Natural flood management, land use and climate change trade-offs

Iacob, Oana; Brown, Iain; Rowan, John

Published in:
Hydrological Sciences Journal

DOI:
10.1080/02626667.2017.1366657

Publication date:
2017

Licence:
Unspecified

Document Version
Peer reviewed version

Citation for published version (APA):
Iacob, O., Brown, I., & Rowan, J. (2017). Natural flood management, land use and climate change trade-offs: the case of Tarland catchment, Scotland. *Hydrological Sciences Journal*, *62*(12), 1931-1948. https://doi.org/10.1080/02626667.2017.1366657

Natural flood management, land use and climate change trade-offs: the case of Tarland catchment, Scotland

Oana Iacob[1], Iain Brown[2*] and John Rowan[3]

[1]*Arup, 63 St Thomas Street, Bristol BS1 6JZ, United Kingdom*
[2]*Stockholm Environment Institute, University of York, York, YO10 5DD, United Kingdom*
[3]*School of Social Sciences, University of Dundee, Dundee, DD1 4HN, United Kingdom*

**Corresponding author:* Iain.Brown@york.ac.uk
Tel: 44-1904-432897
ORCID: *0000-0002-3469-5598*

Natural flood management, land use and climate change trade-offs: the case of Tarland catchment, Scotland

Abstract: A distributed hydrological model (WASIM-ETH) was applied to a meso-scale catchment to investigate natural flood management as a non-structural approach to tackle flooding and climate change. Changes in peak flows were modelled using climate projections (UKCP09) in combination with afforestation-based land use change. Runoff projections showed a significant increase in peak flows from climate change. Afforestation could reduce some of the increased flow, with greatest benefit from coniferous afforestation, especially when replacing lowland farmland. Nevertheless, large-scale woodland expansion was required to maintain peak flows close to present and effects were reduced for more extreme floods. Afforestation was also modelled to increase risks of low flow episodes in summer. Evaluation using land-use scenarios showed catchment-scale trade-offs across multiple objectives were particularly complex when afforestation replaced lowland farmland. Hence, combined structural/non-structural measures may be required here and in similar catchments, with integrated catchment management to synergize across multiple objectives.

Keywords: climate change; land use change; hydrological modelling; catchment management; flood risk

Natural flood management, land use and climate change trade-offs: the case of Tarland catchment, Scotland

1. Introduction

River flooding is a major cause of damage, injury, and loss of life (Jongman *et al*. 2012). Intensification of the hydrological cycle due to climate change is expected to further increase this risk (Milly *et al*. 2002, Hirabayashi *et al*. 2008). Warmer air is both more energetic and can hold more moisture implying an increased likelihood of future extreme events as the climate warms (Allan and Soden 2008, IPCC 2012). Observational evidence suggests that a trend towards increased precipitation rates is evident in some regions and that this can be attributed to climate change (Lehmann et al. 2015). However, relating changes in precipitation to river flows and hence the occurrence of damaging flood events is a complex process that is also contingent on the local context of each river catchment, including factors such as topography, soils, land use and urbanisation (Merz and Blöschl 2003, Whitfield 2012, Ivancic and Shaw 2015). River flow response to a given meteorological event is controlled primarily by the availability of water storage within a catchment, the status of that storage due to antecedent conditions, and the response time of catchment water stores to precipitation inputs (Garner *et al*. 2015).

Results from linked climate and hydrological models identify north-west Europe as a region that is likely to experience increased flood risk (Dankers and Feyen 2008). However, projected future changes show large variations in the magnitude of risk due to assumptions inherent in the choice of hydrological or climate model, or the climate change scenario (Feyen *et al*. 2012, Kundzewicz *et al*. 2017). Furthermore, although the potential for combined effects has been highlighted (Bronstert *et al.* 2002), most quantified projections do not include the impacts of climate change when aggregated with changes in other hydrological drivers. These other drivers, notably land use change, are known from assessments of historic change to have had a significant role in modifying river flows and flooding regimes (Werritty *et al*. 2006, Wilby *et al*. 2008). Hence, despite good evidence that both climate change (Gädeke *et al*. 2013, Steele-Dunne *et al*. 2008) and land use change (Hundecha and Bárdossy 2004, Niehoff *et al*. 2002, Archer *et al*. 2010) can modify flood hydrology, very few studies have explored catchment-scale interactions between these two drivers (Dwarakish and Ganesri 2015). An exception is Bronstert *et al.* (2007) who used 'meteorological forcing' increments and land use change scenarios to highlight the importance of scale in understanding such interactions.

Changes in river flows have important implications for the design of flood protection schemes, challenging conventional design principles that assume stationarity of risk factors (Milly *et al*. 2008). This dichotomy has led to calls for a paradigm shift in concepts and practice of flood risk management in order to facilitate successful adaptation, recognising multiple systemic risk factors influencing both flood hazard exposure and societal vulnerability (Merz *et al*. 2010, Sayers *et al*. 2014). One adaptation strategy is to prioritise the site-specific upgrade of flood defence structures for the vulnerable areas, notably cities and towns, which are experiencing or expected to experience a change in flood risk. However, this strategy has implications not just in terms of additional economic costs but also regarding environmental consequences and amenity values: flood defence structures modify the natural morphology and habitat of the river and its floodplain which can lead to loss of biodiversity and associated ecosystem services (Roquette *et al*. 2011). In addition, irreducible uncertainties inherent within climate change projections mean that setting structural design limits through conventional 'best estimate' risk assessment approaches incurs a possibility of being locked in to a specific future pathway that does not materialise (Lawrence *et al*. 2013). These challenges have therefore led to greater interest in the role of non-structural measures that may act to reduce flood risk (Alfieri *et al*. 2016, Ciullo *et al.* 2017).

Natural flood management (NFM) schemes encompass a wide variety of options that aim to work with natural hydrological and hydromorphological processes to manage sources and pathways of flood waters, thereby reducing flood risk (Environment Agency 2010). This may include restoration, enhancement, or alteration of natural features and characteristics that attenuate rainfall-runoff processes, store water, and attenuate flow regimes of streams and rivers, notably through land and soil management which have been shown to influence local hydrology (O'Connell *et al.* 2007, Hess *et al.* 2010).

Using afforestation as a type of NFM has been demonstrated in a series of studies (e.g. Andréassian 2004, Nisbet and Thomas 2008). Afforestation can modify hydrological pathways through increases in interception (Robinson et al. 2003), infiltration (Bracken and Croke 2007), temporary storage (Ghavasieh *et al.* 2006), or by slowing conveyance (Lane et al. 2007, Thomas and Nisbet 2007) and attenuating runoff (Hundecha and Bárdossy 2004). Increasing woodland in upstream areas has been shown to reduce downstream peak flows using observations from paired catchments (McVicar *et al.* 2007) and model-based assessments (Francés *et al.* 2008, Salazar *et al.* 2012). Experimental evidence from a series of small upland control/treatment plots (12m by 12m) at Pontbren (central Wales) compared 2 years baseline data of intensive agricultural grazing with a similar period when newly planted with broadleaved woodland, finding woodland could enhance soil infiltration rates and reduce bulk runoff coefficients (aggregated runoff/rainfall ratios) by 78% on average; however removal of grazing animals alone reduced runoff coefficients by an average of 48% (Marshall *et al.* 2014). Modelling of flood conveyance processes association with restoration of lowland forested floodplains (20-40% afforestation of the 98km^2 Lymington catchment, S. England) identified reductions in peak discharge of up to 19% over a 25-year period through de-synchronisation of the timings of sub-catchment flood waves (Dixon *et al.* 2016b).

NFM studies have been used to suggest that flood risk management and climate change adaptation could be enhanced by strategic planting of trees and other catchment-scale initiatives; however, evidence appraisals also acknowledge the need for a stronger knowledge base on which to formulate such strategic decisions (Orr *et al.* 2008). Catchment-scale have often been assumed to scale up from small-scale NFM interventions from where most results are obtained, but there is a relative paucity of evidence on the scale of changes required to alleviate flood risk for catchments over 10km^2 in size (O'Connell *et al.* 2007, Parrott *et al.* 2009, Lane and Milledge 2013). As the dominant processes influencing runoff response and flooding are non-linear and hence vary across scales (Blöschl *et al.* 2007, Bronstert *et al.* 2007), it has been cautioned that results at smaller scales should not simply be generalised to larger scales (Deasy *et al.* 2014). The spatial configuration of land use, rather than just areal components, has also been identified as a key factor controlling runoff and catchment discharge (Ludwig *et al*. 2005). Furthermore, there is rather limited evidence on how land-based NFM options modify floods of different magnitudes or in different seasons. Seasonal distinctions are often associated with differences in flood-generating processes: 'long-rain floods', common in winter, are driven by weeks to months of lower-intensity, advective rainfall that exceeds the storage capacity of the soil and results in saturation-excess overland flow; 'short-rain floods', common in summer, are driven by short-duration, high-intensity, convective rainfall that result in infiltration-excess flow at the surface or sub-surface (Merz and Blöschl 2003, Bronstert *et al.* 2007).

The present study aims to improve understanding of catchment-scale NFM as a climate change adaptation strategy, not only regarding peak flows but also in the context of other benefits (Iacob *et al*. 2014, Collentine and Futter 2016). Specific objectives are: (i) to establish the influence of climate change on peak flows; (ii) to evaluate the efficacy of afforestation as a form of NFM in reducing peak flows; (iii) to investigate synergies and trade-offs between NFM and other land use issues.

