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RESEARCH ARTICLE

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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 hydrology, the Don catchment in Yorkshire, UK, was selected. A physically based distributed catchment-scale (DiCaSM) model was applied. The model simulates surface runoff, groundwater recharge and drought indicators such as soil moisture deficit SMD, wetness index WI and reconnaissance drought index RDI. The model's 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 stream flow and groundwater recharge was projected under medium- and high-emission scenarios. Climate change scenarios projected an increase in evapotranspiration and SMD, especially in the latter half of the current century.

Increasing the woodland area had the most significant impact, reducing 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 stream flow and groundwater recharge was more significant than land use change. Drought indices SMD, WI and RDI projected an increase in the severity and frequency of drought events under future climatic change, especially under high-emission scenarios.

KEYWORDS

climate change, DiCaSM hydrological model, Don catchment, land use change, reconnaissance drought index (RDI), soil moisture deficit (SMD)

Résumé

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

*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

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)

1 | INTRODUCTION

Changes in land surface hydrology are attributed to the collective effects of 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, groundwater recharge and change in water storage. In the UK, the land surface has changed slightly due to human intervention that mainly resulted in changes in land use for food production, energy, housing and recreation. Recent land use changes are probably happening faster than at any other time in human history, due to the increase in demand for natural resources, rapid changes in urbanization, and 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 agricultural land use practices which are driven by farmers' decisions, in turn 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 being that 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). In contrast to water supplies in the south-east region, those in the north-east depend on 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 was evident from the 1995 drought event (Fowler and Kilsby, 2002). The studied catchment, the Don, is very significant for 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, urbanization and recreation including navigation (The_Don_Network, 2018).

The historic long-term record of 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 urbanization possibly added urban heat which contributed to the long-term warming trend which resulted in extreme precipitation events. This could potentially affect 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 historic droughts in the UK using the observed data, less focus has been given to studying 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 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 aquifers, surface water reservoirs contribute significantly 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 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 changes in temperature are taken from three emission scenarios: low (IPCC SRES: B1), medium (IPCC SRES: A1B) and high (IPCC SRES: A1F1), which provide 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 (Nakicenovic et al., 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 expected future population growth and economic 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. The 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 important for the Don catchment for managing water abstraction, improvement in water infrastructure and planning for future drought risk under climate change.

2 | MATERIALS AND METHODS

2.1 | 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 areas, 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 moderately permeable bedrock, which covers almost 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 naturalized 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 treated wastewater discharge into the river.

2.2 | Input data and scenarios

2.2.1 | 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

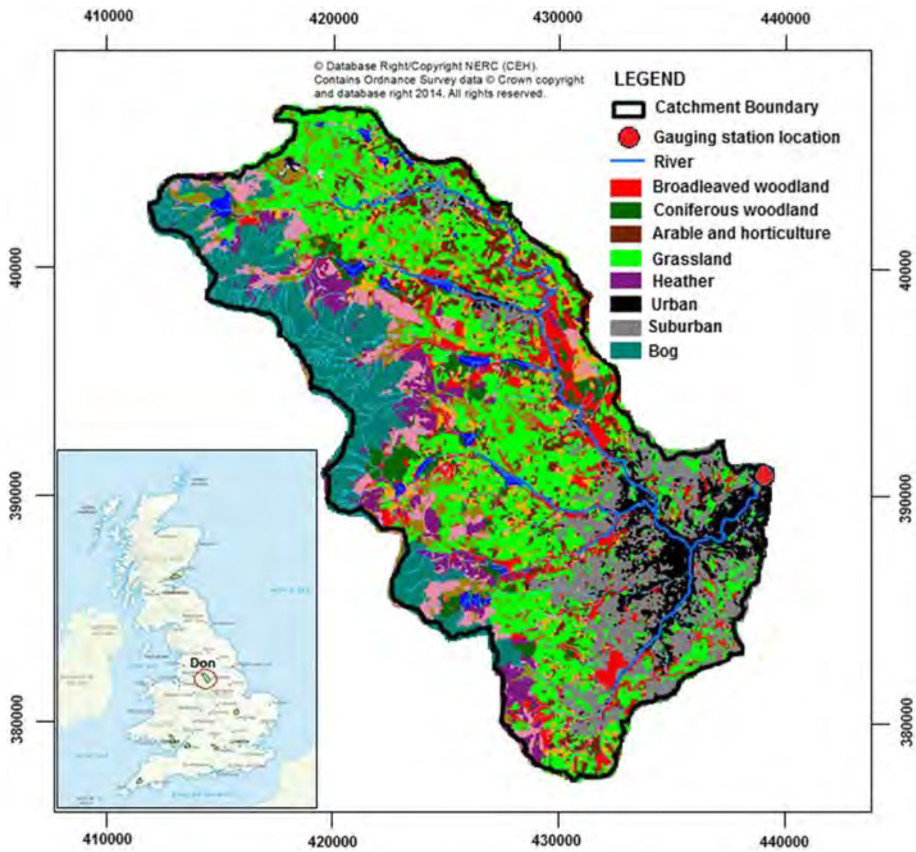


FIGURE 1 The Don catchment: boundaries, land use practices and location of the gauging station, adapted from Morton et al. (2011) [Colour figure can be viewed at wileyonlinelibrary.com]

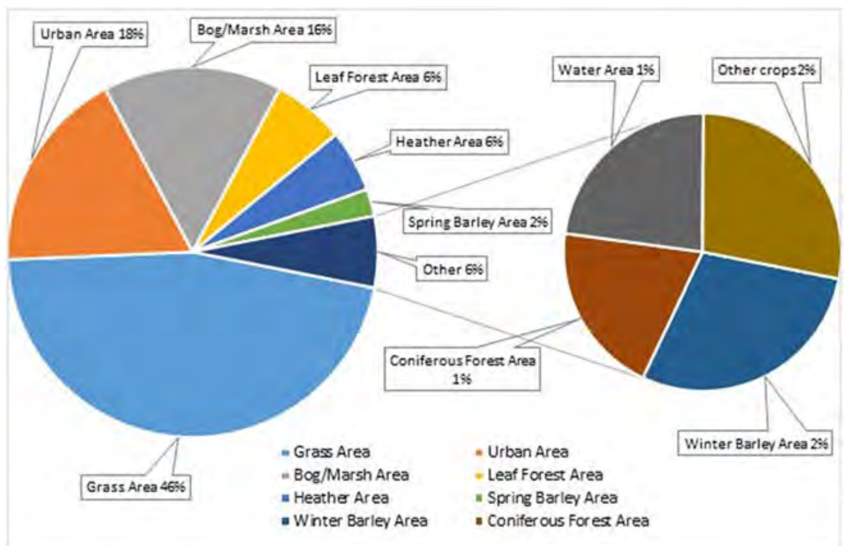


FIGURE 2 Current land use in the Don catchment [Colour figure can be viewed at wileyonlinelibrary.com]

