water sources now and in the future is essential. There are 23 water reservoirs in operation in the Don Catchment. The naturalised discharge (the adjusted river-flow) that takes into account abstraction and discharge into the river was obtained from the Environment Agency and used for model testing. Using naturalized flow was essential as the river flow is affected by presence of the 23 reservoirs, river abstraction for irrigation and industrial use, groundwater abstraction and by treated wastewater discharge into the river.

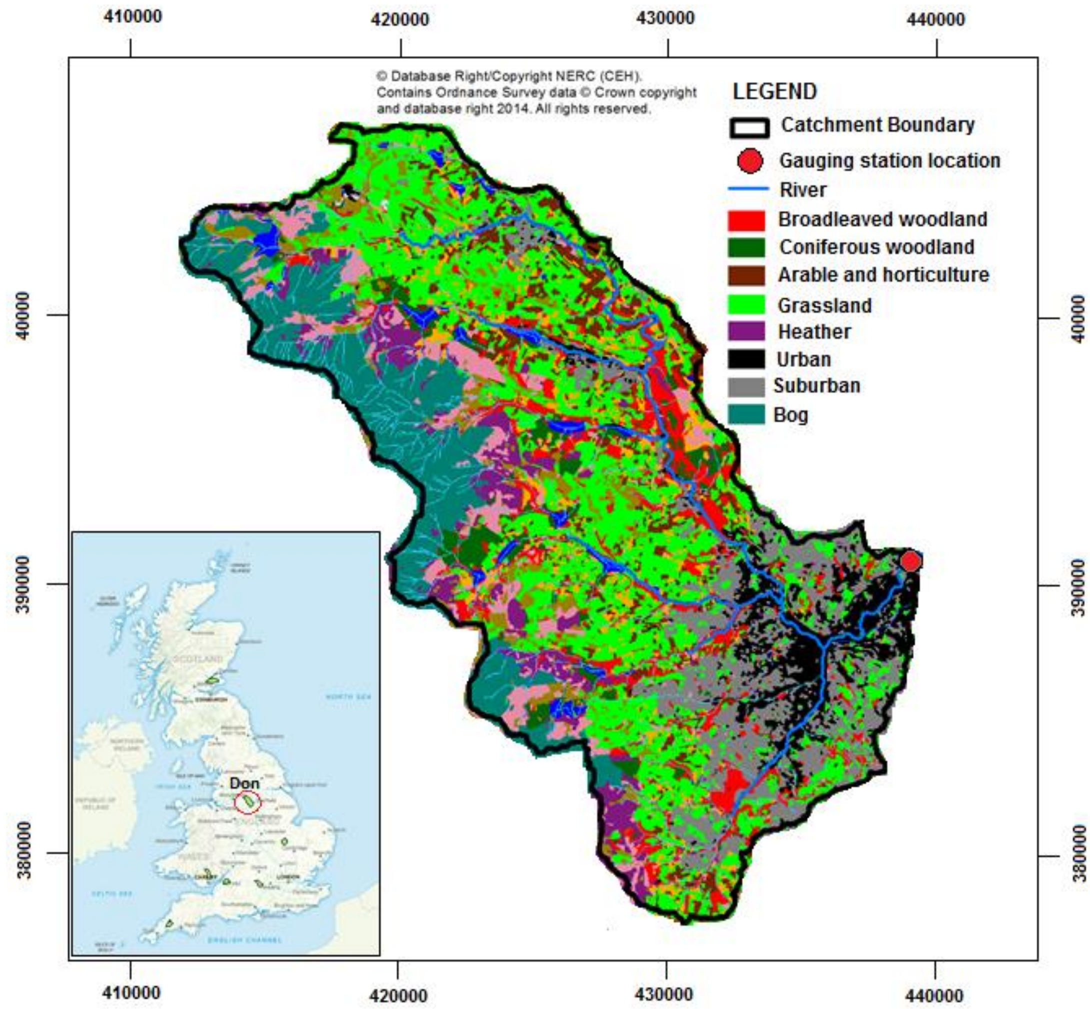


Figure 1. The Don Catchment: boundaries, land use practices and location of the gauging station, adapted from Morton *et al*. (2011)

Input data and scenarios

The model, historic and future climate data, soil map and river flow

The Distributed Catchment Scale Model, DiCaSM, (Ragab and Bromley, 2010) was selected for this study. The model runs on a daily time step and spatial scale of 1 km^2 grid square area. The catchment area is 373 km^2 covered by 435 grid squares (as not all the grid squares were covered in the catchment boundary). The model input requires a number of daily climatic variables including precipitation, temperature, wind speed, daily net radiation or total radiation and vapour pressure. The 1km grid square based distributed climate data were obtained from the Climate Hydrology and Ecology research Support System (*CHESS*) that accounted for the impact of changes in elevation on climatic data (Robinson *et al*., 2015; Tanguy *et al*., 2016) across the catchment. The historic continuous climatic variables and river flow data were available from

1961 until 2012. The catchment boundary and gauging station location data were available from the Centre for Ecology and Hydrology (Morris *et al*., 1990, Morris and Flavin, 1994) and the National River Flow Archive provided data for the daily river flow for the catchment (NRFA, 2014). The river and water body data were collected from the Centre for Ecology and Hydrology, 'Digital Rivers 50 km GB' Web Map Service (UK Centre for Ecology & Hydrology (CEH), 2014). The UK Land cover data were obtained from the Centre for Ecology and Hydrology (Land Cover Map 2007, 25 m raster, GB) Web Map Service (Morton *et al*., 2011). The soil data was obtained from Cranfield University, (1:250,000 Soilscapes for England and Wales Web Map Service).

To study the impact of future climatic change on water supply systems, the UK Climate Projection Scenarios (UKCP09) were used. Two projections the joined probability factors and the UKCP09 weather generated data were considered. In this study three 30-year periods: 2020's (2010-2039), 2050's (2040-2069) and 2080's (2070-2099) for the three greenhouse gas emission scenarios (low, medium and high) were considered. The UKCP09 provides monthly, seasonal and annual, probabilistic changes factors at 25 km by 25 km grid square resolution for precipitation and temperature (Table I). The table shows that the seasonal temperature increases with the level of emission and time, particularly in summer and autumn, whereas the precipitation is showing a decrease in summer and increases in winter relative to the 1961-1990 'baseline' period. The weather generator, WG, of UKCP09 provides daily output data at a 5km^2 grid square resolution for more climate variables such as vapour pressure and sunshine hours, in addition to precipitation and temperature. The sunshine hours were converted into net radiation following the methodology of Allen *et al*. (1998). The joint probability plot was used to generate seasonal climatic change factors (% change in precipitation and change in temperature, ± °C) to apply as an input to the DiCaSM model.

Table I. Probabilistic changes in temperature and precipitation for the Don Catchment under UKCP09 climate change scenarios (joint probability) under three emission scenarios and three selected time periods (Winter: December, January, February; Spring: March, April, May; Summer: June, July, August and Autumn: September, October, November).

		Low emissions				**Medium emissions**				**High emissions**			
		Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn
Change in temperature (°C)	2020s	1.3	1.3	1.5	1.6	1.4	1.3	1.4	1.5	1.4	1.3	1.4	1.6
	2050s	2.0	1.7	2.2	2.3	2.1	1.9	2.0	2.6	2.6	2.3	2.4	2.7
	2080s	2.4	2.2	2.1	2.7	2.7	2.8	3.0	3.3	3.5	3.5	3.8	4.3
Change in precipitation (%)	2020s	4.7	2.2	-6.8	3.2	4.1	1.6	-6.5	2.2	4.8	1.3	-7.3	2.4
	2050s	8.0	1.2	-16.3	1.9	8.5	0.6	-14.8	4.1	9.8	0.7	-16.5	5.0
	2080s	9.6	1.3	-13.4	3.5	11.8	1.5	-20.1	4.6	16.8	1.5	-28.2	5.0

Time period ↓

Increased greenhouse gas emissions →

For the detailed weather generator simulations, 100 realizations of the daily time series data were generated in order to account for the uncertainty associated with the scenarios. Since the climate predictions were associated with the UK baseline data (1960-1990), which is different from the catchment base line data, this data was subjected to bias correction. The latter was carried out using the '*qmap*' package in R statistical tool (Gudmundsson *et al*., 2012) using the 1961-1990 observation data as a reference period. This method has been successfully applied in drought studies including the study of Wang and Chen (2014). Forestieri *et al*. (2018) applied this bias correction method to study the impacts of climate change on extreme precipitation in Italy. De Caceres *et al*. (2018) subjected the daily climate model data to this approach and recently Hakala *et al*. (2018) applied this bias correction method to evaluate climate model simulations.

Historic and current land use

The studied Don catchment is not only significant for agriculture but also significantly contributes to the domestic water supplies. Water supplies in the catchment area come from the twenty-three reservoirs which are located within the catchment boundary. The low river flow can affect navigation, water supplies, and the aquatic ecosystem. Low flow also can result in river pollution due to the low dilution of the sewage effluent and can affect aquatic systems resulting in reducing the recreational activities within the catchment. Agriculture census data reveals that the key land-use in the area is grassland, heather and urban, with less than 10% of the catchment being agriculture (Figure 2).

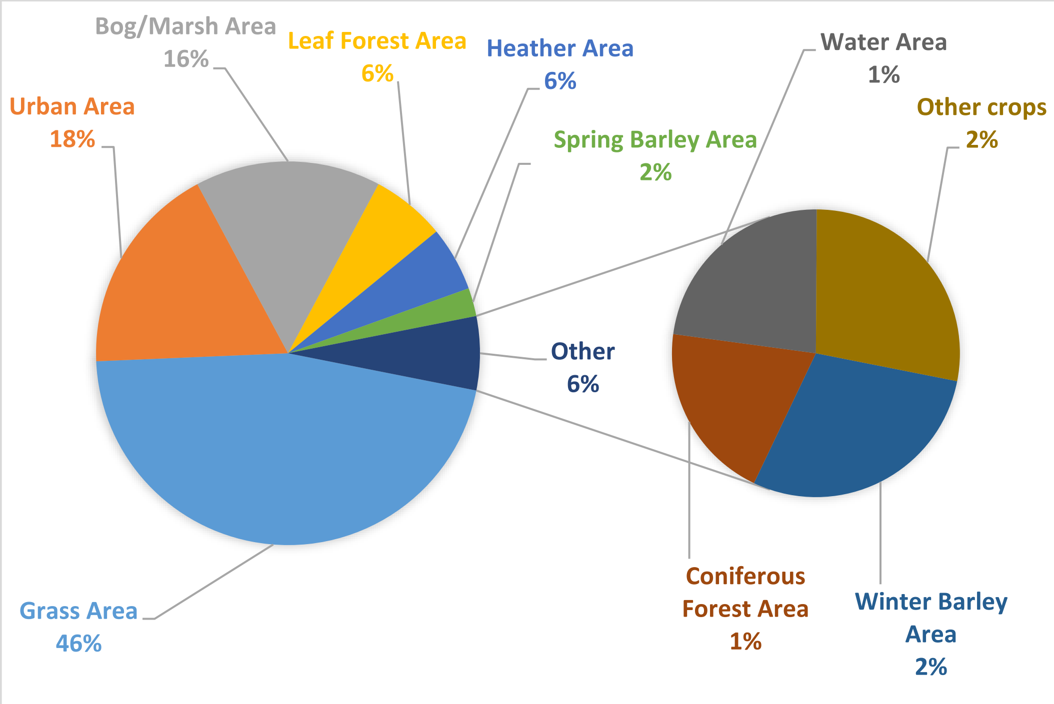


Figure 2. Current land use in the Don catchment

The modelling procedure

The schematic representation of the modelling work is shown in Figure 3 which also shows the data sources used in the study. Both historic and future climatic variables data were used to generate the streamflow, groundwater recharge, net rainfall, potential and actual evapotranspiration, soil moisture deficit (*SMD*), wetness index (*WI*) of the root zone and water losses due to interception. All these variables were directly or indirectly used to calculate the drought risk for both the historic period and for future climate change scenarios. The methodology to calculate each drought index is discussed later.

