The effects of future land-cover change on UK river flows

Simon N. Gosling[1], Elizabeth Lewis[2], Stephen J. Birkinshaw[2], Jamie Tratalos[1], Roy Haines-Young[1]

[1] School of Geography, University of Nottingham

[2] School of Civil Engineering and Geosciences, Newcastle University

Executive Summary

- We use an established physically based distributed hydrological model (SHETRAN) to assess the effects of NEA land-cover change scenarios under on river discharge in 34 UK catchments.
- The experimental design keeps the climate fixed to isolate the effects of land-cover change on river flows. This is the inverse to previous studies that have changed the climate but fixed land-cover.
- The hydrological model generally performs very well, in terms of simulating observed discharge in each catchment (Nash Sutcliffe Efficiencies >= 0.70 for all catchments).
- We consider the effects of land-cover change on three hydrological indicators (average annual discharge, high- and low-flows, and flood hazard).
- Land-cover change has a greater effect on the extremes of discharge (high and low flows and flood hazard) than on average annual discharge. The range across all scenarios and catchments for low flows is -24 % to +27 % compared with -13 % to +6% for average annual discharge.
- Differences between the 34 catchments, both in terms of the magnitude of change between baseline and scenarios, and among the scenarios are particularly important and indicate that, at least with regard to hydrology, the scenarios play out differently in different areas.
- The application of different NEA scenarios can result in different directions of simulated hydrological change, which are generally plausible between scenarios.
- For extreme hydrological events, differences between the 'green' scenarios of Green and Pleasant Land and Nature@Work and the ‘less green’ World Markets, National Security, and Go with the Flow scenarios are more pronounced.

1. Introduction

The aim of this study was to explore the possible effects of a set of land-cover change scenarios on river flows for a number of catchments in the UK. We applied the UK National Ecosystem Assessment (NEA) scenarios, which have been developed to gather insight into how ecosystem services and human well-being might change under a range of plausible futures (Haines-Young et al. 2011). The scenarios explore how emerging driving forces might combine to create different socio-political and economic conditions in the future and describe different ways the world might look in 2060. The scenarios are, as far as possible, evidence-based in terms of the assumptions made about the potential impacts of the various drivers on ecosystem services. When the scenarios were devised, they assumed that future climate change would have two levels of impact (‘high’ and ‘low’), based on UKCP09 (Murphy et al. 2009) data. To this end, each scenario is associated with ‘high’ and ‘low’ storylines.

The “Green and Pleasant Land” (GPL) NEA scenario assumes a preservationist attitude arises because the UK can afford to look after its own backyard without diminishing the ever-increasing standards of living. “Nature@Work” (N@W) is based around the belief that the promotion of ecosystem services through the creation of multifunctional landscapes is essential for maintaining the quality of life in the UK. “Local Stewardship” (LS) is a future where society is more concerned with the immediate surroundings and strives to maintain a sustainable focus on life within that area. The “Go with the Flow” (GwtF) scenario is a projection based on current trends and results in a future UK that is roughly based on today's ideals and targets. “National Security” is a scenario with increases in global energy prices due to climate change, which forces many countries to attempt greater self-sufficiency (and efficiency) in many of their core industries. The sixth scenario, World Markets (WM), assumes high economic growth with a greater focus on removing barriers to trade.

Here, we used a complex numerical hydrological model to simulate the effects of land-cover change, as represented by each of the 12 NEA scenarios (6 “high” and 6 “low”, hereafter referred to as “H” and “L” respectively) on discharge in 34 UK river catchments.

2. Data and methods

2.1. Selection of catchments

We selected 34 catchments across the UK for which the National River Flow Archive (NRFA) (CEH 2013) have data holdings (see **Figure 1** and **Table 1**). Catchment selection was based upon several factors, including:

1) consistency with previous studies – 31 of the 34 catchments were included in previous studies that aimed to attain a representative set of catchments for the UK (Bell et al. 2007; Christierson et al. 2012; Hannaford and Marsh 2006; Hannaford and Marsh 2008) (see **Table 1**);
2) availability of rainfall, temperature and river discharge data over the baseline period (1971-2000);
3) low levels of historical anthropogenic influences such as discharges and abstractions;
4) good hydrological model performance for the catchment (discussed in Section 2.2) (see **Table 1**);
5) catchment elevation, to include a mixture of elevations between upland and lowland catchments (see **Table 1**);
6) the magnitude of the variability in land-cover change under the NEA scenarios – we aimed to include catchments with little land-cover change and also those with high land-cover change under the NEA scenarios (see **Table 1**), which we achieved by calculating for each catchment the variability of land-cover change across all land-cover types and scenarios normalised by the proportion of each land cover type (see **Table 1**); and

7) reasonable geographic spread of catchments across the UK, given the above criteria (see **Figure 1**).

To this end, the 34 catchments are broadly representative of the diversity of catchment characteristics across the UK in terms of size (9 – 1363 km^2), mean daily river flow (0.5 – 23.6 m^3/s) and catchment elevation (39 – 496 m).

Table 1. Catchment characteristics for the 34 study catchments.

ID	Catchment and gauging station	NRFA station No.	Area (km^2)	Gauge elevation (m)	Catchment elevation (m)[a]	Mean flow (m^3/s)	Ref[b]	Land-cover var (%)[e]	NSE
1	Beult at Stile_Bridge	40005	277	12	39	2.06	1,2	911	0.75
2	Coquet at Morwick	22001	570	5	192	8.60	1,3	920	0.70
3	Cothi at Felin_Mynachdy	60002	289	16	229	11.61	3	611	0.76
4	Dane at Rudheath	68003	407	13	94	5.00	1	284	0.78
5	Dearne at Barnsley_Weir	27023	119	43	140	1.37	3	330	0.74
6	Dee at New_Inn	67018	54	164	394	3.12	1,3	347	0.77
7	Derwent at Chatsworth	28043	335	99	326	6.40	1	484	0.80
8	Dove at Izaak_Walton	28046	83	131	315	1.93	1	353	0.77
9	Dyfi at Dyfi_Bridge	64001	471	6	261	23.55	1	785	0.81
10	East_Dart at Bellever	46005	22	309	458	1.25	1	1130	0.70
11	Enborne at Brimpton	39025	148	59	113	1.31	*c*	834	0.74
12	Exe at Thorverton	45001	601	26	235	15.92	2	298	0.79
13	Frome at Ebley_Mill	54027	198	31	182	2.56	2	613	0.70
14	Ithon at Disserth	55016	358	150	318	8.10	3	451	0.86
15	Kent at Sedgwick	73005	209	19	205	9.29	1	544	0.83
16	Leet_Water at Coldstream	21023	113	12	74	1.01	1	773	0.79
17	Leven at Leven_Bridge	25005	196	5	92	1.89	1	518	0.85
18	Monnow at Grosmont	55029	354	58	183	5.94	1	297	0.80
19	Nith at Hall_Bridge	79003	155	173	309	5.79	1	268	0.79
20	Petteril at Harraby_Green	76010	160	20	158	2.18	1	700	0.78
21	Severn at Plynlimon_flume	54022	9	331	496	0.54	3	275	0.77
22	Swale at Crakehill	27071	1363	12	104	20.75	1	561	0.81
23	Taff at Pontypridd	57005	455	45	317	20.67	2	560	0.86
24	Tamar at Gunnislake	47001	917	8	145	22.35	3	526	0.76
25	Tame at Portwood	69027	150	43	238	4.13	3	198	0.75
26	Taw at Umberleigh	50001	826	14	168	18.01	2	869	0.85
27	Tawe at Ynystanglws	59001	227	9.3	259	12.33	2	349	0.80
28	Teise at Stone_Bridge	40009	136	25	91	1.35	*d*	553	0.71
29	Trent at Stoke_on_Trent	28040	53	113	182	0.63	2	562	0.79
30	Uck at Isfield	41006	88	11	67	1.12	*d*	1016	0.71
31	Ure at Kilgram_Bridge	27034	510	88	368	16.08	3	506	0.81
32	Weaver at Ashbrook	68001	622	16	75	5.61	1	295	0.74
33	Wellow_Brook at Wellow	53009	73	44	135	1.29	1,3	935	0.85
34	Wharfe at Flint_Mill_Weir	27002	759	14	258	17.52	2	188	0.79

a. Median catchment altitude is calculated from a 50 m grid across the catchment with a 0.1 m vertical resolution and is derived from the Centre for Ecology & Hydrology's Integrated Hydrological Digital Terrain Model (IHDTM) (CEH 2013).

b. References refer to Hannaford and Marsh (2008) (1), Bell et al. (2007) (2) and Christierson et al. (2012) (3).

c. Added to represent a lowland southern UK catchment.

d. Added to improve inclusion of catchments in the south-east of the UK.

e. Rank (amongst all NRFA catchments) in variability in land-cover change across the NEA scenarios. We calculated the variance in the proportion of total area comprising each land cover class across all scenarios in each catchment, multiplied these values by the mean proportion (across all scenarios) of the land cover in the catchment comprising each land cover class, and then took the mean of these values for each catchment. We then ranked these values against all other NRFA catchments (N = 1,263, Rank 1 = high variability).

