Modelling the impacts of climate change on upland catchments in southwest Scotland using MIKE SHE and the UKCP09 probabilistic projections

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ABSTRACT

Hydrological models of three upland sub-catchments of Loch Dee, southwest Scotland, are calibrated and validated against observed discharge. Perturbed precipitation and potential evapotranspiration (PET) are generated from UKCIP09 projections for Low, Medium and High emissions scenarios for the 2050s and 2080s for probability levels between 10 and 90%. Annual and monthly PET increases for all scenarios. Central estimates of increases in annual PET are up to 10.7% (2050s) and 15.8% (2080s). Precipitation becomes more seasonal, increasing in winter and decreasing in summer for all but the extreme probability levels. Annual precipitation declines for the lowest (up to 30%) probability levels and increases thereafter (up to 5.8% for the 2050s and 10.3% for the 2080s at the 50% level). Changes in discharge are driven by those for precipitation. Although there is uncertainty in changes in annual discharge, most scenarios increase winter discharges (2050s: up to 24.2%; 2080s: up to 50.9% at the 50% level) and reduce summer flows (2050s: up to 34.2%, 2080s: up to 48.7% at the 50% level). Potential impacts include enhanced winter flooding and lower summer reservoir levels with implications for hydropower. Greater seasonality in discharge may impact fisheries and ongoing recovery from surface water acidification.

Key words | climate change, distributed hydrological model, Loch Dee, MIKE SHE, UKCP09, uplands

INTRODUCTION

Climate change during the 21st century is likely to have important consequences for the availability of freshwater resources (Kundzewicz et al. 2007; Bates et al. 2008). Projections for future UK climate, such as those produced by the UK Climate Impacts Programme (e.g. Hulme et al. 2002; Murphy et al. 2009), are characterised by hotter drier summers, warmer wetter winters and more frequent intense precipitation events. The largest changes are predicted in southern and eastern parts of England whilst northern Scotland is, in contrast, projected to experience the smallest changes. Changes in the amount and seasonal distribution of precipitation, coupled with enhanced evapotranspiration, will impact river flows as well as groundwater recharge and soil moisture availability. Projected climate changes have, for example, been used to simulate changes in discharge in a number of UK rivers using a range of hydrological models (e.g. Arnell & Reynard 1996; Limbrick et al. 2000; Arnell 2005; Johnson et al. 2009) and results show increased seasonality of flows. Romanowicz et al. (2006) suggested that by the 2020s, winter flows for a range of UK catchments will be between 4 and 9% higher, whilst summer flows will decline by 1 to 32% (mean 11%). These changes will have implications for water supply (e.g. Fowler et al. 2007) and flood management (e.g. Reynard et al. 2001) as well as impacting water quality (e.g. Whitehead et al. 2009a, b) and riverine ecology (e.g. Johnson et al. 2009).

The UK’s uplands are sensitive environments, which provide a range of ecosystems goods and services (Orr et al. 2008; Reed et al. 2009). Hydrologically they are significant as some of the wettest parts of the UK. An
estimated 70% of the UK’s drinking water is derived from upland catchments (Orr et al. 2008) whilst in Scotland, where 75% of the land surface lies above 300 m, most public and industrial water supplies rely on the uplands (Soulsby et al. 2002). Generation of hydropower is concentrated in these areas of high rainfall and steep gradients and Reed et al. (2009) pointed to their high, but largely unrealised, potential for micro-generation. These goods and services are sensitive to climate change. For example, results of a study by Fowler & Kilsby (2007), which employed regional climate model outputs as inputs to hydrological models, suggested that for the IPCC SRES (Special Report on Emission Scenarios) A2 scenario (IPCC 2000), peak winter flows from high elevation catchments in northwest England may increase by as much as 25% by 2070–2100 compared with a 1961–1990 baseline. Such changes are likely to have implications for downstream flooding. Upland reservoirs, especially small single season ones, will conversely be impacted by summer reductions in mean flow, with declines of 40–80% suggested for the upland northwest. Reductions in the potential, at least at certain times of the year, for hydropower generation might come at a time when the UK is seeking to expand the use of renewable sources, including micro-generation, thereby impacting potential climate change mitigation strategies.

Changes in the flow regimes of upland rivers will have implications for aquatic biota some of which are economically important. For example, populations of salmonids such as Atlantic salmon (Salmo salar) and brown trout (Salmo trutta) may be impacted by changes in both low and high flows (e.g. Gilvear et al. 2002; Walsh & Kilsby 2007). These ecological impacts may be compounded by hydrochemical and geomorphological factors driven by climate induced hydrological changes (Orr et al. 2008). For example, increased precipitation intensity and resulting higher magnitude floods could increase erosion and channel change (e.g. Chiverrell et al. 2007). It has been hypothesised that the recovery of acidified catchments following reductions in sulphur and nitrogen emissions from fossil fuel combustion may be delayed as a result changing hydrological pathways brought about by higher winter rainfall (Evans et al. 2008) whilst it is possible that the increases in dissolved organic carbon (DOC) resulting in the discoloration of water from upland catchments is partly linked to climate change (e.g. Evans et al. 2006).

This study investigates the impacts of projected climate change upon three upland sub-catchments draining to Loch Dee in southwest Scotland. Distributed hydrological models are developed using MIKE Système Hydrologique Europeén (SHE) for each sub-catchment and calibrated/validated against observed stream discharges. Climate change scenarios are developed using the UKCP09 probabilistic projections.

**METHODS**

**The modelled sub-catchments**

Loch Dee is a remote lake in the Galloway Hills of southwest Scotland. It is the source of the River Dee, which outflows from the northeast end of the loch, flows into the impounded Clatteringshaws Loch and contributes water to the Galloway Hydro-electric Power Scheme and subsequently drains to the Solway Firth. The catchment area at the downstream end of the loch is 15.6 km² with 1.0 km² occupied by the loch surface (Burns et al. 1984; Lees 1995). Three main sub-catchments contribute water to the loch (Figure 1; Table 1). The largest (5.7 km² at the gauging station) is the White Laggan, with its tributary the Black Laggan Burn, which discharges in the south of the loch. The Dargall Lane and Green Burn, which are both less than half the size of the White Laggan, flow into Loch Dee in the west and southeast, respectively. These three sub-catchments drain a total area of 10.3 km² and the remaining catchment area (4.3 km²) comprises very small streams, areas that runoff directly to the loch and portions of the three main sub-catchments below their gauging stations. Elevation varies from 225 m OD at the loch shore to 716 m OD at the highest point in the Dargall Lane sub-catchment. Slopes are characteristically steep especially in headwater areas.

Loch Dee’s catchment lies on the southern margin of the Loch Doon igneous complex (Giusti & Neal 1993; Lees 1995). Granitic intrusions into older Ordovician greywackes, shales and siltstones occurred around 400 M years ago resulting in extensive metamorphism (Giusti 1999; Ferrier et al. 2001).
Superficial deposits comprise glacial tills and moraine. Soils are predominately hydromorphic soils or peaty gleys. They are characteristically thin and rock outcrops in steep areas of high elevation. Giusti (1997) suggested that the deepest soils (approaching 1 m) within the Dargall Lane are located in a corrie where peat has accumulated. Unpublished soil auger survey data for 20 locations within the same sub-catchment (C. Curtis, UCL ECRC) show that elsewhere soils are considerably shallower (<5–40 cm in the headwater areas). A similar pattern of declining soil depth with slope and elevation was revealed in a further survey to support this current work in which soil depths were measured at 120 locations within the three sub-catchments. Soil depth in some gently sloping areas characterised by peat accumulation, such as the lower sections of the Green Burn and the White Laggan as well as the corrie within the Dargall Lane, were around 1.5 m. Stream channels incised into these peaty soils flow directly over the underlying bedrock.

