Revised valuation of flood regulation services of existing forest cover to inform natural capital accounts

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Summary

This report provides updated evidence on the value of existing woodland in England, Scotland and Wales in regulating flood flows and reducing flood risk in downstream communities. This is a ground-breaking area of analysis that is attempting to improve on what was previously a significant evidence gap in the economic value of woodland.

The study updates a previous evaluation (Broadmeadow et al., 2018) with improved estimates for the volume of flood water potentially removed by woodland or retained by its hydraulic roughness. The impacts of woodlands are compared with two alternative land uses, short grass and bare soil. The scope of the analysis was also extended to include the contribution of conifer woodlands, small woodlands, and trees outside of woodlands. A companion report (Fitch et al., 2022) is available that applies the approach to other natural capital types, including woodland, although values are not directly comparable due to methodological differences.

As before, the assessment focussed on ‘Flood Risk Catchments’ to identify the area of woodland draining to downstream communities impacted by flooding. Water volumes are expressed in m^3/ha. The analysis assumes that an equivalent level of flood water storage would have to be provided if the woodland cover was absent and replaced by either managed grassland or bare soil. The “replacement” cost of providing such flood water storage (based on seven reservoirs at an average of £14/m^3) was then used as an estimate of the flood alleviation value provided by woodland. Values were estimated for woodland by country across Britain and for the public and private woodland estates.

The natural capital value (over 100 years) of the flood regulation service provided by woodland across Britain, including trees outside woodlands (ToW), was estimated at £25.1 billion (£7,974/ha) compared to bare soil and £12.5 billion (£3,970/ha) compared to grass. Expressing the flood regulation service as an annualised central estimate gave values of £843 million/yr (£268/ha/yr) and £420 million/yr (£133/ha/yr) compared to bare soil and grass, respectively. These values are significantly greater than those generated by the previous assessment, reflecting the improved modelling of woodland water use and the broader range of woodland types in the analysis.

A summary of the average natural capital asset and annualised ecosystem service flow values compared to grass is provided in Table A below. These results show that values are highest in England – where woodland water use is greater due to the warmer and drier climate – and that the ‘hydraulic roughness’ of woodland is of particular value in alleviating flood risk, although this latter effect is focussed on areas where there are woodlands on floodplains.

Further details of the methods used and the scope for further methodological improvements are given in Sections 3 and 6 respectively.

Natural Capital Asset Values:	England	Scotland	Wales	GB Average
Flood storage for all woodland, and trees outside woodland	£4,810/ha	£2,957/ha	£2,589/ha	£3,970/ha
Flood storage for woodland only (NFI)	£5,063/ha	£3,058/ha	£2,820/ha	£4,061/ha
Flood storage for trees outside woodland	£4,204/ha	£1,317/ha	£1,835/ha	£3,641/ha
Floodplain woodland flood storage by hydraulic roughness	£7,305/ha	£7,280/ha	£7,117/ha	£7,280/ha
Annualised Ecosystem Service Flow Values:				
Flood storage for all woodland, and trees outside woodland (ToW)	£161/ha/yr	£99/ha/yr	£87/ha/yr	£133/ha/yr
Flood storage for woodland only (NFI)	£170/ha/yr	£103/ha/yr	£95/ha/yr	£136/ha/yr
Flood storage for trees outside woodland (ToW)	£141/ha/yr	£44/ha/yr	£62/ha/yr	£122/ha/yr
Floodplain woodland flood storage by hydraulic roughness	£245/ha/yr	£244/ha/yr	£239/ha/yr	£244/ha/yr

Table A. Average natural capital asset and annualised ecosystem service flow values for the additional flood regulation service provided by woodland using a central cost estimate, compared to grassland. The assessment of trees outside woodland (ToW) uses the National Tree Map and National Forest Inventory (NFI) survey data to identify small woods (>0.1 ha but <0.5 ha), groups of trees and linear tree features, plus lone trees (>2m tall, unless hedgerow trees, which are >3 m tall). The NFI provides a woodland map for stands of trees (>0.5 ha, and >20m wide) with a canopy cover of at least 20% or having the potential to achieve this.

1. Introduction

The objective of the study was to update the previous work by Broadmeadow et al. (2018) and generate improved estimates of the value of the flood regulation service provided by existing forest cover on a country basis to inform national natural capital accounts. As before, it focuses on the upstream catchment of communities at risk of flooding and builds on our theoretical understanding of the different ways that trees can affect flood runoff. A mix of modelling and expert judgement was used to derive a range of values for the flood regulation service provided by the public and private woodland estates within England, Scotland and Wales. This report addresses a number of the limitations that affected the previous work, namely:

- The parameterization governing the water use of managed grassland and broadleaved and conifer woodland in the JULES model has been improved so that the outputs fit better with process understanding and empirical data for these land covers in the UK.

