Climate Change Impact on Surface and Groundwater Resources: Example from: The UK

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Projected Impacts of Climate Change

<table>
<thead>
<tr>
<th>Global temperature change (relative to pre-industrial)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°C</td>
</tr>
<tr>
<td>1°C</td>
</tr>
<tr>
<td>2°C</td>
</tr>
<tr>
<td>3°C</td>
</tr>
<tr>
<td>4°C</td>
</tr>
<tr>
<td>5°C</td>
</tr>
</tbody>
</table>

**Food**
- 0°C: Falling crop yields in many areas, particularly developing regions
- 1°C: Possible rising yields in some high latitude regions
- 2°C: Falling yields in many developed regions

**Water**
- 0°C: Small mountain glaciers disappear – water supplies threatened in several areas
- 1°C: Significant decreases in water availability in many areas, including Mediterranean and Southern Africa
- 2°C: Sea level rise threatens major cities

**Ecosystems**
- 0°C: Extensive Damage to Coral Reefs
- 1°C: Rising number of species face extinction

**Extreme Weather Events**
- 0°C: Rising intensity of storms, forest fires, droughts, flooding and heat waves
- 1°C: Increasing risk of dangerous feedbacks and abrupt, large-scale shifts in the climate system

Historic droughts in the UK

- 2018
- 2010-12
- 2003-6
- 1995-97
- 1990-92
- 1975-76
- 1959
- 1933-34
- 1921
- 1890-1909
- 1887-88
- 1854-60
- 1798-1808

Major Water Resources Droughts in E & W
(Marsh et al. 2007)

Hydrological data UK

Atlas of Drought in Britain 1975-76

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THE 2006 DROUGHT

Daily Mail 04-01-2006

Drought that has left a key reservoir just one third full

Daily Express 04-01-2006

Unbelievable: Now we face a drought

Snow and sub-zero temperatures are on the way again but what we need is rain

Snow is coming, but pray for rain

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Drought Project - NERC Grant

Table 1. Average annual rainfall (1961-90) in the case study catchments

<table>
<thead>
<tr>
<th>South - North</th>
<th>West –East</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fowey</td>
<td>Fowey</td>
</tr>
<tr>
<td>1436 mm</td>
<td>1436 mm</td>
</tr>
<tr>
<td>Ebwb</td>
<td>Frome</td>
</tr>
<tr>
<td>1456 mm</td>
<td>792 mm</td>
</tr>
<tr>
<td>Don</td>
<td>Pang</td>
</tr>
<tr>
<td>1009 mm</td>
<td>695 mm</td>
</tr>
<tr>
<td>Eden</td>
<td>Bevills Leam</td>
</tr>
<tr>
<td>799 mm</td>
<td>630 mm</td>
</tr>
</tbody>
</table>
Acknowledgement

This Research was funded by the UK Natural Environment Research Council, NERC Grant reference NE/L010292/1 and carried out by the CEH Modelling Team of the DRY Project.

Project leader and contact person: Dr Ragab Ragab, UKCEH, E mail: rag@ceh.ac.uk & ragab@icid.org
Stakeholder Group

• Group involved to date as partners in the project include:
• Canal and River Trust
• Chartered Institution of Building
• Climate Outreach and Information Network
• Emergency Planning Society
• Environment Agency
• Federation of Small Businesses (Regional Office of S&E Yorkshire)
• Natural England
• Natural Resources Wales
• Public Health England
• Scottish Environmental Protection Agency (SEPA)
• Scottish Natural Heritage
• Scottish Water
• The Eden Project
• The Wildlife Trust BCN/ Great Fen Project
• UK Water Industry Research
• Farmers Union
• Allotment society
Modelling of the DRY project catchments

Hydrological modelling of DRY catchment

Model calibration: Year x to Year xx

Model validation: 1961-2012

Historic and future drought indices:
- SPI
- SPEI
- RDI
- SMD
- WI

Future climate change impact:
- Temperature
- Rainfall
- Radiation
- Vapour pressure

UKCP09 Weather Generator

UKCP09 Future climate change scenarios

Future climate change impact:
- Temperature
- Rainfall

Future climate change impact:
- Streamflow
- Groundwater recharge
- Potential & actual evapotranspiration
- Drought risk

Land use change impact:
- Streamflow
- Groundwater recharge
- Potential & actual evapotranspiration
- Drought risk