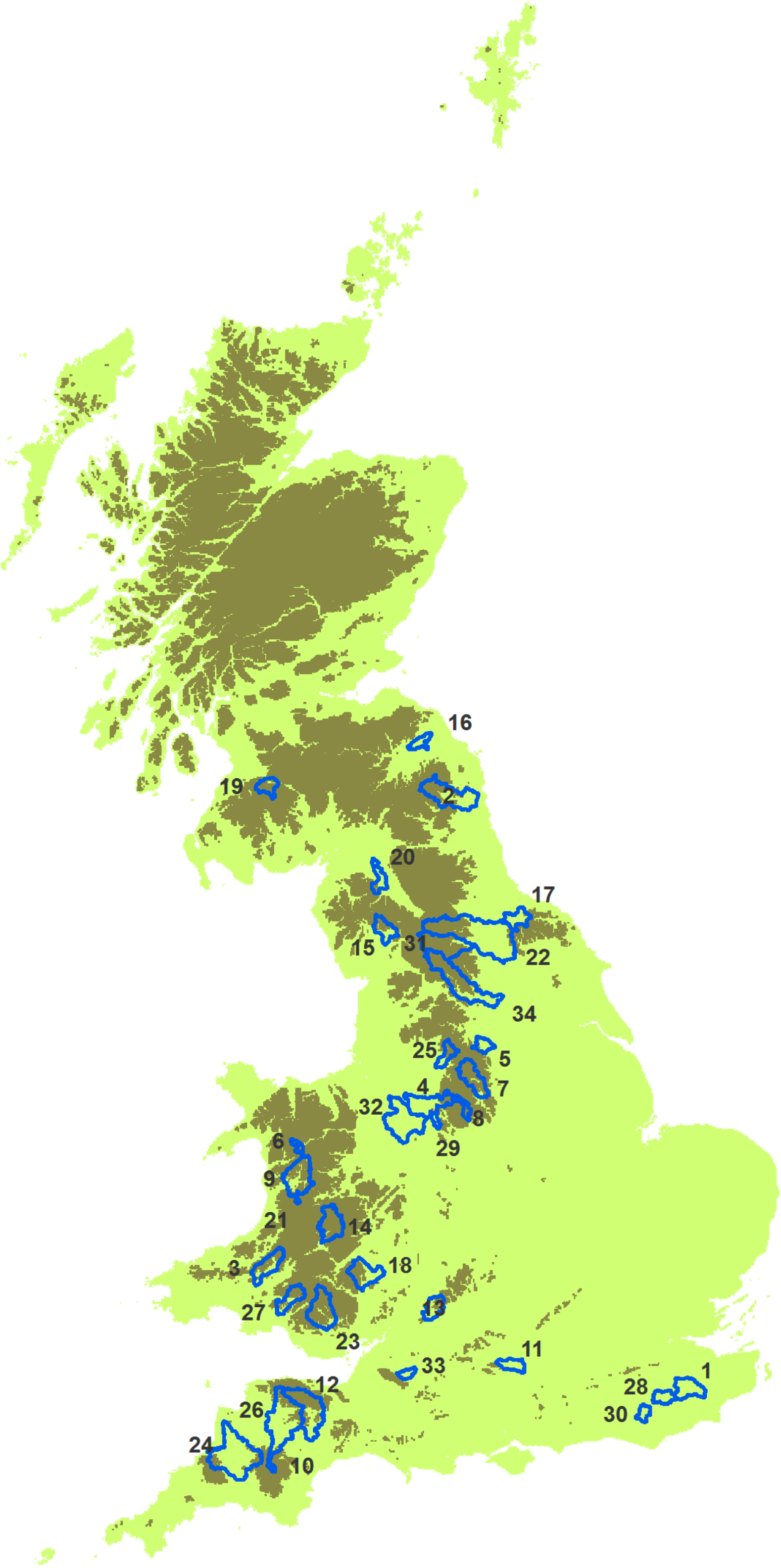

Figure 1. The 34 study catchments. The catchment names are included in Table 1. 1km grid cells where the mean altitude is >= 200 m are dark shaded.

2.2. The hydrological model

There are three main approaches to modelling hydrological systems. These are, in order of increasing model complexity; (1) *empirical-statistical models* that simulate flows based upon statistical equations that describe the relationship between precipitation and river discharge, such as the Antecedent Precipitation Index (*API*) model (Fedora and Beschta 1989). (2) *Conceptual lumped models* that divide the catchment into a small number of "response units" (typically of the order of several km) and estimate discharge from a parameterisation of catchment characteristics for each unit, such as the CATCHMOD model (Cloke et al. 2010). (3) *Distributed physically based models* that divide the catchment into numerous "grid cells" (typically of the order of hundreds of meters) and simulate discharge based upon a numerical representation of the physical processes that take place within the catchment (e.g. interception, infiltration, groundwater flow), such as SHETRAN (Ewen et al. 2000) and MIKE-SHE (Thompson et al. 2013). There is ongoing debate within the hydrological modelling community as to which modelling approach is best (Beven 1989; Carpenter and Georgakakos 2006).

We used a distributed hydrological model called SHETRAN (Ewen et al. 2000; Birkinshaw et al. 2010), which has been used in previous hydrological modelling assessments to assess the effects of land-cover change (Bathurst et al. 2004; Dunn and Mackay 1995). SHETRAN derives from the Système Hydrologique Européen (SHE) model that was developed in the 1980s by a consortium of three European organisations: the Institute of Hydrology (UK), SOGREAH (France) and DHI (Denmark). Its successors are MIKE SHE and SHETRAN. SHETRAN is a three-dimensional (horizontal, vertical and time dimensions) physically based, spatially distributed modelling system for water flow, sediment transport and contaminant migration that is applicable at the scale of the river catchment. It represents the spatial distribution of catchment properties such as topography, channel network, soils and vegetation, rainfall input and hydrological response in the horizontal direction on a grid network and in the vertical direction by a column of horizontal layers at each grid cell (Bathurst et al. 2004). The version of SHETRAN we used here operates with a horizontal grid of 1 km resolution to match the NEA land-cover scenario datasets.

Hydrological models are usually calibrated, which is the process of fine-tuning model parameters until the model produces an acceptable simulation of observed river discharge. Hydrological model calibration is a complex and lengthy process. While calibrating a model for a single-catchment is technically and computationally feasible, calibrating a model several times so that it can be run for many catchments (e.g. 34 in this study) presents a major challenge. To this end, previous UK river flow assessments have run simplified versions of more complex hydrological models, where the model parameters are spatially generalised across the UK (Kay et al. 2006a; Kay et al. 2006b), instead of being individually calibrated for each catchment. We adopted this approach and used a spatially generalised version of SHETRAN which uses the same parameters for each land-cover throughout the UK. Many macro-scale hydrological models operate in the same way, e.g. Mac-PDM.09 (Gosling and Arnell 2011). Model parameters were selected based upon derived relationships to catchment properties across the UK. Spatial generalisation is advantageous to this study because it facilitates the application of a distributed model that includes explicit representation of physical processes that might be affected by land-cover change, across several UK catchments.

While SHETRAN was not calibrated for each of the 34 catchments, it was evaluated to check model performance. We did this by running the model for the period 1992-2002 for 400 catchments and sub-catchments across the UK. This period was chosen because almost all of the catchments had a complete flow record for this period. We then calculated the Nash Sutcliffe Efficiency (NSE; Nash and Sutcliffe (1970)) for each catchment, as:

$$NSE = 1 - \frac{\sum \left(Q_{obs} - Q_{sim} \right)^2}{\sum \left(Q_{obs} - \overline{Q_{obs}} \right)^2}$$

where Q_{obs} is the observed discharge and Q_{sim} is the corresponding simulated value.

A NSE value of 1.00 is a perfect match and a value <=0.00 is no more accurate than predicting the mean value (Jain and Sudheer 2008). Model performance is defined as “very good” for 0.75<NSE<1.00, and “good” for 0.65<NSE<0.75 (Moriasi et al. 2007). To this end a criterion for catchment selection was that the NSE value was >=0.70 for any given catchment. NSE values for the 34 catchments are included in **Table 1**.

The SHETRAN simulations were performed by high throughput computing using Condor, which is a parallel computing jobs management system. This facilitated the running of 442 SHTRAN simulations (12 scenarios x 1 baseline x 34 catchments) in a relatively short timescale. Three runs did not complete and so are excluded from the analysis (Dane at Rudheath for Nature@Work (L), Ithon at Disserth for National Security (L) and Monnow at Grosmont for Go with the Flow (H)).