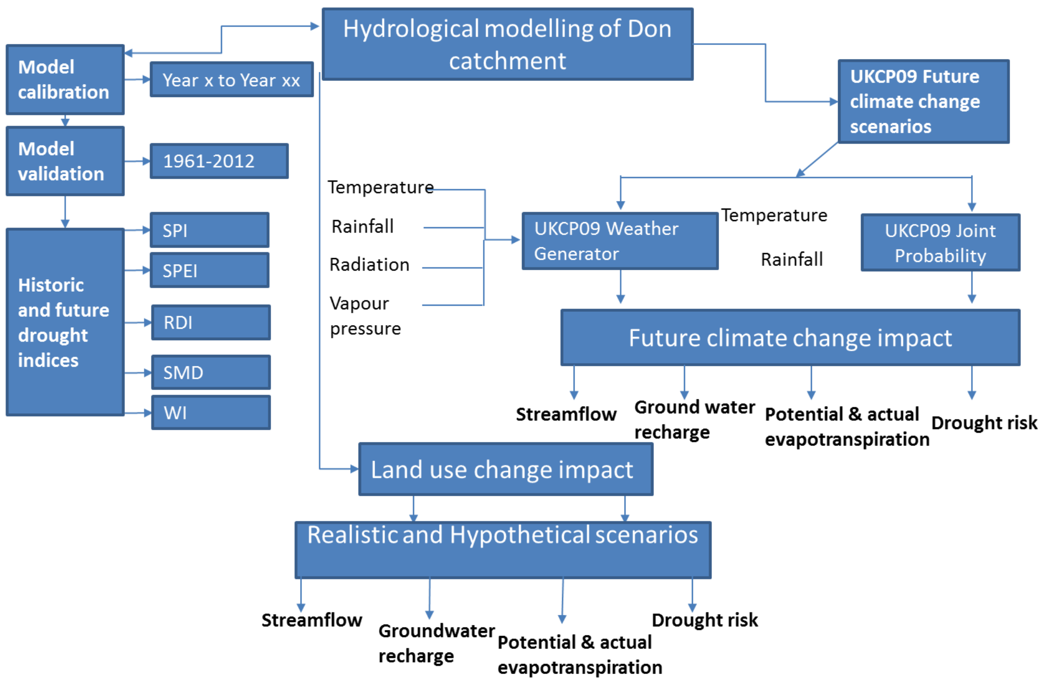


Figure 3. Schematic representation of the modelling procedure

DiCaSM model input data and processes

The hydrological DiCaSM was used to simulate the water balance of the catchment. The key input of the model are the meteorological data (temperature, precipitation, net radiation or total radiation, vapour pressure and wind speed), land use and vegetation (up to 20 land-uses can be assigned per each grid square), land altitude/elevation using the Digital Terrain Model, DTM, vegetation parameters and soil physical properties of each soil layer (saturated soil moisture content, soil moisture content at field capacity, soil moisture content at wilting point, saturated hydraulic conductivity). The model runs on daily time step and produces an output including spatially distributed and time series of potential evapotranspiration, actual evapotranspiration, soil water content, soil moisture deficit (*SMD*), wetness index (*WI*) of the root-zone, groundwater recharge, streamflow and surface runoff (Ragab and Bromley, 2010). The model has a specific facility to simulate the impact of the changes in climate and land use on the catchment water balance.

The model also addresses the heterogeneity of input parameters of soil and land cover within the grid square using three different soil and plants algorithms and therefore, handles up to different 20 land cover and soil types with the grid square.

The model simulates the following processes, precipitation interception by land cover, evapotranspiration, surface runoff, infiltration, groundwater recharge, plant water uptake, bare soil evaporation and stream flows. Further details about the model are given in Ragab *et al*. (2010)

and Ragab and Bromley (2010). For the studied catchment, the vegetation parameters (plant height, Leaf Area Index (*LAI*), and the canopy resistance were obtained from the UK-MORECS system (Hough *et al*., 1997). The model's efficiency (goodness of fit), for the model calibration and validation processes, was carried out using several efficiency indices, including Nash-Sutcliffe Efficiency (NSE), log of Nash-Sutcliffe Efficiency (log NSE) and Coefficient of Determination, R^2, as given below.

The calibration procedure was conducted by adjusting the model parameter values related to stream flow calculations to achieve the best model fit to the observed stream flow. The goodness of fit was assessed using the Nash-Sutcliffe Efficiency (*NSE*) coefficient (Nash and Sutcliffe, 1970). *NSE* is the most widely used coefficient to assess the performance of stream flow (Gupta *et al*., 2009), the value of 100% indicating a perfect match.

$$NSE = 1 - \frac{\sum_{i=1}^{n}(O_i - S_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \quad (1)$$

where O_i and S_i *refers* to the observed and simulated river flow data, respectively, and $\bar{O}$ is the mean of the observed data. Another index 'Log NSE' is commonly used for low flows and based on the stream flow logarithmic values has also been considered (Afzal *et al*., 2015, Krause *et al.*, 2005). In addition, the model performance was also evaluated using the commonly known statistical Coefficient of determination, R^2. The values of this index can range from 1 to 0, with one indicating perfect fit.

The drought indices

The main drought drivers are temperature, radiation, wind speed and relative humidity /vapour pressure (Seneviratne, 2012). Figure 4 shows how these drought drivers are associated with meteorological, agricultural and/or hydrological droughts. A number of drought indices can be used to identify drought events.

Standardised Precipitation Index (SPI)

The most common drought index is the Standardized Precipitation Index (*SPI*) (McKee *et al*., 1993). The SPI index represents the deviation of precipitation from the long-term average, negative values indicate below average 'dry periods' and positive values indicate above average precipitation 'wet periods'. The index helps in finding different types of droughts, as precipitation is the key climatic variable upon which soil moisture deficit, stream flow and groundwater recharge depend. Therefore, it could easily be used to quantify the severity of both dry and wet events. The *SPI* index scale values is: above 2.0 extremely wet, 1.5-1.99 very wet, 1.0 -1.49

moderately wet, -0.99 to 0.99 near normal, -1.0 to -1.49 moderately dry, -1.5 to -1.99 severely dry and -2.0 and less, extremely dry (McKee *et al*., 1993)

Standardised Precipitation Evapotranspiration Index (SPEI)

Another drought index is the standardized precipitation evapotranspiration index (*SPEI*) which is a multiscale drought index, sensitive to global warming (Vicente-Serrano *et al*., 2010). This index has been widely applied in different parts of the world (Bachmair *et al*., 2018, Kunz *et al*., 2018) to study meteorological and agricultural droughts and to study the impacts of drought severity on vegetation health (Bento *et al*., 2018). The equation used to calculate *SPEI* is based on (Thornthwaite, 1948):

$$D_i = P_i - PET_i \tag{2}$$

where *Di* is the difference between the precipitation (*P*) and the potential evapotranspiration (*PET*) for a particular month. The SPEI drought index takes into account both precipitation and potential evapotranspiration (PET), therefore unlike the SPI, this drought index captures the impact of increased temperature on water demand including irrigation. The aim of applying this index was to measure the water surplus or deficit for the analysed period.

Like the *SPI*, a negative value shows dryness and a positive value shows wetness, relative to the long-term average. This drought index has been applied in a number of studies, for example by Tirivaraombo *et al* (2018), and was used recently to study severity of extreme droughts events, like those of Cape Town, South Africa (Solander and Wilson, 2018).

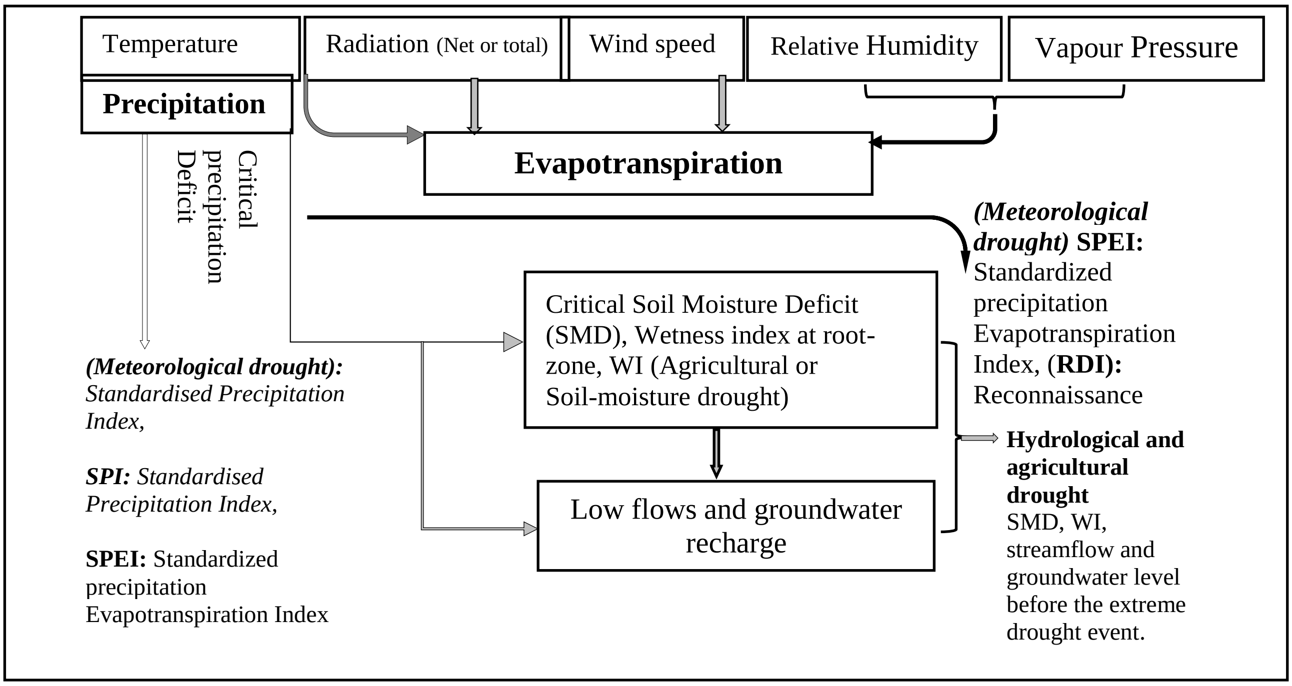


Figure 4. Key drought drivers of the meteorological, agricultural and hydrological droughts

Reconnaissance Drought Index (RDI)