The natural vegetation of the three sub-catchments is heather-grassland dominated by *Molinia caerulea*, *Nardus stricta* and *Calluna vulgaris* with areas of bracken covering lower areas (Giusti & Neal 1993; Winterbottom et al. 1997). *Sphagnum* dominates in areas of peat (Ferrier et al. 2001). Traditional land-use comprised extensive grazing of sheep and some cattle. However, between 1973 and 1982 the Forestry Commission planted the lower areas (up to

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**Table 1** Characteristics of the three modelled sub-catchments

<table>
<thead>
<tr>
<th>Sub-catchment</th>
<th>Area (km²)</th>
<th>Minimum elevation (m OD)</th>
<th>Maximum elevation (m OD)</th>
<th>Forested area (%)</th>
<th>Mean daily flow (m³ s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dargall Lane</td>
<td>2.1</td>
<td>259</td>
<td>716</td>
<td>0.0</td>
<td>0.169</td>
</tr>
<tr>
<td>Green Burn</td>
<td>2.5</td>
<td>228</td>
<td>555</td>
<td>66.9</td>
<td>0.198</td>
</tr>
<tr>
<td>White Laggan</td>
<td>5.7</td>
<td>226</td>
<td>673</td>
<td>16.9</td>
<td>0.410</td>
</tr>
</tbody>
</table>

*a*Elevation of the gauging station in each sub-catchment.

*b*Mean daily flow for the modelled period (01/07/1990 – 30/06/2004).
approximately 450 m OD of the Green Burn and White Laggan, with both native Scots pine (*Pinus sylvestris*) and exotic species, most notably Sitka spruce (*Picea sitchensis*) but also Norway Spruce (*Picea abies*), Japanese Larch (*Larix kaempferi*) and Lodgepole Pine (*Pinus contorta*) (Burns *et al.* 1984; G. Shaw, Forestry Commission, personal communication). Due to its lower elevation over 65% of the Green Burn was afforested whilst just under 17% of the White Laggan sub-catchment area is covered by trees (Table 1). The Dargall Lane was not planted and retains its natural vegetation.

Precipitation is largely associated with passage of North Atlantic depressions (Giusti & Neal 1993). Mean annual precipitation totals for the period 1981–2007 from two recording rain gauges located within the White Laggan sub-catchment (Black Laggan, elevation 235 m OD and Upper Black Laggan, elevation 408 m OD, Figure 1) are 2,517 and 2,876 mm, respectively. The wettest months are October–January (c.45% of annual total) whilst April–July is noticeably drier (c. 22% of annual total). Records from gauging stations towards the downstream ends of the three sub-catchments (Figure 1) show that, as a result of the thin soils and steep slopes, runoff displays a very flashy response to precipitation (Giusti & Neal 1993; Black 1994). The rain gauges and gauging stations were installed as part of the Loch Dee Project (Burns *et al.* 1984). The project, which established a comprehensive hydrological and hydrochemical monitoring programme for the Loch and its sub-catchments, was designed to assess the relative importance of acidic deposition and coniferous afforestation upon fresh-water acidification (see Harriman & Wells 1983). The area was subjected to acid rain with Loch Dee being moderately acidified since the 19th Century (Flower *et al.* 1987). As a result, the Dargall Lane (as well as the adjacent Round Loch of Glenhead) is a site within the UK Acid Waters Monitoring Network (AWMN), established in 1988 to monitor the response of acidified surface waters to reduced sulphur and nitrogen emissions (e.g. Battarbee *et al.* 2010).

**Model development, calibration and validation**

Hydrological models of each of the three sub-catchments were developed using MIKE SHE. MIKE SHE is a deterministic, fully distributed and physically based modelling system developed from the SHE (Abbott *et al.* 1986a, b; Refsgaard *et al.* 2010). A range of options are available to model the major processes within the land phase of the hydrological cycle including overland, unsaturated and saturated subsurface flows, interception and evapotranspiration (Graham & Butts 2005). Catchment characteristics and input data such as elevation, soil, land cover, precipitation and evapotranspiration can be spatially distributed by the discretisation of the catchment into an orthogonal network of grid squares. Vertical variations in soil and hydrogeological characteristics are described in a number of horizontal layers which can vary in depth. Channel flow is simulated using the one-dimensional hydraulic modelling system, MIKE 11 which employs the complete dynamic wave formulation of the Saint Venant equations (Havno *et al.* 1995). Dynamic coupling of MIKE SHE and MIKE 11 evaluates river-aquifer exchange, overland flow to channels and flooding from channels to adjacent grid squares (Thompson *et al.* 2004). MIKE SHE has been employed in a range of environments from small (<50 km² and in some cases <10 km²) catchments (Sahoo *et al.* 2006; Dai *et al.* 2010) and wetlands within catchments (Thompson *et al.* 2004, 2009; Hammersmark *et al.* 2008), through catchments of several hundreds or thousands of km² (e.g. Feyen *et al.* 2000; Huang *et al.* 2010; Singh *et al.* 2010), to major international river basins (Andersen *et al.* 2001; Stisen *et al.* 2008) or for nationwide water resource assessments (Henriksen *et al.* 2003).

Each of the models of the three Loch Dee sub-catchments employed the same structure, parameterisation and input data. A grid size of 80 × 80 m was selected following a series of experimental runs that, in accordance with Vázquez *et al.* (2002), showed little change in simulated stream discharge for grid sizes between 20 and 150 m. Selection of grid size for distributed hydrological models requires a balance between representing catchment attributes and achieving reasonable simulation times (McMichael *et al.* 2006). Topography was provided by 1:10,000 Ordnance Survey Land-Form PROFILE digital terrain model (DTM) data. These data, which have an original 10 × 10 m grid size, were resampled to the 80 × 80 m MIKE SHE grid. Hypsometric curves for the three sub-catchments derived using the original and resampled data are very similar suggesting that the latter give a good representation of topographic characteristics.
The finite-difference saturated zone method was employed and the saturated zone conceptualised as a single layer representing the surface soil/peat layer which it is assumed exerts the dominant influence upon catchment response to precipitation. In the absence of detailed hydro-geological observations, the underlying bedrock was considered impermeable although it is acknowledged that shallow bedrock groundwater, in particular in areas adjacent to stream channels, has been shown to influence stream flow generation processes in other headwater catchments (Haria & Shand 2004, 2006). Slope was established from the Ordnance Survey DTM data (using ArcGIS Spatial Analyst) and classified into four classes ranging from $<10$° to $>40$. The depths of the saturated zone were assigned based on this classification and ranged from 1.5 m to 40 cm in accordance with available field evidence. A further class representing areas of bare rock (identified from areas specified as rock outcrops on Ordnance Survey 1:10000 Raster maps) was assigned a depth of 0.0 m. A simple $3 \times 3$ mean filter was applied to reduce sharp changes in unsaturated zone depth. The hydraulic conductivity (uniform horizontal and vertical) of the saturated zone was varied during model calibration.