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 1 km 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 and Flavin, 1994; Morris *et al.*, 1990) 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 and 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 were 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: 2020s (2010–2039), 2050s (2040–2069) and 2080s (2070–2099) for the three greenhouse gas emission scenarios (low, medium and high) were considered. The UKCP09 provides monthly, seasonal and annual probabilistic change factors at 25 by 25 km grid square resolution for precipitation and temperature (Table 1). The table shows that seasonal temperature increases with the level of emission and time, particularly in summer and autumn, whereas 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 5 km^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.

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 baseline data, these data were subjected to bias correction. The latter was carried out using the 'qmap' package in the 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 that 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 daily climate model data to this approach and recently Hakala *et al.* (2018) applied this bias correction method to evaluate climate model simulations.

2.3 | Historic and current land use

The studied Don catchment is not only significant for agriculture but also importantly contributes to domestic water supplies. Water supplies in the catchment area come from the 23 reservoirs which are located within the catchment boundary. 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 sewage effluent and can affect aquatic systems resulting in reducing recreational activities within the catchment. Agriculture census data reveal that the key land use in the area is grassland, heather and urban, with

TABLE 1 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 ↓

Emission Scenarios →

less than 10% of the catchment being agriculture (Figure 2).

2.4 | 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 stream flow, 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 used directly or indirectly to calculate the drought risk for both the historic period and for future climate change scenarios. The methodology for calculating each drought index is discussed later.

2.5 | DiCaSM model input data and processes

The hydrological DiCaSM was used to simulate the water balance of the catchment. The key inputs 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 to 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 a daily time step and produces an output including spatially distributed and time series of potential evapotranspiration, actual evapotranspiration, soil water content, SMD, WI of the root zone, groundwater recharge, stream flow 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 plant algorithms, and therefore handles up to different 20 land cover and soil types within 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 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

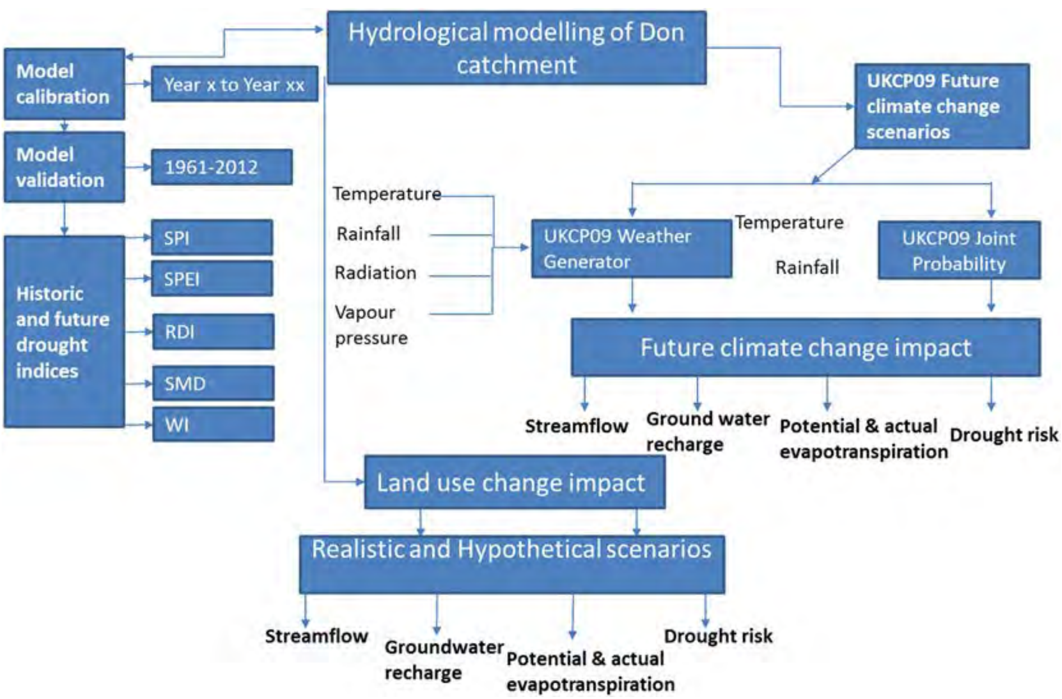


FIGURE 3 Schematic representation of the modelling procedure [Colour figure can be viewed at wileyonlinelibrary.com]

(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 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:

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

where O_i and S_i refer 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 that is based on the stream flow logarithmic values has also been considered (Afzal *et al.*, 2015; Krause *et al.*, 2005). In addition, the model's 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 1 indicating perfect fit.

2.6 | 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.

2.7 | Standardized 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 SMD, 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 are: 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).