A third key drought index used in this study was the Reconnaissance Drought Index (*RDI*) which is based on the work of Tsakiris *et al.* (2007). The standard RDI is calculated using the ratio of total precipitation (mm) to total potential evapotranspiration (mm) over a certain period. It is a good indicator for describing agricultural, hydrological and meteorological droughts. The Reconnaissance Drought Index (*RDI*) was calculated as:

$$a_0^{(i)} = \frac{\sum_{j=1}^{12} P_{ij}}{\sum_{j=1}^{12} PETorAE_{ij}} \tag{3}$$

$$RDI_n^i = \frac{a_0^{(i)}}{\overline{a_0}} - 1 \tag{4}$$

$$RDI_{st\,(k)}^i = \frac{y_k^{(i)} - \bar{y}_k}{\hat{\sigma} yk} \tag{5}$$

where P_{ij} and PET_{ij} are the precipitation and potential evapotranspiration or actual evapotranspiration of the j_{th} month of the i_{th} hydrological year (starting from October), is $\bar{a}_0$the arithmetic means of the a_0 calculated for the number of years. In the above equation y_i is the ln $(a_0^{(i)})$, $\bar{y}_k$ is its arithmetic mean and $\hat{\sigma} yk$ is its standard deviation. This drought index has been used in studies in different parts of the world, including Greece (Vangelis *et al*., 2013). This method is widely accepted and applied as it calculates the aggregated deficit between precipitation and the atmospheric evaporation demand. The method is directly linked to the climate conditions of a region and is comparable to the FAO Aridity Index (Tsakiris *et al*., 2007). In addition to the conventional way of calculating *RDI*, an adjusted *RDI* was calculated using the net rainfall (gross rainfall minus rainfall interception losses by canopy cover) and actual evapotranspiration.

Soil Moisture Deficit (SMD) and Wetness Index (WI)

Further to *SPI*, *SPEI* and *RDI*, two other drought indices were considered: the soil moisture deficit (*SMD*) and the wetness index (*WI*) of the root-zone (Ragab and Bromley, 2010). *WI* ranges from zero to 1. The value of 1 means the catchment is at its maximum soil moisture content and 0 means the catchment at its lowest soil moisture content of the simulated period (Kalma *et al*., 1995). Wetness Index of the root zone (scaled soil moisture calculated as (current soil moisture – minimum soil moisture) / (maximum soil moisture – minimum soil moisture).

The significance and interrelations of the drought indices

Using a range of drought indices helps in identifying different types of droughts (meteorological, hydrological and agriculture), for example SPI for meteorological, *RDI* for hydrological and *WI* and *SMD* for agricultural drought.

All the above indices do have implicit or explicit relationship between them but the scale of severity differs from one type of drought index to the other. For example, SPI, the meteorological drought is based on precipitation. Below average values will stimulate the possible need for irrigation. The SPEI, is based on SPI but accounts for both input as rainfall and output as evaporation losses from vegetation. Should the evaporation become greater than precipitation, possible irrigation might be required, therefore it represents meteorological and agricultural droughts. Similarly, the RDI the reconnaissance drought index is based on ratio of precipitation to evapotranspiration. This similar to SPEI where the input as precipitation and evaporation as losses is considered as output. Should the ratio of precipitation to evapotranspiration gets smaller than threshold value, possible irrigation might be required.

RESULTS

Model streamflow calibration and validation

The river flow calibration was carried out using a built-in optimization sub-model in DiCaSM. The key six model parameters that were used to calibrate the model flow against the observed flow data were: the percentage of surface runoff flow routed to the stream, the catchment storage/time lag coefficient, the exponent function describing the peak flow, a stream storage/time lag coefficient, a base flow factor and the streambed leakage ratio. The other factors on which simulated river flow is indirectly affected by are the soil hydraulic properties and the land cover parameters. The selected time period for calibration was run using auto optimization in which each of the six stream flow parameters was assigned a range described by a minimum and a maximum value. Each range was divided into a number of steps and the number of total iterations is the product of multiplication of the steps of the six key parameters. The number of iterations for each parameter was assigned according to the parameter sensitivity, i.e. a higher number of iterations were assigned to parameters, which showed more impact on the streamflow. The model calculates the Nash-Sutcliffe Efficiency value, *NSE,* ln NSE and R^2 for each iteration. The model optimisation process helps in finding a good set of parameters that produces the best model fit between the simulated and observed stream flow values. Figure 5 (top) shows the model calibration of stream flow during 2011-2012 where model efficiency, measured using the Nash-Sutcliffe Efficiency, was above 87% with less than two percent percentage error in total water volume. The selected calibration period included a dry and a wet period in order to assess the model performance during both conditions. The model performed well both during the rainy and dry events and responded according to soil hydrology status, i.e. during the soil moisture deficit period, a small precipitation event did not generate enough streamflow and during the heavy precipitation event, when the soil was at saturation during the winter months, the model responded extremely well. The model validation (using the calibration parameters unchanged) results during the drought period are shown in Figure 5 (bottom) for the 1970s decade, during this period model efficiency measured using the Nash Sutcliffe Efficiency was above 80%, which indicates a good confidence in the calibration parameters. The results of model prediction efficiency calculated in percentage as Nash Sutcliffe Efficiency, logarithmic Nash Sutcliffe Efficiency and R^2 values are shown in Table II. The model calibration was carried out over a shorter period and validation over a number of 10-year periods and over the entire study period. The overall model performance over the whole period, 1961-2012 was good, (NSE = 83%).

Table II. Don Catchment model performance during the stream flow calibration and validation stages

Periods	NSE	ln NSE	R^2	Square root of R^2	Average+ Simulated flow $m^3 s^{-1}$	Average+ Observed flow $m^3 s^{-1}$	% Error in total volume
2011-2012*	87.1	73.1	0.87	0.93	4.86	4.73	2.61
1991- 2000	87.0	79.1	0.88	0.93	5.10	5.18	-1.60
1981-1990	83.1	76.4	0.84	0.91	5.17	5.13	0.81
1971- 1980	82.2	66.1	0.83	0.91	4.68	4.90	- 4.63
1966-2012	83.1	73.0	0.84	0.91	5.06	5.08	-0.60

*calibration period. + average daily stream flow of the period

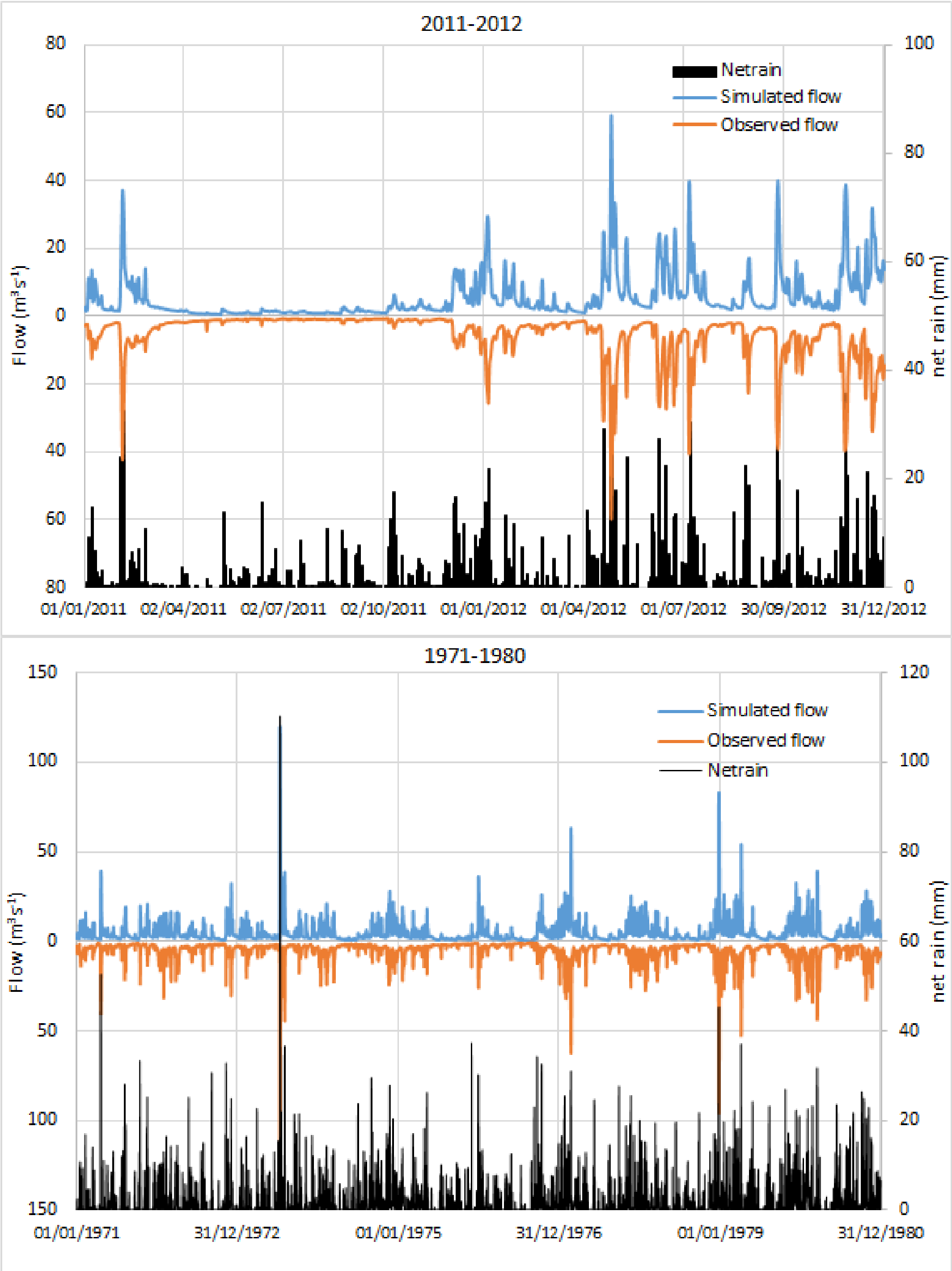


Figure 5. Streamflow calibration (2011-2012) and validation (1971-1980) period

Identification of historic droughts

The standardized precipitation index (SPI) and Standardized Precipitation Evapotranspiration Index (SPEI)

The SPI and SPEI time series are shown in Figure 6 which also illustrates that the SPEI has shown higher severity levels for both dry and wet events, more clearly for the 1970s droughts. Both indices picked up all the drought events which took place in the Don Catchment between 1961 and 2012.

