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 drought events prediction using reliable drought indices
 Afzal, M.^{1,2} and R. Ragab^{1*}

6 Abstract

7 The two key factors that affect the water balance are climate and land-use changes. Although climate 8 change models have been developed for global scale, the implementation of their predictions is 9 commonly applied at catchment scale where the measurements are being carried out and the 10 management takes place. To investigate the impacts of climate and land use changes on the hydrology, the Don Catchment in Yorkshire, UK, has been selected for this study. A physically based 11 distributed catchment-scale (DiCaSM) model has been applied. The model simulates the surface 12 runoff, groundwater recharge and drought indicators such as soil moisture deficit (SMD) and wetness 13 14 index (WI) of the root zone. The model was calibrated and validated against the observed river flow and the model efficiency was evaluated using the Nash-Sutcliffe Efficiency factor (NSE). During the 15 calibration period (2011-2012), NSE was above 91% and during the validation period (1966-2012) 16 was above 83%. To study the impact of climate change on the streamflow and the groundwater 17 18 recharge, UK Climate Projections (UKCP09) data was applied. Under current land use changes under 19 different climate scenarios, the greatest decrease in streamflow and groundwater recharge is projected 20 under medium and high emission scenarios. Considering the projected increase in winter 21 precipitation, the increase did not contribute much into the streamflow and groundwater recharge due 22 to prolonged drier summer and higher temperature during the summer and autumn seasons that 23 resulted in an increase of evapotranspiration and soil moisture deficit (SMD). Climate change 24 scenarios projected an increase in evapotranspiration, soil moisture deficit more importantly in the 25 latter half of the current century and resulted in more extreme and severe drought events in 26 comparison to the baseline period. To study the impact of land use changes on water balance,

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27 different possible scenarios were created. The increasing of woodland had the most significant impact by reducing the stream flow by up to 17% and groundwater recharge by 22%. Urbanization, could 28 29 lead to increase in stream flow and groundwater recharge. The magnitude of the impact of the climate change was much more significant than the land use change on the streamflow and the groundwater 30 31 recharge. All the applied drought indices (SMD, WI, and RDI) identified an increase in the severity of the drought under future climatic change scenarios, especially under high emission scenario where the 32 33 severity was the highest. Findings of the study are of great importance for Don Catchment that has 23 reservoirs for water supply. Some measures were suggested for sustainable management of the land 34 and water resources in order to meet future water demand in the light of diminishing water supplies. 35

36 Key words: Climate change, Land use change; DiCaSM Hydrological model; Don Catchment;

37 Reconnaissance Drought Index (RDI); Soil moisture deficit (SMD) and land-use change.

39 40

1. Introduction

41 Changes in the land surface hydrology are attributed to the collective effects of the changes in the 42 climate, changes in vegetation, and the soil (Wang et al., 2018). Therefore, it is important to understand 43 the impact of climate and land use changes on the water resources availability. In the UK, the land surface has changed slightly due to human interventions that mainly resulted in changes in land use for 44 45 the 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 46 47 resources, rapid changes in urbanisation, an increase in water demands for domestic and agricultural 48 use. This is very significant for the UK where two-thirds of the land area is grassland. Approximately 49 14% of the UK is urban land which has significantly increased (by 300,000 hectares) since 1998 50 (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 51 investment and subsidies (Shiferaw et al., 2009). 52

53 The UK and the study area (North East of England) have experienced a number of droughts, the most 54 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 55 56 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, 57 this suggests that the water supplies in the region are more vulnerable to drought which is evident from 58 59 the 1995 drought event (Fowler and Kilsby, 2002). The studied catchment, the Don is very significant 60 for the water supplies in the region as there are 23 reservoirs within the catchment boundary which are 61 recharged mainly during the winter months. Therefore, the main types of physical modification that 62 affect the Don Catchment are the water storage and supply reservoirs, flood management structures, 63 urbanisation and recreation including navigation (The Don Network, 2018).

64 The historic long-term record of the climate variables for the Sheffield area (part of the Don catchment
65 area), covering the period from 1883 to 2015, suggests a significant annual warming trend (1.0 °C per

66 century), combined with an increase in annual precipitation (69 mm per century) with no significant 67 trend in seasonal precipitation (Cropper and Cropper, 2016). There is a general perception that the 68 urbanisation possibly added urban heat which contributed to the long-term warming trend which 69 resulted in extreme precipitation events. This could potentially affect the water resources availability in 70 the future and increase the drought risk, as water supplies within the catchment significantly depend on 71 the reservoirs. Considering the historic climate and land use changes and likely changes in the future, 72 it is important to study of the impacts of climate and land use changes on the studied catchment.