2.3. Input climate data

SHETRAN requires daily input climate data for precipitation and potential evapotranspiration (PET). Observed values of daily precipitation on a 5x5 km grid were sourced from the latest UK Climate Projections, UKCP09 (UKCP09 2013). UKCP09 is the fifth generation of climate change information for the UK. Precipitation for the 5x5 km grid cells located within the catchment boundaries (**Figure 1**) were extracted and used as a SHETRAN input. PET was calculated following the FAO Penman-Monteith method (Allen et al. 1998) based upon gridded (5x5 km) values of maximum and minimum temperature, sunshine hours, relative humidity and wind speed from UKCP09. For both precipitation and PET, the 5x5 km gridded values were overlain on the SHETRAN 1x1 km grid. While this means that some grid cells with include identical climate data, the application of gridded climate data represents a more advanced treatment of input data when compared with the *lumped* hydrological modelling approach, which tends to calculate a single value of input climate data for the entire catchment, instead of considering the spatial distribution of input climate parameters across a grid.

An overarching aim of this investigation was to explore how catchment hydrology is sensitive to land-cover change. To achieve this, we held the climate constant at present-day conditions when running SHETRAN with the land-cover change scenarios. Thus the climate in 2060 is the same as in present in our simulations. This “fixing-changing” method (Wang et al. 2009) is a technique that involves fixing one factor and changing another factor to assess the effects of the changed factor on model performance and it has been applied previously to assess the impact of land-cover change on catchment hydrology (Tang et al. 2011; Yan et al. 2013). Furthermore, research shows that one of the largest uncertainties in quantifying future river flows arises from the application of climate change scenarios (Arnell and Gosling 2013; Gosling et al. 2011; Haddeland et al. 2011; Hagemann et al. 2013). Within the context of the UK, Kay et al. (2009) found that climate modelling uncertainty is by far the largest source of uncertainty when compared against five other sources of uncertainty, including hydrological model parameter uncertainty. This major source of uncertainty is incorporated into the UKCP09 weather generator climate projections, which are available as ensembles with between 100-10,000 members. Thus the application of climate change scenarios would introduce significant noise that would mask the signal of hydrological change that arises from the land-cover change scenarios.

2.4. River flow indicators

We explored the effects of land-cover change on simulated discharge by investigating three main indicators of river flows that are commonly analysed in hydrological studies; 1) average annual discharge (Christierson et al. 2012); 2) statistics of high and low flows (Arnell and Gosling 2013); and 3) flood hazard (Dankers et al. in press).

For any given scenario and catchment, to determine whether land-cover change was associated with a *significant* change in average annual discharge, a Lilliefors test (Wall 1986) was first conducted to determine whether the simulated discharge was normally distributed. The test indicated that for all 34 catchments, the simulated discharge for baseline and all scenarios was not normally distributed. To this end, a Wilcoxon's Rank Sum test (Wall 1986) was used to test the hypothesis that the means were different between baseline and each scenario, for each of the 34 catchments.

The statistics of high and low flows that we calculated were Q5 and Q95 respectively, where, for instance, Q95 is the daily discharge exceeded 95% of the time and is therefore an indicator of low flows (e.g. drought).

As an indicator of flood hazard we first estimated the 30-year return level of daily river flow (R30) at each catchment for the baseline. R30 is a moderately extreme discharge level that will be exceeded only very infrequently. The probability of the river flow level associated with R30 being exceeded in any given year is 1 in 30, which in any given 10-year period amounts to almost a third. Thus R30 is sometimes referred to as the “1 in 30 years flood”. It is possible to calculate other return levels but we selected R30 because this has been used in previous work (Dankers et al. in press; Dawson et al. 2006; Huang et al. 2013) and because there is a high degree of uncertainty in the estimation of higher return levels (e.g. the 100-year return level) from relatively short datasets.

To calculate R30, the annual maximum daily flow was determined for the baseline 30-year simulation period for each catchment. This resulted in a distribution of 30 annual peak flows for each catchment. A Generalised Extreme Value (GEV) cumulative distribution function (CDF) was fitted separately to these peak flows using a maximum likelihood approach. The GEV distribution combines three probability distributions (Gumbel, Fréchet and Weibull), which are commonly used in extreme value analysis. The GEV distribution is a three-parameter distribution defined by location parameter (μ), scale parameter (σ) and shape parameter (ξ), which has the CDF:

$$F(x;\mu,\sigma,\xi) = \exp\left\{-\left[1+\xi\left(\frac{x-\mu}{\sigma}\right)\right]^{-1/\xi}\right\}$$

for $1+\xi(x-\mu)/\sigma > 0$, where $\mu \in \Re$ is the location parameter, $\sigma > 0$ is the scale parameter and $\xi \in \Re$ is the shape parameter (Coles 2001).

Baseline R30 was calculated by inverting the fitted GEV CDF. To facilitate an analysis of how land-cover change affected flood frequency and probability, the return period of the baseline R30 flood level was calculated for the simulated discharge from each scenario. This was performed by fitting GEV CDFs by maximum likelihood to the annual peak flows of discharge for every scenario, for each catchment. Thus if land-cover change had no effect on flood frequency, the return period of the baseline R30 level would be 1 in 30 in the scenario also. If flood frequency increased due to land-cover change, then the return period of the baseline R30 would be lower in the scenario, e.g. 1 in 20.

3. Results

3.1. Average annual discharge

Table 2 displays the differences in average annual discharge between each NEA scenario and baseline. There are 408 catchment-scenario combinations (34 catchments x 12 scenarios) and annual discharge is significantly different from baseline ($p<0.05$) for 25% (101) of these. Under the National Security (L) scenario almost half the catchments (15) experience a change in discharge that is significantly different from baseline. Thus average annual discharge is most sensitive to the land-cover changes that occur under this scenario. Other scenarios associated with significant differences across several catchments include National Security (H; 11), Nature@Work (12 for H and L) and World Markets (H; 9). Annual discharge is least sensitive to land-cover changes associated with the Local Stewardship scenarios where between 4 and 5 catchments observe significant differences.

The majority of significant ($p<0.05$) catchment-scenario combinations (75) present declines in discharge under the scenarios, ranging between -13 % (Uck at Isfield, Nature@Work (L)) and -0.5 % (Leet Water at Coldstream, Nature@Work (L)). Only 26 of the 101 significant catchment-scenario combinations show increases in discharge and 16 of these are under the World Markets scenarios, where all the significant differences are for increases in discharge. The other 10 significant increases in discharge are simulated exclusively for the Trent at Stoke on Trent.

Figure 2 shows how the direction of change in annual discharge is affected by scenario. Significant *declines* ($p<0.05$) in annual discharge are observed for some catchments in the south of the UK under Nature@Work whereas under World Markets the same catchments experience significant *increases* ($p<0.05$) in discharge. The same pattern is observed across several other catchments across the UK but the differences in discharge are not always statistically significant ($p<0.05$).

Table 2. Differences in average annual discharge between each NEA scenario and baseline (%). Significant differences (*p*<0.05) are shaded according to the relative magnitude of change.