2. Study Area

Tarland Burn catchment (area 72km^2) is a tributary of the River Dee in north-east Scotland (Fig. 1). This location has a history of disruptive flood events including in December 2000, October 2002, December 2005, March 2006, February 2009, July 2009, May 2010, December 2013 and December 2015. Most of these flood events occurred in typical 'winter' conditions due to surface runoff when soils were saturated; events in October 2002 and December 2015 have been categorised as 'major' events due to inundation and damage to properties in Aboyne and Tarland. The catchment is situated in impermeable rocks and spans an elevation range from 100-617m above sea level. Soils are mainly cambisols with humus-iron podsols on higher ground but the low-lying area is underlain by fine-grained alluvium. It supports a variety of land uses, predominantly arable, improved or unimproved grassland, woodland (mostly coniferous) and upland heath. To facilitate agricultural improvement, the low-lying alluvial area was drained in the 19th century. The Tarland Burn is included in an EU Natura2000 Special Protection Area (SPA) designation for the larger Dee catchment based upon biodiversity value. This has led to increased interest in alternative approaches for flood risk management, including non-structural measures. At the same time, the Scottish Government Land Use Strategy has identified a national policy priority for woodland expansion. Hence the role of afforestation for reducing flood risk and providing other benefits has been considered as a potential 'win-win' option. Historically, emphasis has been placed on coniferous plantations because of their faster growth rates and advantages for timber production but recent initiatives also now seek to promote new broadleaved woodland (Brown *et al*. 2014, Nijnik *et al*. 2016).

[Fig. 1 here]

3. Methods

3.1 Model description

Empirical work at catchment scale has significant logistical challenges therefore upscaling from local-scale assessments can often be more rationally facilitated by numerical modelling (Parrott *et al.* 2009, Pattison and Lane 2012). As the present study aimed to investigate spatial and temporal variations in hydrological processes associated with climate and land use change, a distributed hydrological model (WaSIM-ETH) was employed to parameterize catchment variability in soils, topography, land cover, and climate on a regular grid. Calibration and validation of the model were undertaken to adequately capture the hydrology of Tarland Burn catchment, and when a good representation was achieved it was then used to explore variability due to changes in climate and land cover. Change in peak flow was used as the key indicator of modified flood risk.

WaSiM-ETH is a fully-distributed physically-based hydrological model that has been previously used for land use (Hölzel *et al*. 2011, Niehoff *et al*. 2002, Verbunt *et al.* 2005) and climate change investigations (Gädeke *et al*. 2013, Jasper *et al.* 2004). It has also been used to distinguish different flood generation processes within a catchment (Bronstert *et al.* 2007). Vertical movement of water in the soil is assumed to be one-dimensional within the unsaturated zone with no exchange of water taking place between neighbouring cells. Soil cells are vertically defined by horizons and grouped into similar classes based upon soil type. Water in excess of infiltration capacity feeds directly to surface runoff, and the amount of infiltrating water serves as an upper boundary condition in the unsaturated zone. Percolation and capillary rise are determined by the soil properties and simulated by corresponding vertical moisture profiles and fluxes. The Van Genuchten (1980) equation is used to estimate soil-water retention and release based upon hydraulic head and conductivity, soil matrix potential, and the proportion of saturated and residual water content. Water fluxes are calculated on a regular grid using Richards (1931) equations in the unsaturated zone but are complemented by a model extension to simulate preferential flow through macropores direct to the saturated zone when precipitation intensity exceeds a threshold infiltration rate associated with the soil matrix. Linear storage approaches are applied to interflow and direct runoff using a single reservoir cascade method (isochronic with additional retention), requiring the calibration of the recession constants due to flow retention. Surface runoff is generated for each grid cell by including the infiltration excess and saturation overland flow. The generated runoff in each cell is routed to the outlet of the basin by topographic analysis with flow times calculated using the Manning-Strickler equation (Schulla and Jasper 2000). Flow velocities for the different water levels in the channel are calculated using both a kinematic wave approach and simple linear storage.

The type of precipitation is estimated for each grid cell using the interpolated air temperature: both rainfall and snow can occur at the same time within the transition range, and the same temperature-index approach was used to estimate snow melt. Potential evapotranspiration (ET) is calculated using the Penman-Monteith method based upon bulk-surface resistance values referenced for each land cover type (Monteith 1975, Brutsaert 1982). To calculate actual ET, potential ET is reduced by the amount of water equal to the interception storage of the plant canopy followed by a reduction based on soil suction properties and plant physiological properties of the land cover (Schulla and Jasper 2000). Interception storage is estimated using a simple bucket approach dependent on the total leaf coverage and the maximum height of the water layer on the vegetation. The extraction of water by ET from interception storage is considered at a potential rate in the model. If there is a sufficient amount of water held in interception storage, the storage content is reduced by the potential ET, and no water will be lost from the soil. If the interception storage content is smaller than the potential ET rate, the remaining content will be removed from the soil, unless the soil is too dry when the required suction values become too high for plant water availability.

3.2 Model setup and application

WASIM-ETH was set up on an hourly time step and all spatial data configured on a 50 m grid. For topographic data, a Digital Elevation Model (DEM) was derived from the Ordnance Survey Land-Form PROFILE dataset. Baseline land cover data were derived from the UK Land Cover Map 2007 (LCM2007: Morton *et al.* 2011) and grouped into broad classes (Figure 1c), each associated with key model parameters, including leaf area index, rooting depth and aerodynamic roughness (Breuer *et al.* 2003). Soil mapping units were derived from digital versions of 1:25:000 soils maps and attributed according to type profiles in the National Soils Inventory for Scotland (Scotland’s Soils 2016). Field drains in the alluvial area were set at a spacing of 25m based on available site evidence.

WASIM-ETH includes ROSETTA program routines that estimate soil matrix hydraulic properties based upon horizon texture data using pedo-transfer functions (Schaap *et al*. 2001). In addition, WASIM-ETH allows the volume of macropores to be parameterized based upon soil group properties. However, it is known from empirical data that different land uses can modify soil structure and permeability within the same texture class, particularly due to the presence of macropores acting as preferential flow pathways in the rooting zone (Jarvis *et al*. 2013). Gravity is the dominant force for water flow in macropores with capillary flow negligible compared to its role in the soil matrix (Bevan and Germann 2013). Pedo-transfer functions can therefore underestimate the importance of soil structure and overestimate texture in deriving hydraulic properties, particularly close to saturation (Gonzalez-Sosa *et al*. 2010, Vereecken *et al.* 2010). To account for this land use influence, soil saturated hydraulic conductivity (*Ks*) values as estimated by ROSETTA were further modified by incremental adjustments (Table 1) derived from analysis of field data by Archer *et al*. (2013) which, although measured outside Tarland catchment, was based upon land use variability of *Ks* across similar soil groups. These adjustments are consistent with a wider literature identifying that woodland areas have higher hydraulic conductivity and hence infiltration rates compared to other land uses due to the presence of extensive deep-rooting systems, and associated fauna, which increases macropores (Lange *et al*. 2009, Schwärzel *et al*. 2012, Peng *et al*. 2012, Jarvis *et al*. 2013, Marshall *et al*. 2014). On arable land, use of heavy machinery with annual crops has modified soil structure such that macropores are less evident whereas more persistent rooting systems in permanent grassland, especially in less intensively-used semi-natural areas, allow a relative increase in permeability compared to arable (Gonzalez-Sosa *et al*. 2010). Existing evidence was not considered robust enough to quantify different hydraulic properties for coniferous and deciduous woodland (Jost *et al.* 2012). Analysis suggests older woodlands have higher hydraulic conductivity (Archer *et al*. 2016) but as the present study is investigating the comparative influence of newly-planted woodland this age distinction was not

Commented [WU1]: Rosetta program was used (separately) to estimate soil matrix hydraulic properties which was then fed back into Wasim in the soil table.

included. Table 1 hence represents catchment-scale simplification of soil properties that are often highly variable, spatially and temporally (Jirků *et al.* 2013, Archer *et al.* 2016).

[Table 1 here]

3.3 Land use change

The impact of changes in land use was investigated through both sensitivity testing and scenario analysis. For sensitivity testing, proportions of woodland (coniferous or deciduous) were incrementally modified to replace other land uses together with different spatial configurations to explore its influence on hydrology. Scenario analysis investigated concurrent changes in multiple land cover types as a response to large-scale drivers, providing more realistic but more complex landscape configurations against which to explore hydrological change.

To facilitate both types of analysis, the LandsFACTS toolkit was employed to develop different spatial land cover configurations. Based upon a given set of constraints, LandsFACTS will generate multiple spatial and temporal land cover allocations for a landscape (Castellazzi *et al*. 2008). To test the influence of afforestation location, two general layouts were investigated: (i) upland afforestation, with a preference for replacing semi-natural habitats and unimproved grassland; (ii) lowland afforestation, with a preference for replacing cultivated land (arable and improved grassland)

For the scenario analysis, possible future changes in land use for the study area in 2050 were available from a previous cross-sectoral assessment using the combined influence of socio-economic scenarios (IPCC SRES framework) and climate change projections (UKCP09) on land use decisions (Brown and Castellazzi 2014; Table 2; Fig. 2). These scenarios also incorporate prospective responses by decision makers to a warming climate, notably the possibility of an increased area of land capable of being used for intensive agriculture in Scotland. Future scenarios of agricultural intensification associated with a policy priority for food security (National

Enterprise) or globalisation (World Markets) therefore act against increased afforestation in some parts of the catchment, particularly lowland areas. These intensification scenarios have previously been shown as leading to rather different land use patterns in the Tarland catchment when compared to scenarios where environmental regulation (Global Sustainability) or community-level decisions (Local Stewardship) are prioritised (Fig. 3). The Global Sustainability or Local Stewardship scenarios therefore provide more scope for woodland expansion whilst also prioritising native broadleaved rather than non-native coniferous woodland (Fig. 2).

[Table 2 here]

[Fig. 2 here]

[Fig. 3 here]

3.4 Climate change

For model calibration (section 3.5), hourly meteorological data were obtained from the weather station at Aboyne (archived by British Atmospheric Data Centre). Use was made of a WASIM-ETH module to interpolate meteorological parameters from station data across the catchment model grid using regression routines to infer parameter relationships with topography (provided by the DEM). To analyse the influence of climate change, synthetic data were derived using the UKCP09 weather generator (WG) (Jones *et al*. 2009). The UKCP09 project derived probabilistic climate projections from an ensemble of global climate models (GCMs) that were further downscaled to 25 km scale using the HadRM3 regional climate model (RCM) (Murphy *et al.* 2009). The UKCP09 WG allows further downscaling to 5 km based upon the use of statistically derived relationships between parameters as derived from an observed gridded climatology (Perry and Hollis 2005); each run of the WG for future periods represents a stochastic sample from the UKCP09 probability distribution that is constructed as an hourly time series using relationships from the observed climatology. For the present study, 30 years of hourly data were derived from the WG based upon aggregation of the 5km grid cells representing Tarland catchment. For each 30 year period, 100 sample runs of the WG were employed for both baseline (1961-1990) and future periods (2020s, 2050s, 2080s) with future runs based upon the UKCP09 medium emissions scenario (equivalent to IPCC A1B scenario).