73 Although a number of studies including (Burke et al., 2010, Jackson et al., 2015, Wilby et al., 2015, 74 Spraggs et al., 2015) have been carried out to identify the historic droughts in the UK using the observed 75 data, less focus has been given to study the drought risk over catchment scale under different climate 76 and land use change scenarios and their impacts on water resources. This study aims to address this 77 issue in more detail and will also apply a number of indicators for the historic and future climate change 78 which could potentially be used as drought indicators to identify meteorological, agricultural and 79 hydrological droughts. The limited availability or access to the aquifers, the surface water reservoirs 80 significantly contribute to the water supplies of the studied area. As the water available in the reservoirs 81 is vulnerable to climate change, the reliability of water resources availability in the catchment could be 82 at higher risk due to the climatic variability.

The objectives of this study is 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.

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

88

2. Background of the studied catchment

The Don Catchment (NRFA no. 27006) is in the North East of the country with a catchment area of 373
km² (Fig. 1). The naturalised discharge (where the river-flow was adjusted to take into account

91 abstraction and discharge into the river) was obtained from Environment Agency. This was needed as 92 streamflow is affected by presence of the 23 reservoirs, river abstraction for agricultural and industrial 93 use, groundwater abstraction and by treated wastewater discharge. The key land uses of the catchment 94 are: woodland which covers 15.8% of the catchment area, arable land, 6.1%, grassland, 35.6%, heather 95 area, 18.9% and urban area, around 14.0% (Fig. 2). The catchment contains a moderate permeability 96 bedrock which almost covers half of the catchment. Based on historical data, the average annual rainfall 97 for the Don Catchment is around 1085 mm and average temperature 7.8°C for the baseline data, 1961-98 1990, the average annual rainfall for the studied period 1991-2012 was 1089 mm and the average 99 temperature 8.5 °C. The Don catchment is important for drinking water as it supplies conurbations of 100 South Yorkshire. Therefore, protecting drinking water sources now and in the future is essential. There are over twenty Yorkshire water reservoirs in operation. 101



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

105

3. Data, and the methodology

106 *3.1. <u>Historic climate, soil, river flow and future climate data</u>*

107 The Distributed Catchment Scale Model, DiCaSM model was run on a daily time step and spatial scale of 1 km² grid square area. The catchment area is 373 km² covered by 435 grid squares (as not all the 108 grid squares were covered in the catchment boundary), each of which has 1 km² area. The model input 109 requires a number of daily climatic variables including precipitation, temperature, wind speed, daily net 110 111 radiation or total radiation and vapour pressure. Climate data were obtained from the Climate Hydrology and Ecology research Support System (CHESS) that accounted for the impact of changes in 112 elevation on climatic data (Robinson et al., 2015, Tanguy et al., 2016). The historic continuous climatic 113 114 variables and river flow data were available from 1961 until 2012. The catchment boundary and gauging station location data were available from Centre for Ecology and Hydrology (Morris et al., 1990, Morris 115 and Flavin, 1994) and National River Flow Archive provided data for the daily river flow for the 116 117 catchment (NRFA, 2014). The river and water body data were collected from the Centre for Ecology 118 and Hydrology, 'Digital Rivers 50 km GB' Web Map Service (CEH, 2014). The UK Land cover data were obtained from the Centre for Ecology and Hydrology (Land Cover Map 2007, 25m raster, GB) 119 120 Web Map Service (Morton et al., 2011). The soil data was obtained from the Cranfield University, 121 (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 122 123 Scenarios (UKCP09) was used using the joined probability factors and the UKCP09 weather generated 124 data. In this study three 30-year periods: 2020's (2010-2039), 2050's (2040-2069) and 2080's (2070-125 2099) for the three greenhouse gas emission scenarios (low, medium and high) were considered. In 126 UKCP09, Bayesian probability is used in which probability is derived from observations and outputs from a number of climate models, all with their associated uncertainties. The UKCP09 provides 127 monthly, seasonal and annual, probabilistic changes factors at 25 km by 25 km grid square resolution 128 129 for precipitation and temperature (Table 1). The seasonal temperature shows an increase in emissions 130 scenario and time, particularly in summer and autumn, whereas the precipitation is showing rainfall 131 decreases 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 5km² resolution for more climate variables 132 133 such as vapour pressure and sunshine hours, in addition to rainfall and temperature. This data was 134 downscaled using the weighing factors from (CHESS) methodology that accounted for the impact of 135 changes in elevation on climatic data. The sunshine hours were converted into net radiation following 136 the methodology of Allen et al. (1998). For the initial exploratory analysis, simplified change factors 137 were derived from UKCP09 joint probability central estimates. The joint probability plot was used to 138 generate seasonal climatic change factors (% change in rainfall and change in temperature, \pm °C) to 139 apply as an input to the DiCaSM model.

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.