ID	Catchment and gauging station	Gauge	GwtF (H)	GwtF (L)	GPL (H)	GPL (L)	LS (H)	LS (L)	NS (H)	NS (L)	N@W (H)	N@W (L)	WM (H)	WM (L)
1	Beult at Stile_Bridge	**40005**	-1.8	-1.1	-3.6	-6.2	-4.2	-2.8	0.8	1.1	-4.1	-4.4	3.0	3.3
2	Coquet at Morwick	**22001**	0.2	0.1	0.7	0.8	0.0	0.1	-6.2	-5.8	-0.2	-0.3	0.5	0.3
3	Cothi at Felin_Mynachdy	**60002**	-0.1	-0.2	0.1	0.0	0.0	0.0	-1.9	-2.1	-1.4	-1.4	-0.1	-0.1
4	Dane at Rudheath	**68003**	0.8	1.3	0.5	0.4	0.3	0.6	-1.7	-1.1	1.0		2.6	2.7
5	Dearne at Barnsley_Weir	**27023**	-0.7	0.1	-2.9	-2.2	-1.2	-1.5	0.1	-0.1	-4.0	-3.5	4.4	4.6
6	Dee at New_Inn	**67018**	0.2	0.2	0.8	0.7	0.3	0.3	-0.7	-0.7	0.2	0.2	0.1	0.0
7	Derwent at Chatsworth	**28043**	-0.2	-0.2	-0.1	-0.1	-0.1	-0.1	-7.6	-7.0	-0.4	-0.5	0.6	0.5
8	Dove at Izaak_Walton	**28046**	0.0	0.0	-0.1	-0.1	0.0	0.0	-0.7	-0.7	-0.3	-0.4	0.0	0.0
9	Dyfi at Dyfi_Bridge	**64001**	-0.1	-0.1	0.1	0.1	0.0	0.0	-1.3	-1.5	-0.5	-0.5	0.0	0.0
10	East_Dart at Bellever	**46005**	0.0	0.0	0.3	0.6	0.0	0.0	-4.0	-4.2	0.1	-0.3	0.0	0.0
11	Enborne at Brimpton	**39025**	-3.9	-2.8	-3.5	-6.2	-2.5	-2.3	1.0	0.5	-7.4	-7.3	5.8	4.9
12	Exe at Thorverton	**45001**	-0.6	-0.5	-0.3	-0.7	-0.5	-0.5	-1.0	-1.0	-2.2	-2.7	0.1	0.2
13	Frome at Ebley_Mill	**54027**	-2.5	-2.5	-2.8	-6.2	-1.5	-0.8	-1.1	-3.5	-7.5	-7.9	2.4	2.2
14	Ithon at Disserth	**55016**	0.2	0.1	0.3	0.2	0.1	0.1	-0.8		-0.1	-0.1	0.2	0.2
15	Kent at Sedgwick	**73005**	0.0	0.1	0.0	0.0	0.0	0.0	-1.0	-0.6	-0.1	0.0	0.1	0.1
16	Leet_Water at Coldstream	**21023**	-0.6	-0.5	-0.9	-0.9	-0.3	-0.3	-0.2	-0.2	-0.8	-0.5	0.1	-0.2
17	Leven at Leven_Bridge	**25005**	-1.4	-0.9	-1.2	-1.4	-0.9	-0.7	-3.2	-3.0	-3.1	-3.3	0.6	0.6
18	Monnow at Grosmont	**55029**		-0.4	-0.8	-1.1	-0.5	-0.3	-0.7	-3.2	-1.4	-1.9	0.0	-0.2
19	Nith at Hall_Bridge	**79003**	0.2	0.2	0.4	0.3	0.1	0.1	-3.0	-2.6	0.4	0.4	0.1	0.1
20	Petteril at Harraby_Green	**76010**	0.1	0.1	-0.3	-0.3	0.0	0.0	-0.7	-0.8	-1.4	-1.2	0.1	0.2
21	Severn at Plynlimon_flume	**54022**	0.0	0.0	0.0	0.0	0.0	0.0	-0.6	-0.6	0.0	0.0	0.1	0.1
22	Swale at Crakehill	**27071**	-0.1	-0.1	-0.2	-0.2	-0.2	-0.2	-2.5	-2.3	-0.5	-0.4	0.2	0.2
23	Taff at Pontypridd	**57005**	0.2	0.0	0.2	0.1	0.0	0.0	-0.2	-0.8	-0.2	-0.1	0.8	0.8
24	Tamar at Gunnislake	**47001**	-0.2	-0.2	-0.5	-0.4	-0.2	-0.2	-0.4	-0.2	-2.1	-1.7	0.3	0.2
25	Tame at Portwood	**69027**	0.0	0.1	-0.1	0.0	-0.3	-0.2	-3.5	-3.6	-0.1	-0.2	2.7	2.4
26	Taw at Umberleigh	**50001**	-0.7	-0.7	-1.1	-0.7	-0.4	-0.4	-0.8	-0.8	-2.4	-2.6	0.2	0.1
27	Tawe at Ynystanglws	**59001**	-0.1	-0.1	0.0	0.0	0.0	-0.1	-0.5	-0.7	-0.2	-0.2	0.5	0.4
28	Teise at Stone_Bridge	**40009**	-3.1	-3.7	-5.2	-12.1	-3.5	-1.6	-0.3	-2.5	-9.2	-11.7	5.8	0.1
29	Trent at Stoke_on_Trent	**28040**	4.7	3.8	2.9	2.9	2.1	2.6	3.8	3.8	4.7	4.7	5.7	5.7
30	Uck at Isfield	**41006**	-6.8	-5.4	-3.1	-8.3	-5.1	-3.1	-2.4	-4.5	-12.4	-13.0	3.1	0.1
31	Ure at Kilgram_Bridge	**27034**	0.0	0.0	0.1	0.0	0.0	0.0	-3.2	-2.7	-0.1	-0.1	0.0	0.0
32	Weaver at Ashbrook	**68001**	0.6	0.8	0.4	0.2	-0.1	-0.1	0.4	0.8	0.2	0.2	2.0	2.2
33	Wellow_Brook at Wellow	**53009**	0.7	0.8	-0.3	-0.7	-0.1	0.3	1.2	0.2	0.9	0.4	1.9	1.6
34	Wharfe at Flint_Mill_Weir	**27002**	0.0	0.0	-0.1	-0.2	-0.1	-0.1	-4.2	-3.8	-0.5	-0.5	0.4	0.3

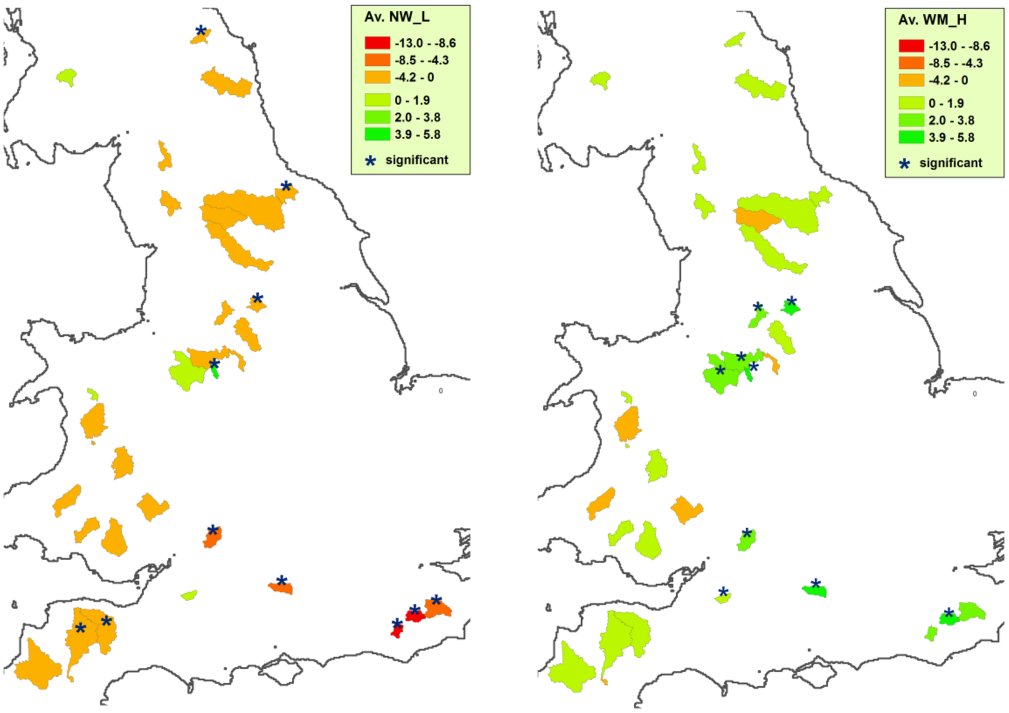

Figure 2. Differences in average annual discharge from baseline (%) under the Nature@Work (L) scenario (left) and World Markets (H) scenario (right). Significant differences (*p*<0.05) are denoted *.

3.2. Q5 and Q95

Differences in Q5 and Q95 under each scenario relative to baseline are displayed in **Table 3** and **Table 4** respectively. The general differences between scenarios reflect the patterns observed for average annual discharge, i.e. the World Markets scenarios are associated with significant increases in Q5 and Q95, whereas the other scenarios are associated with significant declines. However, the magnitude of changes are greater than for average annual discharge, particularly with the indicator of low flows (Q95). The range for change in Q95 across all catchment-scenario combinations is -24 % (Uck at Isfield, Nature@Work (L)) to +27 % (Enborne at Brimpton, World Markets(H)). This compares with the range for average annual discharge of -13 % (Uck at Isfield, Nature@Work (L)) to 6% (Enborne at Brimpton, World Markets(H)) (**Table 2**).

Figure 3 shows the differences in Q5 and Q95 relative to baseline under the Nature@Work and World Markets (L) scenarios. The two scenarios are associated with significant changes in both Q5 and Q95 that may be negative under Nature@Work and positive under World Markets.

Table 3. Differences in the magnitude of Q5 discharge between each NEA scenario and baseline (%). Catchment-scenario combinations where the difference between scenario & baseline average annual discharge is significant (*p*<0.05) are shaded according to the relative magnitude of change in Q5.