The two-layer water balance method, which has shown to be appropriate in shallow groundwater table situations (Yan & Smith 1994; DHI 2005), was employed to represent the unsaturated zone. Surface infiltration rate was varied during model calibration with values of water content at saturation, field capacity and wilting point taken from the literature (Dunne et al. 1975; Marshall et al. 1996). Land cover was specified as coniferous forest, heather-grassland or bare rock. As stated above, the distribution of the latter was established from Ordnance Survey 1:10000 raster map data. These data were employed in combination with an annotated raster map provided by the Forestry Commission to digitise forested areas within the Green Burn and White Laggan sub-catchments. Remaining areas were classified as heather-grassland. Values of root depth and leaf area index for the two vegetation types were specified from the literature (Thompson et al. 1981; Bultot et al. 1990; Kellihier et al. 1993) whilst bare rock was assigned values of 0 for both parameters. The same land cover data were used within the overland flow component to spatially distribute Manning’s $M$ with values varying during calibration.

The plan of the river networks were digitised from Ordnance Survey 1:10000 raster map data and used to define MIKE 11 river networks for each sub-catchment. A uniform Manning’s $n$ roughness coefficient of 0.04 was applied throughout each river model (corresponding to Chow’s (1959) tabulated value for mountainous streams). Consistent cross sections were applied for different stream orders based on a sample of surveyed cross sections and, when available, the literature (Burns et al. 1984). Cross sections were specified as depths relative to the top of the ditch bank and the latter was taken from the appropriate grid square of the MIKE SHE topographic grid (Thompson et al. 2004). The ‘full contact’ river-aquifer exchange method was employed. This assumes that the river is in full contact with the aquifer material so exchange between river and aquifer is influenced directly by the hydraulic conductivity of the aquifer rather than the river bed (DHI 2005). This was considered appropriate as water was observed seeping from the sides of the channels incised into the peaty soils.

Daily data from the two recording rain gauges in the White Laggan sub-catchment provided precipitation input to the MIKE SHE models. The MIKE SHE topographic grid was used to spatially distribute precipitation with data from the lower Black Laggan gauge used in areas with elevations up to 320 m OD (mid-point between the elevation of the two gauges) and the Upper Black Laggan gauge providing data for higher areas. No meteorological stations providing data to evaluate potential evapotranspiration (PET) are located within any of the three modelled sub-catchments. Instead daily minimum, mean and maximum temperatures were acquired for the period January 1980–December 2004 for the Clatteringshaws (178 m OD) and Glenlee (55 m OD) stations located approximately 7.8 and 13.0 km to the east of Loch Dee, respectively. Lapse rates for the three temperature data sets were established and subsequently applied to the Clatteringshaws record to evaluate daily minimum, mean and maximum temperatures for 100 m elevation ranges between 200 and 800 m OD using the mid-point in each range (e.g. 450 m for 400–500 m). Daily Hargreaves PET, recommended by the Food and Agriculture Organization of the United Nations (FAO) in the absence of data to evaluate Penman-Monteith PET (Allen et al. 1998; Kingston et al. 2009), was subsequently derived for each of these elevation ranges. As for precipitation,
spatial distribution of PET was based on classification of the MIKE SHE topographic grid.

A two-stage calibration/validation approach was adopted with simulated mean daily stream discharge being compared with records from the Loch Dee Project gauging stations. Initially, the White Laggan model, which encompasses a wide range of topography (and hence precipitation and PET) and a mixture of land cover, was subject to traditional split sample calibration/validation (e.g. Klemes 1986; Refsgaard 1997). Subsequently, the same calibrated parameter values were applied to the models of the Dargall Lane and Green Burn providing a second validation stage. This form of validation, described by Henriksen et al. (2008) as a proxy-basin test and which has also been adopted by Singh et al. (2010), is appropriate given the close proximity of the three sub-catchments and their similar geology, soil and land cover.

For the initial split sample calibration/validation of the White Laggan model, the 14-year period 01/07/90–30/06/04 with the most complete precipitation, PET and stream flow records was divided into two seven-year periods (01/07/90–30/06/97 and 01/07/97–30/06/04) for calibration and validation, respectively. In both cases, the preceding six months were included as a spin-up period but with results excluded from evaluations of model performance. Given that the number of parameters subject to adjustment during calibration of a distributed hydrological model should be as small as possible (Refsgaard & Storm 1995), the calibration parameters were restricted to the hydraulic conductivity of the saturated zone, the infiltration rate of the two-layer unsaturated zone and the Manning’s M roughness for overland flow. An automatic multiple objective calibration was undertaken based on the shuffled complex evolution (SCE) method (Duan et al. 1992; Madsen 2000, 2003). This was only possible using hydraulic conductivity and infiltration rate as spatially variable overland flow resistance required the specification of a grid with absolute values of Manning’s M, which could not be varied by the autocalibration routine. Therefore, M was initially set to a uniform value of 60 (Sahoo et al. 2006). Minimum and maximum bounds for hydraulic conductivity were defined as $1 \times 10^{-9}$ and $1 \times 10^{-3}$, respectively, with the corresponding values for infiltration rate set as $1 \times 10^{-6}$ and $1 \times 10^{-2}$. Following Butts et al. (2004) two equally weighted calibration criteria, the absolute value of the average error and the RMSE, were employed and these were aggregated into one measure using a transformation that compensates for differences in the magnitudes of the different criteria (Madsen 2003). The performance of the optimal model defined by the autocalibration was subsequently fine tuned through iterative modification of the Manning’s M values for the three land covers whilst retaining a consistent hierarchy such that bare rock exerted the least resistance to overland flow (highest Manning’s M) and forest the highest. Widely used statistical measures of model performance, the Nash-Sutcliffe coefficient (R², Nash & Sutcliffe 1970) and the correlation coefficient (r), as well as the deviation in simulated mean daily flow from the observed mean daily flow ($f_{halt}$, Henriksen et al. 2003) were computed for each model run and used to refine the final calibration. Performance of the White Laggan model for the second seven-year validation period was assessed using these same performance indicators. Similarly, they were also employed when the final values of the calibration parameters were applied to the Dargall Lane and Green Burn models. In these cases the full 14-year simulation period (01/07/90–30/06/04) was utilised with an initial six-month spin up period.

**Simulation of climate change**

Following the approach described by Arnell & Reynard (1996) the impacts of climate change upon runoff from the three Loch Dee sub-catchments were assessed in three stages. The calibrated/validated models described above comprised the first stage. Subsequently, a series of climate change scenarios were defined and the original input climate perturbed accordingly. The three hydrological models were then run using the perturbed climate data and simulated stream discharge compared to the baseline conditions provided by the original calibrated/validated models. Other model parameters such as those representing land cover remained unchanged, an approach which is widely used in hydrological modelling assessments of climate change (e.g. Fowler & Kilsby 2007; Johnson et al. 2009; Kingston et al. 2010; Singh et al. 2010).