		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

143 144

145

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 and alternative timing of events. This data was subject to bias correction, which was carried 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 models
data to this approach and recently Hakala et al. (2018) applied this bias correction method to evaluate
climate model simulations.

155 *3.2. <u>Historic land use and its importance</u>*

The studied Don catchment is not only significant for agriculture but also significantly contribute 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 (Fig. 2).



163

164 **Figure 2:** Current land use in the Don catchment

165 *3.3. <u>Schematic representation of modelling work</u>*

166 The schematic representation of the modelling work is shown in Figure 3 which shows the data sources

used in the study. Both historic and future climatic variables data were used to generate the streamflow,

- 168 groundwater recharge, net rainfall, potential and actual evapotranspiration, soil moisture deficit (*SMD*), 169 wetness index (*WI*) of the root zone and water losses due to interception. All these variables were 170 directly or indirectly used to calculate the drought risk for both the historic period and for future climate
- 171 change scenarios. Methodology about each used drought index is discussed later.



172



174 3.4. <u>DiCaSM model input data and processes</u>

The hydrological DiCaSM is the acronym for the Distributed Catchment Scale Model was used to simulate the water balance of the catchment. The key input of the model are the meteorological data (temperature, rainfall, 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 and temporally distributed series of potential evapotranspiration, actual evapotranspiration, soil water content, soil moisture deficit (*SMD*), wetness index (*WI*) of the rootzone, groundwater recharge, streamflow and surface runoff (Ragab and Bromley, 2010). The model is capable of simulating 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 (Ragab et al., 2010). In the model, runoff is routed between the low points of each grid square along the prevailing slope using the digital terrain model (DTM).

190 The model simulates the following processes, rainfall interception by land cover, evapotranspiration, 191 surface runoff, infiltration, groundwater recharge, plant water uptake, bare soil evaporation and stream 192 flows. Further details about the model are given in Ragab et al. (2010) and Ragab and Bromley (2010). 193 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 194 195 efficiency (goodness of fit), measured during the model calibration and validation, was carried out using 196 several efficiency indices, including Nash-Sutcliffe Efficiency (NSE), log of Nash-Sutcliffe Efficiency (log NSE) and Coefficient of Determination, R^2 as given below. 197

198 <u>3.4.1 Indices of measuring the model efficiency</u>

The calibration procedure consisted of adjusting the parameters related to stream flow calculations to achieve the best model fit, assessed using the *NSE* and log *NSE* of the stream flow. To estimate the model efficiency/goodness of fit , modelled and observed flow data were compared using a number of indices, including 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.

205
$$NSE = 100 - \frac{\sum_{i=1}^{n} (O_i - S_i)^2}{\sum_{i=1}^{n} (O_i - \bar{O})^2}$$
 (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 statistical indicators namely Coefficient of determination, R^2 as:

211
$$R^{2} = \left\{ \frac{1}{N} \frac{\sum \left[(y_{0} - \overline{y_{0}}) \overline{(y_{s} - \overline{y_{0}})} \right]}{\sigma y_{0} - \sigma y_{s}} \right\}$$
(2)

where y_o is the observed value, y_s is the simulated value, N is the total number of observations, \bar{y}_o is the average measured value, \bar{y}_s is the average simulated value, σy_0 is the observed data standard deviation and σy_s is the simulated data standard deviation. The values of this index can range from 1 to 0, with one indicating perfect fit.

216 <u>3.5 Identification of drought indices</u>

The main drought drivers are temperature, radiation, wind speed, relative humidity / vapour pressure 217 218 (Seneviratne, 2012). Figure 4 shows how these drought drivers can cause meteorological, agricultural 219 and/or hydrological droughts. A number of drought indices can be used to identify drought events. The 220 most common one is the Standardized Precipitation Index (SPI) (McKee et al., 1993). The SPI index 221 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 222 helps in finding different types of droughts, as precipitation is the key climatic variable upon which soil 223 224 moisture deficit, stream flow and groundwater recharge depend. Therefore, it could easily be used to quantify the severity of both dry and wet events. Another drought index is the standardized precipitation 225 evapotranspiration index (SPEI) which is a multiscale drought index, sensitive to global warming 226 (Vicente-Serrano et al., 2010). This index has been widely applied in different parts of the world 227 228 (Bachmair et al., 2018, Kunz et al., 2018) to the study meteorological and agricultural droughts and to 229 study the impacts of drought severity on vegetation health (Bento et al., 2018). The equation used to 230 calculate SPEI is based on (Thornthwaite, 1948):

$$231 \quad D_i = P_i - PET_i$$

where *Di* is the difference between the precipitation (*P*) and the potential evapotranspiration (*PET*) for a particular month. The aim of applying this index was to measure the water surplus or deficit for the analysed month.