ID	Catchment and gauging station	Gauge	GwtF (H)	GwtF (L)	GPL (H)	GPL (L)	LS (H)	LS (L)	NS (H)	NS (L)	N@W (H)	N@W (L)	WM (H)	WM (L)
1	Beult_at_Stile_Bridge	**40005**	-3.4	-2.4	-5.6	-7.7	-5.5	-4.2	1.0	1.3	-5.6	-6.1	2.8	3.1
2	Coquet_at_Morwick	**22001**	0.1	-0.1	0.8	1.1	-0.2	-0.2	-6.6	-6.2	-0.3	-0.9	0.4	0.4
3	Cothi_at_Felin_Mynachdy	**60002**	-0.2	-0.2	0.0	-0.2	-0.2	-0.2	-2.2	-2.4	-1.4	-1.3	-0.1	-0.2
4	Dane_at_Rudheath	**68003**	0.7	0.8	0.5	0.5	0.3	0.5	-1.9	-1.3	0.6		2.2	2.4
5	Dearne_at_Barnsley_Weir	**27023**	-1.2	-0.7	-2.9	-2.8	-1.2	-1.3	0.1	-0.5	-3.8	-3.4	2.8	2.9
6	Dee_at_New_Inn	**67018**	0.1	0.1	0.5	0.5	0.1	0.1	-0.3	-0.3	0.1	0.1	0.0	0.0
7	Derwent_at_Chatsworth	**28043**	0.0	0.1	-0.1	0.0	0.0	0.0	-6.4	-5.6	-0.3	-0.3	0.5	0.5
8	Dove_at_Izaak_Walton	**28046**	0.0	0.0	0.0	0.0	0.0	0.0	-0.5	-0.5	-0.1	-0.1	0.0	0.0
9	Dyfi_at_Dyfi_Bridge	**64001**	-0.1	-0.2	0.1	-0.1	0.1	0.1	-0.8	-0.8	-0.3	-0.3	0.0	-0.1
10	East_Dart_at_Bellever	**46005**	0.0	0.0	0.3	0.5	0.0	0.0	-1.8	-1.9	0.1	-0.2	0.0	0.0
11	Enborne_at_Brimpton	**39025**	-2.9	-1.4	-2.7	-5.7	-1.8	-2.0	1.9	1.4	-7.6	-6.7	7.0	6.7
12	Exe_at_Thorverton	**45001**	-1.1	-1.0	-0.5	-1.1	-0.9	-0.7	-1.5	-1.3	-2.5	-2.9	0.0	0.1
13	Frome_at_Ebley_Mill	**54027**	-2.2	-2.7	-2.1	-5.2	-1.6	-0.9	-1.0	-2.7	-5.4	-5.8	1.3	0.8
14	Ithon_at_Disserth	**55016**	0.1	0.0	0.1	0.1	0.0	0.0	-0.8		0.0	0.0	0.0	0.0
15	Kent_at_Sedgwick	**73005**	0.0	0.0	0.0	0.0	0.0	0.0	-1.0	-0.7	-0.1	-0.1	0.0	0.0
16	Leet_Water_at_Coldstream	**21023**	-0.2	-0.1	-0.4	-0.4	-0.2	-0.2	-0.1	-0.1	-0.4	-0.1	0.1	-0.1
17	Leven_at_Leven_Bridge	**25005**	-1.2	-0.8	-0.9	-1.2	-0.5	-0.5	-2.9	-2.6	-2.6	-2.8	0.6	0.7
18	Monnow_at_Grosmont	**55029**		-0.2	-0.7	-1.0	-0.6	-0.3	-0.3	-2.7	-1.2	-2.2	0.0	0.0
19	Nith_at_Hall_Bridge	**79003**	0.2	0.2	0.3	0.2	0.1	0.1	-2.4	-2.2	0.4	0.4	0.2	0.2
20	Petteril_at_Harraby_Green	**76010**	0.0	0.0	-0.2	-0.2	0.0	0.0	-0.4	-0.8	-1.2	-1.1	0.0	0.0
21	Severn_at_Plynlimon_flume	**54022**	0.0	0.0	0.0	0.0	0.0	0.0	-0.2	-0.2	0.0	0.0	0.0	0.0
22	Swale_at_Crakehill	**27071**	0.0	0.0	-0.1	-0.1	-0.2	-0.1	-2.0	-2.0	-0.2	-0.2	0.2	0.2
23	Taff_at_Pontypridd	**57005**	0.1	0.0	0.2	0.1	0.1	0.1	-0.4	-0.9	-0.1	-0.1	0.3	0.3
24	Tamar_at_Gunnislake	**47001**	-0.6	-0.6	-0.9	-0.8	-0.6	-0.6	-0.8	-0.7	-1.8	-1.6	0.1	0.0
25	Tame_at_Portwood	**69027**	0.0	0.0	0.2	0.0	0.0	0.0	-3.5	-3.3	0.0	0.0	2.3	2.3
26	Taw_at_Umberleigh	**50001**	-0.7	-0.8	-1.3	-0.7	-0.6	-0.6	-1.1	-1.0	-2.7	-2.7	0.0	0.0
27	Tawe_at_Ynystanglws	**59001**	-0.1	0.0	0.1	0.1	0.1	-0.1	-0.3	-0.4	-0.2	-0.1	0.1	0.1
28	Teise_at_Stone_Bridge	**40009**	-2.9	-4.1	-4.7	-14.8	-2.9	-0.6	-0.9	-3.5	-10.8	-12.4	3.7	-1.0
29	Trent_at_Stoke_on_Trent	**28040**	1.9	1.5	1.2	1.2	0.6	0.8	1.5	1.5	1.9	1.9	3.0	3.0
30	Uck_at_Isfield	**41006**	-7.1	-4.7	-3.2	-8.2	-4.8	-1.9	-2.2	-4.5	-13.2	-13.3	3.5	0.4
31	Ure_at_Kilgram_Bridge	**27034**	-0.1	0.0	0.3	0.3	0.1	0.1	-2.0	-1.7	0.1	-0.1	0.0	0.0
32	Weaver_at_Ashbrook	**68001**	0.1	0.6	-0.2	-0.2	-0.3	-0.1	0.3	0.7	-0.4	-0.4	1.5	1.8
33	Wellow_Brook_at_Wellow	**53009**	-0.3	0.2	-1.0	-1.1	-0.3	0.0	0.7	0.2	0.3	-0.5	1.7	0.9
34	Wharfe_at_Flint_Mill_Weir	**27002**	0.0	0.0	-0.1	-0.2	-0.1	0.0	-4.0	-3.8	-0.4	-0.5	0.3	0.3

Table 4. Differences in the magnitude of Q95 discharge between each NEA scenario and baseline (%). Catchment-scenario combinations where the difference between scenario & baseline average annual discharge is significant (*p*<0.05) are shaded according to the relative magnitude of change in Q95.