Perturbations to model precipitation and PET were provided by the 2009 UK Climate Projections (UKCP09). As described by Jenkins et al. (2009), UKCP09 provides
probabilistic projections for a number of atmospheric variables under three emissions scenarios, referred to as Low, Medium and High, which correspond to the B1, A1B A1FI scenarios in the IPCC Special Report on Emission Scenarios (SRES, IPCC 2000). Projections for a number of atmospheric variables are provided in the form of a probability distribution function designed to represent the uncertainty in future climate. The methodology used to generate these projections is based on a large perturbed physics ensemble using the Met Office Hadley Centre’s HadCM3 global climate model and results of another set of 12 global climate models. Projections are downscaled to a resolution of 25 km using the HadRM3 regional climate model (Murphy et al. 2009). They are provided for a series of seven overlapping 30-year time slices which step forward by a decade from 2010–2039 to 2070–2099. Changes in atmospheric variables are available for monthly, seasonal and annual average periods and are expressed relative to a 30-year baseline period (1961–1990).

In the current study, projections for the three emissions scenarios for the 2040–2069 and 2070–2099 time slices (referred to as the 2050s and 2080s, respectively) were selected to represent conditions towards the middle and end of the current century. Monthly changes in precipitation (%) as well as minimum, mean and maximum temperatures (°C) were abstracted from the relevant HadRM3 model grid. This was undertaken for probabilities between the 10 and 90% levels in 10% increments. As suggested by Murphy et al. (2009), extreme probabilities outside this range were not used. The range of probabilities employed includes the central estimate of change (the change that is as likely as not to be exceeded, i.e. the 50% probability level) and is bounded by the changes that are very likely to be exceeded (90% probability level) and those which are very unlikely to be exceeded (10% probability level). A total of 54 scenarios were developed which comprised nine different probabilities for each of the three emissions scenarios and in turn each of the two time slices. Throughout this study these scenarios are referred to in the form 2050M50, in this case the 2050 time slice, Medium emissions scenario (A1B), 50% probability level.

The original daily precipitation data for the Black Laggan and Upper Black Laggan rain gauges were multiplied by the UKCP09 monthly percentage changes to provide new time series for each scenario. Similarly, projected changes in minimum, mean and maximum temperatures were used to modify these three time series for each of the six 100 m high elevation ranges and Hargreaves PET recalculated. The same approach used in the calibrated/validated models was employed to spatial distribute the perturbed precipitation and PET data. Climate change simulations were run for all three sub-catchments for the complete 14-year period (01/07/90–30/06/04) with an initial six-month spin up period. Results were compared with those for the same period provided by the respective calibrated/validated model. As the simulation period falls predominantly outside the UKCP09 baseline period, results are likely to be representative of conditions towards the latter part of each time slice (Thompson et al. 2009).

Disaggregation of the climate change signal for stream discharge into that attributable to precipitation and PET was investigated by running models with perturbed precipitation and PET data and vice versa. For illustrative purposes this was undertaken for the White Laggan sub-catchment for each emissions scenario, for both time slices and for probability levels between 10 and 90% in 20% increments.

RESULTS

Model calibration/validation

Values of the calibration parameters at the end of the calibration/validation procedure (Table 2) are within the ranges reported by MIKE SHE modelling studies of similar environments (e.g. Sahoo et al. 2006; Dai et al. 2010; Singh et al. 2010). Performance measures for the White Laggan model for both the calibration and validation periods as well as the complete 14-year simulation period are shown in Table 3. According to the classification of Henriksen et al. (2008) the performance is classed as either ‘excellent’ ($F_{sai}$ for all periods) or ‘very good’ (R2 for all periods) with superior results obtained for the validation period compared to the calibration period. Figures 2(a) and (b) show the observed and simulated daily discharge of the White Laggan for the calibration and validation periods, respectively. Good sequencing of individual flood events is achieved although some of the largest winter events tend to be overestimated. The good performance of the model
is further demonstrated by the very similar monthly mean discharges derived from the observed and simulated daily flows for the complete 14-year period (Figure 2(c)). Some, but not all, of the seasonal peaks are slightly overestimated whilst discharges in some summer low flow periods are underestimated. The simulated flow regimes (mean monthly discharges) for both the calibration and validation periods (Figures 2(d) and (e), respectively) as well as the complete 14-year period (Figure 3(a)), are close to the observed but with the slight over- (under-)estimation of winter peak (summer low) flows. Flow duration curves for the observed and simulated discharges are also similar although low flows are underestimated (Figure 4(a)).

The proxy-basin test, in which the values of the calibration parameters shown in Table 2 were specified within the models of the Dargall Lane and Green Burn, produced very favourable results (Table 3). Although the measures are lower than those for same period for the White Laggan model, they are still classed as either ‘excellent’ ($F_{\text{bal}}$) or ‘very good’ (R2). The correspondence between observed and simulated mean daily and monthly flows for these two sub-catchments (not shown) were as close as those for the White Laggan shown in Figures 2(a–c).

Figures 3(b) and (c) show that both models closely reproduce the regimes of the two sub-catchments albeit with slightly higher discharges in October and lower flows at the height of the summer. The correspondence between observed and simulated flow duration curves for these two sub-catchments is similar to that achieved for the White Laggan (Figures 4(b) and (c)) although the degree of under-estimation of low flows is greater in the case of the Dargall Lane. Overall, however, these results suggest a robust calibration, enabling the use of the model for assessments of climate change impacts. The success of the proxy-basin test also suggest that this modelling approach could be used to provide initial estimates of stream discharges from similar adjacent catchments for which records are not available. However, caution should be applied in situations where catchment characteristics such as land cover, soil type and slopes differ from the three modelled sub-catchments.

### Table 2 | Calibrated MIKE SHE parameters values

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Calibrated value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydraulic conductivity (m s$^{-1}$)</td>
<td>$6.027 \times 10^{-7}$</td>
</tr>
<tr>
<td>Unsaturated zone infiltration rate (m s$^{-1}$)</td>
<td>$4.156 \times 10^{-4}$</td>
</tr>
<tr>
<td>Manning’s $M$ roughness for overland flow</td>
<td></td>
</tr>
<tr>
<td>Bare rock</td>
<td>30</td>
</tr>
<tr>
<td>Heather grassland</td>
<td>16</td>
</tr>
<tr>
<td>Forest</td>
<td>8</td>
</tr>
</tbody>
</table>

### Table 3 | Statistical measures of the performance of the three MIKE SHE models

<table>
<thead>
<tr>
<th>Sub-catchment</th>
<th>Period</th>
<th>MDFo ($m^3$ s$^{-1}$)</th>
<th>MDFS ($m^3$ s$^{-1}$)</th>
<th>$F_{\text{bal}}$ (%)</th>
<th>R2</th>
<th>r</th>
</tr>
</thead>
<tbody>
<tr>
<td>White Laggan</td>
<td>Calibration</td>
<td>0.4071</td>
<td>0.4101</td>
<td>0.73*****</td>
<td>0.708*****</td>
<td>0.843</td>
</tr>
<tr>
<td></td>
<td>Validation</td>
<td>0.4120</td>
<td>0.4132</td>
<td>0.30*****</td>
<td>0.756*****</td>
<td>0.871</td>
</tr>
<tr>
<td></td>
<td>Full</td>
<td>0.4095</td>
<td>0.4115</td>
<td>0.48*****</td>
<td>0.730*****</td>
<td>0.856</td>
</tr>
<tr>
<td>Dargall Lane</td>
<td>Full</td>
<td>0.1687</td>
<td>0.1658</td>
<td>-1.76*****</td>
<td>0.677*****</td>
<td>0.824</td>
</tr>
<tr>
<td>Green Burn</td>
<td>Full</td>
<td>0.1981</td>
<td>0.1887</td>
<td>-4.74*****</td>
<td>0.726*****</td>
<td>0.854</td>
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</table>