3.5 Model calibration and validation

WASIM-ETH was trained using meteorological data for the period January 2004 to June 2009 and calibrated against flow data for Tarland Burn using gauging stations at Aboyne and Coull. The data record from Coull gauge has problems with consistency after 2007 due to channel modification, whereas Aboyne gauge records had some missing data. Hence, calibration was based upon the 2005 data from Coull, referenced against Aboyne data for goodness-of-fit purposes, whilst validation used 2006 data from Coull and 2006-2008 data from Aboyne. Calibration was conducted using a non-linear parameter estimation routine (PEST) that fits model to observation data by minimizing the weighted sum squared error using a robust variant of Gauss-Marquardt-Levenberg method that requires fewer model runs compared with similar algorithms to solve non-linear problems (Doherty and Skahill 2006, Singh *et al.* 2012). Nash-Sutcliffe efficiency (NSE) coefficients (Nash and Sutcliffe 1970) were calculated for each calibration step and if the results were considered unsatisfactory (coefficient value <0.5), model parameter data were refined before running another set of simulations and re-calculating the efficiency coefficients.

Commented [WU2]: Is model training covering both calibration and validation? I would have thought it is just calibration. Perhaps we can rephrase to 'The calibration and validation of the model was undertaken for the period January 2004 to June 2009'

Commented [WU3]: We used 2004 to run the model and level the water storages in the model; should we mention this as we then refer to calibration starting from 2005?

Commented [WU4]: Due to level logger mulfunctions

3.6 Flow analysis

The overall response of flow regimes to land use and climate change was summarised using flow duration curves (FDCs) to show discharge values exceeded for a given percentage of time e.g. 5% time for Q_5 discharge (Vogel and Fennessey 1994). To evaluate changes to extreme high flows, additional analysis was conducted, distinguishing 'summer' and 'winter' model calibration to allow for differing seasonal antecedent conditions, notably that storage capacity would typically be more limited during typical 'winter' conditions when 'long rain' events and saturated soils predominate. Extreme flows were generated from annual maxima of the 30-year WG time series data by using the General Extreme Values (GEV) probability distribution and L-moments fitting technique to calculate large return period events; this approach has previously been found to provide a robust technique for frequency analysis (Fowler and Kilsby 2003, Svensson and Jones 2010). Total rainfall for the chosen return periods events was distributed back to an hourly time step for 7-hour and 15-hour events using depth-duration-frequency model design profiles provided by the UK Flood Estimation Handbook on a 1km grid as derived from local rain gauges (with at least 10 years of data) and catchment descriptors (Institute of Hydrology 1999). The 7-hour event is identified as the critical design period based upon catchment size whereas a longer duration is represented by the 15-hour event. Extreme rainfall data were then modelled by WaSiM-ETH for summer and winter antecedent conditions in different climate and land use combinations.

4. Results

4.1 Model calibration and validation

The main parameters required for catchment-specific calibration of WASIM-ETH (Wriedt and Rode 2006) were set using the PEST tool (Table 3) to provide a satisfactory calibration ($R^2 = 0.76$ at Coull; $R^2 = 0.75$ at Aboyne; NSE=0.76 at Coull; NSE=0.68 at Aboyne). Validation at the two gauge sites showed a good general fit between observed and modelled discharge ($R^2 = 0.76$ at Coull; $R^2 = 0.75$ at Aboyne; NSE=0.63 at Coull; NSE=0.6 at Aboyne) indicating the model performed well in simulating the overall flow regime (Supplementary Material). However, there is an indication that the model is underestimating some high flow peaks in winter, which may be related to difficulties in simulating snowmelt or rain-on-snow events because of their sensitivity to small temperature changes and other local meteorological interactions (Beven 2012). To a lesser extent, the model may also underestimate some flow peaks in summer; this may be related to difficulties in identifying small-scale convectional events that produce locally intense rainfall but which are only partially represented in the weather station data or have an unusual relationship with catchment topography.

Modelling simulates saturated overland flow as dominant throughout the catchment during winter-type flood events, which is consistent with observations. During summer-type flood events, infiltration-excess is simulated for cambisols (mainly agricultural uses) and podsols on slopes around the basin, with this water routed by overland flow and inter-flow to the flat basin floor underlain by alluvial soils where both infiltration-excess and saturation occur as the capacity of the field drains is exceeded. Summer-type events are therefore rather more variable in terms of the relative dominance of flood generating processes, related to differing precipitation rates and antecedent soil moisture conditions, and as flood events are rarer they are more difficult to compare against limited observations.

4.2 Climate change and high flows

Extreme value analysis based upon the WG data and hydrological modelling shows that the magnitude of precipitation events and extreme high flow events could increase substantially (Table 4). These results suggest that by the 2080s, 1 in 100 year extreme flows could increase by up to ca.26% for both winter and summer 7-hour duration events, with possible greater changes for longer 15-hour events in summer. The larger increases have been inferred for the more extreme (1 in 100 year return) events, although this needs to be interpreted with caution because of the limited data on which it is based. Nevertheless, an increase in extreme precipitation values would be consistent with previous work in Scotland that has analysed UKCP09 and HadRM3 data (Kay *et al*. 2014b).

[Table 4 here]

4.3 Afforestation and high flows

Sensitivity testing (Fig. 4) showed a general relationship between increased afforestation extent and reduction in high flows (Q_5 metric), flow reduction being proportional to the increase in woodland area. For example, a 24% increase in new woodland decreases Q_5 flow by up to 19%. Woodland expansion with coniferous trees has a larger effect in reducing high flows; differences in flow reduction between coniferous and deciduous woodland were found greatest in winter when most flood events occur. Modelled reduction in high flows was therefore greatest for full catchment afforestation with coniferous woodland, albeit with the major caveat that such an outcome would be highly unlikely to happen because of the importance of agriculture in the study area (see section 4.6). Greater reduction in high flows was found for woodland planted in the lowland zone replacing cultivated agricultural land: 10% new woodland produced a 8% reduction in Q_5 for coniferous and 1% reduction for deciduous woodland. Results for the same proportion of new upland afforestation were smaller: 5% reduction in Q_5 for coniferous and 0.5% for deciduous woodland.

[Fig. 4 here]

Results for extreme high flows (Table 5) suggest some differences compared to general Q_5 high flows. Assuming no climate change, full catchment afforestation with coniferous woodland decreased the winter 7-hour 1 in 10 year return period event (12.5 m^3s^1) by 30% (compared with 62% for Q_5), although such a large land use change is considered unlikely. However, smaller increases in afforestation produced a lesser proportional reduction in extreme high flows than this upper potential value and less reduction than found with Q_5 flows. This suggests a diminution in the capacity of new woodland to reduce peak flows for the more extreme flood events, especially in summer albeit for smaller magnitude events.

[Table 5 here]

Results also suggest that afforestation can contribute to flood risk management by delaying the time taken to reach peak flow. Model simulations show full afforestation (100% cover) with coniferous woodland delayed the time to peak flow by 2 hours in the summer, and by 1 hour in the winter, for a 1 in 10 year return period 15-hour duration event. An increase in woodland to 75% cover delayed time to peak flow by 1 hour for the same reference event (1 in 10 year/ 15 hour duration) but only in summer. Similar results were found for larger magnitude events: for full coniferous afforestation, the 1 in 100 year / 15-hour event was found to take 1 hour longer to reach its peak; however, there is little difference in time for 75% afforestation, suggesting that large land use changes are required to induce this delayed flood peak and that they may be less effective for the largest extreme events.

4.4 Afforestation and low flows

Sensitivity testing also showed that woodland expansion would cause flow reductions across the flow duration curve, and not just for high flows (Fig. 5). Modelled reductions in low flows (as represented by the Q_{95} metric), which would occur mainly during the summer, were found to be proportional to the extent of additional woodland in the catchment and were found to be greatest for coniferous woodland. For example, 75% conifer afforestation was found to reduce Q_{95} discharge by greater than 50%, whilst 100% conifer afforestation was found to reduce Q_{95} by greater than 70% (Fig. 4).

[Fig. 5 here]

4.5 Afforestation and high flows with climate change

When land cover changes are combined with future climate projections, results continue to show that afforestation could reduce high flows when compared to existing land use (Table 5). With full catchment coniferous afforestation, maximum reductions of 30% peak flow are modelled for a 1 in 10 year 7-hour winter event for the 2080s compared to existing land use. For the same comparison in summer conditions, reductions could be even higher (up to 65%) but flow peaks are of smaller magnitude.

However, although peak flows are reduced by afforestation relative to existing land use, Table 5 also shows that the actual magnitude of flood events will still increase in future. Hence, the increase in flood risk due to climate change appears to exceed the capacity of land use change by afforestation to counteract it. Only full afforestation with coniferous woodland was able to reduce the magnitude of flood risk for the larger events (in winter) to be at a similar level to the baseline period by the 2080s, and this is more of a theoretical option rather than a realistic choice for the study area due to the importance of agriculture.

4.6 Land use change scenarios

In all cases, reductions in peak flow from the scenario analysis (Table 6) were rather less than the potential maximum changes from the sensitivity testing which used arbitrary afforestation increases without reference to the driving factors influencing land-use change. All land use scenarios showed a summer reduction in peak flow compared to the present land use, generally ca. 4-8%, which may be attributed to the expansion in woodland area (Table 6). Surprisingly, for both 1 in 10 and 1 in 100 year 7-hour and 15-hour events the National Enterprise (NE) scenario showed slightly higher reductions than other scenarios; although only a small expansion of coniferous woodland (+4%) was involved in this scenario it was mainly located in the lower part of the catchment close to the Coull station. For winter conditions, all scenarios showed reductions in peak flow compared to present land use but with larger variations between scenarios in a consistent pattern for different magnitude events, although smaller reductions are simulated for larger magnitude events. Hence, World Markets (WM) has the smallest reductions (2-3%) similar to the NE scenario (2-3%, except 5% reduction for 1 in 10 year 7-hour events). Global Sustainability (GS) has the largest reductions (4-8% depending on size of event) similar to Local Stewardship (LS) (4-7%), both of these scenarios having larger expansions of new woodland.