(3)



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

252 Like the SPI, a negative value shows dryness and a positive value shows wetness, relative to the longterm average. This drought index has been applied in a number of studies for example (Tirivarombo et 253 al., 2018) and was used recently to study severity of extreme droughts events, like those of Cape Town, 254 South Africa (Solander and Wilson, 2018). Another key drought index used in this study was the 255 Reconnaissance Drought Index (RDI) which is based on Tsakiris et al. (2007). The standard RDI is 256 calculated using the ratio of precipitation to potential evapotranspiration over a certain period. It is a 257 258 good indicator for describing agricultural, hydrological and meteorological droughts. The 259 Reconnaissance Drought Index (RDI) was calculated as:

260
$$a_0^{(i)} = \frac{\sum_{j=1}^{12} P_{ij}}{\sum_{j=1}^{12} PETOTAE_{ij}}$$
 (4)

261
$$RDI_n^i = \frac{a_0^{(i)}}{\overline{a_0}} - 1$$
 (5)

262
$$RDI_{st\ (k)}^{i} = \frac{y_{k}^{(i)} - \bar{y}_{k}}{\hat{\sigma}yk}$$
(6)

where P_{ij} and PET_{ij} are the precipitation and potential evapotranspiration of the j_{th} month of the i_{th} 263 hydrological year (starting from October), is \bar{a}_0 the arithmetic means of the a_0 calculated for the 264 number of years. In the above equation y_i is the $\ln(a_0^{(i)})$, \overline{y}_k is its arithmetic mean and $\hat{\sigma}yk$ is its 265 266 standard deviation. This drought index has been used in studies in different parts of the world, 267 including Greece (Vangelis et al., 2013) and Iran (2015). This method is widely accepted and applied 268 as it calculates the aggregated deficit between precipitation and the atmospheric evaporation demand. 269 The method is directly linked to the climate conditions of a region and is comparable to the FAO 270 Aridity Index (Tsakiris et al., 2007). In addition to the conventional way of calculating RDI, an 271 adjusted RDI was calculated using the net rainfall (gross rainfall minus rainfall interception losses by 272 canopy cover) and actual evapotranspiration. Further to SPI, SPEI and RDI, two other drought indices 273 were considered: the soil moisture deficit (SMD) and the wetness index (WI) of the root-zone (Ragab 274 and Bromley 2010). WI ranges from zero to 1. The value of 1 means the catchment is at its maximum 275 soil moisture content and 0 means the catchment at its lowest soil moisture content of the simulated 276 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). 277 278 Using a range of drought indices helps in identifying different types of droughts (meteorological, 279 hydrological and agriculture), for example SPI for meteorological, RDI for hydrological and WI and 280 SMD for agricultural drought.

- 281
- 282

4.1 Model calibration/validation for the streamflow

4. Results

The key six model parameters that were used to calibrate the model against the observed flow data were: the percentage of surface runoff flow routed to the stream, the catchment storage/time lag coefficient, an exponent function describing the peak flow, a stream storage/time lag coefficient, a base flow factor and the streambed leakage. The other factors on which model performance is also affected 287 by are the soil hydraulic properties and the land cover parameters. The selected time period for calibration was run using a simple iteration algorithm for optimization in which each of the six stream 288 flow parameters was assigned a range described by a minimum and a maximum value. Each range was 289 divided into a number of steps and the number of total iterations is the product of multiplication of the 290 291 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 292 293 more sensitivity to the streamflow. The model calculates the Nash-Sutcliffe Efficiency value, NSE, In NSE and R^2 for each iteration. The model optimisation process helps in finding a good set of parameters 294 295 that produces a good model efficiency value. Figure 5 (top) shows the model calibration during 2001-296 2012 where model efficiency, measured using the Nash-Sutcliffe Efficiency, was above 87% with less 297 than two percent percentage error. The selected calibration period included a dry and a wet period in 298 order to assess the model performance during both conditions.

299 The model performed well both during the rainy and dry events and responded according to soil 300 hydrology status, i.e. during the soil moisture deficit period, a small rainfall event did not generate 301 enough streamflow and during the heavy rainfall event, when the soil was at saturation during the winter 302 months, the model responded extremely well. The model validation results during the drought period 303 are shown in Figure 5 (bottom) for the 1970s decade, during this period model efficiency measured 304 using the Nash Sutcliffe Efficiency was above 80%, which shows good confidence in the used model 305 efficiency parameters. The results of model prediction efficiency calculated in percentage as Nash Sutcliffe Efficiency, In Nash Sutcliffe Efficiency or R² values are shown in Table 2. The model 306 calibration was carried out over a shorter period and validation over a number of 10-year periods and 307 over the entire study period. The overall model performance over the whole period, 1961-2012 was 308 good, (NSE = 83%). The correlation between the observed and simulated flow of different time periods 309 310 is shown in Figure 6. The figure shows the model's capability to reasonably predict stream flows both 311 during the model calibration and validation periods for both dry and wet periods.