<table>
<thead>
<tr>
<th>Performance indicator*</th>
<th>Excellent</th>
<th>Very good</th>
<th>Fair</th>
<th>Poor</th>
<th>Very poor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dr</td>
<td>&lt;5%</td>
<td>5–10%</td>
<td>10–20%</td>
<td>20–40%</td>
<td>&gt;40%</td>
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<td>0.20–0.50</td>
<td>&lt;0.20</td>
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*Calibration: 01/07/90–30/06/97, validation: 01/07/97–30/06/97.
*Observed mean daily flow.
*Simulated mean daily flow.
*Deviation in simulated mean daily flow from observed mean daily flow.
*Based on Henriksen et al. (2008).
Projected changes in precipitation and PET

Changes in the mean monthly distribution of precipitation and PET for each of the emissions scenarios for the 2050s and 2080s are summarised in Figure 5. For clarity results are shown for probabilities between 10 and 90% in 20% increments. Results for the intervening probabilities (i.e. 20, 40, 60 and 80%; not shown) lie approximately mid-way between those of the adjacent probabilities. These results are based on weighting the perturbed precipitation and PET data by the proportion of the combined three subcatchments that fall within the two precipitation and six PET elevation zones. They thus represent the mean changes over the Loch Dee catchment. There are some very subtle differences when these results are calculated for each subcatchment. For example, when a scenario results in an increase in precipitation, the absolute magnitude of this increase is largest in the Dargall Lane because a larger
proportion (just over 97%) of its area is within the higher elevation zone which has higher precipitation under baseline conditions. In such circumstances the smallest absolute increases are within the Green Burn sub-catchment which has a larger proportion (just under 40%) of its area within the lower, and slightly drier, elevation zone. The reverse is the case when a scenario is associated with reduced precipitation. For similar reasons, absolute changes in PET decline from the lower elevation (higher temperature) Green Burn through the intermediate White Laggan to the higher (lower temperature) Dargall Lane. However, the magnitude of differences between sub-catchments is small (e.g. typically around 20 mm in the case of mean annual precipitation for the Dargall Lane and Green Burn sub-catchments). The differences are less than 1% of both mean annual precipitation and PET and results for the combined three sub-catchments (Figure 5) thus provide a good approximation of the projected changes in each of the three sub-catchments.

As expected, PET increases in every month under the majority of the scenarios. Small declines in PET only occur in July for the 10% probability levels as a result of projected declines in maximum temperature for some emissions scenarios. The largest absolute increases in PET occur in the warmest months between June and September (Figure 5) although, in percentage terms, the differences between changes in these and other months are generally smaller. For any given month within a particular emissions scenario the magnitude of gains in PET increases with probability level. For example, under baseline conditions the monthly PET in July is 76.3 mm. Under the 2050s Medium emissions scenario this increases by a very modest 0.9 mm (1.2%) for the 10% probability level (i.e. 2050M10). The corresponding increases for the 2050M50 and 2050M90 scenarios are 7.8 mm (10.3%) and 16.5 mm (21.6%), respectively. Unsurprisingly, for a given probability level, changes in PET are larger with the progressively higher emissions scenario (e.g. changes for July under 2050L50 are 7.7 mm (10.1%) compared to the previously reported 7.8 mm (10.3%) for 2050M50 and 9.4 mm (12.3%) under 2050H50). The 2080s time slice is associated with larger changes than the 2050s (e.g. July PET under 2080M50 increases by 11.8 mm or 15.5%).

Figure 3 | Observed and simulated mean monthly discharge for the full 14-year simulation period (July 1990–June 1997): (a) White Laggan; (b) Dargall Lane; (c) Green Burn (Note different y-axis scales).

Figure 4 | Flow duration curves derived from observed and simulated daily discharge for the full 14-year simulation period (July 1990–June 1997): (a) White Laggan; (b) Dargall Lane; (c) Green Burn.
Figure 5 | Monthly mean catchment precipitation and PET for the baseline scenario and probabilities between 10 and 90% for each emissions scenario (L – Low, M – Medium, H – High) for the 2050s and 2080s (Note different y-axis scales for precipitation and PET).
These trends are summarised in Figure 6, which shows mean annual, summer (defined by the UKCP09 as June–August) and winter (December–February) PET (and precipitation, discussed below) for all the scenarios. The progressive increase in PET for each of these periods with higher probability level, emission scenario and future time slices is clearly demonstrated. Annual PET, which under baseline conditions is 450.7 mm, is by the 2050s very likely to exceed (10% probability level) between 455.6 (1.1% increase, 2050L10) and 458.8 mm (1.8% increase, 2050H10) and very unlikely to exceed (90% probability level) between 529.6 (17.5% increase, 2050L90) and 544.0 mm (20.7% increase, 2050H90). Annual PET for the central estimates of change (50% probability level) is between 490.9 (8.9% increase, 2050L50) and 499.1 mm (10.7% increase, 2050H50). By the 2080s these changes increase so that for the central estimates of change PET is between 498.1 (10.5% increase, 2080L50) and 522.3 mm (15.8% increase, 2080H50). In percentage terms changes in summer and winter PET, as well as those for spring (September–November) and autumn (September–November) (not shown) are similar to those for annual totals.

The perturbed precipitation data show the expected increases in the magnitude of changes with progressively higher emissions scenario and future time slice (Figure 5). Absolute changes in precipitation are predominantly larger than those for PET. However, as noted by Jenkins et al. (2009), changes at different probability levels not only vary in magnitude but also in direction. At the 50% probability level for all three emissions scenarios within both time slices precipitation increases during the eight months between October and May. The largest increases in both absolute and percentage terms occur in December, the second wettest month under baseline conditions (317.6 mm), and vary between 46.4 (14.8%) and 70.6 mm (22.2%) for the 2050s (i.e. 2050L50 and 2050H50, respectively), and 78.1 mm (24.6%) and 141.8 mm (44.8%) for the 2080s (i.e. 2080L50 and 2080H50, respectively). Percentage changes in total precipitation during the eight months of October–May (2,047.9 mm for the baseline) are

Figure 6 Projected mean annual, summer and winter catchment precipitation and PET for the baseline scenario (BL) and probabilities between 10 and 90% for each emissions scenario for the 2050s and 2080s (Note different y-axis scales).
approximately half of those for December. The reductions in total precipitation for the months June–September (710.9 mm for the baseline) are small and vary between 2.7 (2050L_{50}) and 5.8% (2050H_{50}) for the 2050s, and 5.6 (2080L_{50}) and 10.3% (2080M_{50}).