[Table 6 here]

Differences between scenarios can be partially explained by the significantly larger extent of afforestation for the GS and LS scenarios compared to smaller changes in the NE and WM scenarios. However, differences due to afforestation extent are partly offset because the NE and WM scenarios prioritise coniferous afforestation which, as shown by the sensitivity testing, was more effective at reducing peak flows than deciduous woodland (as favoured in GS and LS scenarios). In relative terms, the results suggest that the much larger expansion of woodland in the GS and LS scenarios is more effective than the type of tree in alleviating winter extreme flows but that the type and location of tree may be more effective than just large-scale planting in alleviating summer extreme flows. However, similar findings to the sensitivity testing apply in absolute terms, namely that the land use changes are insufficient by themselves to counter the increase in peak flows due to climate change. This is particularly applicable because of the much lower reductions in peak flows of the scenarios compared to the sensitivity tests.

It should be noted that land use scenarios do not include the possibility of large increases in coniferous woodland in the Tarland catchment, which would seem to offer the greatest potential reduction in flood risk, as other priorities act against this outcome (notably either maximising agricultural production or delivering environmental stewardship outcomes).

4. Discussion

5.1 Benefits of afforestation for NFM

Greater reductions were modelled for peak flows with coniferous compared to deciduous woodland highlighting the differing influence of interception and evaporation of water from the tree canopy. Coniferous trees, with higher overall leaf cover, have higher ET rates than deciduous trees (Cannell 1999). Differences in interception between coniferous and deciduous stands can vary by as much as 35%, hence UK coniferous woodland has been estimated to intercept and evaporate 25-45% of total annual precipitation, with the equivalent value for broadleaved woodland being 10-25% (Calder *et al*. 2003). By contrast, although forest transpiration rates are influenced by rooting network, leaf area index, stomatal response, albedo, and aerodynamic turbulence, they do not appear to show as large variations between deciduous and coniferous (Jackson *et al*. 2001).

Modelled reductions in peak flows for coniferous afforestation are consistent with previous research. Fahey and Jackson (1997) reported reduced peak flows of 55-65% from 67% afforestation of a small grassland catchment by comparison to an adjacent control catchment (both 200-300ha in area). Lane *et al.* (2005) recorded flow peak reductions based upon 10 paired catchments varying from 34-100%. Similarly, greater modelled peak flow reductions for afforestation on cultivated lowland compared to uncultivated upland is also consistent with previous work (Farley *et al.* 2005). By contrast, there appears less consensus about the effects of broadleaved woodland on catchment peak flows (Calder 2007, Roberts and Rosier 2005).

Reduced runoff rates from afforestation can also occur through increased infiltration rates associated with improved soil structure and macroporosity (Eldridge and Freudenberger 2005). In the present study, this was represented by land-use modifications to reference parameter values for soil hydraulic conductivity based upon field data (Archer *et al*. 2013). However, interactions between land use and soil processes are complex and dynamic (Robinson *et al.* 2003, Bens *et al*. 2006, Hümann *et al.* 2011, Archer *et al.* 2016), indicating that further investigation of land use influence on soil hydraulic properties, including for different woodland types, would be advantageous. Soil hydrology has also been further modified in some locations by the presence of artificial drainage systems to improve agriculture or forest productivity, but data on the type and spacing of drains is often limited (Brown 2017). Improved drainage systems to counteract soil waterlogging and promote tree growth is common practice for non-native conifer species in Scotland, although good practice guidelines are now meant to minimise disruption to local hydrology.

Further land-use related modification to runoff processes could occur through altered hydraulic roughness of vegetation, but this was not included in modelling for the present study. Previous studies suggest this could provide additional local benefits from afforestation: for example, Odoni *et al.* (2011) found that riparian woodland and debris dams could reduce peak flows by 8-10% whilst Dixon *et al.* (2016b) inferred reductions of up to 19% in peak flows from riparian woodland.

Differences in results between typical 'winter' and 'summer' conditions occur because soil storage capacity will generally be greater in summer when ET rates are higher and water tables are lower, by comparison to winter in Scotland when soils are typically close to saturation (Brown 2017). Seasonal differences are further increased for deciduous trees by reduced interception in winter due to leaf loss. Hence, potential peak flow reduction by afforestation decreases in winter because of less opportunity to divert precipitation away from runoff through alternative hydrological pathways. Consequently, a high proportion of precipitation in impermeable-bedrock catchments such as Tarland becomes surface runoff in winter through saturation excess; this proportion increases further during higher-magnitude precipitation events as any available storage is soon exceeded. Seasonal distinctions therefore have important implications for the effectiveness of NFM options throughout the year: results indicate a relatively reduced flood alleviation potential in winter following 'long-rain' events when most flood events occur. Benefits of afforestation are more apparent during summer when alleviating risks of 'flash flood' events from intense 'short-rain' convective events due to infiltration excess, but these are rarer events in NE Scotland.

In addition to peak flow reduction, benefits of afforestation have also been suggested to occur through delays in time taken to reach peak flow. Results from the catchment-scale modelling, suggesting an additional delay of 1-2 hours before peak flow, are consistent with those obtained from riparian woodland in similar catchments (e.g. Nisbet and Thomas 2008). This delay can provide additional time for flood warnings and other risk mitigation measures in downstream locations (e.g. evacuation of high-risk properties). However, modelling also suggested that relatively large increases in afforestation would be required to achieve this goal. Implications of changes in the flood hydrograph for inundation extents and land or property affected would require further assessment using hydraulic modelling.

Regarding distribution of land use within the catchment, the main factor identified herein has been that lowland afforestation produced greater reductions of peak flows compared to upland afforestation, which is attributed to the reduction in area of arable or improved grassland with lower infiltration capacities. There is also an indication from the NE scenario that siting new woodland closer to flow recording stations, and hence potentially adjacent to locations of high vulnerability, may also reduce peak flows areas if planting was strategically targeted, but again this is apparently beneficial only for rarer summer-type floods.

5.2 Data and model uncertainties

UKCP09 projections and the HadRM3 climate model ensemble have been used in several previous studies of hydrology and climate change (Bell *et al*. 2012, Cloke *et al*. 2010, Kay and Jones 2012, Kay *et al.* 2014a, 2014b). Nevertheless, challenges remain with the use of RCM data in hydrological modelling due to uncertainties in parametrization of key physical processes, notably local precipitation patterns (Smith *et al*. 2014). Climate data therefore often represent the dominant source of uncertainty in future projections of fluvial flooding (Prudhomme *et al.* 2010, Najafi *et al.* 2011) with the challenge compounded by the need to both downscale projections to catchment level and to accurately simulate different types of extreme event (Cloke *et al.* 2013).

The present study utilised a stochastic weather generator calibrated against a baseline observed dataset to provide downscaled spatial (5 km) and temporal data (hourly) at the level needed to accurately model changing flood risk in meso-scale catchments. Weather generators assume stationarity of local meteorological processes into the future and may therefore be too conservative in representing the dynamics of climate change (Dixon *et al.* 2016a). RCMs and GCMs use a more dynamic but much more computationally intensive procedure to evaluate such interactions. Derivation of high-resolution spatial and temporal climate data is therefore currently at the limit of skill for climate change modelling (Chapman *et al.* 2015). As highlighted above, challenges are further exacerbated by difficulties in parameterizing distributed hydrological models, particularly soil and vegetation properties, to represent spatial and temporal variations in hydrological response. These limitations necessitate caution when interpreting results on the actual magnitude of hydrological change associated with dynamic climate and land cover parameters. Nevertheless, in relative terms, the benefit of afforestation in reducing flood risk compared to existing land uses appears a reasonably robust outcome. The key issue for NFM would therefore appear to be identifying the scale, type and location of afforestation required to achieve significant advantages for flood risk management whilst also being cognisant of other societal issues associated with this land use change.

5.3 Trade-offs and climate change adaptation

Despite potential for afforestation to reduce flood risk, case study findings also suggest that climate change will continue to increase overall risk levels as heavy precipitation events increase in magnitude. Even large changes in land use seem insufficient to maintain flood risk at a similar level to the present, implying other catchment-based adaptation measures are likely to be required, either structural defences or other non-structural NFM initiatives (e.g. debris dams; reconnecting floodplains). A more radical alternative would be to accept a higher residual flood risk which would become the default strategy if improved flood protection, either through NFM or structural defences, is not implemented (Alfieri *et al.* 2016).

The NFM benefits of afforestation appear constrained because of limited capacity to reduce flooding in winter when most large events occur. Even for summer, results also suggest afforestation to be more effective at reducing risk for smaller events compared to larger extreme events, consistent with other studies suggesting benefits are greatest for return periods less than 5-10 years and rather smaller for more extreme floods (Beschta *et al*. 2000, Lane *et al.* 2005, Francés *et al*. 2008, Salazar *et al*. 2012). Similarly, results are consistent with research in the Rhine basin (Bronstert *et al*. 2007) in suggesting greater benefits in alleviating flood risk from extreme convectional short-rain events (typically summer) compared to advective long-rain events, whereas the latter is the dominant risk. Nevertheless, even small contributions to flood alleviation may provide an important contribution to risk management (van Dijk *et al*. 2009, Bathurst *et al*. 2011). Furthermore, there is some evidence that convective events are increasing in frequency and magnitude due to climate warming, increasing the prevalence of 'summer' type risks (Ye *et al*. 2017).

An important issue not generally considered for flood risk alleviation schemes (including NFM) is their potential impact on low flows. Case study results showed that woodland expansion also reduces low flow discharge and that this is most pronounced for coniferous woodland. A shift in catchment hydrology towards increased forest interception and ET rates has previously been linked with reduced base flows (Bosch and Hewlett 1982, Robinson *et al.* 2003). Sensitivity analysis for an upland catchment in central Wales found a 1.5-2% general reduction in water yields for every 10% of additional mature coniferous forest (Calder *et al.* 2009). When combined with potential flow reductions due to projected trends towards warmer drier summers in the UK (Christiersen *et al*. 2012), poorly-planned afforestation may exacerbate low flow problems and cause adverse impacts on aquatic ecology and water quality. An additional factor is that if summer drought risk also increases then some tree species such as Sitka spruce, the current dominant conifer species in Scotland, may become increasingly vulnerable to water stress (Green *et al*. 2008); any resulting physiological damage (e.g. leaf loss) may subsequently disrupt ecohydrological function during wetter conditions and hence reduce their flood alleviation role.