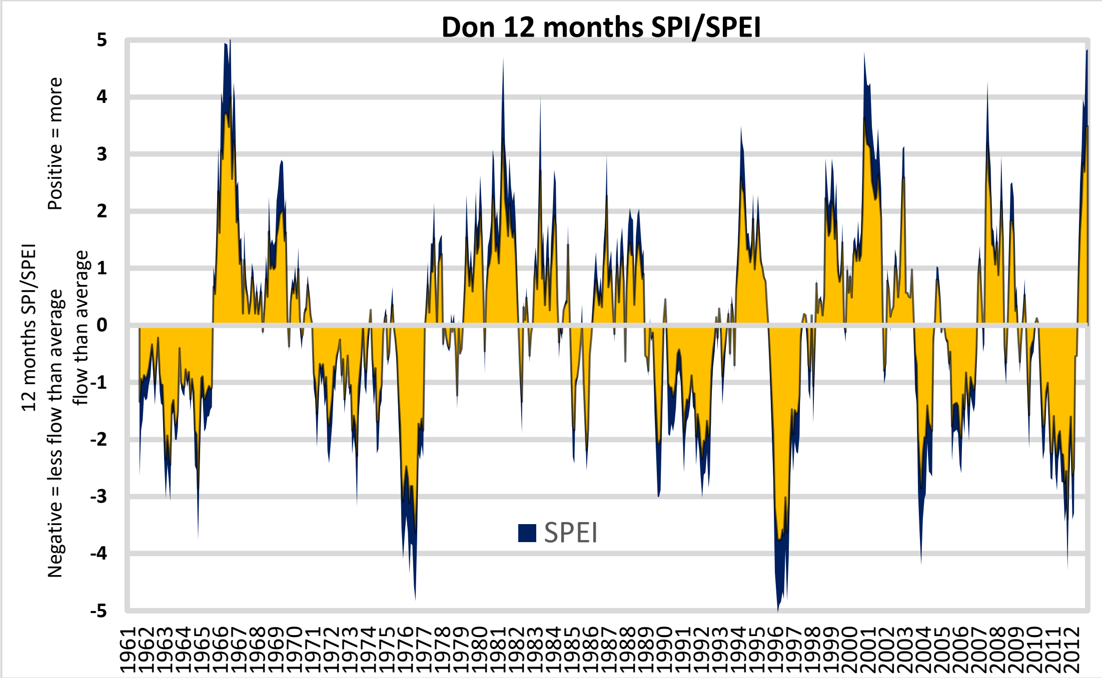


Figure 6. The standardized precipitation index (SPI) and standardised precipitation potential evapotranspiration index (SPEI) of the Don Catchment from 1961 to 2012

As the SPEI accounts for precipitation and evapotranspiration, it is expected to better represent the severity of the drought when compared to SPI. Both *SPI* and SPEI indices crossed over the 'extremely severe' drought level during the most well-known 1970s droughts which affected most parts of the UK and Europe. The catchment experienced two extreme drought events which took place in the mid-1970s and the mid of 1990s. These drought indices show that the Don Catchment was subjected to drought events which significantly affected Southern England, the Anglian regions, Southern and Eastern England and the Midlands (Parry *et al*., 2016). The *SPI* and *SPEI* indices, crossed over the 'extreme drought' level during both the 1970s and the 1990s droughts. Not only the occurrence of the drought events (frequency) but also the duration and drought strength significantly affect the streamflow and the groundwater recharge.

Therefore, the *SPI* and *SPEI* indices could be used as good indicators for the meteorological and hydrological drought. The *SPI* and *SPEI* indices over 52 years elucidated the successive dry events, like those occurred in the 1970s and the 1990s. The *SPI* and *SPEI* indices also help in identifying smaller magnitude drought events, or drier periods, which took place in the late 1960s, early 1990s, in 2005-2006 and in 2010. The magnitude of the severity of drought was considered as severe in the mid-1970s, in 1976 and in 1996 when *SPI* and *SPEI* indices were well below -2, ‘extreme drought’ level.

Reconnaissance Drought Index (RDI)

Figure 7 shows the comparison between the adjusted *RDI* and the classical RDI. Both picked up all the drought events, which were detected by the *SPI and SPEI*. However, the advantage of applying the *RDI* over SPI is that RDI does not rely on one factor only, i.e. precipitation as is the case with SPI. The adjusted *RDI* showed slightly different severity levels, especially during the extreme drought events. In addition, there is a strong correlation between the two ways of calculating the *RDI* and the *SPI/SPEI*. Figures 6 and 7 show that the extreme drought conditions of 1976, 1996 and 2006 were picked up similarly by both *SPI/SPEI* and *RDI/adjusted RDI.* Drier than average events (*SPI*/SPEI less than -10% or *RDI* less than -1) were also observed in 1964, 1975, 1990, 1996, 2003, 2005, 2011. Both drought indices also picked up extreme drought events that took place in 1976, 1989 and 1996. However, the severity of the drought events was slightly higher when applied reconnaissance drought index using the gross rainfall and the potential evaporation in most of the cases. Based on both types of RDIs and SPI/SPEI drought indices, the total percentage of wet years were higher than total percentage of dry years.

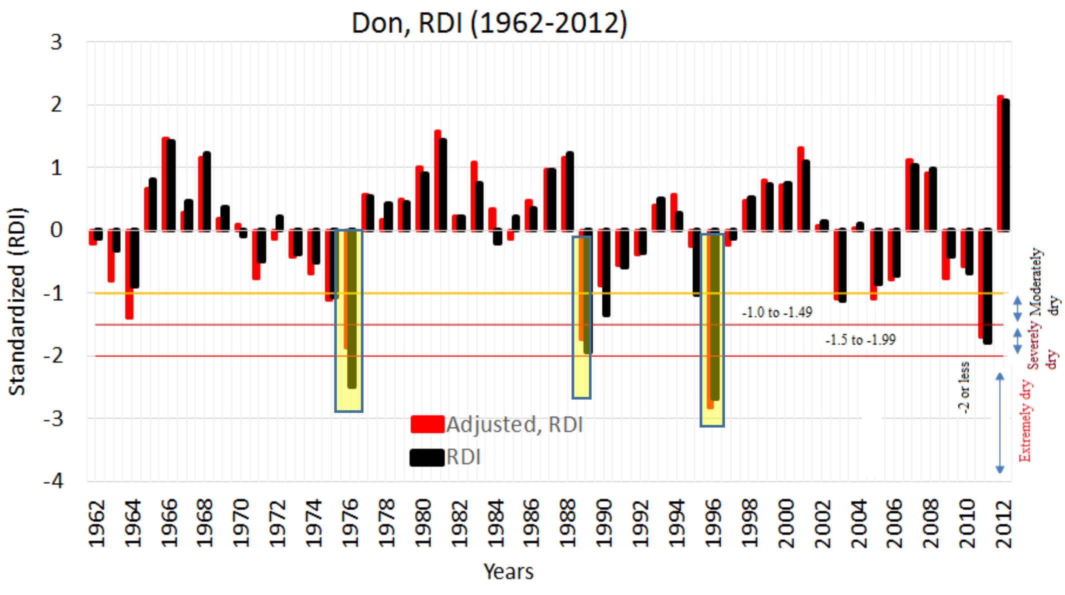
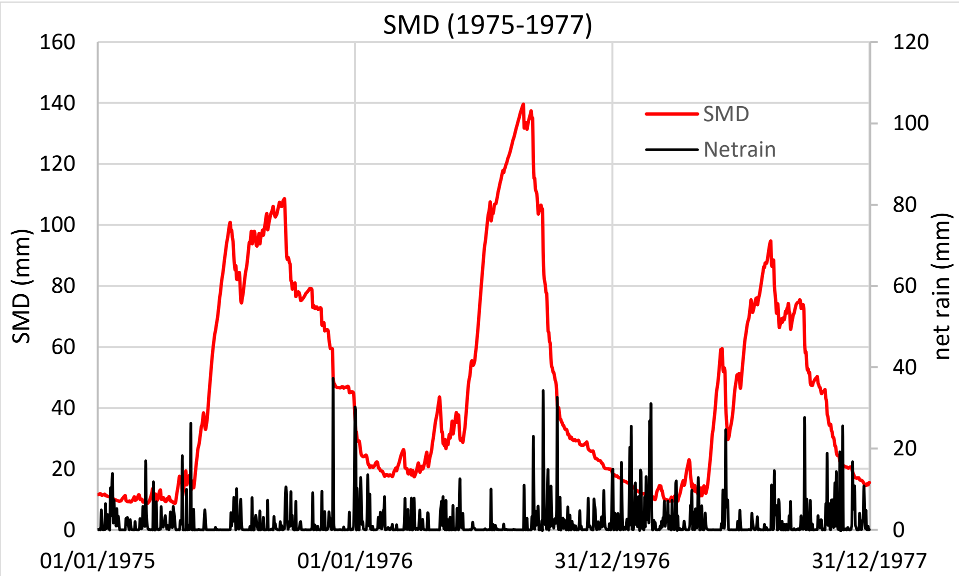


Figure 7. Standard RDI (Reconnaissance drought index) based on potential evapotranspiration and total precipitation and the adjusted RDI, calculated using net-rainfall and actual evapotranspiration, for the Don Catchment during the 1962-2012 period

Soil moisture deficit, *SMD* and Soil Wetness Index, *WI* as drought indicators

For agriculture drought, the soil moisture deficit, *SMD* and the wetness index, *WI* of the root-zone are more appropriate (Figure 8). The wetness index, *WI* represents how relatively wet or dry the catchment is over the period. The WI is a scaled soil moisture status that accommodates the spatial variability of soil types, elevation, vegetation cover, etc. across the catchment. The Soil Moisture Deficit, *SMD* represents the deviation of soil moisture from the soil moisture at field capacity. Here zero means, the catchment's soil moisture is at field capacity level. The deviation gets larger when the soil moisture starts to fall below the field capacity, especially during summer and during drought periods. Examples of both indices are shown in Figure 8 which clearly shows the significant change in soil moisture indicators *WI* and *SMD* during the dry summer months, especially during the extreme droughts in 1975 and 1976 and the recovery in 1977 for the SMD. In the dry summer months of 1975, the soil moisture deficit exceeded 100 mm and during the 1976 dry summer period, soil moisture deficit was over 140 mm.



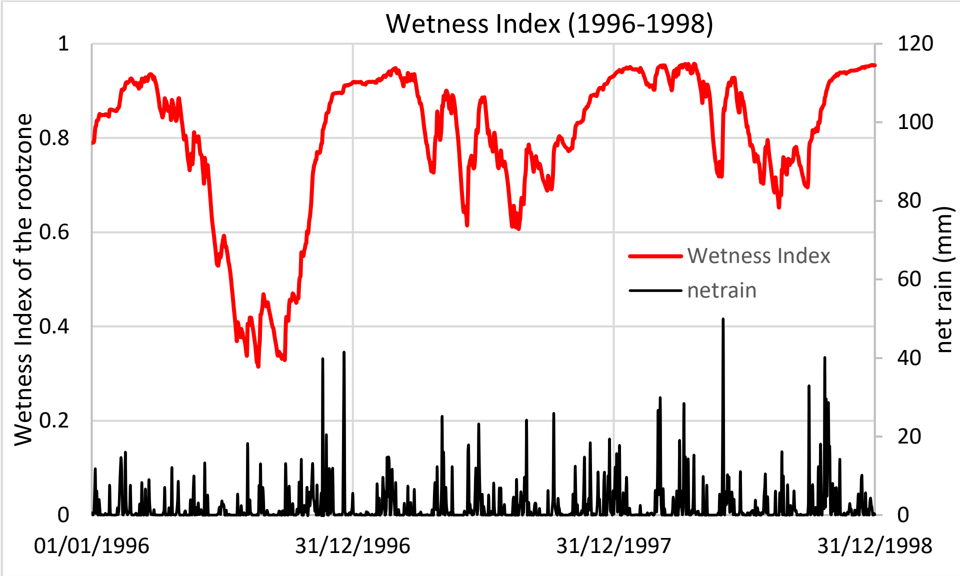


Figure 8. Soil moisture deficit from 1975 to 1977 (top) and Wetness Index of the root-zone from 1996 to1998 (bottom) for the Don Catchment

The figure also shows the severity of the dry spell as a result of the continuation of the dry seasons including the 1975-1976 winter months as the *SMD* did not drop down to zero, whereas in the 1977 winter months, above average winter precipitation brought the *SMD* back to zero after persistent precipitation events during the 1977 winter months. It can also be seen that the *WI* dropped below the winter value of 1.0 to 0.3 during the extreme drought of the summer of 1976 and mirrored the other drought indices including the SPEI/SPI and the RDI.