At progressively lower probability levels below 50% (i.e. those associated with changes which are increasingly likely to be exceeded) the number of months in which precipitation is projected to increase, as well as the magnitude of increases when they occur, both decline. Within all the emissions scenarios and both time slices the 10% probability level only produces increases in precipitation for one month (December) with the exception of 2050L_{10}, which results in a reduction in mean monthly precipitation for every month. The maximum projected increase in December precipitation is only 34.8 mm (11.0%) for 2080H_{10} and the lowest 5.9 mm (1.9%) for 2080L_{10}. The number of months with higher precipitation does, however, increase with the 20% probability level to between two and four autumn/winter months. Declines in precipitation, especially those in summer, are also larger for the lower probability levels. In June, the driest month under baseline conditions (157.8 mm), precipitation declines for the 10% probability level range from 54 mm (34.4%) for 2050L_{10} to 82.2 mm (52.8%) for 2080H_{10}. Conversely at high probability levels beyond 50% the number of months in which mean precipitation is above the baseline increases and the magnitude of the increases become larger. At the 90% probability level (changes which are very unlikely to be exceeded) every month experiences increases in precipitation which are as much as an additional 301.9 mm (95.0%) for 2080H_{90} down to 110 mm (35.0%) for 2080L_{90}.

Figure 6 shows that, for probability levels between 10 and 30% (10 and 40% for 2050L), mean annual precipitation declines whilst it increases for higher probability levels. Central estimates of change are increases of between 2.7 and 5.8% for the 2050s, and 5.6 and 10.3% for the 2080s. There is, however, an overwhelming trend towards enhanced winter precipitation, with reductions during this season being limited to the 10% probability level for all scenarios and, in addition, the 20% level for 2050L. Conversely, summer precipitation is projected to decline in all but the most extreme high probability levels (80 and 90%). Changes in autumn precipitation (not shown) generally follow those for winter with those for spring lying mid-way between winter and summer. In most scenarios, therefore, precipitation becomes more concentrated in the wetter autumn and especially winter months. The difference between winter and summer precipitation consequentially increases systematically with increasing emissions scenario and time slice. Under baseline conditions mean summer precipitation is 61% of winter precipitation. For M_{50} it is 44% for the 2050s and 41% for the 2080s whilst for 2080L_{50} it equals 44% and declines to 35% for 2080H_{50}.

Simulated changes in stream discharge

Figure 7 shows the mean monthly discharge of the White Laggan abstracted from simulation results for each emissions scenario for the 2050s and 2080s as well as for the baseline scenario. Climate change results are shown for probabilities between 10 and 90% in 20% increments. Simulated mean monthly discharges for the intervening probabilities, which are not shown to retain clarity, lie approximately mid-way between adjacent probabilities. Results for the White Laggan are shown due to its use for calibration/validation, and its larger size and hence larger discharges into Loch Dee. The impacts of the climate change scenarios on the other two sub-catchments are very similar. This finding is illustrated in Figure 8, which shows mean annual discharge as well as both minimum (June) and maximum (December) mean monthly discharges for all the scenarios for each of the three sub-catchments. It also demonstrates the consistent changes in these three terms with increasing probability level with those not included in Figure 7 falling between those that are shown.

Simulated changes in stream discharge closely follow the projected changes in precipitation. There is some uncertainty over the direction of change in mean annual discharge, which is in turn influenced by the number of months in which mean discharge increases or decreases (Figure 9). In all three sub-catchments, mean discharge decreases for probability levels between 10 and 30% for all emissions scenarios and both time slices with the exception of 2050L for which declines in mean discharge also occur with the 40% probability level. This pattern is consistent with the projected changes in annual precipitation discussed above. In all of these scenarios, no more than four (five in the case of
2050L40) months experience increases in mean discharge which declines in all other months (Figure 9). Mean discharge increases are primarily in the winter months (Figure 7). The magnitude of the decline in mean annual discharge for the White Laggan, which are very similar to those predicted for the Dargall Lane and Green Burn, range from 17.8% (2050L10) to 1.7% (2080H30). For probability levels of 40% and higher (50% in the case of 2050L) mean discharge increases systematically with, for any given probability level, changes being larger for the progressively higher emissions scenario (Figure 8). At least six months experience increases in mean discharge and this number increases with higher probability levels (Figure 9). The central estimate of change (i.e. the 50% probability level) is associated with increases for the White Laggan mean discharge for the 2050s of between 2.9 and 6.3% (2050L50 and 2050H50, respectively) and for the 2080s of 5.9 and 12.3% (2080L50 and 2080H50, respectively). The same trend is evident in the other two sub-catchments albeit with slightly lower magnitudes of change (on average 0.2 and 1.2% lower for the Green Burn and Dargall Lane, respectively). Increases in mean discharge for the White Laggan that are very unlikely to be exceeded (i.e. 90% probability level) range between 28.2 and 37.4% for the 2050s (2050L90 and 2050H90, respectively). Comparable changes for the Dargall Lane are on average 5.2% lower and for the Green Burn 1.1% higher. All or nearly all months experience increases in mean discharge at this high probability level (Figure 9).

Similar changes occur for total inflow to Loch Dee, which was evaluated by normalising simulated mean annual discharge from each sub-catchment for each scenario by sub-catchment area. Mean flow per unit catchment area for each scenario was subsequently multiplied by the ungauged catchment area (4.3 km²) and combined with the annual flows for each of the three modelled sub-catchments. Figure 10 shows that reductions in annual Loch Dee inflow for the lowest probability level range between $6.1 \times 10^6$ m³ (17.6%, 2050L10) to $5.7 \times 10^6$ m³ (16.5%, 2050H10) for the 2050s and $5.4 \times 10^6$ m³ (15.8%, 2080L10) and $6.3 \times 10^6$ m³ (18.2%, 2080H10) for the 2080s. Changes at this probability level are, however, very likely to be exceeded. Reductions associated with the 30% probability level range between 6.3 and 3.6% for the 2050s and 1.4 and 2.0% for the 2080s. Changes which are as likely as not to be exceeded (50% probability) are associated with relatively modest increases for the 2050s (between $0.92 \times 10^6$ m³ or 2.7% for 2050L50 and $2.1 \times 10^6$ m³ or 6.0% for 2050H50) and $2.0 \times 10^6$ m³ (3.6%) and $4.0 \times 10^6$ m³ (11.5%) for 2080L50 and 2080H50, respectively. The
largest, very unlikely to be exceeded (90% probability), increases in Loch Dee inflow are for the 2050s between $9.5 \times 10^6$ m$^3$ (27.5%, Low) and $12.5 \times 10^6$ m$^3$ (36.4%, High) and for the 2080s $11.9 \times 10^6$ m$^3$ (34.5%, Low) and $20.19 \times 10^6$ m$^3$ (58.7%, High).