A further reality check is that afforestation is normally more preferred as a land use option on lower quality land where there is less competition from agriculture (Slee *et al*. 2014). In Scotland, this has led to a preference for new woodland to be planted on uncultivated uplands (Brown *et al*. 2015). A shift towards more lowland afforestation would therefore imply that it is integrated with existing agricultural land uses (e.g. as agroforestry or riparian woodland), which raises further issues regarding the scale of intervention required to significantly alleviate flood risk. As shown by the scenario analysis, 'optimal' land-use change to deliver NFM benefits is probably unlikely to be fully realised because of the influence of other drivers on land use decisions. Hence, in reality, flood risk management decisions have to be made in a landscape of diverse land uses with differing societal benefits and each influenced by drivers of change. When aggregated at catchment scale this typically implies complex trade-offs are required.

The diversity of catchment contexts and inherent trade-offs suggest that, despite the benefits of NFM schemes, it may not be appropriate to consider them as universal 'win-win' solutions, particularly with regard to climate change adaptation. Afforestation options evaluated in the case study would involve land use changes over a significant proportion of the catchment and, in addition to potential trade-offs between low and high flow objectives, are likely to have major consequences for other ecosystem services, notably loss of productive agricultural land for crops and livestock (Brown and Castellazzi 2014, Collentine and Futter 2016). Benefits from new woodland also need to be considered in the context of the growth rates of different types of woodland. The faster growth rates of coniferous trees mean they offer greater benefits for timber production and carbon sequestration, in addition to apparent greater benefits for flood risk alleviation. However, deciduous woodland may be considered more multifunctional due to added benefits for native biodiversity, recreation and amenity value (Brown and Castellazzi 2014). Trees, particularly conifers, also significantly increase risk of transfer of acidifying pollutants from air to soil and surface waters (Cannell 1999). Trade-offs and synergies imply that NFM benefits from woodland expansion need to be more explicitly integrated with related initiatives, including land use planning and water management (Rouillard *et al.* 2015). This would allow NFM concepts to be advanced within the wider context of an integrated catchment management strategy to deliver multiple ecosystem services (Calder and Aylward, 2006, Iacob et al. 2014).

5. Conclusions

Model-based investigation of afforestation NFM options in Tarland catchment (NE Scotland), employing both sensitivity testing and scenario analysis, has shown it can reduce peak high flows, particularly coniferous woodland. Significantly, peak flow reductions appear to be less for higher magnitude extreme events and less in typical 'winter' UK conditions when soils are saturated and ET rates lower. This suggests that afforestation-based NFM may only have a limited effect in mitigating the largest extreme flood events that typically occur during the winter.

Catchment afforestation was unable to counteract a general increase in peak flows due to climate change. A possible exception may be provided by full catchment conifer afforestation, but this option is considered implausible because a large proportion of land has high agricultural value. Similarly, although sensitivity analysis showed greater NFM benefits for new woodland replacing cultivated agricultural lowlands, such an 'optimal' solution would involve loss of land for crop and livestock production. Scenario analysis showed that complex interactions between land use, climate change and policy drivers mean that optimum land use configurations for flood risk reduction are unlikely to be achieved. Hydrological modelling also showed that afforestation could reduce low flows, particularly for coniferous woodland despite it providing the greater benefits for reducing high flows, highlighting that options appraisal needs to consider integrated management of low and high flows in a changing climate.

These findings support the use of afforestation as an important contributor to flood risk management. However, they also identify that it needs to be linked with other risk management measures within an integrated catchment management and climate change adaptation strategy. Furthermore, measures need to be designed to best suit local contexts and priorities rather than assuming a universal 'win-win' solution. Risk management strategies may therefore need to include other compatible NFM and structural approaches. A strategic advantage of land-use related NFM options may be that they can help provide a flexible 'low regrets' approach to risk management which can adapt and evolve in the context of changing circumstances and knowledge (Ciullo *et al*. 2017).

Acknowledgements

The authors acknowledge the advice of the anonymous reviewers in improving the quality of the original manuscript.

Disclosure statement

No potential conflict of interest is reported by the authors.

Funding

This work was supported by the Scottish Government through its ClimateXChange initiative and the Strategic Research Programme (Environmental Change).

References

Allan, R.P., Soden, B.J., 2008. Atmospheric warming and the amplification of precipitation extremes. *Science,* 321, 1481–1484.

Andréassian, V., 2004. Waters and forests: from historical controversy to scientific debate. *Journal of Hydrology,* 291, 1-27.

Alfieri, L., Feyen, L. and Di Baldassarre, G., 2016. Increasing flood risk under climate change: a pan-European assessment of the benefits of four adaptation strategies. *Climatic Change*, 136, 507-521.

Archer, N.A.L., Bonell , M., Coles, N., MacDonald, A.M., Anton, C.A., Stevenson, R., 2013. Soil characteristics and landcover relationships on soil hydraulic conductivity at hillslope scale: a view towards local flood management. *Journal of Hydrology*, 497, 208–222.

Archer, D.R., Climent-Soler, D., Holman, I., 2010. Changes in discharge rise and fall rates applied to impact assessment of catchment land use. *Hydrology Research*, 41, 13-26.

Bathurst, J.C., Iroumé, A., Cisneros, F., Fallas, J., Iturraspe, R., Novillo, M.G., Urciuolo, A., De Bièvre, B., Borges, V.G., Coello, C., Cisneros, P., 2011. Forest impact on floods due to extreme rainfall and snowmelt in four Latin American environments 1: Field data analysis. *Journal of Hydrology*, 400, 281-291.

Bell, V.A., Kay, A.L., Cole, S.J., Jones, R.G., Moore, R.J., Reynard, N.S., 2012. How might climate change affect river flows across the Thames Basin? An area-wide analysis using the UKCP09 Regional Climate Model ensemble. *Journal of Hydrology*, 442, 89-104.

Bens, O., Wahl, N.A., Fischer, H., Hüttl, R.F., 2007. Water infiltration and hydraulic conductivity in sandy cambisols: impacts of forest transformation on soil hydrological properties. *European Journal of Forest Research*, 126, 101-109.

Beschta, R.L., Pyles, M.R., Skaugset, A.E., Surfleet, C.G., 2000. Peakflow responses to forest practices in the western cascades of Oregon, USA. *Journal of Hydrology*, 233, 102-120.

Beven, K., 2012. Rainfall-runoff modelling: the primer. 2nd ed. Chichester, UK: Wiley-Blackwell.

Beven, K., Germann, P., 2013. Macropores and water flow in soils revisited. *Water Resources Research*, *49*, 3071-3092.

Blöschl G., Ardoin-Bardin S., Bonell M., Dorninger M., Goodrich D., Gutknecht D., Matamoros, D., Merz, B., Shand, P., Szolgay, J., 2007. At what scales do climate variability and land cover change impact on flooding and low flows? *Hydrological Processes*, 21, 1241–1247.

Bosch, J.M., Hewlett, J.D., 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. *Journal of Hydrology*, 55, 3-23.

Bracken, L.J., Croke, J., 2007. The concept of hydrological connectivity and its contribution to understanding runoff-dominated geomorphic systems. *Hydrological Processes*, 21, 1749-1763.

Breuer, L., Eckhardt, K., Frede, H.G., 2003. Plant parameter values for models in temperate climates. *Ecological Modelling*, 169, 237-293.

Bronstert, A., Niehoff, D., Burger, G., 2002. Effects of climate and land-use change on storm runoff generation: present knowledge and modelling capabilities. *Hydrological Processes*, 16, 509-529.

Bronstert, A., Bardossy, A., Bismuth, C., Buiteveld, H., Disse, M., Engel, H., Fritsch, U., Hundecha, Y., Lammersen, R., Niehoff, D., Ritter, N., 2007. Multi-scale modelling of land-use change and river training effects on floods in the Rhine basin. *River Research and Applications*, 23, 1102-1125.

Brutsaert, W.H., 1982 Evaporation into the atmosphere: Theory, history, and applications. Dordrecht: Reidel Publishing.

Brown, I., 2017. Climate change and soil wetness limitations for agriculture: risk assessment framework with application to Scotland. *Geoderma* doi:10.1016/j.geoderma.2016.09.023

Brown, I., Castellazzi, M., 2014. Scenario analysis for regional decision making on sustainable multifunctional landscapes. *Regional Environmental Change,* 14*,* 1357-1371.

Brown, I., Castellazzi, M., Feliciano, D., 2014. Comparing path dependence and spatial targeting of land use in the implementation of climate change responses. *Land,* 3, 850-873.

Calder, I.R., 2007. Forests and water—ensuring forest benefits outweigh water costs. *Forest Ecology and Management*, 251, 110-120.

Calder, I.R., Aylward, B., 2006. Forest and floods: Moving to an evidence-based approach to watershed and integrated flood management. *Water International*, 31, 87-99.

Calder, I.R., Nisbet, T., Harrison, J.A., 2009. An evaluation of the impacts of energy tree plantations on water resources in the United Kingdom under present and future UKCIP02 climate scenarios. *Water Resources Research*, 45 doi: 10.1029/2007WR006657

Calder, I.R., Reid, I., Nisbet, T.R., Green, J.C., 2003. Impact of lowland forests in England on water resources: Application of the Hydrological Land Use Change (HYLUC) model. *Water Resources Research*, 39 doi: 10.1029/2003WR002040

Cannell, M.G., 1999. Environmental impacts of forest monocultures: water use, acidification, wildlife conservation, and carbon storage. *New Forestry*, 17, 239-262.

Castellazzi, M.S., Matthews, J., Angevin, F., Sausse, C., Wood, G.A., Burgess, P.J., Brown I., Conrad, K.F., Perry J.N., 2010. Simulation scenarios of spatio-temporal arrangement of crops at the landscape scale. *Environmental Modelling & Software,* 25, 1881-89.