Future climate change impact on the water resources

Changes in streamflow

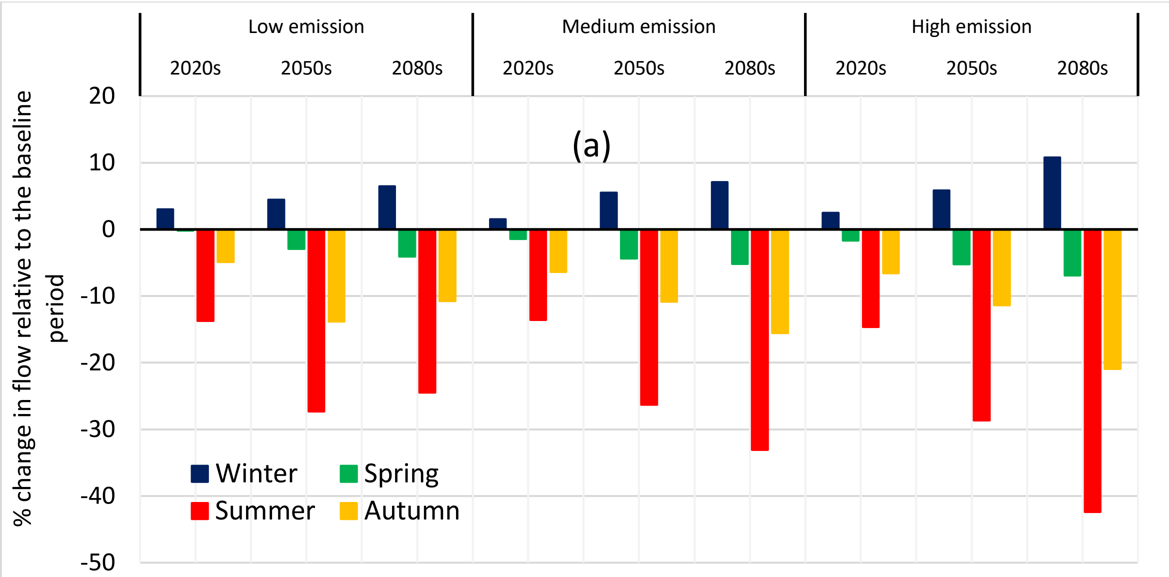
The future climate change scenarios (UKCP09) suggest an increase in temperature under all emission scenarios and a decrease in precipitation, during the summer months (Table I). To study the impact of climate change on the hydrology of the Don catchment, the future climate projections were derived using two approaches based on UKCP09 outputs: simplified change factors based on joint probability data and the weather generator data. Using the joint probability approach, nine scenarios (three time periods and three emission scenarios) were investigated. The seasonal climate change factors (relative to the baseline data, 1961-1990) of temperature (± change in °C) and precipitation (% change in precipitation) at the most likelihood (central estimate) probability level were input into the DiCaSM model and applied on the 1961-1990 baseline climate data (Table I).

A significant change in streamflow was observed using both approaches. The simplified change factor (joint probability) approach suggests that streamflow is likely to increase in winter (December, January, February) by up to 10% in the 2080s under high emission scenarios due to an increase in winter precipitation. Similar results were also observed using the weather generator data for the winter months, but the decrease in streamflow was not that significant (Figure 9). This is of greater significance for the Don Catchment which significantly contributes to the water supplies in the region as there are 23 reservoirs within the catchment boundary which are recharged mainly during the winter months.

In the spring (March, April, May) season, there is little difference in the change in streamflow under three emission scenarios and the three selected time periods. With an exception in the 2020s, under low and medium emission scenarios, where the streamflow in spring is likely to decrease by -2.1 to -5.5% under low emission scenarios, -1.5 to -4.8% under medium emission scenarios and within -1.4 to -4.5% under high emission scenarios, relative to the baseline period. During the spring season, the evaporation is low relative to the precipitation and the soil is more saturated except during the latter part of spring (Figure 10).

During the 2020s period, in summer, a significant decrease in streamflow is projected under all emission scenarios. In the 2020s, the summer streamflow is likely to decrease, by 13 to15% using the joint probability approach, whereas under the weather generator only a small decrease of up to 4.5% is projected. In 2050s a significant decrease of 12.8 to 17.9% relative to baseline period is projected using the weather generator data, whereas under the joint probability, a decrease is projected from 27 to 29% with no significant variation under different emission scenarios. During the summer season in the 2080s, using the joined probability approach, the stream flow is likely to decrease by 24 to 42%, whereas using the weather generator data, streamflow is likely to decrease by 16.1 to 25.5%, depending on the emission scenario.

The severity of the change, particularly during the summer season, could lead to very low stream flows, possibly leading to a high risk of inadequate domestic, industrial and agricultural water supply. The latter is more significant for the Don catchment, as river water abstraction is very significant. The streamflow is likely to decrease in the summer season because the soils are not saturated in comparison with winter and spring, as a results soil moisture deficit is likely to increase. The combined effect of decreasing precipitation with the increasing temperature could result in higher evapotranspiration during the summer season, which in turn could result in reduced flow especially under high emission scenarios. This is because the temperature is likely to increase by 4.6 °C and precipitation to decrease by up to 34% by the end of the century. The relationship between the precipitation and the hydrological response is much more dependent on antecedent catchment conditions. With reductions in precipitation in autumn and spring (enhanced by higher evaporation), saturated conditions will occur less frequently, and precipitation events will be less likely to generate high runoff flows.



(b)

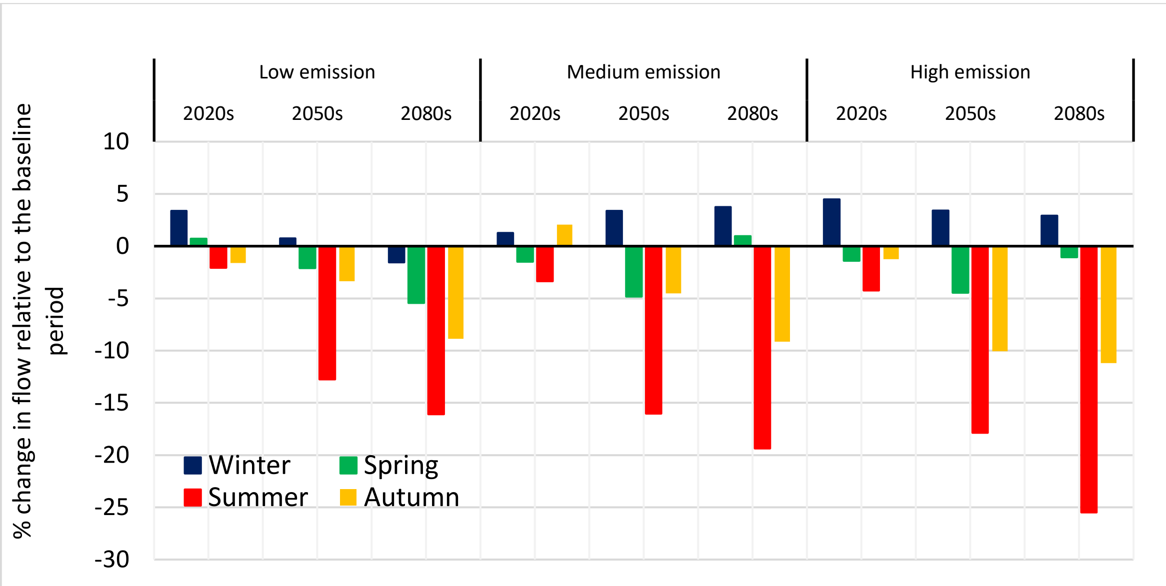


Figure 9. Percentage change in streamflow relative to the baseline period (1961-1990) over seasonal scale under low, medium and high emission scenarios for the 2020s, 2050s and 2080s, under UKCP09 joined probability (a) and under UKCP09 weather generator (b)

In autumn, streamflow is likely to decrease slightly under low and high emission scenarios, and a slight increase under medium emission scenarios in the 2020s. Overall, there isn't much variation among the emission scenarios in the 2020s. However, in the 2050s, more significantly under medium and high emission scenarios, up to 10% decrease under both joint probability and the weather generator approach was observed. No significant change in precipitation is projected under medium and high emission scenarios, but an increase in temperature and reduced rainfall in summer would lead to higher soil moisture deficit during both the summer and autumn seasons, combined by an increase in autumn temperature this would result in reduced streamflow in autumn due to higher water losses by evapotranspiration. The simplified change factor (joint probability) showed slightly higher change compared to the weather generator as joint probability method only consider two climate variables (rainfall and the temperature).

Overall, in all seasons, the severity of the change in streamflow more particularly during the summer season could lead to very low stream flows, possibly leading to a high risk of inadequate domestic, industrial and agricultural water supply. The summer streamflow is more significant for the Don catchment as there are twenty-three reservoirs within the catchment, which significantly contribute to the water supply systems.