- Separate values were estimated for existing conifer and broadleaf woodland using the National Forest Inventory woodland map dated 2018, although these were combined for the main accounts.

- Tree cover outside of woodlands has been added to the national woodland area, while recently felled land and young woodlands have been removed to reflect their limited contribution to the flood regulation service.

- The flood regulation service provided by woodland has been compared with two alternative counterfactual land covers, grass and bare soil. These results are presented in separate sections.

In a separate study, Fitch et al. (2022) applied a similar approach to calculate natural capital values for a wider range of land cover types, namely, grass, crops, shrubs, bare soil and broadleaved and conifer woodland. This necessitated some methodological changes, which resulted in the calculated values not being directly comparable to those presented here. The main methodological differences were:

1. Fitch et al. (2022) derived their land cover statistics from the UKCEH Land Cover Map (LCM) (2018), while we used the National Forest Inventory. This changed the woodland extent since although both map all woodland >0.5 ha in area, we excluded all felled ground and young woodland (since not considered to be contributing to the woodland flood regulating service). We also included an assessment of ToW, such as individual lines of trees (e.g. in hedges), small groups of trees and single trees.

2. A different method was used to calculate potential belowground flood water storage. We calculated average daily soil water storage for winter and summer periods across the hydrological year, while Fitch et al. (20220) used the average soil water storage on the day prior to "flood generating rainfall" within individual calendar years, defined as days with >25 mm rainfall.

3. Fitch et al. (2022) were unable to account for the potential additional flood storage generated by the higher hydraulic roughness of floodplain woodland.

4. For the grass and bare soil counterfactuals, we calculated the value of the woodland flood regulation service as the difference between that provided by woodland vs grass or bare soil, while Fitch et al. (2022) valued the service provided by each individual habitat compared to bare soil.

2. Background

Forests have long been associated with an ability to reduce flood flows, although the issue is complex and continues to be explored (Ngai et al. (2017); Nisbet and Old (2020)). While there is strong process understanding of how trees and their management can affect the generation and conveyance of flood waters, there remains a lack of measurements to fully quantify effects at the catchment scale, particularly on large floods and within large river basins (Nisbet and Thomas, 2021). This means that we continue to largely rely on modelling studies to estimate impacts (Cooper et al., 2021).

Valuing the contribution that forest cover makes to downstream flood alleviation is very difficult given the multiple factors and associated uncertainties involved. Work is ongoing to provide estimates for specific sites and catchments but these are few in number and leave the much greater challenge of upscaling results to a region or country level. In principle, process data and models are available to support a larger scale assessment, but the challenge is constraining this potentially huge task within available resources and a sensible time scale.

This study improves on previous work but the overall approach remains relatively simple and subject to a number of the original caveats (see Broadmeadow et al., 2018).

3. Approach

A flow chart showing the main steps involved in the methodology is displayed in Figure 1. A detailed description of the approach is provided below.

Figure 1 Flow chart displaying main steps in the methodology.

Step 1: Identify Flood Risk Catchments (FRC) and map their woodland cover.

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Step 2: Use JULES model to estimate average daily water loss by conifer and broadleaved woodland wet canopy evaporation in m^3/ha for all days with >25 mm rainfall (2006-2015). Multiply by the area of existing woodland cover within each FRC, adjusted for felled ground, young woodland and trees outside woodland.

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Step 3: Use JULES model to estimate the average daily soil water content to 3 m depth in m^3/ha for conifer and broadleaved woodland verses a replacement grass or bare soil cover, for the growing season, winter and annual periods (2006-2015). Multiply the difference in soil water content between woodland, grassland and bare soil by the area of existing woodland within each FRC.

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Step 4: Map existing woodland within Flood Zone 2 in each FRC. Multiply area of floodplain woodland by a gross estimate for the average rise in floodwater depth in m^3/ha for floodplain woodland compared to a grassland cover derived from site-based modelling studies.

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Step 5: Sum above woodland quantities for storm day evaporation loss, difference in soil water content to 3 m depth and average rise in floodwater depth for floodplain woodland in FRC by country, for GB and for the Public and Private Forest Estate.

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Step 6: Calculate the economic value of the sum of the additional 'effective' floodwater storage provided by woodland within the FRC based on the replacement cost of providing the same volume by constructing and operating a flood storage reservoir. Use average costs per m^3 derived from selected reservoir storage schemes with equivalent storage volumes. Calculate equivalent annualised values.

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Step 7: Sum economic values for all woodland in FRC by country, for GB and for the Public and Private Forest Estate, vs grass and bare soil.