ID	Catchment and gauging station	Gauge	GwtF (H)	GwtF (L)	GPL (H)	GPL (L)	LS (H)	LS (L)	NS (H)	NS (L)	N@W (H)	N@W (L)	WM (H)	WM (L)
1	Beult_at_Stile_Bridge	**40005**	-5.7	-5.7	-4.2	-14.0	-9.0	-2.8	2.3	2.3	-11.0	-12.7	7.5	7.3
2	Coquet_at_Morwick	**22001**	0.5	0.3	1.6	2.0	-0.1	0.4	-11.7	-10.9	-0.4	-0.6	0.9	0.5
3	Cothi_at_Felin_Mynachdy	**60002**	-0.6	-1.2	0.1	-0.6	-0.4	-0.4	-5.5	-6.2	-5.0	-5.0	-0.1	0.1
4	Dane_at_Rudheath	**68003**	2.1	3.8	0.8	0.8	1.4	1.4	-5.1	-3.3	2.3		6.2	6.5
5	Dearne_at_Barnsley_Weir	**27023**	0.6	2.0	-3.9	-1.4	-1.5	-1.6	0.1	0.6	-6.0	-5.1	11.4	11.3
6	Dee_at_New_Inn	**67018**	1.0	1.0	1.8	1.3	1.4	1.4	-6.6	-6.6	1.0	1.0	0.6	0.0
7	Derwent_at_Chatsworth	**28043**	-1.3	-1.4	-0.3	-0.5	-0.3	-0.4	-16.0	-15.4	-1.0	-1.8	2.0	1.2
8	Dove_at_Izaak_Walton	**28046**	0.0	0.0	-1.0	-1.0	-0.1	-0.1	-2.6	-2.6	-1.6	-1.8	0.0	0.0
9	Dyfi_at_Dyfi_Bridge	**64001**	-0.3	-0.6	0.8	0.4	0.2	0.2	-4.7	-5.4	-1.6	-1.5	0.0	-0.1
10	East_Dart_at_Bellever	**46005**	-0.2	-0.2	0.6	1.6	0.0	0.0	-12.7	-12.8	0.3	-1.2	0.0	0.0
11	Enborne_at_Brimpton	**39025**	-10.7	-10.5	-10.6	-17.7	-7.1	-9.5	7.0	0.8	-18.2	-19.3	26.7	22.1
12	Exe_at_Thorverton	**45001**	-1.3	-1.2	-0.5	-1.6	-1.3	-1.2	-1.4	-1.5	-5.0	-6.1	0.4	0.6
13	Frome_at_Ebley_Mill	**54027**	-4.4	-4.0	-5.4	-12.5	-2.6	-1.1	-2.2	-6.7	-14.6	-15.3	4.8	4.7
14	Ithon_at_Disserth	**55016**	1.3	0.9	1.4	1.6	0.4	0.4	-3.1		0.8	0.4	0.7	0.7
15	Kent_at_Sedgwick	**73005**	-0.5	-0.5	-0.5	-0.5	0.0	0.0	-3.9	-2.5	-0.7	-0.6	0.1	0.1
16	Leet_Water_at_Coldstream	**21023**	-4.0	-4.0	-6.4	-6.4	-2.3	-2.3	-2.1	-2.2	-6.4	-4.0	0.1	-2.2
17	Leven_at_Leven_Bridge	**25005**	-5.4	-2.8	-6.9	-6.0	-3.6	-3.3	-6.4	-7.1	-12.6	-13.3	1.7	1.7
18	Monnow_at_Grosmont	**55029**		-1.6	-1.9	-2.6	-1.5	-1.3	-2.2	-9.4	-3.6	-4.6	-1.1	-1.5
19	Nith_at_Hall_Bridge	**79003**	0.9	0.9	1.1	1.1	0.3	0.3	-8.6	-7.5	1.5	1.4	0.1	0.1
20	Petteril_at_Harraby_Green	**76010**	0.1	0.1	-0.9	-0.9	0.0	0.0	0.1	0.1	-2.5	-2.5	0.1	0.2
21	Severn_at_Plynlimon_flume	**54022**	0.0	0.0	0.0	0.0	0.0	0.0	-3.9	-3.9	0.0	0.0	0.3	0.3
22	Swale_at_Crakehill	**27071**	-0.4	-0.4	-0.5	-0.6	-0.4	-0.4	-8.0	-7.5	-1.3	-1.3	0.8	0.5
23	Taff_at_Pontypridd	**57005**	0.7	0.0	0.8	0.3	0.3	0.2	0.0	-2.1	-0.3	-0.3	3.0	2.2
24	Tamar_at_Gunnislake	**47001**	-0.9	-1.0	-1.6	-0.9	-0.6	-0.6	-0.8	-0.7	-5.8	-4.5	0.7	0.6
25	Tame_at_Portwood	**69027**	0.0	0.0	0.0	0.0	-1.2	-0.7	-10.4	-11.1	-0.3	-0.6	6.8	6.2
26	Taw_at_Umberleigh	**50001**	-2.0	-1.8	-4.0	-2.5	-1.0	-1.1	-1.8	-1.8	-6.8	-6.9	0.5	0.4
27	Tawe_at_Ynystanglws	**59001**	-0.7	-0.7	-0.4	-0.5	-0.2	-0.4	-1.2	-1.7	-0.7	-0.8	1.8	1.7
28	Teise_at_Stone_Bridge	**40009**	-3.2	-7.8	-9.0	-19.3	-7.3	-2.7	4.9	-2.7	-11.1	-19.8	8.3	-0.4
29	Trent_at_Stoke_on_Trent	**28040**	13.4	8.5	5.2	5.2	3.7	4.7	8.5	8.5	13.4	13.4	17.7	17.7
30	Uck_at_Isfield	**41006**	-17.5	-13.8	-9.7	-18.8	-16.4	-8.8	-6.2	-14.5	-24.2	-24.3	-2.2	-6.1
31	Ure_at_Kilgram_Bridge	**27034**	0.0	0.0	0.2	0.1	0.1	0.1	-6.5	-5.5	-0.1	-0.2	0.1	0.1
32	Weaver_at_Ashbrook	**68001**	3.4	3.2	2.8	2.6	0.3	0.4	1.2	1.5	1.0	1.1	7.2	7.3
33	Wellow_Brook_at_Wellow	**53009**	1.2	1.2	-1.1	-1.9	-1.1	0.7	2.0	-0.6	1.3	0.0	3.2	3.0
34	Wharfe_at_Flint_Mill_Weir	**27002**	-0.4	-0.3	-0.6	-0.9	-0.8	-0.4	-9.3	-8.5	-2.1	-2.0	1.0	0.5

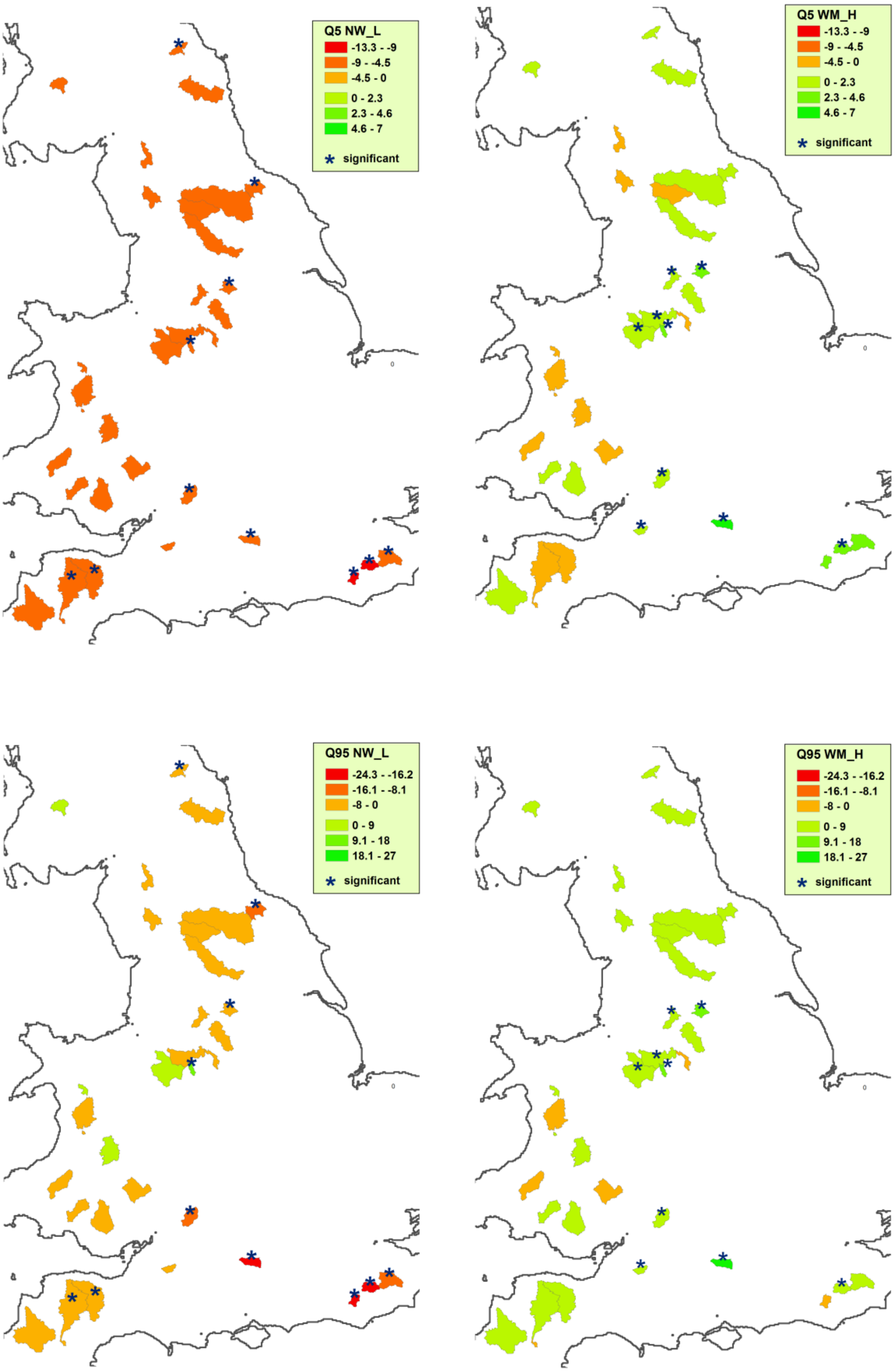

Figure 3. Differences from baseline (%) in magnitude of Q5 (top panels) and Q95 (bottom panels) discharge under the Nature@Work (L) scenario (left panels) and World Markets (H) scenario (right panels). Catchments where the difference between scenario and baseline average annual discharge is significant (*p*<0.05) are denoted *.