Periods	NSE	ln NSE	R ²	Square root of R ²	Average Modelled flow m ³ s ⁻¹	Average Observed flow m ³ s ⁻¹	% Error
2001-2012*	87.08	73.1	0.87	0.93	4.86	4.73	2.61
1991-2000	87.03	79.1	0.88	0.93	5.10	5.18	-1.60
1981-1990	83.13	76.4	0.84	0.91	5.17	5.13	0.81
1971- 1980	82.21	66.1	0.83	0.91	4.68	4.90	- 4.63
1966-2012	83.06	73.0	0.84	0.91	5.06	5.08	-0.60

Table 2: Don Catchment model performance during the stream flow calibration and validation stages.

314 *calibration period





Figure 5: Don Catchment calibration (2011-2012) and validation (1971-1980) period.



Figure 6: Relationship between the observed the simulated flow during the model calibration and

325 model validation over a decadal time scale and over the entire period.

326 <u>4.2 Identification of historic droughts</u>

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

The *SPI* is the most commonly used drought index to describe the deviation of the precipitation from the average precipitation. The *SPI* index scale values mean: 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). The SPI and SPEI time series are
shown in Figure 7 which also illustrates that the SPEI has shown higher severity for both dry and wet
events, more clearly for the 1970s drought. Both indices picked up all the drought events which took
place in the Don Catchment between 1961 and 2012.





Figure 7. The standardized precipitation index (SPI) and standardised precipitation potential
evapotranspiration index (SPEI) of the Don Catchment from 1961 to 2012.

339 As the evapotranspiration calculation in the model is dependent on climatic data as well as on a number of soil and plant parameters, the SPEI is expected to better represent the severity of the drought. Both 340 341 SPI and SPEI indices crossed over the 'extremely severe' drought level during the most well-known 342 1970s drought which affected most parts of the UK and Europe. The catchment experienced two 343 extreme drought events which took place in the mid-1970s and the mid of 1990s. These drought indices 344 show that the Don Catchment was subjected to drought events which significantly affected Southern 345 England, the Anglian regions, Southern and Eastern England and the Midlands (Parry et al., 2016). The 346 drought termination rate showed a west-east divide in 1995-1998, which was more apparent in the Midlands and Southern and Eastern England. This is evident from both the *SPI* and *SPEI* indices, which 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.

357 4.2.2. Reconnaissance Drought Index (RDI)

358 Figure 8 shows the comparison between the adjusted RDI and the classical RDI. Both picked up all the drought events, which were detected by the SPI. However, the advantage of applying the RDI over SPI 359 360 is that it does not rely on one factor only, i.e. precipitation. The adjusted *RDI* showed slightly different 361 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 7 and 8 show that the extreme 362 drought conditions of 1976, 1996 and 2006 was picked up similarly by both SPI/SPEI and RDI/adjusted 363 364 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 365 366 which took place in 1976, 1989 and 1996. However, the severity of the drought event was slightly higher when applied reconnaissance drought index using the gross rainfall and the potential evaporation in 367 most of the cases. Based on both types of RDIs and SPI/SPEI drought indices, the total percentage of 368 369 wet years were higher than total percentage of dry years.



370

Figure 8: Standard RDI (Reconnaissance drought index) based on potential evapotranspiration and
total rainfall and the adjusted RDI, calculated using net-rainfall and actual evapotranspiration, for the
Don Catchment during the 1962-2012 period.

401 4.2.3. Soil moisture deficit, *SMD* and Soil Wetness Index, *WI* as a drought indicator

In addition to the *SPI/SPEI* and *RDI* drought indices, which are more commonly used to predict meteorological and hydrological droughts, two other drought indices soil moisture deficit and wetness index of the root-zone, which are more appropriate for the agriculture drought, were applied in the study. For agriculture drought, the soil moisture deficit, *SMD* and the wetness index, *WI* of the rootzone are more appropriate (Fig. 9). The wetness index, *WI* represents how relatively wet or dry the catchment is over the period.





⁴¹³ The WI is a scaled soil moisture status that accommodates the spatial variability of soil types, elevation, 414 vegetation cover, etc. across the catchment. The Soil Moisture Deficit, SMD represents the deviation of 415 soil moisture from the soil moisture at field capacity. Here zero means, the catchment's soil moisture is 416 at field capacity level. The deviation gets larger when the soil moisture starts to fall below the field 417 capacity, especially during summer and during drought periods. Examples of both indices are shown in 418 Figure 9 which clearly shows the significant change in soil moisture indicators WI and SMD during the 419 dry summer months, especially during the extreme droughts in 1975 and 1976 and the recovery in 1977 420 for the SMD. In the dry summer months of 1975, the soil moisture deficit exceeded 100 mm and during 421 the 1976 dry summer period, soil moisture deficit was over 140 mm. The figure also shows the severity

422 of the dry spell as a result of the continuation of the dry seasons including the 1975-1976 winter months 423 as the *SMD* did not drop down to zero, whereas in the 1977 winter months, above average winter rainfall 424 brought the *SMD* back to zero after persistent rainfall events during the 1977 winter months. It can also 425 be seen that the *WI* dropped below the winter value of 1.0 to 0.3 during the extreme drought of the 426 summer of 1976 and mirrored the other drought indices including the SPEI/SPI and the RDI.