3.1 Identifying Flood Risk Catchments

The adopted approach recognises that flood risk varies across GB and some areas have few or no impacts. Consequently, efforts focused on catchments draining to known communities at risk from flooding (denoted as Flood Risk Catchments (FRC)). Forest cover is assumed to provide a flood risk benefit to all downstream affected communities and therefore the most downstream community at risk is used to define the outlet for determining the upstream catchment. This means that in very large catchments such as the River Thames, calculations are based on all woodland above the lowest town or city, in this case London, since in principle the upstream flood storage generated will have some value by reducing the flood volume reaching the city, albeit by a small margin. Efforts concentrated on communities at risk from fluvial flooding due to the added difficulty of defining contributing areas for groundwater and surface water flooding (coastal flooding was also excluded).

For Scotland, the Scottish Environment Protection Agency coordinates efforts to tackle flooding through fourteen local Flood Risk Management Strategies. These identify areas of high risk for targeting investment, called Potentially Vulnerable Areas (PVA). FRC were defined as areas draining to one or more downstream PVA. There were 241 PVA in Scotland (as of 2018) located in 170 catchments, totalling 45,503 km^2 in area. These contain 8,966 km^2 of woodland canopy, comprising 2,213 km^2 of broadleaves and 6,753 km^2 of conifer. This represents 62% of the mapped woodland in Scotland (FC, 2018).

A different strategy has been adopted by English and Welsh agencies and similar spatial data for potential vulnerable areas is not available. In 2011 Local Authorities in England and Wales prepared preliminary flood risk assessments, which identified locations with a significant risk of flooding. Cluster areas of high risk were defined by Defra and the Welsh Government as those with populations of >30,000 people in England and >5,000 people in Wales. Consequently, only large urban centres in England and South Wales were included in the final maps.

Use of cluster areas was thought to seriously underestimate the actual population at risk of flooding across England and Wales and thus an alternative approach was adopted. This drew on the Environment Agency's Indicative Flood Map, which identifies areas at risk of fluvial flooding, and combined with the National Receptor Dataset (NRD) showing the location of properties, to identify assets at risk. The most downstream dwelling was used to define the outflow of each FRC, resulting in the majority of woodland in England (98%) and Wales (97%) draining to a community at risk. A total of 1,012 FRC were identified with an area of 145,640 km^2, containing 24,715 km^2 of woodland cover (Figure 2). This comprised 12,781 km^2 of broadleaved woodland and 11,934 km^2 of conifer.

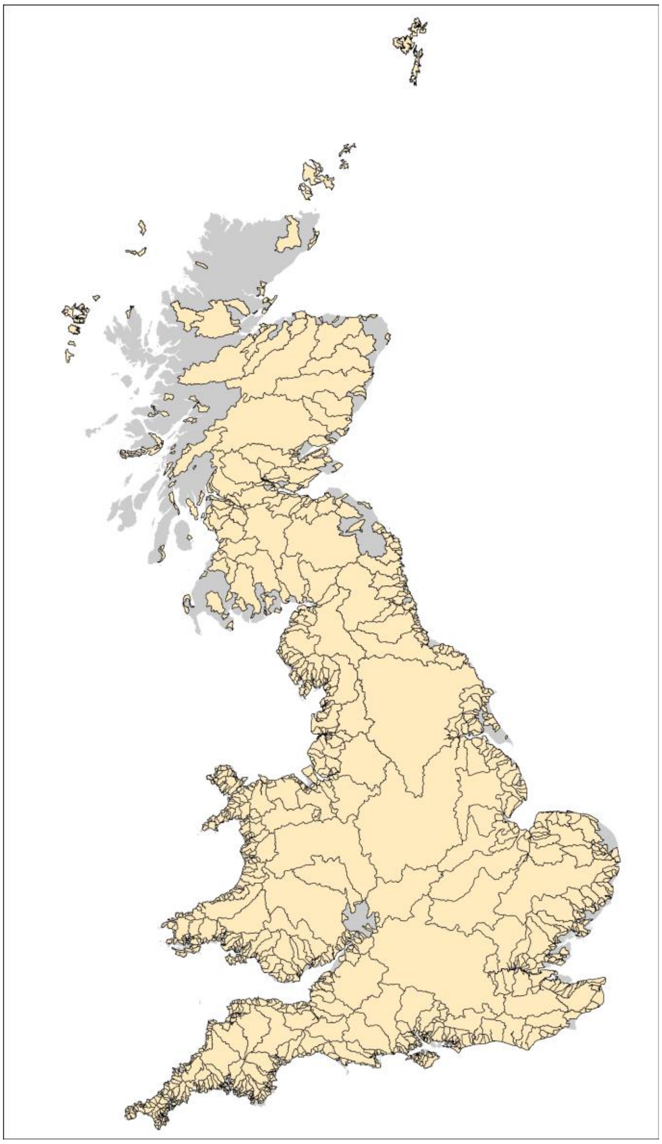

Figure 2 The distribution of FRC across GB delineated as individual areas of land bounded by black lines. FRC naturally become smaller closer to the coast. Areas lying outside FRC are shaded grey.