Chapman, S.C., Stainforth, D.A., Watkins, N.W., 2015. Limits to the quantification of local climate change. *Environmental Research Letters*, 10, 094018 doi:10.1088/1748-9326/10/9/094018

Christiersen, B.V., Vidal, J-P., Wade, S.J., 2012. Using UKCP09 probabilistic climate information for UK water resource planning. *Journal of Hydrology*, 424, 48–67.

Ciullo, A., Viglione, A., Castellarin, A., Crisci, M., Di Baldassarre G., 2017. Socio-hydrological modelling of flood-risk dynamics: comparing the resilience of green and technological systems. *Hydrological Sciences Journal*, 62, 880-891. doi: 10.1080/02626667.2016.1273527

Cloke, H.L., Jeffers, C., Wetterhall, F., Pappenberger, F., Byrne, T., Lowe, J., 2010. Climate impacts on river flow: projections for the Medway catchment UK with UKCIP and CATCHMOD. *Hydrological Processes*, 24, 3476–3489.

Cloke, H.L., Wetterhall, F., He, Y., Freer, J.E. Pappenberger, F., 2013. Modelling climate impact on floods with ensemble climate projections. *Quarterly Journal of the Royal Meteorological Society*, 139, 282-297.

Collentine, D. and Futter, M.N., 2016. Realizing the potential of Natural Water Retention Measures in catchment flood management: Tradeoffs and matching interests. *Journal of Flood Risk Management*, doi:10.1111/jfr3.12269

Dankers, R., Feyen, L., 2008. Climate change impact on flood hazard in Europe: An assessment based on high-resolution climate simulations. *Journal of Geophysical Research*, 113, D19105.

Deasy, C., Titman, A., Quinton, J., 2014. Measurement of flood peak effects as a result of soil and land management, with focus on experimental issues and scale. *Journal of Environment Management*, 132, 304-312.

Dixon, K.W., Lanzante, J.R., Nath, M.J., Hayhoe, K., Stoner, A., Radhakrishnan, A., Balaji, V., Gaitán, C.F., 2016a. Evaluating the stationarity assumption in statistically downscaled climate projections: is past performance an indicator of future results? *Climatic Change,* 135, 395-408.

Dixon, S. J., Sear, D. A., Odoni, N. A., Sykes, T., Lane, S. N., 2016b. The effects of river restoration on catchment scale flood risk and flood hydrology. *Earth Surfaces Processes and Landforms,* 41, 997–1008.

Doherty, J., Skahill, B.E., 2006. An advanced regularization methodology for use in watershed model calibration. *Journal of Hydrology*, 327, 564-577.

Dwarakish, G.S., Ganesri, B.P., 2015. Impact of land use change on hydrological systems: A review of current modeling approaches. *Cogent Geosciences*, 1, 1115691 http://dx.doi.org/10.1080/23312041.2015.1115691

EC, 2007. Directive 2007/60/EC of the European Parliament and of the council on the assessment and management of flood risks.

Eldridge, D.J., Freudenberger, D., 2005. Ecosystem wicks: woodland trees enhance water infiltration in a fragmented agricultural landscape in eastern Australia. *Austral Ecology*,30, 336-347.

Environment Agency, 2010.Working with Natural Processes to Manage Flood and Coastal Erosion Risk: A Guidance Document. **Bristol, UK:** Environment Agency.

Fahey, B., Jackson, R., 1997. Hydrological impacts of converting native forests and grasslands to pine plantations, South Island, New Zealand. *Agricultural and Forest Meteorology*, 84, 69–82.

Farley, K.A., Jobbágy, E.G., Jackson, R.B., 2005. Effects of afforestation on water yield: a global synthesis with implications for policy. *Global Change Biology*, 11, 1565-1576.

Feyen, L., Dankers, R., Bódis, K., Salamon, P., Barredo, J. I., 2012. Fluvial flood risk in Europe in present and future climates. *Climatic Change,* 112, 47–62.

Fowler, H. J., Kilsby, C. G., 2003. A regional frequency analysis of United Kingdom extreme rainfall from 1961 to 2000. *International Journal of Climatology*, 23, 1313–1334.

Francés, F., García-Bartual, R., Ortiz, E., Salazar, S., Miralles, J. L.,Blöschl, G., Komma, J., Habereder, C., Bronstert, A.,Blume, T. , 2008. Efficiency of non-structural flood mitigationmeasures: ‘room for the river’ and ‘retaining water inthe landscape’. CRUE Research Report No I-6, London, UK. Available at: http://www.crue-eranet.net/Calls/Room_for_the_River_final_report.pdf [Accessed 5 September 2016]

Gädeke, A., Hölzel, H., Koch, H., Pohle, I. and Grünewald, U., 2014. Analysis of uncertainties in the hydrological response of a model-based climate change impact assessment in a subcatchment of the Spree River, Germany. *Hydrological Processes*, 28, 3978-3998.

Garner, G., van Loon, A.F., Prudhomme, C., Hannah, D.M., 2015. Hydroclimatology of extreme river flows. *Freshwater Biology*, 60, 2461–2476.

Ghavasieh, A.R., Poulard, C., Paquier, A., 2006. Effect of roughened strips on flood propagation: assessment on representative virtual cases and validation. *Journal of Hydrology*, 318, 121-137.

Gonzales-Sosa, E., Braud, I., Dehotin, J., Lassabatère, L., Angulo-Jaramillo, R., Lagouy, M., Branger, F., Jacqueminet, C., Kermadi, S., Michel, K., 2010. Impact of land use on the hydraulic properties of the topsoil in a small French catchment. *Hydrological Processes*, 24, 2382–2399.

Green, S., Hendry, S.J., Redfern, D.B., 2008. Drought damage to pole-stage Sitka spruce and other conifers in north-east Scotland. *Scottish Forestry*, 62, 10–18.

Hess, T.M., Holman, I.P., Rose, S.C., Rosolova, Z., Parrott, A., 2010. Estimating the impact of rural land management changes on catchment runoff generation in England and Wales. *Hydrological Processes*, 24, 1357-1368.

Hirabayashi, Y., Kanae, S., Emori, S., Oki, T., Kimoto, M., 2008. Global projections of changing risks of floods and droughts in a changing climate. *Hydrological Science Journal*, 53, 754–772.

Hölzel, H., Rössler, O. and Diekkrüger, B., 2011. Grope in the Dark–Hydrological modelling of the artificial Chicken Creek catchment without validation possibilities. *Physics and Chemistry of the Earth ABC*, 36, 113-122.

Hundecha, Y., Bárdossy, A., 2004. Modeling of the effect of land use changes on the runoff generation of a river basin through parameter regionalization of a watershed model. *Journal of Hydrology*, *292*, 281-295.

Hümann, M., Schüler, G., Müller, C., Schneider, R., Johst, M., Caspari, T., 2011. Identification of runoff processes–The impact of different forest types and soil properties on runoff formation and floods. *Journal of Hydrology*, 409, 637-649.

Iacob, O., Rowan, J.S., Brown, I., Ellis, C., 2014. Evaluating wider benefits of natural flood management strategies: an ecosystem-based adaptation perspective. *Hydrology Research*, 45, 774–787.

Institute of Hydrology, 1999. Flood Estimation Handbook, 5 volumes. Wallingford, UK.

IPCC, 2012. Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. Cambridge, UK: Cambridge University Press.

Ivancic, T.J., Shaw, S.B., 2015. Examining why trends in very heavy precipitation should not be mistaken for trends in very high river discharge. *Climatic Change*, 133, 681-693.

Jackson, R.B., Carpenter, S.R., Dahm, C.N., McKnight, D.M., Naiman, R.J., Postel, S.L., Running, S.W., 2001. Water in a changing world. *Ecological Applications*, 11, 1027-1045.

Jarvis, N., Koestel, J., Messing, I., Moeys, J., Lindahl, A., 2013. Influence of soil, land use and climatic factors on the hydraulic conductivity of soil. *Hydrology and Earth Systems Science*, 17, 5185–5195.

Jasper, K., Calanca, P., Gyalistras, D., Fuhrer, J., 2004. Differential impacts of climate change on the hydrology of two alpine river basins. *Climate Research*, 26, 113-129.

Jirků, V., Kodešová, R., Nikodem, A., Mühlhanselová, M. and Žigová, A., 2013. Temporal variability of structure and hydraulic properties of topsoil of three soil types. *Geoderma 204*, 43-58.

Jones , P.D., Kilsby, C.G., Harpham, C., Glenis, V., Burton, A., 2009. UK climate projections science report: projections of future daily climate for the UK from the weather generator. Newcastle, UK: University of Newcastle.

Jongman, B., Ward, P. J., Aerts, J. C. J. H., 2012. Global exposure to river and coastal flooding: Long term trends and changes. *Global Environmental Change*, 22, 823–835.

Jost, G., Schume, H., Hager, H., Markart, G., Kohl, B., 2012.A hillslope scale comparison of tree species influence on soil moisture dynamics and runoff processes during intense rainfall. *Journal of Hydrology,* 420-421, 112–124.

Kay, A.L., Jones, D.A., 2012. Transient changes in flood frequency and timing in Britain under potential projections of climate change. *International Journal of Climatology*, 32, 489–502.

Kay, A.L., Crooks, S.M., Davies, H.N., Prudhomme, C., Reynard, N.S., 2014a. Probabilistic impacts of climate change on flood frequency using response surfaces I: England and Wales. *Regional Environmental Change*, 14, 1215-1227.

Kay, A.L., Crooks, S.M., Davies, H.N., Reynard, N.S., 2014b. Probabilistic impacts of climate change on flood frequency using response surfaces II: Scotland. *Regional Environmental Change*, 14, 1243-1255.

Kundzewicz, Z.W., Krysanova, V., Dankers, R., Hirabayashi, Y., Kanae, S., Hattermann, F.F., Huang, S., Milly, P.C.D., Stoffel, M., Driessen, P.P.J. and Matczak, P., 2016. Differences in flood hazard projections in Europe–their causes and consequences for decision making. *Hydrological Sciences Journal*, 62, pp.1-14.