2.8 | Standardized precipitation evapotranspiration index (SPEI)

Another drought index is the standardized precipitation evapotranspiration index (SPEI) which is a multi-scale 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 also the impacts of drought severity on vegetation health (Bento *et al.,* 2018). The equation used to calculate SPEI is based on Thornthwaite (1948):

$$D_i=P_i-\mathrm{PET}_i \tag{2}$$

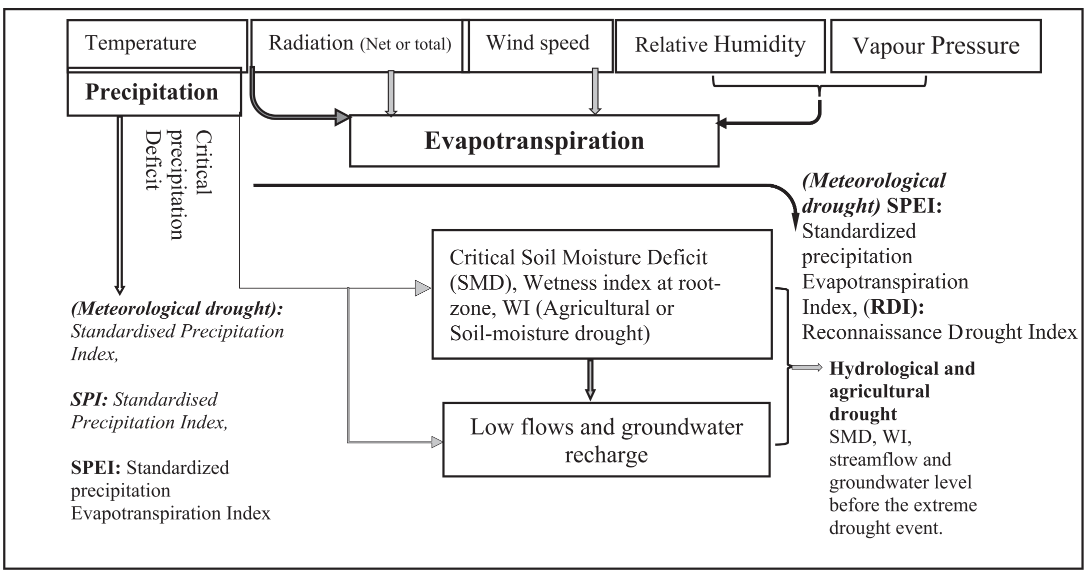


FIGURE 4 Key drought drivers of meteorological, agricultural and hydrological droughts

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 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 Tirivarombo *et al.* (2018), and was used recently to study the severity of extreme droughts events, like those of Cape Town, South Africa (Solander and Wilson, 2018).

2.9 | 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 RDI was calculated as

$$a_0^{(i)} = \frac{\sum_{j=1}^{12} P_{ij}}{\sum_{j=1}^{12} \mathrm{PETor}AE_{ij}} \quad (3)$$

$$\mathrm{RDI}_n^i = \frac{a_0^{(i)}}{\bar{a}_0} - 1 \quad (4)$$

$$\mathrm{RDI}_{st\,(k)}^i = \frac{y_k^{(i)} - \bar{y}_k}{\hat{\sigma} yk} \quad (5)$$

where P_{ij} and $\mathrm{PET}_{\mathrm{ij}}$ are the precipitation and potential evapotranspiration or actual evapotranspiration of the jth month of the ith hydrological year (starting from October), and $\bar{a}_0$ is 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 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 the canopy cover) and actual evapotranspiration.

2.10 | 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 0 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). WI of the rootzone (scaled soil moisture) is calculated as (current soil moisture – minimum soil moisture) / (maximum soil moisture – minimum soil moisture).

2.11 | The significance and interrelations of the drought indices

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

All the above indices do have implicit or explicit relationships between them but the scale of severity differs from one type of drought index to another. 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 is based on ratio of precipitation to evapotranspiration. This is similar to SPEI where the input as precipitation and evaporation as losses is considered as output. Should the ratio of precipitation to evapotranspiration become smaller than the threshold value, possible irrigation might be required.

3 | RESULTS

3.1 | Model stream flow calibration and validation

The river flow calibration was carried out using a built-in optimization submodel in DiCaSM. The key six model parameters that were used to calibrate 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 stream bed leakage ratio. The other factors by which simulated river flow is indirectly affected are the soil hydraulic properties and 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 parameter sensitivity, i.e. a higher number of iterations were assigned to parameters which showed more impact on the stream flow. The model calculates the Nash–Sutcliffe efficiency value, NSE, ln NSE and R^2 for each iteration. The model optimization 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 NSE, was above 87% with less than 2% error in total water volume. The selected calibration period included a dry and a wet period in order to assess model performance during both conditions. The model performed well during both the rainy and dry events and responded according to soil hydrology status, i.e. during the SMD period, a small precipitation event did not generate enough stream flow 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 decade of the 1970s; during this period model efficiency measured using the NSE was above 80%, which indicates good confidence in the calibration