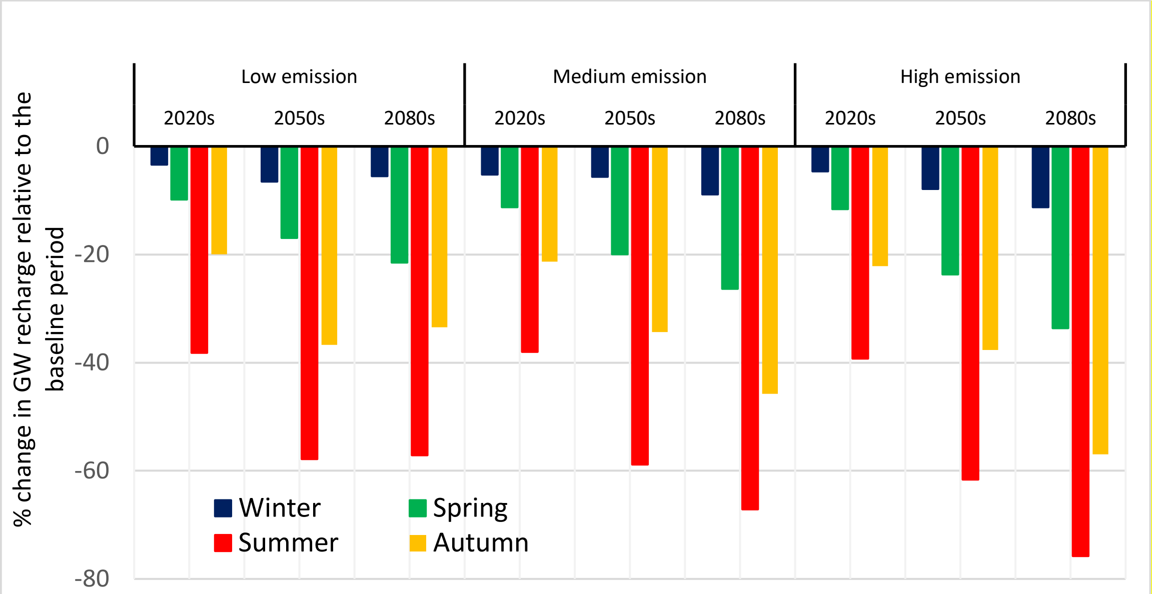
Changes in groundwater recharge

The analysis using the weather generator and joint probability, under all emission scenarios and for the selected time periods showed that the groundwater recharge would decrease, with some exceptions under weather generator in the 2020s more significantly under high emission scenarios when groundwater recharge increased by 4.3% compared to the baseline period (Figure 10b). This increase in winter precipitation seems to have been counterbalanced by the higher water losses by the increased evapotranspiration (due to increased temperature) which resulted in a small increase in groundwater recharge. The groundwater recharge projections under joint probability suggest that the groundwater recharge is likely to decrease from 3.4% to 11.3% under all emission scenarios during the winter months (December, January, and February). Without exception, groundwater recharge decreased for the three selected time periods, but the decrease will be slightly less under low emission scenarios, compared to the medium and high emission. This is due to a smaller increase in precipitation under low emission scenarios. Considering the change in precipitation under all emission scenarios, the likely increase in the groundwater recharge is lower than expected, due to losses by evapotranspiration that causes an increase in soil moisture deficit and subsequently a decrease in groundwater recharge in all seasons. Other factor which could reduce the groundwater recharge in all seasons, is that the winter precipitation is expected to come as extreme events and over a short period of time, as reported in Alexander *et al*. (2005). The groundwater recharge is also likely to decrease in spring due to milder increase in spring temperature and the insignificant change in precipitation.

A significant decrease in groundwater recharge is projected in summer months due to increasing temperature and a decrease in precipitation, which result in higher water losses due to evapotranspiration, higher soil moisture deficit and subsequently lower the groundwater recharge.

Using joint probability, the groundwater recharge is likely to decrease by over 60% under medium emission scenarios in the 2080s and up to 75% under high emission scenarios. The percentage change in groundwater recharge was not that high when using the weather generator data. The highest decrease in summer groundwater recharge projected for the 2080s is likely to be over 40%. Such a significant decrease in groundwater recharge could be the result of increased soil moisture deficit. Under all emission scenarios and observed time periods, the groundwater recharge is likely to decrease by -38% to -58% under joint probability and -10% to -30% under the weather generator under the low emission scenarios; while under medium emission scenarios the decrease in groundwater recharge would fall within -38 to -67% with joint probability and -13 to -35% with the weather generator; the highest decrease is projected under high emission scenarios with -39 to -76% under joint probability and -13 to -40.2% under the weather generator, all changes are in comparison to the baseline period.

(a)



(b)

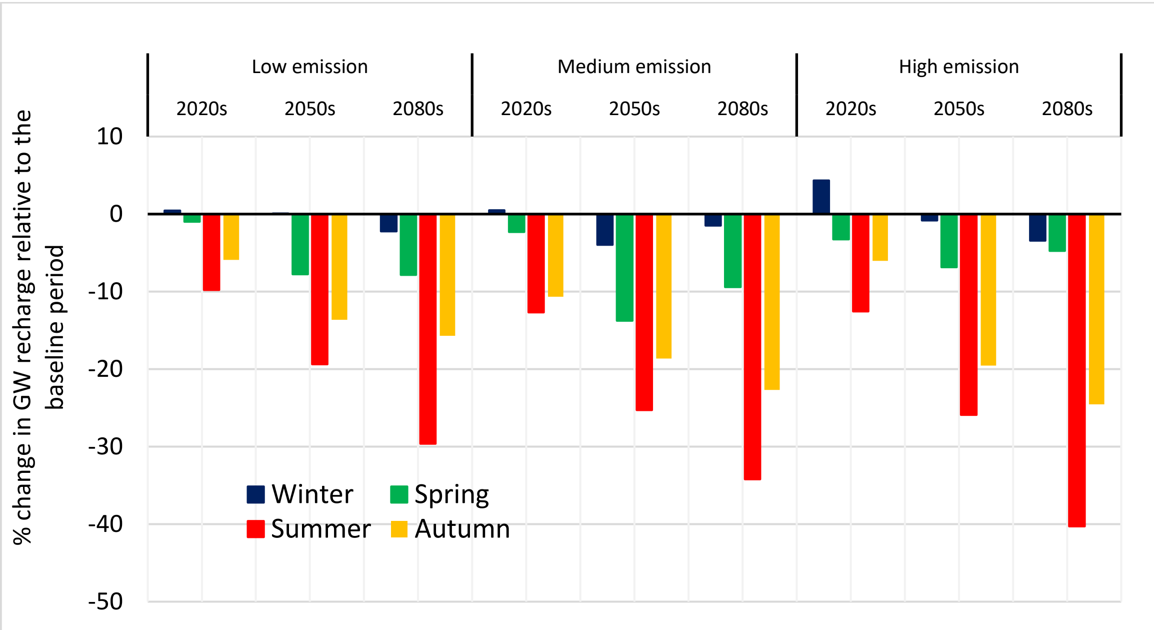


Figure 10. Percentage change in groundwater recharge in the Don Catchment for the different seasons over a selected time period, based on joint probability (a) and Weather Generator (b) of UKCP09 under different climate change scenarios

In summer months (June, July, August) enhanced evapotranspiration, together with the decreased precipitation, would result in reduced streamflow and groundwater recharge. Higher evapotranspiration combined with lower precipitation during the summer months would result in an increase in soil moisture deficit, which would result in low groundwater recharge during the autumn months under all emission scenarios. However, the severity of the decrease is much higher in the second half of the century under high emission scenarios. Under low emission scenarios the groundwater recharge is likely to decrease by -2.2 to -12.0%, under medium emission the likely decrease will be within the -5.9 to -14.9% range and under high emission scenarios the projected likely decrease will be within -4.0 to -25.8% range. The higher decrease in groundwater recharge under high emission scenarios would result due to the increase in soil moisture deficit during the summer months. Studies carried out in the Midlands suggest that maintaining water supplies in the 2050s may be challenging due to the limited availability of the water resources (Wade *et al*., 2013), suggesting that demand-side measures would be required to match the future water supplies availability (Wade *et al*., 2013).

Drought indices

As a result of expected future drier and warmer climatic conditions, higher water losses by evapotranspiration, higher soil moisture deficit and low wetness index were observed (Figure 11). To illustrate the impact of decreasing precipitation and increasing water losses due to evapotranspiration, the standardized reconnaissance drought index, *RDI* was calculated. The adjusted RDI was calculated from the net rainfall and actual evapotranspiration of the selected time periods: 2020s, 2050s and 2080s for three emission scenarios (Figure 12). The analysis revealed an increase in number of moderate and severe drought events, more importantly under the medium and high emission scenarios. In comparison to the baseline period, extreme drought events are likely to double in the later part of the century. Not only extreme dry events but also, severe drought events are likely to increase in the future. In addition, the frequency of moderately drought events (RDI -1 to -1.5) is likely to increase in the future, more specifically under medium and high emission scenarios.

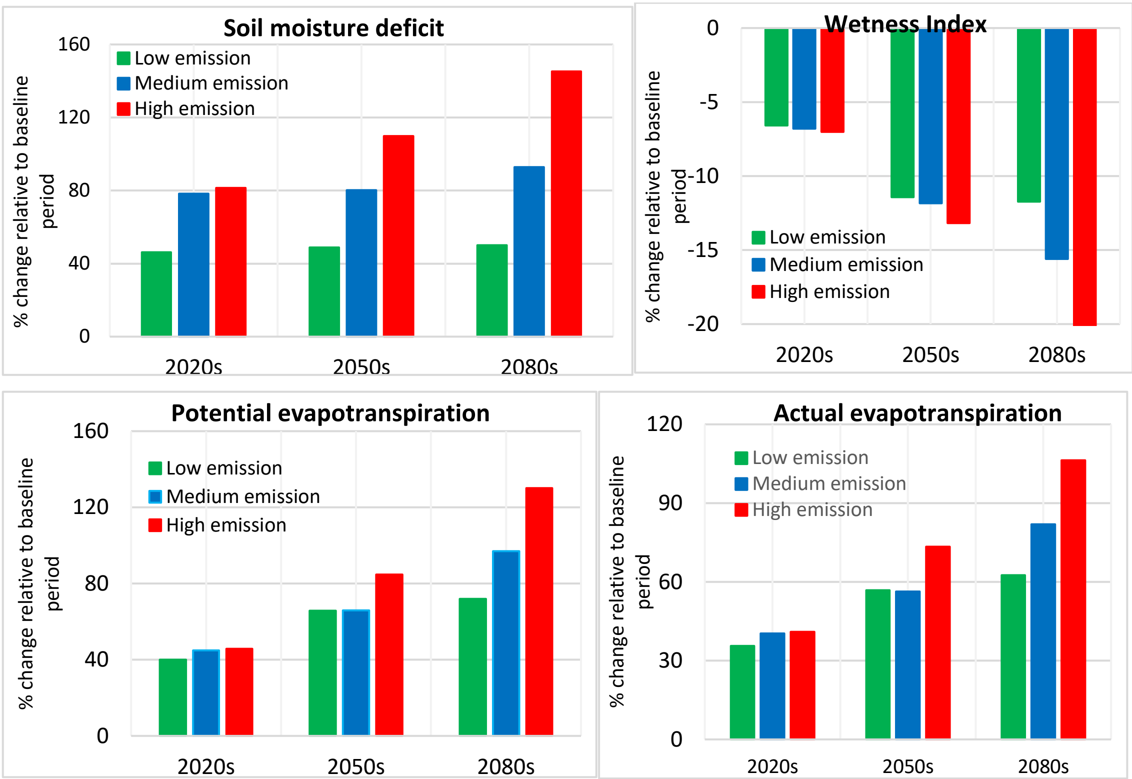
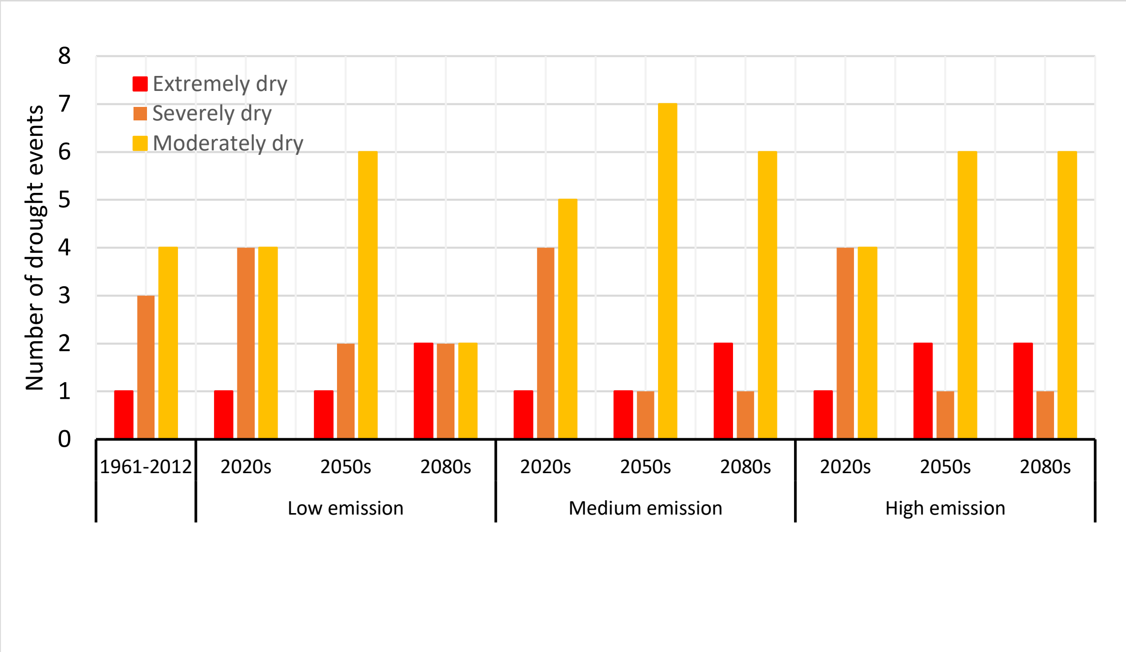