427

4.3. Future climate change impact on the water resources

428 <u>4.3.1 Changes in streamflow</u>

429 The future climate change scenarios (UKCP09) suggest an increase in temperature under all emission 430 scenarios and a decrease in rainfall, during the summer months (Table 1). To study the impact of climate change on the hydrology of the Don catchment, the future climate projections were derived using two 431 approaches based on UKCP09 outputs: simplified change factors based on joint probability data and 432 the weather generator data. Using the joint probability approach, nine scenarios (three time periods and 433 three emission scenarios) were investigated. The seasonal climate change factors (relative to the 434 baseline data, 1961-1990) of temperature (± change in °C) and rainfall (% change in rainfall) at the 435 most likelihood (central estimate) probability level were input into the DiCaSM model and applied on 436 437 the 1961-1990 baseline climate data (Table 1).

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 rainfall. Similar results were also observed using the weather generator data for the winter months, but the decrease in streamflow was not that significant (Fig. 10). 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 underthree emission scenarios and 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 -2.11% to -5.45%
under low emission scenarios, -1.48% to -4.82% under medium emission scenarios and within -1.39%
to -4.45% 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 (Fig. 10).

452 During the 2020s period, in summer, a significant decrease in streamflow is projected under all emission 453 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 454 455 projected. In 2050s a significant decrease of 12.75 to 17.86 % relative to baseline period is projected using the weather generator data, whereas under the joint probability, a decrease is projected from 27 456 to 29 % with no significant variation under different emission scenarios. During the summer season in 457 458 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 16.05 to 25.5%, depending 459 460 on the emission scenario.

461 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. 462 The latter is more significant for the Don catchment, as river water abstraction is very significant. The 463 streamflow is likely to decrease in the summer season because the soils are not saturated like they are 464 465 during winter and spring, as a results soil moisture deficit is likely to increase. The combined effect of 466 decreasing rainfall with the increasing temperature could result in higher evapotranspiration during 467 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 ^oC and rainfall to decrease by up 468 469 to 34% by the end of the century. The relationship between the precipitation and the hydrological 470 response is much more dependent on antecedent catchment conditions. With reductions in 471 precipitation in autumn and spring (enhanced by higher evaporation), saturated conditions will occur 472 less frequently, and precipitation events will be less likely to generate high runoff flow flows.



473



Figure 10: Percentage change in streamflow relative to the baseline period (1961-1990) over seasonal 476 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). 477

478 In autumn, streamflow is likely to decrease slightly under low and high emission scenarios, and a slight 479 increase under medium emission scenarios in the 2020s. Overall, there is not much variation among the emission scenarios in the 2020s. However, in 2050s, more significantly under medium and high 480 emission scenarios, up to 10% decrease under both joint probability and the weather generator approach 481

was observed. No significant change in rainfall 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 latter is more significant for the Don catchment as there are twenty-three reservoirs within the catchment, which significantly contribute to the water supply systems.

493

4.3.2. Changes in groundwater recharge

494 The analysis using the weather generator and joint probability, under all emission scenarios and for the 495 selected time periods showed that the groundwater recharge would decrease, with some exceptions 496 under weather generator in the 2020s more significantly under high emission scenarios when 497 groundwater recharge increased by 4.32% compared to the baseline period (Fig. 11b). The increase in winter precipitation would be counterbalanced by the higher water losses by the increased 498 499 evapotranspiration (due to increased temperature) which resulted in a small increase in groundwater recharge in comparison to the baseline period in the 2020s. The groundwater recharge projections under 500 501 joint probability suggest that the groundwater recharge is likely to decrease from 3.39 to 11.25% under 502 all emission scenarios during the winter months (December, January, and February). Without exception, 503 groundwater recharge decreased for the three selected time periods, but the decrease will be slightly 504 less under low emission scenarios, compared to the medium and high emission. This is due to a smaller 505 increase in precipitation under low emission scenarios. Considering the change in precipitation under 506 all emission scenarios, the likely increase in the groundwater recharge is lower than expected, due to 507 losses by evapotranspiration that causes a decrease in stream flow and 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.