There is comparably less uncertainty in the direction of change in stream discharge for peak and low flows periods. Peak winter (December) stream flow increases in every scenario except 2050L10 (Figure 7) and reductions in discharge for this scenario are very small (c. 1.4% for all three sub-catchments, Figure 8). Given that this probability level is associated with changes which are very likely to be exceeded, results suggest that winter discharges can be expected to increase. Increases for the central estimate of change (50% probability) for the 2050s vary between 16.3 (2050L50) and 24.2% (2050H50) for the White Laggan with comparable changes (within 2%) for the Dargall Lane and Green Burn sub-catchments. For the 2080s the equivalent increases are 26.6 (2080L50) and 50.9% (2080H50). Increases in mean December discharge within the White Laggan that are very unlikely to be exceeded (90% probability) vary between 40.1 and 59.3% for the 2050s (i.e. 2050L90 and 2050H90, respectively), and 66.4 and 119.6% for the 2080s (i.e. 2080L90 and 2080H90, respectively). Changes in the other two smaller sub-catchments are similar, albeit slightly lower (by on average 4.5% for the Dargall Lane and 1.5% for the Green Burn).
In contrast, summer (June) low flows decrease in the majority of scenarios (Figures 7 and 8). In the case of the White Laggan increases in flows in this month with the lowest mean discharge only occur at the highest probability level (i.e. 90%, and so very unlikely) for the Low and Medium emissions scenarios (i.e. L90 and M90) for both time slices. Increases are relatively small, the largest (9.0%) being associated with 2050L90. The High emission scenario at this probability level produces declines of 0.6 and 10.6% for the 2050s and 2080s (i.e. 2050H90 and 2080H90, respectively). Changes for the Dargall Lane and Green Burn lie on either side of those for the White Laggan, with smaller (by on average 5.0%) reductions for the former and larger (on average 5.4%) for the latter. These changes at the 10% probability level are, however, likely to be exceeded (i.e. reductions are very unlikely to be as large). Decreases in summer minimum discharges for the central estimate of change (i.e. the 50% probability level) are still substantial and, for the White Laggan, range between 25.4 and 34.2% for the 2050s (2050L50 and 2050H50, respectively), and 30.6 and 48.7% for the 2080s (2050L50 and 2050H50, respectively). Again changes for the other two sub-catchments lie on either side of the White Laggan. On average reductions in the higher elevation, and therefore wetter, Dargall Lane are 7.4% lower, whilst those for the lower Green Burn are 5.3% higher.

Higher winter stream discharges and lower flows in summer result in enhanced seasonality which is similar to that reported for precipitation. Table 4 presents mean June discharge expressed as a percentage of mean December discharge for each emissions scenario and time slice as well as the baseline. In all scenarios within all three sub-catchments the relative difference between winter and summer flows increases. For a given probability level, the difference increases with progressively higher emissions scenarios and future time slice. The
largest differences within a given time slice/scenario are associated with the lowest (10%) probability level but even at the other extreme probability level (90%) the difference between winter and summer flows are proportionally greater compared with the baseline. Differences between summer low and winter peak flows are generally smallest in the Dargall Lane as a result of the higher elevation and hence higher precipitation throughout the year and lower PET, especially in summer. In contrast, the relatively low elevation of the Green Burn, which is associated with lower precipitation and higher PET, results in the largest differences between winter and summer flows.

Table 4 | Seasonality and high and low flows in the three sub-catchments for the baseline scenario (BL) and probabilities between 10 and 90% (in 20% increments) for each emissions scenario for the 2050s and 2080s. Shaded cells indicate when values for a climate change scenario are higher than the baseline.

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summer discharge whilst the seasonal difference in discharge within the White Laggan, which has an intermediate range of elevations, lies between the other two sub-catchments.

The impact of the different climate change scenarios on the full range of flows is illustrated in Figure 11, which shows flow duration curves for the White Laggan for each emission scenario and time slice. Results are again restricted to probabilities between 10 and 90% in 20% increments. Changes in the character of the flow duration curves for the White Laggan, which indicate an expansion in the range of flows, are representative of those in the other sub-catchments. This situation is demonstrated in Table 4 which also provides Q5 and Q95 (the discharges exceeded 5 and 95% of the time, respectively) for the three sub-catchments. In accordance with the reported changes in mean June discharge, Q95 declines in the majority of scenarios. Only at the 90% probability level (i.e. very unlikely) for all three emissions scenarios and sub-catchments for the 2050s does Q95 increase. For the 2080s, Q95 also decreases for the 90% probability level in all three sub-catchment for the High emissions scenario and within the Green Burn for the Medium emissions scenario. Q5 decreases for the lowest probability levels (10–20% for all scenarios/sub-catchments, 10–30% for 2050L in all sub-catchments and 2050H for the White Laggan) whilst for all other scenarios/sub-catchment combinations it increases demonstrating a predominance of the higher peak flows discussed above.

Figure 12 shows mean discharge for the White Laggan from the experimental specification of perturbed precipitation and baseline PET data and vice versa. It demonstrates the very close similarity between results when both precipitation and PET are perturbed and when only precipitation is perturbed. On average, mean discharge with perturbed precipitation and baseline (i.e. lower) PET is only $6.8 \times 10^{-3}$ m$^3$ s$^{-1}$ (1.4%) higher than when both precipitation and PET are perturbed. The

![Flow duration curves for the White Laggan sub-catchment for probabilities between 10 and 90% for each emissions scenario for the 2050s and 2080s (L — Low, M — Medium, H — High).](https://iwaponline.com/hr/article-pdf/43/4/507/371135/507.pdf)
maximum difference (for 2080H90) between perturbed and baseline mean discharge increases from 0.25 m$^3$/s (60.3%) to 0.26 m$^3$/s (64.1%). In contrast, the expected reductions in mean discharge when perturbed (higher in the majority of scenarios) PET is employed whilst holding precipitation at baseline levels, are small with a maximum deviation from the baseline scenario of 1.61 × 10$^{-2}$ m$^3$/s (3.9%).

**DISCUSSION**

Southwest Scotland is characterised by high annual precipitation, which under baseline conditions is on average over six times greater than PET. Small percentage changes in precipitation are therefore associated with relatively large absolute changes compared with those for PET for the same scenario. At the 50% probability level increases in annual precipitation range between 74.7 (2.7%, 2050L50) and 159.6 mm (5.8%, 2050H50) for the 2050s and 154.8 mm (5.6%, 2080L50) and 285.3 mm (10.3%, 2080H50) for the 2080s. In contrast, increases in annual PET for the same scenarios are between 40.2 (8.9%) and 48.4 mm (10.7%) for the 2050s and 47.4 mm (10.5%) and 58.7 mm (13.0%) for the 2080s. The disparity between the magnitude of changes in precipitation and PET generally increases with progressively higher emissions scenario, future time slice and probability level. At its extreme (2080H90) a 1327.0 mm (48.1%) increase in mean annual precipitation compares with an increase in PET of only 114.3 mm (25.4%). The division of the climate change signal for stream discharge between that attributable to precipitation and PET demonstrated the overwhelming influence of changes in precipitation. This finding is not unexpected given the high precipitation and relatively low PET over the Loch Dee catchment. In other parts of the UK where the differences between precipitation and PET are smaller and where PET may exceed precipitation, enhanced sensitivity to projected changes in PET, as well as the method used to evaluate and subsequently perturb PET could be expected to increase (e.g. Thompson et al. 2009).

There is some uncertainty with respect to changes in total annual precipitation and in turn mean stream discharge and the total catchment inflow into Loch Dee. For all emissions scenarios, and both time slices, the lowest probability levels (10 to 30% and 40% in the case of 2050L) are associated with reductions in total annual precipitation and annual stream discharge from the three sub-catchments. Scenarios involving higher probability levels produce increases in annual precipitation, mean stream discharge and inflows to the loch. The central estimate of change (50% probability level) is associated with relatively small increases (in the case of Loch inflows up to 6.0% for the 2050s and 11.5% for the 2080s) whilst the very largest positive changes, which are very unlikely to be exceeded (90% probability level) increases loch inflows by between a third and half compared to baseline conditions. Modest increases in loch inflow may benefit existing use of water resources such as the generation of electricity through the Galloway Hydro-electric Power Scheme. Clearly, declining water availability simulated for the lower probability levels, which is likely to apply to all the other streams and rivers that
contribute to the hydro-power scheme, would have negative implications for this use of water as well as for ecological conditions within the loch and the downstream river system. Conversely, the larger annual flows associated with the higher probability levels scenarios do not necessarily mean that the potential for hydropower will increase by the same amount. In order to benefit from enhanced annual water availability, sufficient storage will be necessary to utilise the larger flows.