Realistic and Hypothetical scenarios

Potential & actual evapotranspiration

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DiCaSM Model data requirement

- Rainfall & climate data (Distributed or lumped)
- Land cover % for each grid square
- Soil Series % for each grid square
- Elevation (DTM) for each grid square
- Land cover properties (e.g. plant height, LAI, canopy conductance, sowing-harvest dates)
- Soil Series Properties
- Data on abstraction, irrigation, wastewater discharge to river, water bodies, etc.
Don catchment main land use

(Land Cover Map 25 m raster, GB)

- Catchment area: 373 km²
- 23 reservoirs
Don Land Use

- Grass Area: 46%
- Bog/Marsh Area: 16%
- Leaf Forest Area: 6%
- Heather Area: 6%
- Spring Barley Area: 2%
- Other: 6%
- Coniferous Forest Area: 1%
- Urban Area: 18%
- Water Area: 1%
- Winter Barley Area: 2%
- Other crops: 2%

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Natural Environment Research Council

NERC Science of the Environment
Modelling the Don catchment

Model grid square size is optional, default is 1km by 1km grid square.

Daily time step.

435 grid squares
Modelling the Don catchment
Don catchment calibration: stream flow

Nash-Sutcliffe Efficiency ($NSE = 91.5\%$)
Don validation (1971-1980): stream flow

Nash-Sutcliffe Efficiency ($NSE=82.2\%$)
The Drought Indices

Key drought drivers of meteorological, agricultural and hydrological droughts

(Meteorological drought) SPEI: Standardized precipitation
Evapotranspiration Index, (RDI): Reconnaissance Drought Index

Hydrological and agricultural drought
SMD, WI, streamflow and groundwater level before the extreme drought event.

(Meteorological drought) Standardised Precipitation Index,

SPI: Standardised Precipitation Index.

Critical precipitation Deficit (Critical precipitation Deficit)

Evapotranspiration

Critical Soil Moisture Deficit (SMD), Wetness index at root-zone, WI (Agricultural or Soil-moisture drought)

Low flows and groundwater recharge

Precipitation

Temperature

Radiation (Net or total)

Wind speed

Relative Humidity

Vapour Pressure

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The SPI represents the deviation of precipitation from the long-term average. 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’. SPEI = P - PET
The reconnaissance Drought Index (RDI)

The above drought index was adapted from (Tsakiris et al. 2007) following these equations:

\[
a_0^{(i)} = \frac{\sum_{j=1}^{12} P_{ij}}{\sum_{j=1}^{12} PET_{ij}} \quad (1)
\]

\[
RDI_{n}^{i} = \frac{a_0^{(i)}}{a_0} - 1 \quad (2)
\]

\[
RDI_{st}^{i} (k) = \frac{y_k^{(i)} - \overline{y_k}}{\hat{\sigma}} \quad (3)
\]

Tsakiris et al 2007, Water Resources Management 21: 821-833, Regional Drought Assessment Based on the Reconnaissance Drought Index
Standard RDI is the ratio of sum of rainfall to sum of potential evapotranspiration. Adjusted RDI is the ratio of sum of Net rainfall to the sum of actual evapotranspiration.
SMD is the difference between current soil moisture and the maximum water holding capacity of the soil known as “Field Capacity”.

Don: Soil moisture deficit, SMD (1975-1977)
The WI reduces the spatial variability between different locations (network of Neutron probes or model grid squares. On a certain day WI can be calculated as:

$$ WI = \frac{\sum \left[ (SM_Z) - (SM_Z)_{\text{min}} \right]}{\sum \left[ (SM_Z)_{\text{max}} - (SM_Z)_{\text{min}} \right]} $$
Don: Wetness index of the root-zone, WI

WI is the scaled soil moisture: 1 means, soil water content at maximum value, 0: means the soil water content at its minimum value. The WI accounts for the spatial variability of soil types, elevation, vegetation cover, etc. across the catchment.
Actual Evapotranspiration – Don dry vs average year

Day: 10/08/1976
Act Evap Tran Plus Int Loss
Units: mm

Day: 10/08/2008
Act Evap Tran Plus Int Loss
Units: mm
Wetness Index – Don. Dry vs Average year

Day: 10/08/1976
Wet Index RZ
Units:

Day: 10/08/2008
Wet Index RZ
Units:
• Joint Probability plot: provides % change in future precipitation and ± change in temperature. Seasonal and Monthly changes.