Lane, P. N. J., Best, A.E., Hickel, K.,Zhang, L., 2005. The response of flow duration curves to afforestation. *Journal of Hydrology*, 310, 253–265.

Lane, S.N., Milledge, D.G., 2013. Impacts of upland open drains upon runoff generation: a numerical assessment of catchment-scale impacts. *Hydrological Processes*, 27, 1701-1726.

Lane, S.N., Tayefi, V., Reid, S.C., Yu, D., Hardy, R.J., 2007. Interactions between sediment delivery, channel change, climate change and flood risk in a temperate upland environment. *Earth Surface Processes and Landforms*, 32, 429-446.

Lange B, Luescher P, Germann PF., 2009. Significance of tree roots for preferential infiltration in stagnic soils. *Hydrology and Earth System Sciences*, 13, 1809–1821.

Lawrence, J., Reisinger, A., Mullan, B., Jackson, B., 2013. Exploring climate change uncertainties to support adaptive management of changing flood-risk. *Environmental Science & Policy*, 33,133–142

Lehmann, J., Coumou, D., Frieler, K., 2015. Increased record-breaking precipitation events under global warming. *Climatic Change*, 132, 501–515.

Ludwig, J.A., Wilcox, B.P., Breshears, D.D., Tongway, D.J., Imeson, A.C., 2005. Vegetation patches and runoff–erosion as interacting ecohydrological processes in semiarid landscapes. *Ecology*, 86, 288-297.

Marshall, M.R., Ballard, C.E., Frogbrook, Z.L., Solloway, I., McIntyre, N., Reynolds, B., Wheater, H.S., 2014. The impact of rural land management changes on soil hydraulic properties and runoff processes: results from experimental plots in upland UK. *Hydrological Processes,* 28, 2617-2629.

McVicar, T.R., Li, L., Van Niel, T.G., Zhang, L., Li, R., Yang, Q., Zhang, X., Mu, X., Wen, Z., Liu, W. and Zhao, Y.A., 2007. Developing a decision support tool for China's re-vegetation program: Simulating regional impacts of afforestation on average annual streamflow in the Loess Plateau. *Forest Ecology and Management*, *25*, 65-81.

Merz, R., Blöschl, G., 2003. A process typology of regional floods. *Water Resources Research*, 29, 1340.

Merz, B., Hall, J., Disse, M., and Schumann, A., 2010. Fluvial flood risk management in a changing world. *Natural Hazards and Earth Systems Science*, 10, 509-527.

Milly, P., Wetherald, R., Dunne, K., Delworth, T., 2002. Increasing risk of great floods in a changing climate. *Nature,* 415, 514–517.

Milly, P.C.D., Betancourt, J., Falkenmark, M., Hirsch, R.M., Kundzewicz, Z.W., Lettenmaier, D.P. and Stouffer, R.J., 2008. Stationarity Is dead: whither water management? *Science*, 319, 573-574.

Monteith, J.L., 1975. Vegetation and the Atmosphere. Vol. 1. Principles. London: Academic Press.

Morton, D., Rowland, C., Wood, C., Meek, L., Marston, C., Smith, G., Wadsworth, R., 2011. Countryside Survey: Final Report for LCM2007- the new UK Land Cover Map. Lancaster, UK.: Centre for Ecology & Hydrology.

Murphy, J.M., Sexton, D.M.H., Jenkins, G.J., Booth, B.B.B., Brown, C.C., Clark, R.T., Collins, M., Harris, G.R., Kendon, E.J., Betts, R.A., Brown, S.J., Humphrey, K.A., McCarthy, M.P., McDonald, R.E., Stephens, A., Wallace, C., Warren, R., Wilby, R., Wood, R.A., 2009. UK Climate Projections Science Report: Climate Change Projections. Exeter, UK: Met Office Hadley Centre.

Najafi, M.R., Moradkhani, H., Jung, I.W., 2011. Assessing the uncertainties of hydrologic model selection in climate change impact studies. *Hydrological Processes*, 25, 2814-2826.

Nash, J.E., Sutcliffe, J.V., 1970. River flow forecasting through conceptual models. Part I: A discussion of principles. *Journal of Hydrology,* 10, 282–290.

Niehoff, D., Fritsch, U., Bronstert, A., 2002. Land-use impacts on storm-runoff generation: scenarios of land-use change and simulation of hydrological response in a meso-scale catchment in SW-Germany. *Journal of Hydrology,* 267, 80-93.

Nijnik, M., Nijnik, A., Brown, I., 2016. Exploring the linkages between multi-functional forestry goals and the legacy of spruce plantations in Scotland. *Canadian Journal of Forest Research*, doi: 10.1139/cjfr-2015-0399

Nisbet, T. R., Thomas, H., 2008. Restoring Floodplain Woodland for Flood Alleviation. Final Report. Defra, London, UK. Available at:
http://www.forestry.gov.uk/pdf/defra_floodplain_report_15june2008.pdf/
[Accessed 5 April 2016]

O'Connell, P. E., Ewen, J., O'Donnell, G., Quinn, P., 2007. Is there a link between agricultural land-use management and flooding? *Hydrology and Earth System Science*, 11, 96–107.

Odoni, N. A., Nisbet, T. R., Broadmeadow, S. B., Lane, S. N., Huckson, L. V, Pacey, J. , Marrington, S., 2010. Evaluating the effects of riparian woodland and large woody debris dams on peak flows in Pickering Beck. North Yorkshire, UK. Project RMP55455: Slowing the flow at Pickering. Available at http://www.forestry.gov.uk/pdf/ [Accessed 3 May 2016]

Orr, H., Wilby, R., Hedger, M., Brown I., 2008. Climate change in the uplands: a UK perspective on safeguarding regulatory ecosystem services. *Climate Research*, 37, 77- 98.

Parrott, A., Brooks, W., Harmar, O., Pygott, K., 2009. Role of rural land use management in flood and coastal risk management. *Journal of Flood Risk Management*, 2, 272-284.

Pattison, I., Lane, S.N., 2012. The link between land-use management and fluvial flood risk: A chaotic conception? *Progress in Physical Geography*, 36, 72-92.

Peng, S.L., Wu, J., You, W.H., 2012. Recovery of saturated hydraulic conductivity along a forest successional series from abandoned land to mature, evergreen broad-leaved forest in eastern China. *Soil Research,* 50, 257–266.

Perry, M., Hollis, D., 2005. The generation of monthly gridded datasets for a range of climatic variables over the UK. *International Journal of Climatology*, 25,1041–1054.

Prudhomme, C., Kay, A.L., Crooks, S. Reynard, N., 2013. Climate change and river flooding: Part 2 sensitivity characterisation for British catchments and example vulnerability assessments. *Climatic Change,* 119, 949-964.

Richards, L.A., 1931. Capillary conduction of liquids through porous mediums. *Physics,* 1, 318-333.

Roberts, J., Rosier, P., 2005. The impact of broadleaved woodland on water resources in lowland UK: I. Soil water changes below beech woodland and grass on chalk sites in Hampshire. *Hydrology and Earth System Science*, 9, 596-606.

Robinson, M., Cognard-Plancq, A.L., Cosandey, C., David, J., Durand, P., Führer, H.W., Hall, R., Hendriques, M.O., Marc, V., McCarthy, R., McDonnell, M., 2003. Studies of the impact of forests on peak flows and baseflows: a European perspective. *Forest Ecology and Management*,186, 85-97.

Rouillard, J. J., Ball, T., Heal, K. V., Reeves, A. D., 2015. Policy implementation of catchment-scale flood risk management: Learning from Scotland and England. *Environmental Science & Policy,* 50, 155–165.

Rouquette, J.R., Posthumus, H., Morris, J., Hess, T.M., Dawson, Q.L., Gowing, D.J.G., 2011. Synergies and trade-offs in the management of lowland rural floodplains: an ecosystem services approach. *Hydrological Sciences Journal*, 56, 1566–1581.

Salazar, S., Francés, F., Komma, J., Blume, T., Francke, T., Bronstert, A., Blöschl, G., 2012. A comparative analysis of the effectiveness of flood management measures based on the concept of "retaining water in the landscape" in different European hydro-climatic regions. *Natural Hazards and Earth Systems Science,* 12, 3287-3306.

Sayers, P., Galloway, G., Penning-Rowsell, E., Yuanyuan, L., Fuxin, S., Yiwei, C., Kang, W., LeQuesne, T., Wang, L. Guan, Y. 2014. Strategic flood management: ten 'golden rules' to guide a sound approach. *International Journal of River Basin Management*, 13, 137-151.

Schaap, M.G., Leij, F.J., van Genuchten, M. Th., 2001. Rosetta: a computer program for estimating soil hydraulic parameters with hierarchical pedotransfer functions. *Journal of Hydrology,* 251,163-176.

Scotland's Soils, 2016. National Soil Inventory of Scotland. Available from: http://www.soils-scotland.gov.uk/data/nsis [Accessed 12 June 2016]

Schulla, J., Jasper, K., 2007. Model description WASIM-ETH. Institute for Atmospheric and Climate Science, Swiss Federal Institute of Technology, Zürich.

Schwärzel K, Ebermann S, Schalling N., 2012. Evidence of double funnelling effect of beech trees by visualization of flow pathways using dye tracer. *Journal of Hydrology,* 470, 184–192.

Singh, S. K., Liang, J., Bárdossy, A., 2012. Improving the calibration strategy of the physically-based model WaSiM-ETH using critical events. *Hydrological Sciences Journal,* 57, 1487–1505.

Slee, B., Brown, I., Donnelly, D., Gordon, I., Matthews, K., Towers, W., 2014. The Squeezed Middle: identifying and addressing conflicting demands on intermediate quality farmland. *Land Use Policy*, 41, 206-216.

Smith, A., Bates, P., Freer, J., Wetterhall, F., 2014. Investigating the application of climate models in flood projection across the UK. *Hydrological Processes*, 28, 2810–2823.

Steele-Dunne, S., Lynch, P., McGrath, R., Semmler, T., Wang, S., Hanafin, J., Nolan, P. 2008. The impacts of climate change on hydrology in Ireland. *Journal of Hydrology,* 356, 28–45.