3.2 Woodland cover

The National Forest Inventory (NFI) provides a woodland map for stands of trees (>0.5 ha, and >20m wide) with a canopy cover of at least 20% or having the potential to achieve this. The definition relates to land use rather than cover, so integral areas of open space such as felled areas and ground prepared for planting are included in the woodland map. Although much of the open space is temporary, it remains a consistent feature/phase of woodland management that will contribute less to the flood regulation service, so should be excluded from the woodland area. The tree canopy in the NFI map is classed by category and ArcGIS was used to create a map of woodland canopy cover (represented by the Broadleaf, Conifer and Assumed Woodland) within each 1 km (100 ha) grid of the JULES model output data (i.e. excluding felled land and ground prepared for planting). The Assumed Woodland comprises younger woodland that is not differentiated by conifer vs broadleaved, so had to be spilt into these two canopy types. This was done using the combined ratio of conifer to broadleaves for New Planting and Restocking for 2018 within each country, as reported in the published national statistics in the Forestry Commission's Forestry Facts and Figures 2018 (Table 1).

Canopy type	England	Scotland	Wales
Broadleaf	0.5	0.24	0.58
Conifer	0.5	0.76	0.42

Table 1. The ratio between canopy type of the combined reported areas of new planting and restocking (2018) in the three countries.

The woodland map was split between the private and public sector using spatial data for the land holdings of Forestry England, Forestry and Land Scotland and Natural Resources Wales. Other public sector woodland (e.g. owned by local authorities) was included in the privately owned woodland.

The NFI also provides statistics on the extent and distribution of tree cover outside the NFI woodland area (FC, 2017). The assessment of ToW uses the National Tree Map and NFI survey data to identify small woods (>0.1 ha but <0.5 ha), groups of trees and linear tree features, plus lone trees (>2m tall, unless hedgerow trees, which are >3 m tall). We used these data to estimate the extent of ToW in each flood risk catchment based on the published % of woodland cover for individual NFI regions. ToW cover 3.2% of GB (742,000 ha in total) but its distribution is highly uneven, with 91% occurring in the lowlands (below 200 m) and therefore skewed to the south and east of the country (e.g. cover in south-east England and London (6%) is ten times greater than in north Scotland (0.6%)). Percentage cover is similar in England (4.3%) and Wales (4.5%) but less extensive in Scotland (1.1%). All tree cover outside woodland was assumed to be broadleaf canopy and privately owned.

Lastly, the extent of NFI woodland canopy within Flood Zone 2, defined by the EA and SEPA as land having >0.1% probability of fluvial flooding in any year, was determined for each FRC.

Summary figures for woodland cover by country and for all GB are presented in Table 2.

Area (ha)	England	Scotland	Wales	GB Total
Total tree canopy including ToW	1,800,524	952,351	395,827	3,148,702
Woodland canopy	1,271,894	896,662	302,954	2,471,510
Broadleaf woodland	891,300	221,319	165,483	1,278,102
Conifer woodland	380,594	675,343	137,471	1,193,408
ToW	528,630	55,689	92,873	677,192
Floodplain woodland	79,361	25,658	12,044	117,063
Broadleaf FZ	69,277	15,911	10,597	95,785
Conifer FZ	10,084	9,747	1,447	21,278
Public Forest Estate	212,571	267,506	116,166	596,243
PFE Broadleaf	76,739	34,903	34,874	146,516
PFE Broadleaf FZ	1,613	891	455	2,959
PFE Conifer	135,832	232,604	81,292	449,728
PFE Conifer FZ	1,149	1,979	432	3,560
Private woodland includind ToW	1,587,953	684,844	279,661	2,552,458
Private Broadleaf woodland	814,561	186,416	130,609	1,131,586
Private Broadleaf canopy (incl ToW)	1,343,191	242,105	223,482	1,808,778
Private Broadleaf FZ	67,664	15,020	10,142	92,826
Private Conifer woodland	244,762	442,739	56,179	743,680
Private Conifer FZ	8,935	7,768	1,015	17,718

Table 2. Area (ha) of woodland by country, canopy type and ownership in FRC. PFE – Public Forest Estate (owned and managed by Forestry England, Forestry and Land Scotland and Natural Resources Wales); FZ – Flood zone; ToW – Trees outside woodland. Some numbers contribute to values of other rows, while the floodplain woodland is a subset of woodland canopy and values are not additive.