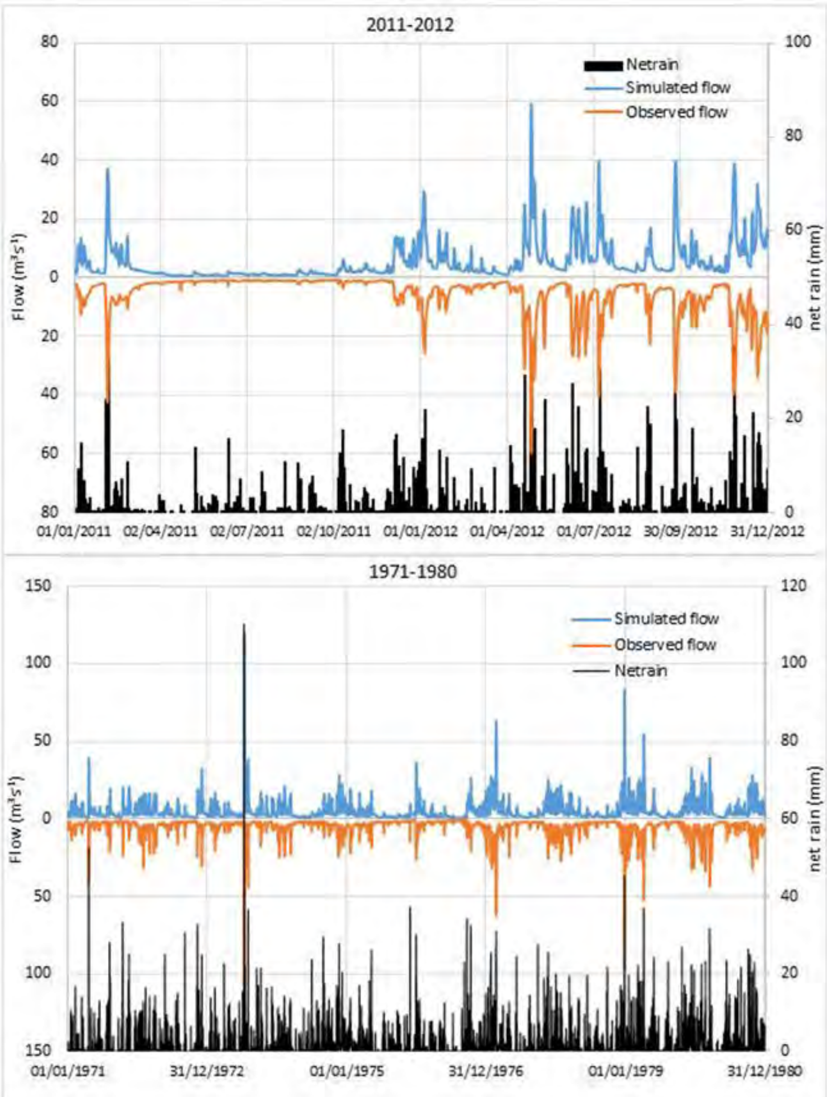


FIGURE 5 Stream flow calibration (2011–2012) and validation (1971–1980) period [Colour figure can be viewed at wileyonlinelibrary.com]

parameters. The results of model prediction efficiency calculated in percentages as NSE, log NSE and R^2 values are shown in Table 2. 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%).

3.2 | Identification of historic droughts

3.2.1 | 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 shows 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.

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 exceeded 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-1990s. These drought indices show that the Don catchment was subjected to drought events which significantly affected southern England, the Anglian regions and the Midlands (Parry *et al.*, 2016). The SPI and SPEI indices crossed over exceeded 'extreme drought' level during both the 1970s and the 1990s droughts. Not only the occurrence of the drought events (frequency) but also their duration and strength significantly affect stream flow and groundwater recharge.

Therefore, the SPI and SPEI indices could be used as good indicators for meteorological and hydrological drought. The SPI and SPEI indices over 52 years elucidated the successive dry events, such as those occurring in the 1970s and the 1990s. The SPI and SPEI indices also help to identify 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 severity of drought was considered severe in the mid-1970s, in 1976 and in 1996 when SPI and SPEI indices were well below −2, 'extreme drought' level.

TABLE 2 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 ($m^3 s^{-1}$)[a]	Average observed flow ($m^3 s^{-1}$)[a]	% Error in total volume
2011–2012[b]	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

[a]Average daily stream flow of the period.
[b]Calibration period.

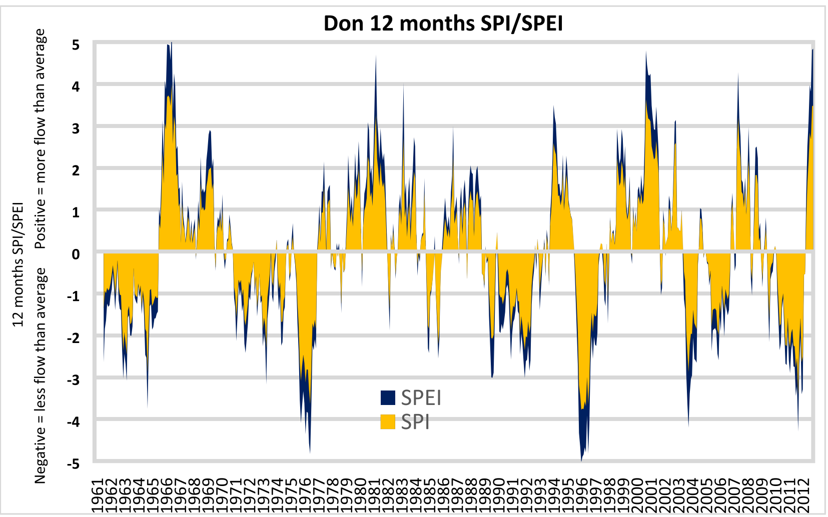


FIGURE 6 The standardized precipitation index (SPI) and standardized precipitation evapotranspiration index (SPEI) of the Don catchment from 1961 to 2012 [Colour figure can be viewed at wileyonlinelibrary.com]

3.2.2 | Reconnaissance drought index (RDI)

Figure 7 shows a comparison between adjusted RDI and classical RDI. Both picked up all the drought events, which were detected by SPI and SPEI. However, the advantage of applying 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 extreme drought events. In addition, there is a strong correlation between the two ways of calculating RDI and 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 and 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 RDI was applied using gross rainfall and potential evaporation in most of the cases. Based on both types of RDI and SPI/SPEI drought indices, the total percentage of wet years was higher than that of dry years.

3.3 | Soil moisture deficit, SMD and soil wetness index, WI as drought indicators

For agricultural drought, the soil moisture deficit, SMD and the wetness index, WI of the root zone are more appropriate (Figure 8). WI represents how relatively wet or dry the catchment is over the period. WI is a scaled soil moisture status that accommodates the spatial variability of soil types, elevation, vegetation cover, etc. across the catchment. SMD represents the deviation of soil moisture from that at field capacity. Here zero means the catchment's soil moisture is at field capacity level. The deviation becomes larger when soil moisture starts to fall below 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 SMD exceeded 100 mm and during the 1976 dry summer period, it was over 140 mm.

The figure also shows the severity of the dry spell as a result of the continuation of the dry season 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. It can also be seen that 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.