Svensson, C., Jones, D. A., 2010. Review of rainfall frequency estimation methods. *Journal of Flood Risk Management*, 3, 1-33

Thomas, H., Nisbet, T. R., 2006.An assessment of the impact of floodplain woodland on flood flows. *Water and Environment Journal*, 21, 114–126.

Van, D.I.J.K., Albert, I., Van Noordwijk, M.E.I.N.E., Calder, I.R., Bruijnzeel, S.L., Schellekens, J., Chappell, N.A., 2009. Forest–flood relation still tenuous. Comment on ‘Global evidence that deforestation amplifies flood risk and severity in the developing world. *Global Change Biology*,15, 110-115.

Van Genuchten, M.T., 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Science Society of America Journal*, 44, S.892-898

Verbunt, M., Zwaaftink, M.G., Gurtz, J., 2005. The hydrologic impact of land cover changes and hydropower stations in the Alpine Rhine basin. *Ecological Modelling*, 187, 71-84.

Vereecken, H., Weynants, M., Javaux, M., Pachepsky, Y., Schaap, M. G., and van Genuchten, M. T., 2010. Using pedotransfer functions to estimate the van Genuchten-Mualem soil hydraulic properties: a review. *Vadose Zone Journal*, 9, 795–820.

Vogel, R.M., Fennessey, N.M., 1994. Flow-duration curves. I: New interpretation and confidence intervals. *Journal of Water Resources Planning and Management*, 120, 485-504.

Werritty, A., Paine, J. L., Macdonald, N., Rowan, J. S., McEwen,L. J., 2006. Use of proxy flood records to improve estimates of flood risk: Lower Tay, Scotland. *Catena,* 66, 107–119.

Wilby, R.L., Beven, K.J., Reynard, N.S., 2008. Climate change and fluvial flood risk in the UK: more of the same? *Hydrological Processes*, 22, 2511–2523.

Whitfield, P.H., 2012. Floods in future climates: a review. *Journal of Flood Risk Management*, 5, 336-365.

Wriedt, G., Rode, M., 2006. Investigation of parameter uncertainty and identifiability of the hydrological model WaSiM-ETH. *Advances in Geosciences,* 9, 145–150.

Ye, H., Fetzer, E.J., Wong, S., Lambrigtsen, B.H., 2007. Rapid decadal convective precipitation increase over Eurasia during the last three decades of the 20th century. *Science Advances,* 3, e1600944. DOI: 10.1126/sciadv.1600944

Table 1. Modified soil saturated hydraulic conductivity (Ks) based upon land cover type

Land cover	*Adjusted Ks*
Arable	**k**
Grassland	**2k**
Semi-natural	**4.5k**
Woodland	**8k**

Table 2. Land use change scenarios (% area of each land use)

	Woodland	Arable	Improved Grassland	Semi-natural
Present-day	26	15	29	20
World Markets	30	14	28	18
National Enterprise	30	29	13	18
Global Sustainability	47	11	25	9
Local Stewardship	47	28	13	3

NB Other land uses (water and settlements) not included

Table 3. Model calibration data

Module	Parameters	Description	Calibrated values
Precipitation	TO	Snow rain temperature (°C)	0.458
	Rb	Correction parameter for liquid precipitation	0.702
	Ra	Correction parameter for liquid precipitation	0.049
	Sb	Correction parameter for solid precipitation	0.93
	Sa	Correction parameter for solid precipitation	0.05
Snow	TOR	Temperature limit for rain (°C)	2.431
	C0	Degree day factor (mm/day/°C)	2.34
Unsaturated zone	Dr	Drainage density (m^{-1})	1
	Kd	Recession constant for direct runoff (h)	12
	Ki	Recession constant for interflow (h)	36
	sdf	Fraction of snow melt that is direct runoff	0.124

Table 4. Changes for 1 in 10 and 1 in 100 return period events for Tarland catchment: (a) precipitation (mm) (b) peak flow (m^3s^{-1}) for Tarland Burn at Coull

Commented [IB5]: Is there an error in the last column – 15 hr events smaller than 7 hr???? but graphs suggest higher flows for longer time

(a)

	10 year return period		**100 year return period**	
	7h	15h	7h	15h
Baseline	38.6	47.9	57.2	74.7
2020s	40.2 *(+4.1%)*	51.4 *(+7.3%)*	63.4 *(+9.0%)*	82.1 *(+10.0%)*
2050s	42.6 *(+10.3%)*	55.4 *(+15.7%)*	67.7 *(+18.3%)*	84.9 *(+13.7%)*
2080s	43.7 *(+13.2%)*	57.4 (*19.9%)*	69.8 *(+22.0%)*	95.1 *(+27.3%)*

All values based upon the 50th percentile from the UKCP09 Weather Generator

(b)

	Summer 10 year return period		**Summer 100 year return period**		**Winter 10 year return period**		**Winter 100 year return period**	
	7h	15h	7h	15h	7h	15h	7h	15h
Baseline	3.4	4.3	6.0	8.4	7.1	8.5	12.5	12.6
2020s	3.7 *(+8.6%)*	4.9 *(+15.4%)*	6.8 *(+14.1%)*	10.1 *(+20.4%)*	7.8 *(+9.6%)*	9.1 *(+6.6%)*	14.3 *(+14.0%)*	14.0 *(+10.9%)*
2050s	3.9 *(+14.3%)*	5.2 *(+25.3%)*	7.5 *(+24.5%)*	11.0 *(+31.8%)*	8.2 *(+15.6%)*	9.4 *(+10.7%)*	15.6 *(+24.5%)*	14.7 *(+16.7%)*
2080s	4.0 *(+17.2%)*	5.4 *(+32.6%)*	7.6 *(+26.4%)*	12.1 *(+45.4%)*	8.4 *(+18.5%)*	9.7 *(+13.9%)*	15.9 *(+26.7%)*	15.6 *(+23.7%)*

Commented [IB6]: Check these values

Table 5. Peak flows (m^3/s) for afforestation options and UKCP09 WG climate change scenarios (mean value; medium emissions

Climate scenario	Afforestation option*	Summer 10 year return period		Summer 100 year return period		Winter 10 year return period		Winter 100 year return period	
		7h	15h	7h	15h	7h	15h	7h	15h
Baseline	Current use	3.4	4.3	6.0	8.4	7.1	8.5	12.5	12.6
	50% con	2.7	3.5	4.9	6.9	6.3	8.0	11.4	11.9
	50% dec	3.3	4.2	5.8	8.1	7.0	8.5	12.3	12.5
	75% con	2.0	2.7	3.7	5.5	5.5	7.5	10.2	11.3
	75% dec	3.2	4.1	5.7	7.9	6.9	8.4	12.0	12.5
	100% con	1.2	1.6	2.2	3.6	4.4	6.7	8.7	10.3
	100% dec	2.4	3.2	4.3	6.1	6.3	8.1	11.2	11.9
2020s	Current use	3.7	4.9	6.8	10.1	7.8	9.1	14.3	14.0
	50% con	3.0	4.0	5.6	8.4	6.9	8.6	13.0	13.2
	50% dec	3.6	4.7	6.7	9.8	7.7	9.0	14.0	13.9
	75% con	2.1	3.0	4.3	6.7	6.1	8.0	11.7	12.5
	75% dec	3.5	4.6	6.5	9.5	7.5	9.0	13.6	13.8
	100% con	1.3	1.9	2.6	4.5	4.9	7.2	10.0	11.5
	100% dec	2.6	3.5	5.0	7.5	6.9	8.6	12.6	13.3
2050s	Current use	3.9	52	7.5	11.0	8.2	9.4	15.6	14.7
	50% con	3.1	4.3	6.1	9.3	7.3	8.9	14.3	14.0
	50% dec	3.8	5.1	7.3	10.7	8.1	9.4	15.3	14.6
	75% con	2.3	3.3	4.7	7.5	6.4	8.3	12.8	13.2
	75% dec	3.7	4.9	7.1	10.4	7.9	9.3	14.9	14.5
	100% con	1.4	2.0	2.9	5.0	5.2	7.5	11.0	12.2
	100% dec	2.8	3.8	5.4	8.3	7.3	8.9	13.7	14.0
2080s	Current use	4.0	5.4	7.6	12.1	8.4	9.7	15.9	15.6
	50% con	3.2	4.5	6.2	10.3	7.5	9.1	14.5	14.8
	50% dec	3.9	5.3	7.4	11.8	8.3	9.7	15.7	15.5
	75% con	2.4	3.4	4.8	8.3	6.6	8.6	13.0	14.0
	75% dec	3.7	5.1	7.2	11.5	8.1	9.6	15.0	15.4
	100% con	1.4	2.1	2.9	5.6	5.4	7.7	11.1	12.9
	100% dec	2.9	4.0	5.5	9.1	7.4	9.2	13.9	14.8

***** con=coniferous dec=deciduous

Table 6. Changes in peak flows (mean) for land use change scenarios and climate change projections (UKCP09 medium emissions) for the 2050s

Land Use Scenario	**Summer 10 year return period**		**Summer 100 year return period**		**Winter 10 year return period**		**Winter 100 year return period**	
	7h	15h	7h	15h	7h	15h	7h	15h
World Markets	-5.6%	-4.5%	-5.4%	-4.2%	-2.3%	-2.9%	-1.9%	-1.1%
National Enterprise	-7.8%	-7.7%	-7.6%	-6.1%	-4.5%	-2.5%	-1.7%	-1.8%
Global Sustainability	-5.4%	-5.2%	-4.2%	-4.2%	-8.2%	-3.8%	-6.0%	-2.7%
Local Stewardship	-5.5%	-5.3%	-4.4%	-4.1%	-7.9%	-3.7%	-4.2%	-2.6%

Figures

Fig. 1. Tarland catchment: (a) location; (b) topography; (c) land cover

Fig. 2. Land use scenario storylines (after Brown and Castellazzi 2014)

Fig. 3. Illustrative land use scenarios for Tarland catchment in 2050 (after Brown and Castellazzi 2014)

Fig. 4. Change (%) in Q_5 and Q_{95} from baseline of different afforestation scenarios

Fig. 5. Changes in flow duration curves for catchment afforestation sensitivity testing