3.3 Quantifying the contribution of existing woodland to flood risk management

Four ways are recognised by which woodland can reduce flood flows: by the potentially high water use by trees; the high infiltration rates of woodland soils; the high hydraulic roughness exerted by trees, shrubs and large woody debris; and the ability of trees to protect the soil from erosion and interrupt the delivery of sediment via run-off to watercourses. Our ability to estimate the relative contribution of these varies between the individual processes, mainly reflecting the way that they act. Effects on the timing of run-off and river flows are very difficult to estimate due to the high dependency on catchment characteristics (particularly physiographic features, channel morphology and location of affected communities) and are not considered here. Instead, we focused on assessing how woodlands contribute to flood storage in terms of volume of water lost by water use or stored below or above ground. This was applied to both woodland and ToW since the water use of the latter is expected to be similar to or larger than the former due to the greater exposure and edge effect of ToW, enhancing wet canopy evaporation. It proved too difficult to assess the contribution of the greater soil infiltration rates and reduced sediment delivery associated with woodland cover compared to other land uses and so these processes are excluded from the evaluation.

3.3.1 Volume of water lost by forest water use

The contribution of the higher water use of trees compared to shorter vegetation was estimated by woodland type (conifer and broadleaves) and converted to cubic metre (m^3) equivalent flood water storage per hectare. This comprised two components: the direct evaporation of water due to wet canopy evaporation (commonly known as interception) during an actual flood event; and the additional potential available water storage within woodland soils created by the higher woodland water use over consecutive days leading up to a flood event.

The Joint UK Land Environment Simulator (JULES) model was used to estimate both of these components of water use compared to two alternative baselines; a grass cover, which was selected as the dominant alternative land cover for existing woodland, and bare soil. JULES is a process-based model that couples land surface processes to Met. Office global circulation models (Best et al, 2011). It simulates fluxes of carbon, water, energy and momentum between the land surface and atmosphere to facilitate weather forecasting and climate change prediction. Different versions of the JULES model have been developed for investigating the impact of climate change on land carbon sinks, methane emissions from wetlands, atmospheric aerosols and tropospheric ozone.

For this study, an expert workshop was held to discuss changes to canopy interception model parameters to reflect previously highlighted issues. It was not possible to find a common set of parameters for baseline and storm interception to match process understanding and so separate parameter sets were used. The revised values provided a better match with observed data, although a close match could not be achieved without the model becoming unstable. Changes were agreed and Dr Emma Robinson, UKCEH, ran the latest version of the JULES model to compare the effect of four land covers on water fluxes at a 1 km grid scale across GB. Ten years of observed CHESS meteorological data (2006-2015; Robinson et al., 2020) were used to generate daily average values for canopy interception, transpiration and soil water content for complete

GB coverage of bare soil, managed grass, broadleaf and conifer woodland. The JULES model produced 2d gridded netCDF files, from which Alice Fitch, UKCEH, created 1 km grid rasters of various model output parameters, which were then analysed by Samantha Broadmeadow, Forest Research, using ArcGIS.

3.3.1.1 Canopy interception

For canopy interception, we were particularly interested in evaporation losses on very wet days that were more likely to be associated with generating flood events. Consequently, the modelled data were processed to extract values for individual days with >25 mm rainfall, which was considered to be the minimum storm size likely to generate a flood event. As expected, the number of storm days varied between years and across the country, with over 100 days with >25 mm rainfall in western, upland regions and less than ten days for many parts of central England (Figure 3).

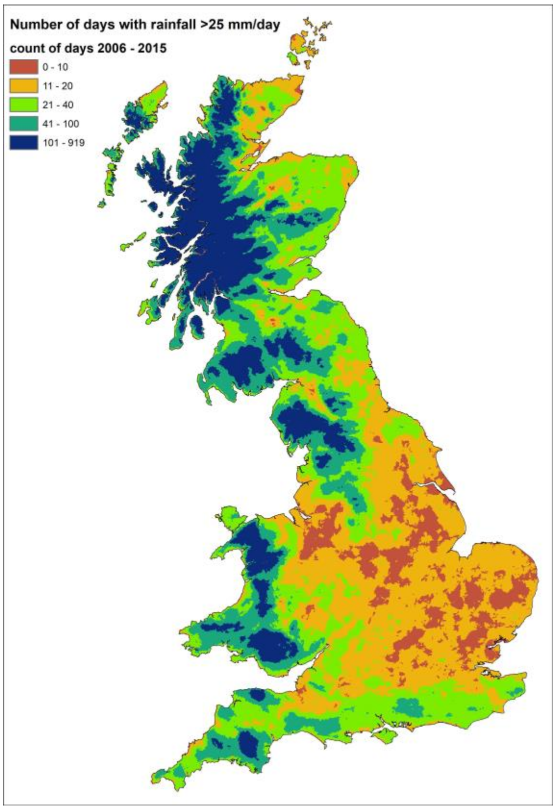

Figure 3 Number of days (2006 – 2015) with rainfall >25 mm used to estimate storm day interception loss for potential flood events.