• Weather Generator: Provides daily prediction of precipitation, temperature, sunshine hours and relative humidity.
Scenarios Modelling

Climate change

Simple initial approach: change factors (UKCP09)

- Change in precipitation and temperature (Seasonally)
- UKCP09 joint probability plots
- 1961 – 1990 ‘baseline’ climate

Future time period and three emissions scenarios (High, Medium and low):

- 2020s (2010 – 2039)
- 2050s (2040 – 2069)
- 2080s (2070 – 2099)
Progression of UK Hadley Centre climate models

HadCM3
- 20 levels in ocean
- 1.25° long
- 2.5° lat
- 3.75° long
- 90 km
- 270 km
- 30 km deep

HadGEM/HiGEM
- 38 levels in atmosphere
- 0.83° lat
- 1.25° long
- 90 km
- 0.33°

www.themegallery.com
The UKCP09 provides monthly, seasonal and annual probabilistic change factors at 25 by 25 km grid square resolution for precipitation and temperature.
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 using the ‘qmap’ package in the R statistical tool using the 1961–1990 observation data as a reference period.
Don: future climate change scenarios – Joint Probability

Climate modelling ‘central estimates’ (UKCP09) compared to 1961-1990 ‘baseline’ period (average annual rainfall 1456 mm; average temperature 8.4°C)

- Temperatures increase with emissions scenario and time, particularly in summer and autumn
- Precipitation (rainfall) decreases in summer but increases in winter

**Increased greenhouse gas emissions**
Monthly changes in climate variables

UKCP09 Scenarios applied:
Three, 30 years periods: 2020’s (2010-2039), 2050’s (2040-2069), 2080’s (2070-2099) and three greenhouse gas emission scenarios: high, medium & low
DON: STREAM FLOW USING JOINT PROBABILITY DATA

% change in stream flow relative to the baseline period

<table>
<thead>
<tr>
<th></th>
<th>Low emission</th>
<th>Medium emission</th>
<th>High emission</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020s</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2050s</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>2080s</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Legend:
- Winter
- Spring
- Summer
- Autumn
Don: % change in other hydrological variables using Joint Probability

**Soil moisture deficit**
- Low emission
- Medium emission
- High emission

- 2020s
- 2050s
- 2080s

**Wetness Index**
- 2020s
- 2050s
- 2080s

**Potential evapotranspiration**
- Low emission
- Medium emission
- High emission

- 2020s
- 2050s
- 2080s

**Actual evapotranspiration**
- Low emission
- Medium emission
- High emission

- 2020s
- 2050s
- 2080s
Don: Reconnaissance Drought Index, RDI (using Weather Generator data)

Don drought events severity level comparison

- Extremely dry: RDI ≤ -2
- Severely dry: -1.5 to -1.99
- Moderately dry: -1 to -1.49

<table>
<thead>
<tr>
<th>Period</th>
<th>Low emission</th>
<th>Medium emission</th>
<th>High emission</th>
</tr>
</thead>
<tbody>
<tr>
<td>1961-1990</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>2020s</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>2050s</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>2080s</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Extremely dry RDI ≤ -2, Severely dry RDI -1.5 to -1.99, Moderately dry RDI -1 to -1.49
### Don: Climate Change scenario comparison

<table>
<thead>
<tr>
<th>Hydrological variable</th>
<th>Joint Probability method</th>
<th>Weather generator method</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2020s</td>
<td>2020s</td>
</tr>
<tr>
<td>River flow (Summer)</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>medium</td>
<td>medium</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>2020s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2050s</td>
<td></td>
<td></td>
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<tr>
<td>2080s</td>
<td></td>
<td></td>
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<tr>
<td>Actual evapotranspiration (annual)</td>
<td>2020s</td>
<td>2020s</td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td>Low</td>
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<td></td>
<td>medium</td>
<td>medium</td>
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<td></td>
<td>High</td>
<td>High</td>
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<tr>
<td>2020s</td>
<td>+</td>
<td>+</td>
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<tr>
<td>2050s</td>
<td>++</td>
<td>++</td>
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<tr>
<td>2080s</td>
<td>+++</td>
<td>+++</td>
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<tr>
<td>Soil moisture deficit (summer)</td>
<td>2020s</td>
<td>2020s</td>
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<tr>
<td></td>
<td>Low</td>
<td>Low</td>
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<td>medium</td>
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<td></td>
<td>High</td>
<td>High</td>
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<tr>
<td>2020s</td>
<td>+</td>
<td>+</td>
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<tr>
<td>2050s</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>2080s</td>
<td>+++</td>
<td>+++</td>
</tr>
<tr>
<td>Groundwater recharge (Winter)</td>
<td>2020s</td>
<td>2020s</td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>medium</td>
<td>medium</td>
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<tr>
<td></td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>2020s</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2050s</td>
<td>-</td>
<td>-</td>
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<tr>
<td>2080s</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