Utilisation of any enhanced annual flows may be hindered by the seasonal distribution of predicted changes in stream flow. Unlike changes in annual precipitation, mean stream discharge and annual total loch inflows, results of this study suggest that, in the majority of scenarios, precipitation and, in turn, stream discharge becomes more seasonal. Increases in both are concentrated in the winter (discharge increase by 16.3–24.2% for the 2050s and 26.6–50.9% for the 2080s at the 50% probability level) whilst summer precipitation and stream flows decline (discharge by 25.4–34.2% for the 2050s and 30.6–48.7% for the 2080s, again at the 50% probability level). Similar trends have been reported in other modelling studies of climate change impacts on UK upland river discharge (e.g. Fowler & Kilsby 2007). The concentration of enhanced river flows within winter may limit opportunities for utilisation of additional water resources as existing reservoirs are more likely to be close to capacity at this time of year. Higher winter discharges are also likely to result in more regular flooding further downstream as well as in adjacent catchments. Dumfries and Galloway experienced extensive flooding in November 2009 which was described as the worst for 30 years (Dumfries and Galloway Standard 2009). Results of this study, which show increases in Q5 for the majority of scenarios, suggest that such flooding may become more common in the future. Conversely, lower summer river discharge is likely to lead to larger draw downs within Loch Dee as well as other water bodies downstream such as Clatteringshaws Loch. This situation will in turn reduce generating capacity and the potential for other forms of abstraction.

The projected changes in the magnitude and temporal distribution of flows may have important ecological impacts. For example, all three streams contain brown trout (Salmo trutta) (Burns et al. 1984; Winterbottom et al. 1997), an economically important salmonid (e.g. Gilvear et al. 2002). Populations within the Dargall Lane have shown some signs of recovery from surface water acidification (Malcolm et al. 2010). This cold water fish shows limited tolerance to high-water temperatures and during drought relies on deeper pools as refuges from high temperatures and low oxygen concentrations (e.g. Elliott 2000). The stress imposed by higher water temperatures, especially in summer, which can be expected as a result of climate change, is likely to be exacerbated by the projected lower discharges during the low flow period which will reduce the deeper water refuges (e.g. Matulla et al. 2007). Floods on the other hand may provide an advantageous function by de-silting the stream bed gravels in which trout spawn. However, large floods, which are projected to increase in most scenarios, have had the effect elsewhere in Scotland of washing out eggs laid in the gravels with consequent impacts on salmonid populations in subsequent years (Gilvear et al. 2002).

Other ecological impacts of the projected hydrological changes may be associated with changes in water quality. Relatively short-lived periods of low pH (‘acid episodes’) are a potential confounding factor impacting the ongoing recovery from surface water acidification (e.g. Lepori & Ormerod 2005; Battarbee et al. 2010). It has, for example, been suggested that with increased rainfall, flow paths such as overland flow, pipe flow and near surface through-flow will become more dominant (e.g. Evans et al. 2005). These flow paths are associated with water that is relatively acidic, base-cation dilute and enriched in organic acids. The impact of acidic episodes is more pronounced in catchments, such as those modelled in this study, where rapid changes in discharge result in the shift between highly acidic storm flow and buffered baseflow (Evans et al. 2008). Surface water acidity may also be impacted by the lower summer flows which would lead to increases in solute concentrations (Evans 2005; Evans et al. 2005). Possible changes in flow path are also a potential confounding factor for the projected changes in stream discharge. Higher winter temperatures are likely to reduce the incidence of frosts which can reduce infiltration rates and promote runoff (e.g. Cherkauer & Lettenmaier 1999; Jyrkama & Sykes 2007). Conversely increased cracking of organic soils as a result of elevated summer temperatures may increase the role of macropore flow thereby creating
alternative flow paths (e.g. Worrall et al. 2007). Continued monitoring of stream hydrology, hydrochemistry and ecology through initiatives such as the AWMN will be necessary to determine the nature of these changes.

**CONCLUSIONS**

Distributed hydrological models have been developed for three upland sub-catchments draining to Loch Dee, southwest Scotland. Following calibration and validation using both the traditional split sample approach and a proxy-basin test, the models successfully reproduced observed discharges.

The 54 climate change scenarios developed using UKCIP09 projections show increasing magnitude of changes in precipitation and PET with progressively higher emissions scenario and future time slice. Annual and, with one exception, monthly PET increases consistently for all probability levels. Central estimates of change (50% probability) in annual PET range between 8.9 and 10.7% for the 2050s, and 10.5 and 15.8% for the 2080s. In contrast, the direction of change in annual precipitation varies with probability level decreasing with those levels which are more likely to be exceeded (10–30%) and increasing at higher probability levels. Central estimates of change are increases of between 2.7 and 5.8% for the 2050s, and 5.6 and 10.5% for the 2080s. In all scenarios, precipitation becomes more seasonal, with the difference between winter and summer precipitation increasing with increasing emissions scenario and time slice.

Changes in stream discharge are shown to be driven by changes in precipitation with only minor modifications resulting from enhanced PET. Although there is uncertainty in changes in total annual discharge to Loch Dee (reductions for probability levels up to 50%, increases at higher levels with up to 6.0% increases for the 2050s and 11.5% for the 2080s at the 50% probability level), most scenarios project enhanced winter discharges (up to 24.2 and 50.9% for the 2050s and 2080s, respectively at the 50% probability level) and lower summer flows (2050s up to 34.2%, 2080s up to 48.7% at the 50% level). The difference between peak winter flows and summer low flows increases for all the scenarios indicating enhanced seasonality. These changes are likely to have implications for water resources as well as stream ecology and emphasise the need to continue monitoring within these sensitive upland environments.

**ACKNOWLEDGEMENTS**

Roger Flower and Raj Singh (UCL) assisted in the soil depth survey undertaken within the three modelled sub-catchments. Chris Curtis (UCL) provided additional soil depth data for the Dargall Lane. Geoff Shaw (Forestry Commission, Newton Stewart) provided information on forestry activities within the Loch Dee catchment including a digital map showing the location of forestry plantations. Precipitation, temperature and stream discharge data were acquired from the British Atmospheric Data Centre and the National River Flow Archive (Centre for Ecology and Hydrology). Some additional flow data were provided by John Burns (Scottish Environment Protection Agency). Ordnance Survey Land-Form PROFILE and 1:10000 raster map data are ©Crown Copyright 2010 and are an Ordnance Survey/EDINA supplied service. JRT is grateful for the comments on a draft manuscript provided by Jon French and Roger Flower. Valuable comments were also received from two reviewers.

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First received 3 November 2010; accepted in revised form 17 March 2011. Available online 27 January 2012.