The annual mean value for interception loss (mm) for all days with >25 mm rainfall over the ten-year period 2006-2015 was calculated for each grid square for the four land cover scenarios and presented in Table 3. The very low numbers for grass and bare soil are in line with process understanding, while those for woodland are notably higher than those generated by the previous application of the JULES model (mean values of 1.4 mm/d for both broadleaf and conifer (Broadmeadow et al., 2018)). The revised mean values for woodland are closer to plot measurements but fall within the lower end of the range of observed values (1.5 to 39.4 mm/d) published by Page et al. (2020), and much lower than those (100+ mm) recorded for some multi-day, very large storms.

Figure 4 illustrates the spatial variation in interception loss across GB for the four land cover scenarios. As expected, interception losses are greatest in the wet and windy climate of the western coastal fringe. The pattern is also evident in the broadleaf data although the interception losses are smaller.

	Mean (mm)	St.dev.	Min (mm)	Max (mm)
Bare soil	-0.01	0.01	-0.09	0.0
Grass	0.56	0.10	0.18	1.08
Broadleaf	3.05	0.63	0.99	6.93
Conifer	6.47	1.40	2.76	13.20

Table 3. GB mean (2006-2015) modelled daily interception loss (mm) for days with >25 mm rainfall, for each land cover scenario.

The potential contribution of storm day interception to flood storage was taken as the difference in mean daily interception loss (days with >25mm rainfall) between the woodland canopy and each of bare soil and grass. Spatial analyst tools were used to estimate the average loss for each country and for GB in Table 4.

(4a) Woodland canopy interception loss compared to bare soil:			
	England	**Scotland**	**Wales**
Woodland (mm)	4.68	4.86	5.40
Broadleaf (mm)	3.07	2.70	2.91
Conifer (mm)	6.29	7.01	7.88
(4b) Woodland canopy interception loss compared to managed grassland:			
	England	**Scotland**	**Wales**
Woodland (mm)	4.10	4.33	4.80
Broadleaf (mm)	2.49	2.17	2.31
Conifer (mm)	5.70	6.48	7.28

Table 4. Estimated flood water storage due to canopy interception on storm days (average values for days >25 mm rainfall between 2006-2015) for woodland cover compared to (a) bare soil and (b) managed grassland.