3.4 | Future climate change impact on the water resources

3.4.1 | Changes in stream flow

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 1). To study the impact of climate change on the hydrology of the Don catchment, 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

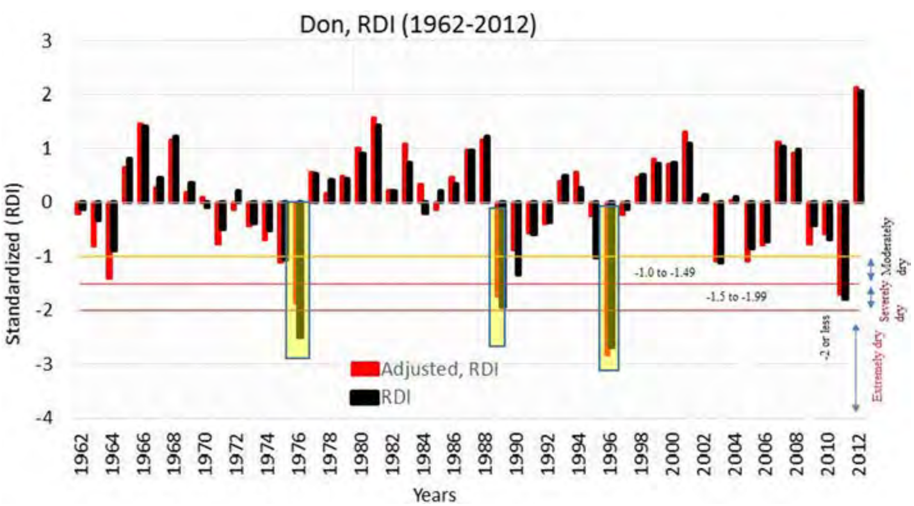


FIGURE 7 Standardized RDI (reconnaissance drought index) based on potential evapotranspiration and total precipitation and the adjusted RDI, calculated using net rainfall and actual evapotranspiration, for the Don catchment during the 1962–2012 period [Colour figure can be viewed at wileyonlinelibrary.com]

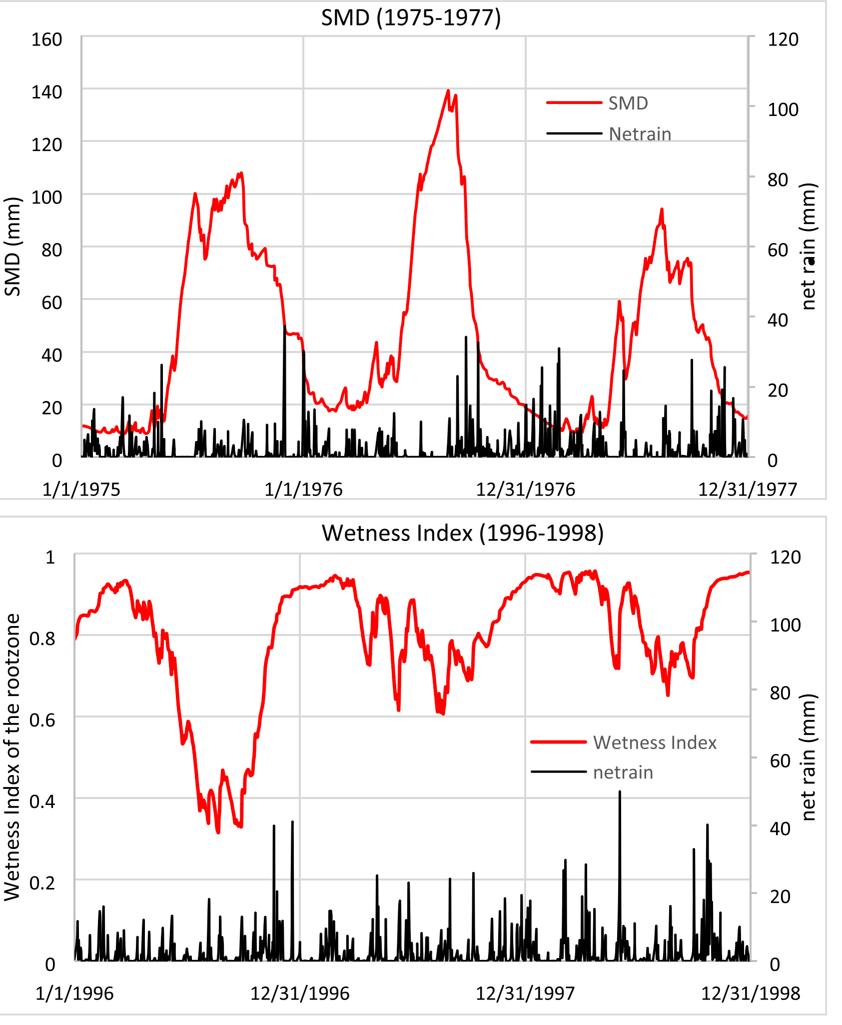


FIGURE 8 Soil moisture deficit from 1975 to 1977 (top) and wetness index of the root zone from 1996 to1998 (bottom) for the Don catchment [Colour figure can be viewed at wileyonlinelibrary.com]

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 to the 1961–1990 baseline climate data (Table 1).

A significant change in stream flow was observed using both approaches. The simplified change factor (joint probability) approach suggests that stream flow 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 stream flow was not that significant (Figure 9). This is of greater significance for the Don catchment which contributes significantly 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 stream flow under the three emission scenarios and three selected time periods. There is an exception in the 2020s, under low- and medium-emission scenarios, where the stream flow 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 from −1.4 to −4.5% under high-emission scenarios, relative to the baseline period. During the spring season, evaporation is low relative to 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 stream flow is projected under all emission scenarios. In the 2020s, summer stream flow is likely to decrease by 13–15% using the joint probability approach, whereas under the weather generator only a small decrease of up to 4.5% is projected. In the 2050s a significant decrease of 12.8–17.9% relative to the baseline period is projected using the weather generator data, whereas under 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 joint probability