Figure 11. Seasonal changes in soil moisture deficit, actual evapotranspiration and the wetness index of the root zone for the Don Catchment under all emission scenarios base on UKCP09 joint probability

(a)



(b)

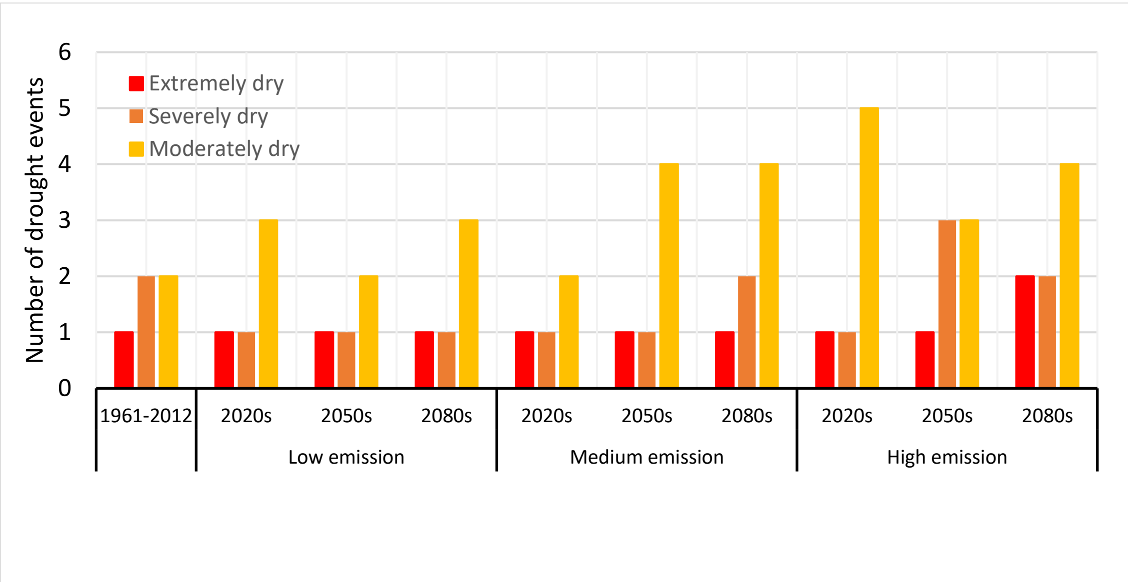


Figure 12. The severity of drought events observed in the Don Catchment under the three emission scenarios for the 2020s, 2050s and 2080s (a) under joint probability and using the weather generator data

Impacts of land use changes on the water resources

To study the impact of land use changes on the water balance, a number of possible land change scenarios based on the views of the local stakeholders and catchment authorities, were examined (Table III). The land use changes scenarios results can be summarized as:

- replacing grass area by winter barley, would lead to increase in stream flow between 3%

and 6% while groundwater recharge is likely to increase between 1 and 7%;

- replacing grass area by oil seed rape, would lead to a decrease in stream flow by up to 3% in all seasons apart from autumn where it is likely to slightly increase by < 3%, while groundwater is likely to decrease by only 2% apart from autumn where the recharge is likely to increase by only 2%;
- expanding the urban area by 40% at the expenses of grass and arable area, would lead to tiny increase in stream flow by 1% and groundwater recharge by 2%;
- replacing 50% of winter barley by oil seed rape, would lead to a decrease in stream flow by 2% and groundwater recharge by ~3%;
- converting the whole catchment apart from the urban area into grass area, would lead to a decrease in a stream flow by 2% to 8% and groundwater recharge by 5% to 9%.;
- converting the whole catchment apart from the urban area into a broad leaf forest area, would lead to a decrease in the stream flow by 9% to 17% and groundwater recharge by 10% to 22%.

The expansion of the broadleaf forest would be likely to result in an increase of soil moisture deficit, more specifically during the spring and summer seasons when plants are at their maximum growth rate and take up much of soil water to satisfy the evapotranspiration demand. Urban expansion could result in increased streamflow (likely to increase flood risk) and increase in groundwater recharge. Increasing conventional crops, like barley replacing grass, could result in a slight increase in river flow and a decrease in soil moisture deficit, compared with oilseed rape, which takes up more water during the spring season (Table III). These results are of great value for the local authorities for future planning taking into account the impact of any land use change on surface and ground water.

Sensitivity analysis to see the combined effect of both climate and land use changes revealed that in most cases (apart from introducing large broad leaf forest areas), the effect of the land use changes on the hydrological variables was relatively less than the effect of climate change. However, considering the possible changes in climatic variables and extreme events in the future, sustainable land use practices is essential to mitigate the impact of climate change as the studied catchment is of significance for the water supplies in the Sheffield area.

Table III. Impact of land use changes in the Don Catchment on stream flow and groundwater recharge

Hydrological variables	Land use types						
	100% Grass area replaced by winter barley		Grass area replaced by oil seed rape	40% urban expansion replacing grass and arable area	Replacing 50% of winter barley by oil seed rape	Whole catchment as grass area	Whole catchment as Broad leaf forest area
River flow	Season	%	% change	% change	% change	% change	% change
	Winter	6.46	-2.80	1.14	-1.35	-2.64	-12.40
	Spring	6.10	-1.20	1.13	-0.50	-5.22	-16.60
	Summer	3.39	-0.31	0.42	-0.10	-8.35	-14.40
	Autumn	3.57	2.40	-0.05	-1.14	-3.90	-9.01
Groundwater recharge	Winter	6.53	-2.01	1.40	-0.47	-7.80	-13.48
	Spring	5.21	-0.05	1.90	0.30	-6.10	-15.21
	Summer	0.60	-1.95	1.40	0.58	-9.10	-21.90
	Autumn	6.48	3.91	1.80	-3.13	-5.30	-9.65

DISCUSSION

The impact of climate and land use changes on the water cycle was investigated by estimating the changes in water cycle elements such as rainfall interception, evaporation, runoff, stream flow, groundwater recharge and the change in soil moisture storage. As the focus of this work was the drought events occurrence, great attention was given to describe the drought by a number of drought indices.

The drought indices investigated in the study were able to identify all the historical drought events. The adjusted reconnaissance drought index calculated using the actual evapotranspiration and the net rainfall, in addition, to the conventional *RDI*, *SPI*/*SPEI*, *SMD* and *WI* of the root-zone were used as indicators to identify future drought events. The standardized precipitation index, *SPI/SPEI* indicated the significantly negative deviation from the average precipitation in the 1970s, specifically in 1975-1976 and 1995-1996. The 1975/1976 drought has been reported in a number of studies including Perry (1976) and Marsh *et al*, (2007). During the 1995/1996 drought period, water resources availability in Northern England and in the Midlands remained fragile as

April to November 1995 precipitation was the second lowest in the 228 years for England and Wales (Marsh and Turton, 1996). All the applied drought indices including reconnaissance drought index (*RDI*), soil moisture deficit, *SMD* and the Wetness index, *WI* of the root-zone (Figures 7-9) identified these drought events. During these drought events, the *RDI*, *SPI*/*SPEI* were well below -2, which identifies them as 'extreme drought' events (caused by extremely low precipitation and high evapotranspiration). Keeping the current land use practices, future prediction indicates a possible further increase in likelihood of extreme drought events, specifically under medium and high emission scenarios in the middle and the latter part of the century (Figure 12). Due to the increase in temperature (resulting in higher water losses by evapotranspiration) and the decrease in precipitation (resulting in an increase in soil moisture deficit), there is a possibility of more frequent and severe drought to occur in the future.

The land use type would significantly change in the future, especially due to urbanisation, as urbanisation would further increase pressure on water resources for domestic use in the Don catchment. The other key land use changes are the agricultural land use practices, which are driven by the farmers' decisions which are market based, as well as the availability of investment, subsidies and the socio-cultural attributes of individual farmers. Increasing woodland area would significantly reduce both stream flow and groundwater recharge.

The application of a wider range of drought indices could be used to identify different types of droughts. For example, in agriculture, when soil moisture deficit, *SMD* or Wetness Index, *WI* of the root zone, reach a critical level, crops will require irrigation, particularly during the summer months. This will require reliable water supplies to secure adequate yield. The *WI* value, if close to 1, would indicate a wet catchment with a possible runoff generation during the next precipitation event, therefore, it is a help to reservoir managers to know the *WI* in real time. *RDI* would be helpful for short and long-term planning by water authorities and water companies. Therefore, the findings from the modelling work could be used to review the future surface water abstraction regulations to be in line with the water resources availability as predicted by calibrated and validated hydrological models and in possible planning of building new water infrastructure to increase the water storage in relation to increasing future water demand.

The DiCaSM model proved to be a good tool to predict river flow and recharge to groundwater and can simulate the effects of climate change on the different elements of the hydrological cycle. The future climate change scenarios suggested a significant decrease in groundwater recharge although climate models project an increase in winter precipitation, but such increase could be counter balanced by an increase in evapotranspiration and increase of soil moisture deficit during the summer and autumn seasons. The streamflow decrease would affect the Don catchment more as there are 23 reservoirs within the catchment, which are recharged during the winter season. Considering the possible decrease in groundwater recharge and streamflow and the increasing possibility of droughts in the future. New investment will be required if water demand is not met through enhancing water use efficiency or by alternative sources to traditional reservoirs, such as rainwater harvesting systems (Zhang and Hu, 2014) or by reducing evaporation from the reservoirs by, for example, floating solar panels, spreading ecologically friendly agents on water surface or an ultra-thin layer of organic molecules on their surface (Alamaro *et al*., 2012). The implication of surface water abstractions during drought and low flow periods would reduce river flows possibly below the minimum environmental flow. Alternatively, restrictions on abstraction to maintain the minimum environmental flows may restrict crop yields and food production.