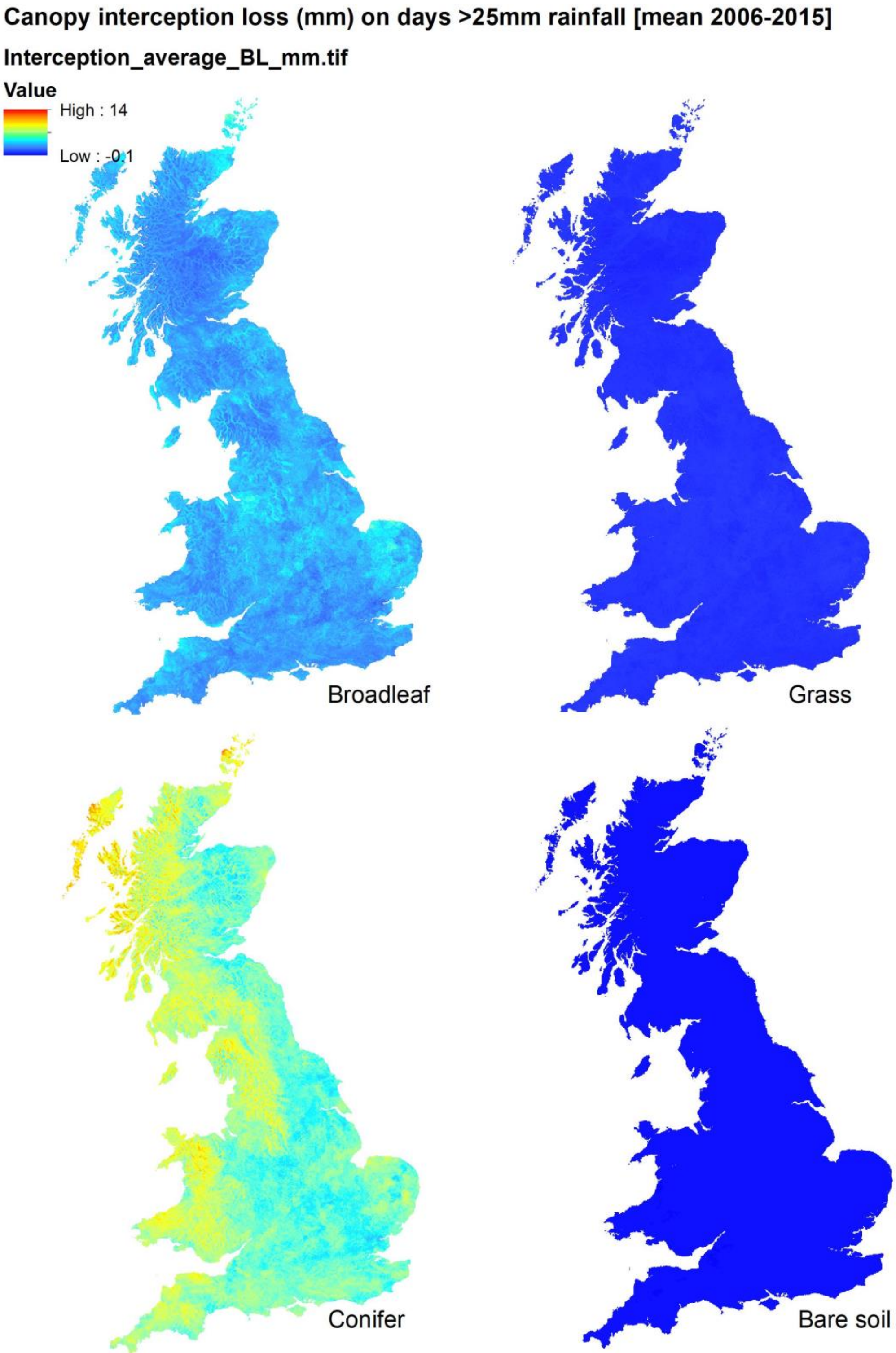

Figure 4 Spatial variation in mean daily interception loss on days with >25 mm rainfall (2005-2016) for the four land covers.

The flood water storage provided by canopy interception on storm days for all woodland was calculated as the sum of interception loss for (i) conifer landcover {(conifer – *alternative cover* interception) * the extent of existing conifer woodland} + (ii) broadleaf landcover {(broadleaf – *alternative cover* interception) * the extent of broadleaf woodland} for each 1 km (100 ha) grid square across the country. The zonal statistics tools in ArcGIS were used to sum the 1 km values within each FRC, including fractions of grid squares, and then using an Excel Pivot Table, summed by country. The separate values for conifer and broadleaf woodland were combined based on the proportion of each woodland type present. The results in m^3/ha and mm (1 mm = 10 m^3/ha) for all FRC are summarised in m^3/ha for each country in Table 5.

(a) Storm day interception compared to Bare soil	**England**	**Scotland**	**Wales**	**GB Total**
Combined woodland cover (M m^3)	51.3	53.3	15.6	120
Broadleaf woodland (M m^3)	27.4	6.0	4.8	38.2
Conifer woodland (M m^3)	23.9	47.3	10.8	82.1
(b) Storm day interception compared to Grass	**England**	**Scotland**	**Wales**	**GB Total**
Combined woodland cover (M m^3)	43.9	48.6	13.8	1063
Broadleaf woodland canopy (M m^3)	22.2	4.8	3.8	30.8
Conifer woodland canopy (M m^3)	21.7	43.8	10.0	75.5

Table 5. Total flood water storage (Million (M) m^3) due to storm day interception by all woodland within all FRC in each country and for GB compared to (a) bare soil and (b) managed grassland.

3.3.1.2 Soil Water storage

The accumulated woodland interception loss over consecutive wet days results in soils being generally drier under woodland compared to grass (woodland transpiration can also exceed that of grass and contribute to drier soils, particularly on drought prone soils). This means that there is greater potential for woodland soils to store more flood water below ground before saturation results in rapid runoff and flood generation. The summary statistics for the modelled seasonal (April to September and October to March; selected to represent the growing season (which we call summer) and the rest of the year (called winter)) soil water content under the four land covers is shown in Table 6. The conifer and broadleaf soils are on average 393 m^3/ha (39.3 mm) and 163 m^3/ha (16.3 mm) drier than grass in the summer, compared to 455 m^3/ha (45.5 mm) and 277 m^3/ha (27.7 mm) in the winter, respectively.

		Mean	St dev	Min	Max
Broadleaf woodland	Summer m³/ha	9,605	4,000	2,790	19,148
	Winter m³/ha	9,953	4,042	3,047	20,056
Conifer woodland	Summer m³/ha	9,375	3,980	2,490	19,025
	Winter m³/ha	9,775	4,023	2,820	19,981
Bare Soil	Summer m³/ha	10,284	4,020	3,735	19,435
	Winter m³/ha	10,444	4,083	3,823	20,072
Managed Grass	Summer m³/ha	9,768	4,013	3,088	19,210
	Winter m³/ha	10,230	4,063	3,527	20,103

Table 6. GB modelled daily soil water content (m³/ha to 3 m depth) under four land covers (2006-2015) during the summer (April – September) and winter (October – March). [10,000 m³/ha = 33% volumetric soil water content].