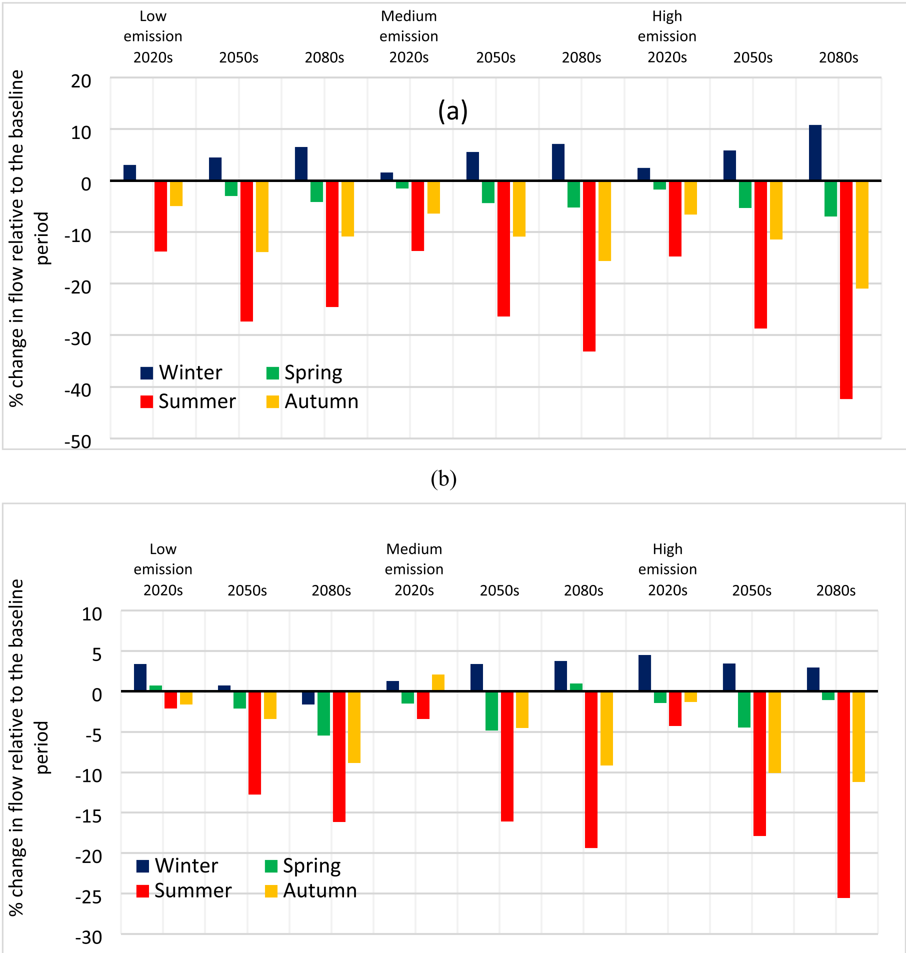


FIGURE 9 Percentage change in stream flow relative to the baseline period (1961–1990) over seasonal scale under low-, medium- and high-emission scenarios for the 2020s, 2050s and 2080s, under (a) UKCP09 joint probability and (b) under UKCP09 weather generator [Colour figure can be viewed at wileyonlinelibrary.com]

approach, stream flow is likely to decrease by 24–42%, whereas using the weather generator data, stream flow is likely to decrease by 16.1–25.5%, depending on the emission scenario.

The severity of 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. Stream flow is likely to decrease in the summer season because the soils are not saturated in comparison with winter and spring, as a result SMD is likely to increase. The combined effect of decreasing precipitation with 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 precipitation and 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.

In autumn, stream flow is likely to decrease slightly under low- and high-emission scenarios, and a slight increase under medium-emission scenarios in the 2020s. Overall, there is not 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 approaches 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 SMD during both the summer and autumn seasons; combined with an increase in autumn temperature this would result in reduced stream flow in autumn due to higher water losses by evapotranspiration. The simplified change factor (joint probability) showed slightly higher change compared to the weather generator, since the joint probability method only considered two climate variables (rainfall and temperature).

Overall, in all seasons, the severity of change in stream flow more particularly during the summer season could lead to very low stream flows, possibly leading to a

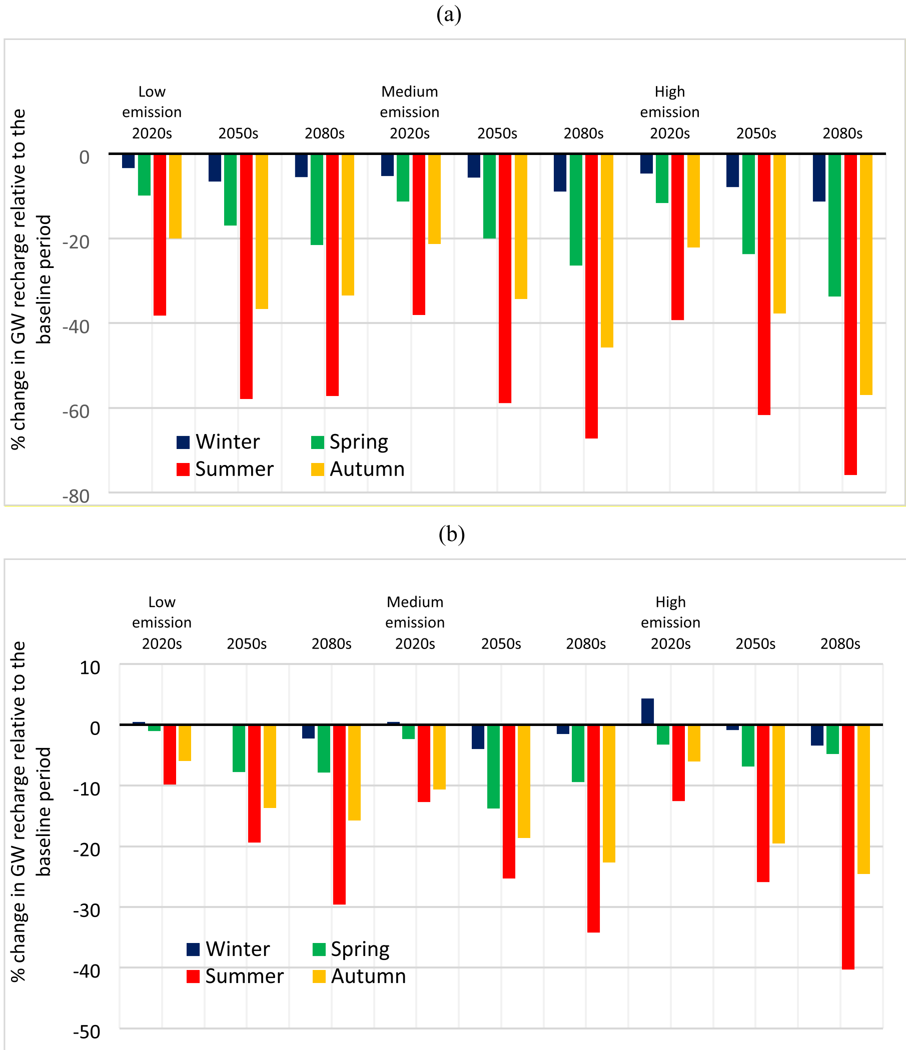


FIGURE 10 Percentage change in groundwater recharge in the Don catchment for the different seasons over a selected time period, based on joint probability (a) and weather generator (b) of UKCP09 under different climate change scenarios [Colour figure can be viewed at wileyonlinelibrary.com]

high risk of inadequate domestic, industrial and agricultural water supply. The summer stream flow is more significant for the Don catchment as there are 23 reservoirs within the catchment, which significantly contribute to the water supply system.