512 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 513 evapotranspiration, higher soil moisture deficit and lower the groundwater recharge. Using joint 514 probability, the groundwater recharge is likely to decrease by over 60% under medium emission 515 516 scenarios in the 2080s and up to 75% under high emission scenarios. The percentage change in 517 groundwater recharge was not that high when using the weather generator data. The highest decrease 518 in summer groundwater recharge projected for the 2080s is likely to be over 40%, compared to the 519 baseline period. Such a significant decrease in groundwater recharge could be the result of increased 520 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 521 generator under the low emission scenarios; while under medium emission scenarios the decrease in 522 523 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 -524 76% under joint probability and -13% to -40.2% under the weather generator, all changes are in 525 comparison to the baseline period. 526





530 Figure 11: 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.

533 In summer months (June, July, August) enhanced evapotranspiration, together with the decreased precipitation, would result in reduced streamflow and groundwater recharge. Higher evapotranspiration 534 535 combined with lower rainfall during the summer months would result in an increase in soil moisture 536 deficit, which would result in low groundwater recharge during the autumn months under all emission 537 scenarios. However, the severity of the decrease is much higher in the second half of the century under 538 high emission scenarios. Under low emission scenarios the groundwater recharge is likely to decrease 539 by -2.15% to -12%, under medium emission the likely decrease will be within the -5.93% to -14.87% 540 range and under high emission scenarios the projected likely decrease will be within -3.99% to -25.77% 541 range. The higher decrease in groundwater recharge under high emission scenarios would result due to 542 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 543 544 of the water resources (Wade et al., 2013), suggesting that demand-side measures would be required to 545 match the future water supplies availability (Wade et al., 2013).

546 <u>4.3.3. Drought indices</u>

547 To investigate the impact of climate change, a number of drought indices including soil moisture deficit, wetness index of the root-zone, and reconnaissance drought index were considered. As a result of the 548 549 drier and warmer climatic conditions, higher water losses by the evapotranspiration, higher soil moisture deficit and low Wetness index were observed (Fig. 12). To illustrate the impact of decreasing 550 551 rainfall and increasing water losses due to the evapotranspiration, the standardized reconnaissance drought index, RDI was applied. The adjusted RDI was calculated from the net rainfall and actual 552 553 evapotranspiration of the selected time periods: 2020s, 2050s and 2080s for three emission scenarios 554 (Fig 13). The analysis revealed an increase in number of moderate and severe drought events, more 555 importantly under the medium and high emission scenarios. In comparison to the baseline period, the 556 extreme drought events are likely to double in the later part of the century. Not only the extreme dry events but also, severe drought events are also likely to increase in the future. In addition, the frequency 557

of moderately droughts events (RDI -1 to -1.5) is likely to increase in the future, more specifically under



559 medium and high emission scenarios.

Figure 12: 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.



Figure 13: 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 (b).

570 *4.3. Impacts of land use changes on the water resources*

565

To study the impact of land use changes on the water balance a number of possible plausible and
hypothetical land scenarios were examined (Table 3). The number of tested possible and hypothetical
land use changes and the impacts are:

- 1. 100% Grass area replaced by winter barley: Stream flow is likely to increase between 3% and 6%
 while groundwater recharge is likely to increase between 1 and 7%.
- 576
 2. Grass area replaced by oil seed rape: Stream flow is likely to decrease by up to 3% in all seasons apart
 577 from autumn where it is likely to slightly increase by <3%, while groundwater is likely to decrease
 578 between ~ 2% apart from autumn where the recharge is likely to increase by ~2%.
- 579 3. 40% urban expansion replacing grass and arable area: Stream flow is likely to increase by ~1% and
 580 groundwater recharge by ~2%.
- 581 4. Replacing 50% of winter barley by oil seed rape: Stream flow is likely to decrease by ~2% and
 582 groundwater recharge by ~3%
- 583 5. Whole catchment as grass area: Stream flow is likely to decrease by ~2% and 8% and groundwater
 584 recharge by ~5% and 9%.
- 585
 6. Whole catchment as Broad leaf forest area: The stream flow is likely to decrease between 9% and 17%
 586 and groundwater recharge between 10% and 22%.

587 The expansion of the wooded broadleaf forest would be likely to result in an increase of soil moisture588 deficit, more specifically during the spring and summer seasons when plants at maximum growth rate

and take up much of water and transpiration rates are significant. Urban expansion could result in

590 increased streamflow (likely to increase in flood risk) and increase in groundwater recharge.

591 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 3).