CONCLUSION

The DiCaSM hydrological model used in the study showed a good agreement between the observed and the simulated flow during the model calibration and validation stages and overall model efficiency using the *NS* index was above 82% for the 52 years' study period. In addition to the stream flow, the DiCaSM hydrological model identified all the past drought events of the 1970s, the 1980s, the 1990s and the most recent ones in 2010-2012 using the drought indices: *RDI*, *SMD*, and the *WI*. The analysis revealed that the standard *RDI*, based on gross rainfall and potential evapotranspiration, showed slightly higher severity than the adjusted *RDI*. The latter is based on realistic input of net rainfall (excluding interception losses by vegetation cover) and actual evapotranspiration, which reflects the actual losses from soil and plants. Under the UKCP09 climate change projection, the streamflow and the groundwater recharge significantly decreased, more specifically during the summer months, while the severity of the drought events significantly increased over time. All the applied drought indices (*SMD*, *WI*, and *RDI*) identified an increase in the severity of the drought under future climatic change scenarios. Under high emission scenarios, the severity was higher as this severity was associated with the increasing temperature and subsequently increasing water losses by evapotranspiration, thus reducing soil moisture availability, surface runoff to streams and recharge to groundwater. These findings would help in planning for perhaps extra water infrastructure work if needed, such as building more reservoirs or water transfer pipelines from water-rich to water-poor regions and planning for irrigation water demand under different climatic conditions. The study catchment is of significance as there are twenty-three reservoirs in the catchment boundary, which significantly contribute into the water supply of the catchment.

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REFERENCES

Afzal M, Gagnon, AS, Mansell MG. 2015. The impact of projected changes in climate variability on the reliability of surface water supply in Scotland. *Water Science and Technology: Water Supply*, 15**,** 736-745.

Alamaro M, Emanuel K, Langer RS. 2012. Surface film distribution system and method thereof. Google Patents.

Alexander LV, Teit SF, Jonsson T. 2005. Recent observed changes in severe storms over the United Kingdom and Iceland. *Geophysical Research Letters*, 32.

Allen RG, Pereira LS, Raes D, Smith M. 1998. *Crop evapotranspiration-Guidelines for computing crop water requirements*. FAO Irrigation and drainage paper 56. Fao, Rome, Italy. 300**,** D05109.

Bachmair S, Tanguy M, Hannaford J, Stahl K. 2018. How well do meteorological indicators represent agricultural and forest drought across Europe? *Environmental Research Letters,* 13**,** 034042.

Bento VA, Gouvela CM, Dacamara CC, Trigo IF. 2018. A climatological assessment of drought impact on vegetation health index. *Agricultural and Forest Meteorology,* 259**,** 286-295.

Burke EJ, Perry RH, Brown SJ. 2010. An extreme value analysis of UK drought and projections of change in the future. *Journal of Hydrology,* 388**,** 131-143.

Cropper TE, Cropper PE. 2016. A 133-year record of climate change and variability from Sheffield, England. *Climate,* 4**,** 46.

De Caceres M, Martin-Stpaul N, Turco M, Cabon A, Granda V. 2018. Estimating daily meteorological data and downscaling climate models over landscapes. *Environmental Modelling & Software,* 108**,** 186-196.

Forestieri A, Arnone E, Blenkinsop S, Candela A, Fowler H, Noto LV. 2018. The impact of climate change on extreme precipitation in Sicily, Italy. *Hydrological Processes,* 32**,** 332-348.

Fowler H, Kilsby C. 2002. A weather-type approach to analysing water resource drought in the Yorkshire region from 1881 to 1998. *Journal of Hydrology,* 262**,** 177-192.

Gudmundsson L, Bremnes J, Haugen J, Engen-Skaugen T. 2012. Downscaling RCM precipitation to the station scale using statistical transformations-a comparison of methods. *Hydrology and Earth System Sciences,* 16**,** 3383.

Gupta HV, Kling H, Yilmaz KK, Martinez GF. 2009. Decomposition of the mean squared error and NSE performance criteria: Implications for improving hydrological modelling. *Journal of Hydrology,* 377**,** 80-91.

Hakala K, Addor N, Seibert J. 2018. Hydrological Modeling to Evaluate Climate Model Simulations and Their Bias Correction. *Journal of Hydrometeorology,* 19**,** 1321-1337.

Hough M, Palmer S, Weir A, Lee M, Barrie I. 1997. The Meteorological Office rainfall and evaporation calculation system: MORECS version 2.0 (1995). *An update to hydrological memorandum,* 45**,** 80.

Jackson CR, Bloomfield JP, Mackay JD. 2015. Evidence for changes in historic and future groundwater levels in the UK. *Progress in Physical Geography,* 39**,** 49-67.

Kalma J, Bates B, Woods R. 1995. Predicting catchment-scale soil moisture status with limited field measurements. *Hydrological processes,* 9**,** 445-467.

Krause P, Boyle D, Bäse F. 2005. Comparison of different efficiency criteria for hydrological model assessment. *Advances in geosciences,* 5**,** 89-97.

Kunz J, Lőffler G, Bauhus J. 2018. Minor European broadleaved tree species are more drought-tolerant than Fagus sylvatica but not more tolerant than Quercus petraea. *Forest Ecology and Management,* 414**,** 15-27.

Marsh T, Cole G, Wilby R. 2007. Major droughts in England and Wales, 1800–2006. *Weather,* 62**,** 87-93.

Marsh T, Green S. 1997. *UK hydrological review 1997*. 2nd ed.: Centre for Ecology and Hydrology. Wallingford, United Kingdom.

Marsh T, Turton P. 1996. The 1995 drought—a water resources perspective. *Weather,* 51**,** 46-53.

McKee TB, Doesken NJ, Kleist J. 1993. The relationship of drought frequency and duration to time scales. In: Proceedings of the 8th Conference on Applied Climatology. American Meteorological Society Boston, MA, USA. 179-183.

Morris D, Flavin R. 1994. *Sub-set of the UK 50 m by 50 m hydrological digital terrain model grids*. NERC, Institute of Hydrology, Wallingford, United Kingdom.

Morris D, Flavin R, Moore R. 1990. *A digital terrain model for hydrology*.UKCEH, Wallingford, UK.

Morton D, Rowland C, Wood C, Meek L, Marston C, Smith G, Wadworth R, Simpson I. 2011. *Final Report for LCM2007-the new UK land cover map*. Countryside Survey Technical Report No 11/07. UKCEH, Wallingford, UK.

Nash JE, Sutcliffe JV. 1970. River flow forecasting through conceptual models part I—A discussion of principles. *Journal of hydrology,* 10**,** 282-290.

National River flow Archive (NRFA). 2014. *National River flow Archive* [Online]. Available: http://nrfa.ceh.ac.uk/ 2014].

Parry S, Wilby RL, Prudhomme C, Wood PJ. 2016. *A systematic assessment of drought termination in the United Kingdom*. UKCEH, Wallingford, UK

Perry A. 1976. The long drought of 1975–76. *Weather,* 31**,** 328-336.

Ragab R, Bromley J. 2010. IHMS—Integrated Hydrological Modelling System. Part 1. Hydrological processes and general structure. *Hydrological processes,* 24**,** 2663-2680.

Ragab R, Bromley J, Dőrflinger G, Katsikides S. 2010. IHMS—Integrated Hydrological Modelling System. Part 2. Application of linked unsaturated, DiCaSM and saturated zone, MODFLOW models on Kouris and Akrotiri catchments in Cyprus. *Hydrological processes,* 24**,** 2681-2692.

Robinson E, Blyth E, Clark D, Comyn-Platt E, Finch J, Rudd A. 2015. *Climate hydrology and ecology research support system potential evapotranspiration dataset for Great Britain* (1961-2015)[CHESS-PE].

Rouncevell M, Reay D. 2009. Land use and climate change in the UK. *Land Use Policy,* 26**,** S160-S169.

Seneviratne S. I. 2012. Climate science: Historical drought trends revisited. *Nature,* 491**,** 338.

Shiferaw BA, Okello J, Reddy RV. 2009. Adoption and adaptation of natural resource management innovations in smallholder agriculture: reflections on key lessons and best practices. *Environment, development and sustainability,* 11**,** 601-619.

Solander KC, Wilson CJ. 2018. *The Cape Town drought: what is happening and will it happen again?* Los Alamos National Lab.(LANL), Los Alamos, NM, USA..

Spraggs G, Peaver L, Jones P, Ede P. 2015. Re-construction of historic drought in the Anglian Region (UK) over the period 1798–2010 and the implications for water resources and drought management. *Journal of hydrology,* 526**,** 231-252.

Tanguy M, Dixon H, Prosdocimi I, Morris D, Keller V. 2016. Gridded estimates of daily and monthly areal rainfall for the United Kingdom (1890–2015)[CEH-GEAR]. *NERC Environmental Information Data Centre, doi,* 10.

The_Don_Network. 2018. *Our plan for the River Don* [Online]. Available: https://dcrt.org.uk/wp-content/uploads/2013/05/6541-1+Don+Network+Report+lo+res.pdf [Accessed 24/10/2018 2018].

Thornthwaite CW. 1948. An approach toward a rational classification of climate. *Geographical review,* 38**,** 55-94.

Tirivarombo S, Osupile D, Eliasson P. 2018. Drought monitoring and analysis: Standardised Precipitation Evapotranspiration Index (SPEI) and Standardised Precipitation Index (SPI). *Physics and Chemistry of the Earth, Parts A/B/C.*

Tsakiris G, Pangalou D, Vangelis H. 2007. Regional drought assessment based on the Reconnaissance Drought Index (RDI). *Water resources management,* 21**,** 821-833.

UK Centre for Ecology & Hydrology (UKCEH). 2014. UK*CEH digital river network of Great Britain web map service* [Online]. Available: https://data.gov.uk/dataset/3c7ea82e-83e0-45a3-9a3f-8ba653b3211b/ceh-digital-river-network-of-great-britain-web-map-service 2014].

Vangelis H, Tigkas D, Tsakiris G. 2013. The effect of PET method on Reconnaissance Drought Index (RDI) calculation. *Journal of Arid Environments,* 88**,** 130-140.

Vicente-Serrano SM, Begueria S, Lopez-Moreno J. I. 2010. A multiscalar drought index sensitive to global warming: the standardized precipitation evapotranspiration index. *Journal of climate,* 23**,** 1696-1718.

Wade SD, Rance J, Reynard N. 2013. The UK climate change risk assessment 2012: assessing the impacts on water resources to inform policy makers. *Water Resources Management,* 27**,** 1085-1109.

Wang H, Tetzlaff D, Soulsby C. 2018. Modelling the effects of land cover and climate change on soil water partitioning in a boreal headwater catchment. *Journal of Hydrology,* 558**,** 520-531.

Wang L, Chen W. 2014. A CMIP5 multimodel projection of future temperature, precipitation, and climatological drought in China. *International Journal of Climatology,* 34**,** 2059-2078.

Wilby RL, Prudhomme C, Parry S, Muchan K. 2015. Persistence of hydrometeorological droughts in the United Kingdom: A regional analysis of multi-season rainfall and river flow anomalies. *Journal of Extreme Events,* 2**,** 1550006.

Zarch MAA, Sivakumar B, Sharma A. 2015. Droughts in a warming climate: A global assessment of Standardized precipitation index (SPI) and Reconnaissance drought index (RDI). *Journal of Hydrology,* 526**,** 183-195.

Zhang X, Hu M. 2014. Effectiveness of rainwater harvesting in runoff volume reduction in a planned industrial park, China. *Water resources management,* 28**,** 671-682.