3.4.2 | Changes in groundwater recharge

Analysis using the weather generator and joint probability, under all emission scenarios and for the selected time periods, showed that groundwater recharge would decrease, with some exceptions under the 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 from increased evapotranspiration (due to increased temperature) which resulted in a small increase in groundwater recharge. The groundwater recharge projections under joint probability suggest that 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 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 groundwater recharge is lower than expected, due to losses by evapotranspiration that cause an increase in SMD and subsequently a decrease in groundwater recharge in all seasons. Another factor which could reduce groundwater recharge in all seasons is that winter precipitation is expected to occur as extreme events and over a short period of time, as reported in Alexander *et al.* (2005). Groundwater recharge is also likely to decrease in spring due to a milder increase in spring temperature and 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 SMD and subsequently lower groundwater recharge. Using joint probability, 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 as 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 SMD. Under all emission scenarios and observed time periods, 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 between −38 and −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 being in comparison to the baseline period.

In summer months (June, July, August) enhanced evapotranspiration, together with decreased precipitation, would result in reduced stream flow and groundwater recharge. Higher evapotranspiration combined with lower precipitation during the summer months would result in an increase in SMD, 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 groundwater recharge is likely to decrease by −2.2 to −12.0%, under medium emissions 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 the −4.0 to −25.8% range. The higher decrease in groundwater recharge under high-emission scenarios would result from the increase in SMD 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 water resources (Wade *et al.,* 2013), suggesting that demand-side measures would be required to match future water supplies availability (Wade *et al.,* 2013).

3.5 | Drought indices

As a result of expected future drier and warmer climatic conditions, greater water losses by evapotranspiration, higher SMD and low WI were observed (Figure 11). To illustrate the impact of decreasing precipitation and increasing water losses due to evapotranspiration, the

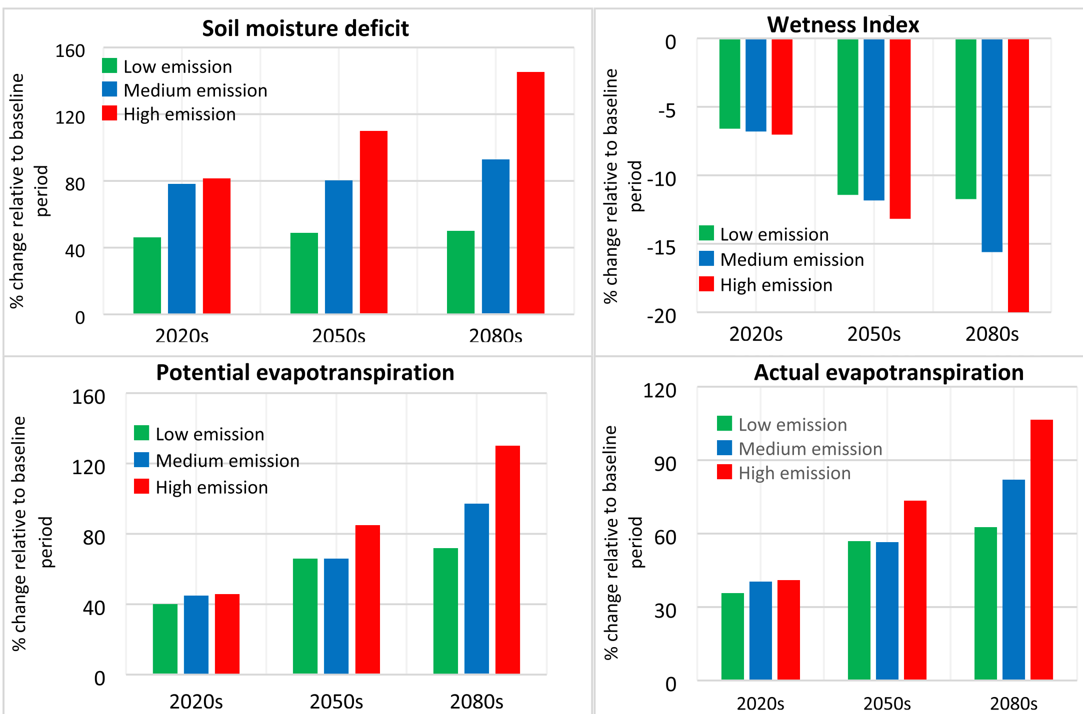


FIGURE 11 Seasonal changes in SMD, actual evapotranspiration and WI of the root zone for the Don catchment under all emission scenarios based on UKCP09 joint probability [Colour figure can be viewed at wileyonlinelibrary.com]

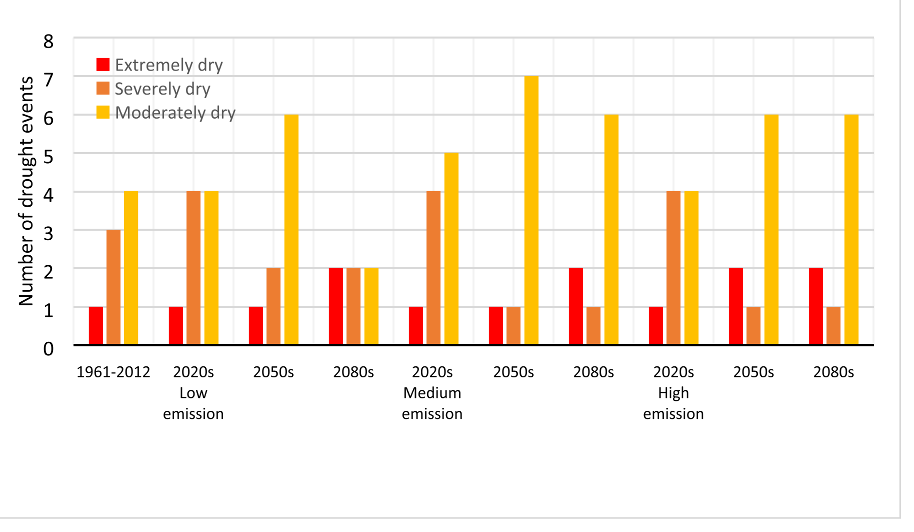
standardized RDI was calculated. The adjusted RDI was calculated from the net rainfall and actual evapotranspiration of the selected time periods: 2020s, 2050s and 2080s for three emission scenarios (Figure 12). The analysis revealed an increase in number of moderate and severe drought events, more importantly 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 extremely dry events but also severe drought events are likely to increase in the future. In addition, the frequency of moderate drought events (RDI −1 to −1.5) is likely to increase in the future, more specifically under medium- and high-emission scenarios.