594 Sensitivity analysis to see the combined effect of both climate and land use changes revealed that

overall, the effect of the land use changes on the hydrological variables was much less than the effect

of climate change. Considering the possible changes in climatic variables and extreme events in the

597 future, sustainable land use practices could potentially be used to mitigate the impact of climate

- 598 change as the studied catchment is of significance for the water supplies in the Sheffield area
- 599
- 600
- 601

Hydrological variables	Land use types										
	100% Gras replaced b winter bar	s area y ley	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	-2.8	1.14	-1.35	-2.64	-12.4				
	Spring	6.10	-1.2	1.13	-0.50	-5.22	-16.6				
	Summer	3.39	-0.31	0.42	-0.10	-8.35	-14.4				
	Autumn	3.57	2.4	-0.05	-1.14	-3.90	-9.01				
Groundwater	Winter	6.53	-2.01	1.40	-0.47	-7.80	-13.48				
recharge	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				

Table 3: Impact of land use changes in the Don Catchment on stream flow and groundwater recharge.

618 The drought indices used in the study were able to identify all the historical drought events. The adjusted 619 reconnaissance drought index calculated using the actual evapotranspiration and the net rainfall, in 620 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 621 significantly negative deviation from the average precipitation in the 1970s, specifically in 1975-1976 622 623 and 1995-1996. The 1975/1976 drought has been studied in a number of studies including (Perry, 1976, 624 Marsh et al., 2007). During the 1995/1996 drought period, water resources in the Northern England and 625 in the Midlands remained fragile as April to November 1995 rainfall was the second lowest in the 228 years for England and Wales (Marsh and Turton, 1996). All the applied drought indices including 626 627 reconnaissance drought index (RDI), soil moisture deficit, SMD and the Wetness index, WI of the root-628 zone (Figures 7-9) identified these drought events. During these drought events, the RDI, SPI/SPEI 629 were well below -2, which identifies them as 'extreme drought' events (caused by extremely low rainfall and high evapotranspiration). Under current land use practices, a further increase in likelihood of 630 extreme drought events, specifically under medium and high emission scenarios in the middle and the 631 632 latter part of the century (Figure 13) due to an increase in temperature, resulting in higher water losses by evapotranspiration, a decrease in rainfall, an increase in soil moisture deficit consequently would 633 result in more frequent and severe drought in the future. This would further increase the pressure on 634 635 water resources due to changes in land use practices.

The land use type would significantly change in the future, especially due to urbanisation, as urbanisation would further increase pressure on water resources 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. 642 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, 643 reach a critical level, crops will require irrigation, particularly during the summer months. This will 644 require reliable water supplies to secure adequate yield. The WI value, if close to 1, would indicate a 645 646 wet catchment with a possible runoff generation during the next rainfall 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 647 648 by water authorities and water companies. Therefore, the findings from the modelling work could be 649 used to review the future surface water abstraction regulations to be in line with the water resources 650 availability as predicted by the hydrological models and in possible planning of building new water 651 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 652 653 simulate the effects of climate change on the different elements of the hydrological cycle. The future 654 climate change scenarios suggested a significant decrease in groundwater recharge although climate models project an increase in winter rainfall but such increase could be counter balanced by an increase 655 in evapotranspiration and increase of soil moisture deficit during the summer and autumn seasons. The 656 657 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 658 groundwater recharge and streamflow and the increasing possibility of droughts in the future. New 659 investment will be required if water demand is not met through greater water use efficiency or by 660 661 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 662 663 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 664 665 periods would reduce river flows possibly below the minimum environmental flow. Alternatively, 666 restrictions on abstraction to maintain the minimum environmental flows may restrict crop yields and food production. 667

669 The model calibration and validation results showed a good agreement between the observed the 670 simulated flow and overall model efficiency using the NS index was above 82% for the 52 years' study 671 period. In addition to the stream flow, the DiCaSM hydrological model identified all drought events 672 using the drought indices: RDI, SMD, and the WI in the 1970s but also during the 1980s, 1990s and the 673 most recent ones in 2010-2012. The analysis revealed that the standard RDI, based on gross rainfall and 674 potential evapotranspiration, showed slightly higher severity than the adjusted RDI. The latter is based 675 on realistic input of net rainfall (excluding interception losses by vegetation cover) and actual 676 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 677 678 specifically during the summer months, while the severity of the drought events significantly increased 679 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 680 higher as this severity was associated with the increasing temperature and subsequently increasing water 681 losses by evapotranspiration, thus reducing soil moisture availability, surface runoff to streams and 682 683 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-684 poor regions and planning for irrigation water demand under different climatic conditions. The study 685 catchment is of significance as there are twenty-three reservoirs in the catchment boundary, which 686 687 significantly contribute into the water supply of the catchment. The findings of this study can also be useful in revising the "Catchment Abstraction Management Strategies, CAMS" for the Don catchment. 688

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698 Rivers 50km GB' Web Map Service). Land cover data from Centre for Ecology and Hydrology (Land

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- Ecology & Hydrology. Soils data courtesy of Cranfield University (1:250 000 Soilscapes for England
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