3.3. Flood hazard

The return period of the baseline R30 flood level was calculated for the simulated daily discharge from each scenario (see Section 2.4). The differences (in return period years) between baseline and scenario are displayed in **Table 5**. *Negative* values indicate an *increase* in flood hazard in the scenario relative to baseline; e.g. -10 indicates that the baseline 30-year return level is only equivalent to a 20-year return level in the scenario. *Positive* values indicate a *decrease* in flood hazard in the scenario relative to baseline; e.g. +10 indicates that the baseline 30-year return level is equivalent to a 40-year return level in the scenario. If the flood hazard is *unchanged* in the scenario relative to baseline, then the value in **Table 5** will be zero. A significant change in flood hazard was identified as when the probability of the baseline R30 level being exceeded in the scenario in any given year is <= 1 in 25 (increase in flood hazard) or >= 1 in 35 (decrease in flood hazard).

There are significant changes in the return period of the baseline R30 flood level for 39 of the 408 catchment-scenario combinations. While this is a smaller number of catchments than the number that experience significant changes in average annual discharge, the two hydrological indicators are not comparable because “significance” was computed differently for each indicator.

Flood hazard increases significantly for only 4 catchment-scenario combinations. These are under the World Markets and National Security scenarios for the Enborne at Brimpton. The return period of the R30 flood level decreases from 1 in 30 years to around 1 in 15 (World Markets) and 1 in 22 (National Security) years. Flood hazard declines significantly across 35 catchment-scenario combinations. Where the declines are significant, the return period of the baseline R30 flood level ranges between 1 in 35 (Beult at Stile Bridge, Green and Pleasant Land (H)) to 1 in 66 (Derwent at Chatsworth, National Security (H)).

Different scenarios can result in large differences in the direction of change in flood hazard. **Figure 4** shows the change in the return period of the baseline R30 flood level under the Nature@Work (L) and World Markets (H) scenarios. Several catchments show increases in flood hazard under World Markets but decreases in flood hazard under Nature@Work (although many of the flood hazard changes are small and not significant). The most striking inter-scenario difference in **Figure 4** is observed for Enborne at Brimpton, where the R30 flood hazard increases from 1 in 30 to 1 in 15 years under World Markets but decreases to 1 in 45 years under Nature@Work.

Table 5. The effect of land-cover change on the return period (years) of the R30 flood level under each scenario, e.g. +10 indicates that the baseline 30-year return level is equivalent to a 40-year return level in the scenario (indicative of a decrease in flood hazard). Catchments where the return period increases or decreases by more than 5 years are shaded according to the relative magnitude of change.

ID	Catchment and gauging station	Gauge	GwtF (H)	GwtF (L)	GPL (H)	GPL (L)	LS (H)	LS (L)	NS (H)	NS (L)	N@W (H)	N@W (L)	WM (H)	WM (L)
1	Beult_at_Stile_Bridge	**40005**	6.0	4.0	5.1	12.1	7.5	3.8	-0.6	-1.0	10.3	10.4	-3.0	-3.5
2	Coquet_at_Morwick	**22001**	-0.4	-0.2	-0.6	-0.6	0.1	-0.3	9.0	8.8	0.5	0.5	-0.3	-0.3
3	Cothi_at_Felin_Mynachdy	**60002**	0.0	0.4	-0.5	-0.6	-0.3	-0.4	3.8	4.9	3.8	3.1	0.3	0.2
4	Dane_at_Rudheath	**68003**	-0.3	-0.5	-0.3	-0.1	0.0	0.1	4.0	3.4	-0.4		-1.0	-1.1
5	Dearne_at_Barnsley_Weir	**27023**	4.7	1.3	5.4	4.7	1.9	2.5	0.0	-0.2	18.7	14.3	-4.0	-4.0
6	Dee_at_New_Inn	**67018**	0.5	0.5	1.7	1.2	1.0	1.0	-1.3	-1.3	0.5	0.5	0.6	0.0
7	Derwent_at_Chatsworth	**28043**	0.1	0.2	0.1	0.1	-0.2	0.0	36.4	30.2	0.8	0.9	-0.5	-0.5
8	Dove_at_Izaak_Walton	**28046**	0.0	0.0	-1.2	-1.2	0.0	0.0	0.2	0.2	-1.2	0.0	0.0	0.0
9	Dyfi_at_Dyfi_Bridge	**64001**	-0.3	-0.5	-0.2	-0.4	-0.1	-0.1	-0.6	-0.4	-0.9	-1.0	0.0	-0.1
10	East_Dart_at_Bellever	**46005**	0.0	0.0	-2.4	-2.6	0.0	0.0	4.2	4.3	-0.1	2.0	0.0	0.0
11	Enborne_at_Brimpton	**39025**	2.5	-0.4	2.1	23.5	-1.3	2.2	-9.2	-7.5	14.7	15.4	-15.9	-14.9
12	Exe_at_Thorverton	**45001**	1.8	1.3	1.1	1.3	1.1	0.9	2.0	2.5	3.2	3.5	0.4	0.5
13	Frome_at_Ebley_Mill	**54027**	2.2	2.7	1.9	6.3	1.7	1.1	0.7	2.3	6.0	5.9	-0.2	-0.2
14	Ithon_at_Disserth	**55016**	-1.3	-0.6	-1.3	-0.6	-0.3	-0.3	2.3		-0.6	-0.2	0.0	0.0
15	Kent_at_Sedgwick	**73005**	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0
16	Leet_Water_at_Coldstream	**21023**	0.1	0.1	0.8	0.8	0.1	0.1	0.1	0.1	0.8	0.1	0.0	0.1
17	Leven_at_Leven_Bridge	**25005**	0.5	0.4	0.7	0.9	0.9	0.9	3.2	3.0	1.0	1.0	-0.1	-0.1
18	Monnow_at_Grosmont	**55029**		0.3	1.7	2.5	0.9	0.2	0.4	5.0	3.4	3.6	-0.2	-0.1
19	Nith_at_Hall_Bridge	**79003**	-0.5	-0.5	-0.2	-0.2	-0.4	-0.4	4.0	3.9	-0.3	-0.3	-0.1	-0.1
20	Petteril_at_Harraby_Green	**76010**	0.0	0.0	0.3	0.3	0.0	0.0	0.2	0.2	0.4	0.3	0.0	0.0
21	Severn_at_Plynlimon_flume	**54022**	0.0	0.0	0.0	0.0	0.0	0.0	-0.8	-0.8	0.0	0.0	0.1	0.1
22	Swale_at_Crakehill	**27071**	0.5	0.3	0.7	0.9	0.5	0.4	5.5	5.4	1.3	1.1	-0.4	-0.2
23	Taff_at_Pontypridd	**57005**	-0.3	0.1	-0.6	-0.2	0.0	0.1	0.7	3.6	0.6	0.5	-1.3	-1.1
24	Tamar_at_Gunnislake	**47001**	0.0	-0.1	0.2	0.1	0.0	0.0	0.0	0.0	1.0	0.9	-0.1	-0.1
25	Tame_at_Portwood	**69027**	0.0	-0.1	-0.6	0.0	0.0	-0.1	12.0	11.0	-0.2	0.0	-1.6	-1.2
26	Taw_at_Umberleigh	**50001**	0.4	0.5	1.8	0.6	0.5	0.5	0.8	0.8	2.1	2.6	0.2	0.0
27	Tawe_at_Ynystanglws	**59001**	0.0	0.0	0.0	0.0	0.0	0.0	0.2	-0.2	0.1	0.0	-0.2	-0.2
28	Teise_at_Stone_Bridge	**40009**	5.7	3.7	3.9	12.7	5.8	1.6	1.4	3.5	15.1	17.3	-0.7	2.2
29	Trent_at_Stoke_on_Trent	**28040**	-3.3	-1.4	-1.0	-1.0	0.0	-0.4	-1.4	-1.5	-3.3	-3.3	-4.9	-4.9
30	Uck_at_Isfield	**41006**	7.3	3.8	0.1	6.9	5.2	3.0	3.0	3.7	11.2	11.4	1.3	1.4
31	Ure_at_Kilgram_Bridge	**27034**	0.0	0.0	-0.2	-0.2	0.0	0.0	3.5	3.1	0.0	0.1	-0.1	-0.1
32	Weaver_at_Ashbrook	**68001**	-0.5	-0.5	-0.4	-0.2	-0.1	-0.1	-0.2	-0.4	0.3	0.2	-1.5	-1.7
33	Wellow_Brook_at_Wellow	**53009**	0.9	0.5	3.0	3.0	1.6	0.8	-0.8	1.1	0.4	1.9	-2.2	-1.0
34	Wharfe_at_Flint_Mill_Weir	**27002**	0.2	0.2	0.3	0.5	0.1	0.1	8.9	7.7	0.9	0.9	-0.2	-0.2