3.6 | Impacts of land use changes on 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 local stakeholders and catchment authorities, were examined (Table 3). The land use changes scenarios results can be summarized as:

- replacing grass areas with winter barley would lead to an increase in stream flow between 3 and 6%, while groundwater recharge is likely to increase between 1 and 7%;
- replacing grass areas with oilseed 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 recharge is likely to increase by only 2%;
- expanding the urban area by 40% at the expenses of grass and arable areas would lead to a tiny increase in stream flow by 1% and groundwater recharge by 2%;
- replacing 50% of winter barley with oilseed rape would lead to a decrease in stream flow by 2% and groundwater recharge by ~3%;

(a)



(b)

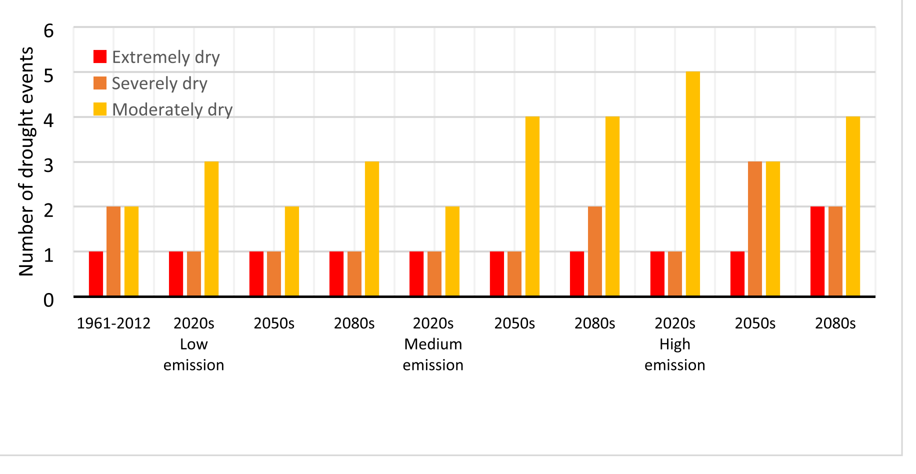


FIGURE 12 The severity of drought events observed in the Don catchment under the three emission scenarios for the 2020s, 2050s and 2080s (a) under joint probability and (b) using the weather generator data [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 3 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 oilseed rape	40% urban expansion replacing grass and arable area	Replacing 50% of winter barley with oilseed rape	Whole catchment as grass area	Whole catchment as broadleaf 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

- converting the whole catchment apart from the urban area into grass areas would lead to a decrease in stream flow by 2–8% and groundwater recharge by 5–9%.;
- converting the whole catchment apart from the urban area into a broadleaf forest area would lead to a decrease in stream flow by 9–17% and groundwater recharge by 10–22%.

The expansion of broadleaf forest would be likely to result in an increase of SMD, more specifically during the spring and summer seasons when plants are at their maximum growth rate and take up much of the soil water to satisfy the evapotranspiration demand. Urban expansion could result in increased stream flow (likely to increase flood risk) and an increase in groundwater recharge. Increasing conventional crops, like barley replacing grass, could result in a slight increase in river flow and a decrease in SMD, compared with oilseed rape, which takes up more water during the spring season (Table 3). These results are of great value for local authorities for future planning taking into account the impact of any land use change on surface and groundwater.

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

4 | 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 this study were able to identify all the historical drought events. The adjusted RDI calculated using actual evapotranspiration and 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 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 228 years for England and Wales (Marsh and Turton, 1996). All the applied drought indices including RDI, SMD and WI of the root zone (Figures 7–9) identified these drought events. During these drought events, the RDI and SPI/SPEI were well below −2, which identifies them as 'extreme drought' events (caused by extremely low precipitation and high evapotranspiration). Keeping 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 SMD), there is a possibility of more frequent and severe drought occurring in the future.

The land use type would significantly change in the future, especially due to urbanization, as this would further increase pressure on water resources for domestic use in the Don catchment. The other key land use changes are agricultural land use practices, which are driven by farmers' decisions which are market based, as well as the availability of investment, subsidies and sociocultural 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 drought. For example, in agriculture, when SMD or 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 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 whether future surface water abstraction regulations were in line with water resources availability as predicted by calibrated and validated hydrological models and in possible planning of new water infrastructure to increase 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 counterbalanced by an increase in evapotranspiration and increase of SMD during the summer and autumn seasons. Stream flow 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 ground water recharge and stream flow and the increasing possibility of droughts in the future, new investment will be required if water demand is not met by 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 reservoirs by, for example, floating solar panels, spreading ecologically friendly agents on the water surface or an ultra-thin layer of organic molecules on their surface (Alamaro *et al.,* 2012). The implication of surface water abstraction during drought and low-flow periods would reduce river flows possibly below the minimum environmental flow. Alternatively, restrictions on abstraction to maintain minimum environmental flows may restrict crop yields and food production.

5 | CONCLUSION

The DiCaSM hydrological model used in the study showed good agreement between observed and simulated flows during the model calibration and validation stages and overall model efficiency using the NS index was above 82% for the 52-year study period. In addition to 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 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, stream flow and 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 drought under future climate change scenarios. Under high-emission scenarios, the severity was higher as it was associated with 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 23 reservoirs in the catchment boundary, which significantly contribute to the water supply of the catchment.

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