- Magnitude of decrease (up to 10%)
- Magnitude of increase (up to 10%)
Climate Change Impact on water resources

- UKCP09 projected more rain in winter and reduced rain in summer.
- However, the increase in winter rain did not produce a similar increase in the stream flow or ground water recharge.
- Modelling results indicated a decrease in summer river flows, groundwater recharge with time and with increasing emission levels.
The Drought Indicators

- The severity and frequency of the drought events will significantly increase with time and the emission level in all catchments.
- All the applied drought indices ($SMD$, $WI$, and $RDI$) identified an increase in the severity of the drought with time and with increasing the emission level.
Impact of Land use change on water resources

• Increasing broadleaf woodland area reduces river flows and groundwater recharge but increases evapotranspiration.

• Increasing heather or grass or crops areas by replacing trees would increase river flows, groundwater recharge and reduce evapotranspiration.

• The impact of climate change was greater than the impact of land use change on water resources. This is not a general conclusion as this dependant on the catchment and % of land use change + type of change (from what to what).
Generalized Likelihood Uncertainty Estimation, GLUE indicated that the model captures above 70% of the observed river flow (Containment ratio CR) i.e. more than 70% observed values are included in the 5%-95% likelihood-weighted quantiles envelope.

This gives confidence in model stream flow prediction.
Don: Model uncertainty plots - stream flow

Containment ratio = 76%

Containment ratio = 85%
Don: Model uncertainty monthly plots - stream flow

Cumulative probability

Volume (\(\text{Mm}^3\text{month}^{-1}\))

- observed
- simulated
Don future supply vs demand under climate change

Water demand

Water supply

Year

% change in water demand and supply

-40
-20
0
20
40
60
2020
2040
2060
2080
2100

water demand: uncontrolled (EA, 2009)
water demand: sustainable behaviour (EA, 2009)
water demand (Yorkshire Water, 2018)
streamflow (Low emission)
streamflow (Medium emission)
streamflow (High emission)
Groundwater (Low emission)
Groundwater (Medium emission)
Groundwater (High emission)
REFERENCES

- ICID publications of the working Group – Climate: [https://icid-ciid.org/inner_page/111](https://icid-ciid.org/inner_page/111) And ICID website: [https://icid-ciid.org/home](https://icid-ciid.org/home)
- Muhammad Afzal, Nikolaos Vavlas and Ragab Ragab.2020. Modelling study to quantify the impact of future climate and land use changes on water resources availability at catchment scale. J. water & Climate Change. Published on line, https://doi.org/10.2166/wcc.2020.117
The gap between future water demand and future water supply

- In all 7 catchments apart from Eden in Scotland, there will be a gap between future water supply and future water demand and that gap is widening over time up to 2099 if water demand is not sustainably managed and controlled.
The uncertainties in climate predictions arise from our imperfect knowledge of:

- Future rates of human-made emissions & how these will change the atmospheric concentrations of greenhouse gases.

- The responses of climate to these changed conditions.
Uncertainty in results could be attributed to:

- Model assumptions, processes descriptions, mechanisms, mathematical formulation & the numerical scheme.

- In nature all processes operate simultaneously while in model they don't (they follow order of execution based on flow chart). If evaporation comes after infiltration, expect recharge, soil moisture to be different from the other way around.

- Linearity exists in model processes but not in nature where nothing is linear.

- Measurements (e.g., stream flow, soil moisture, groundwater levels, etc.) and parameters values (hydraulic conductivity, soil physical and plant parameters, etc.)

- The mismatch between the scale of model application (e.g. 1km² and the scale of observation, e.g. Point Scale).

- Assumptions in climate change scenarios and predictions.
No one trusts a model except the man who wrote it; everyone trusts an observation except the man who made it.

Harlow Shapley

In modelling a complex system:
It is better to be approximately right than precisely wrong!!
Thank You!