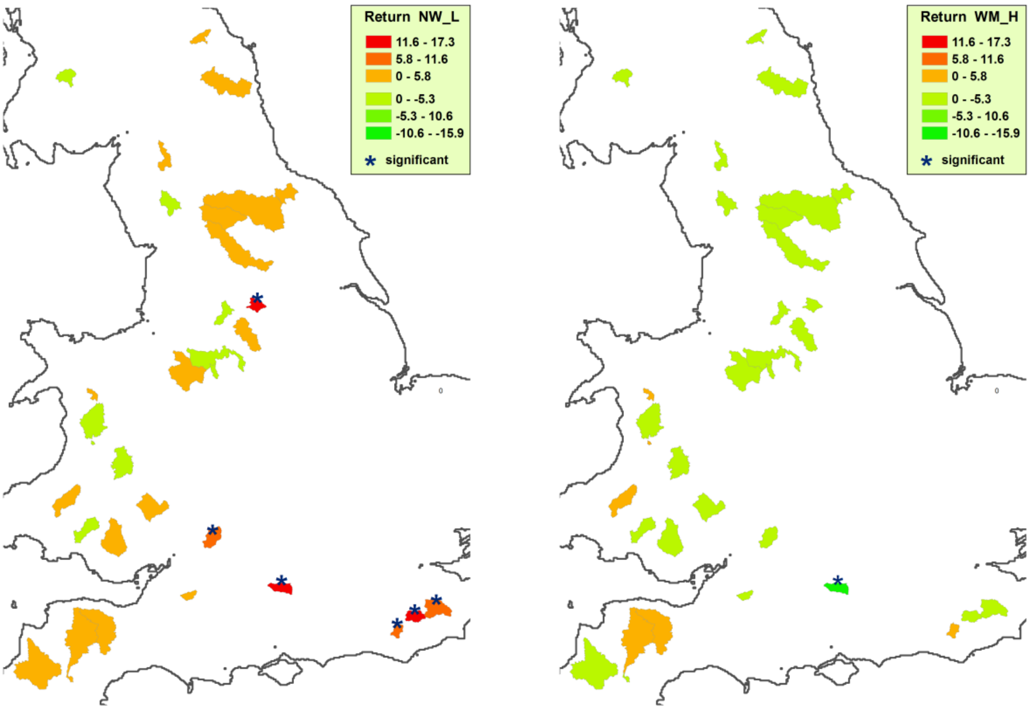

Figure 4. **The effect of land-cover change on the return period (years) of the baseline R30 flood level under the Nature@Work (L) scenario (left panel) and World Markets (H) scenario (right panel), e.g. +10 indicates that the baseline 30-year return level is equivalent to a 40-year return level in the scenario (indicative of a decrease in flood hazard). Catchments where the return period increases or decreases by more than 5 years are denoted *.**

4. Discussion and Conclusions

A number of general conclusions can be drawn from the analysis.

1) The application of different NEA scenarios can result in different signs of simulated hydrological change. We demonstrated this with particular reference to maps for the Nature@Work and World Markets scenarios for all river flow indicators. Importantly, for some catchments, both scenarios were associated with *significant* changes that were different in sign. The direction of change is generally plausible between scenarios - for example, Nature@Work and Green and Pleasant Land are scenarios where ecosystem services are generally protected better than under World Markets and National Security. The former two scenarios are associated with declines in both flood hazard and extreme high flows (Q5) relative to baseline. The baseline is somewhere between these two sets of scenarios in its environmental performance and performs correspondingly under the SHETRAN simulations. The high sensitivity to land-cover change exhibited by some catchments emphasises the importance of carefully considering the implications of land-cover changes that might be associated with different land management options.

2) The observation that differences between the 'green' scenarios of Green and Pleasant Land and Nature@Work and the ‘less green’ World Markets, National Security, and Go with the Flow scenarios are more pronounced for extreme hydrological events (e.g. Q5) than average annual discharge is particularly interesting, and has implications for flood and drought management. This is particularly apparent for the Enborne at Brimpton, which is a catchment underlain by impervious clays and so where surface and near-surface hydrological pathways are relatively important (Wade et al. 2012).

3) Each catchment responds differently to the same NEA scenario. For some hydrological indicators such as Q95 this is particularly evident. To this end, it is not possible to infer from one catchment, what the same scenario might mean for a different catchment elsewhere. The variability in response across catchments is in large part due to the spatial variability in land-cover associated with the scenarios. Hydrological response at the catchment scale is a function of many factors including climate, topography, soil types and vegetation cover and so to some extent, the hydrological response verifies the plausibility of the NEA scenarios.

4) The relatively good fit between the simulated and observed discharge data (estimated by NSE) indicates that the land cover data can be used to calculate plausible representations of discharge under different land-cover scenarios. The 1 km resolution of the UK NEA scenarios was highly appropriate for this hydrological modelling exercise and represented a higher input spatial resolution than the best available climate data (5 km).

5) Although for some catchments changes in discharge were relatively small among the scenarios and between the scenarios and baseline, this is what might be expected, a priori. This is because land-cover in most areas does not change radically between 2000 and the scenarios, and it is not radically different between the scenarios. It should also be noted that discharge is affected by many other factors that we kept constant across the baseline and scenario simulations, including topography and climate.

6) An important finding is that the changes in the magnitude of low flows are almost always greater than the changes in high flows. Increasing the discharge during periods of low flow, as well as the average flow, may be thought more important in catchments where drought is more of an issue than flooding, such as in catchments which supply major reservoirs. Specifically, there are differences between scenarios such as Green and Pleasant Land, which we have found likely to be associated with lower levels of high flows, higher risk of low flows and declines in average flows, and World Markets, where the opposite is the case. These differences need to be considered on a catchment by catchment basis, taking into account the main users of water within the catchment, current and projected water management strategies, and the role of water in general. To this end, our study, limited to 34 UK catchments, suggests that whether one scenario is “preferable” or not varies by location, with the majority of catchments little affected by changes in land cover under the scenarios, but with worsening of flooding or drought in some areas. To some extent, this means that within the context of water resources management, qualification of “good land management” is catchment-specific. I.e. one type of land-management practice might benefit water resources for one catchment but not for another. Phase One of the NEA

> (Maltby and Ormerod 2011) noted the ”slowing-down” of water as a key-need in future water resource management – our results indicate that under the scenarios we considered the magnitude to which water can be “slowed-down” by land-cover change is catchment-specific. This conclusion is largely supportive of the UK Government’s “Catchment Based Approach” (Defra 2013) to river management, which aims to meet the Government’s targets under the European Water Framework Directive, by encouraging greater local participation in decision-making at the catchment scale.

It should be acknowledged that we did not consider the uncertainty that might arise from alternative but plausible hydrological model parameter combinations. While the model was evaluated for each catchment by calculating NSE values, the simulated results would be different if different parameter combinations were applied to the model. Moreover, if spatial generalisation was not adopted and individual catchment parameters were calibrated instead, then the results would be different. However, individual catchment calibration would require substantial resources many times greater than those required under spatial generalisation. It is for this reason that other studies have adopted the spatial generalisation approach for simulating river discharge across the UK (Kay et al. 2006a; Kay et al. 2006b). We also note that an alternative approach to numerical modelling of environmental change under different scenarios is expert elicitation (Kriegler et al. 2009).

We acknowledge that the “fixing-changing” method (Wang et al. 2009) is unrealistic but this type of controlled experiment was favoured in order to isolate the effects of land-cover change on river flows. The majority of studies that have investigated how river discharge might change under various “future” scenarios have tended to apply climate change scenarios but keep land-cover and other factors that can affect the climate-runoff relationship constant at present-day distributions/values (Kingston et al. 2011; Christierson et al. 2012; Gosling et al. 2011; Xu et al. 2011; Hughes et al. 2011; Thompson et al. 2013). The most recent of such studies with a UK context is described by Christierson et al. (2012). In this study the authors applied the UKCP09 climate change scenarios but assumed that in the future there will be no changes in land-cover, water use and water management. This approach allowed Christierson et al. (2012) to isolate and quantify the effect of climate change on catchment hydrology, independent of other factors. Our approach is similar, in that we keep all other factors constant (including the climate) except the land-cover, and this is a novelty of our research. The net effect of our application of the “fixing-changing” approach means that our estimates of the effects of land-cover change on discharge should not to be taken too literally as actual impacts but rather as an indication of the relative effects of different land-cover scenarios. River flows across the UK in 2060 will be affected by factors other than land-cover change. To this end, in line with Christierson et al. (2012), we provide no information in our assessment about the actual magnitude of flows projected under the land-cover scenarios – all estimates are presented in relative terms such as percentage changes in discharge or change in return period years (instead of presenting actual flood levels).

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