The JULES model relies on the open source, free to use FAO Harmonized World Soil Database (HWSD). We assigned GB soils to 6 soil classes (5 mineral and 1 organic) for deriving soil hydraulic parameters, as defined by Wösten et al. (1999). Soil type exerts a far greater influence on soil water content than land cover, although differences between land covers and seasons are evident in the variation within each soil type (Figure 5).

(a) Grass - summer (b) Conifer - summer

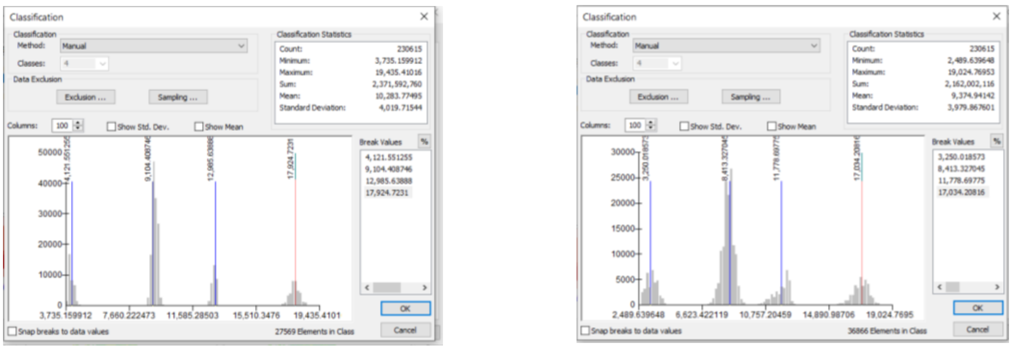

Figure 5 Distribution of soil moisture content values (m³/ha) across four main soil types: (a) grass – summer and (b) conifer – summer.

The seasonal additional potential below ground flood water storage provided by broadleaf, conifer and combined woodland compared to (a) bare soil and (b) grassland is presented in Table 7. The values are based on the national mean difference in daily soil water content to 3 m depth for 2006-2015 predicted using the JULES model. The available flood storage is larger in the summer when compared to bare soil but greater in the winter in relation to grass, reflecting the seasonal carryover of the greater drying effect of the latter land cover. Potential flood storage under conifer is approximately double (x 2.1) that for broadleaf in summer compared to x1.3 in winter.

(a) Below ground flood storage compared to Bare soil		England	Scotland	Wales	GB Total
Combined woodland	Summer m^3/ha	697.7	384.4	464.2	592.9
	Winter m^3/ha	551.3	238.0	300.9	441.5
Broadleaf woodland	Summer m^3/ha	685.3	326.2	453.9	547.6
	Winter m^3/ha	562.7	193.0	304.9	409.7
Conifer woodland	Summer m^3/ha	710.0	442.6	474.4	601.7
	Winter m^3/ha	539.9	282.9	296.9	446.7

(b) Below ground flood storage compared to Grass		England	Scotland	Wales	GB Total
Combined woodland cover	Summer m^3/ha	262.8	106.2	107.8	178.1
	Winter m^3/ha	352.1	140.9	169.0	263.0
Broadleaf woodland	Summer m^3/ha	211.4	48.7	64.4	112.7
	Winter m^3/ha	339.3	96.1	151.6	220.9
Conifer woodland	Summer m^3/ha	314.1	163.6	151.2	237.8
	Winter m^3/ha	364.9	185.7	186.4	292.3

Table 7. Seasonal potential below ground flood water storage beneath woodland compared to (a) bare soil and (b) grassland for summer (April – September) and winter (October – March) periods (values are 10y (2006-2015) average m^3/ha [10 m^3/ha = 1 mm]).

Figure 6 illustrates the spatial variation in the average difference in potential below ground flood water storage for the two seasons. Negative values indicate potential below ground storage, i.e. the soil is drier under woodland compared to counterfactual land covers. As expected, differences are greatest for bare soil and for the drier and warmer areas of the east, southeast and the Midlands of England and Wales. Values tend to be higher outside the growing season in relation to grass, reflecting the carryover of soil water deficits and delayed rewetting.

The total volume of below ground flood storage for all woodland was calculated for each season as the sum of i) conifer woodland {(conifer – *alternative* landcover seasonal soil storage) * the extent of existing conifer woodland} and ii) broadleaf woodland {(broadleaf – *alternative* landcover seasonal soil storage) * by the extent of broadleaf woodland} for each 1 km grid cell. ArcGIS was then used to sum the 1 km values within each FRC, including fractions of grid squares (see Excel file in Appendix), and Excel Pivot Tables used to calculate total below ground storage by country (Table 8). The separate values for conifer and broadleaf woodland were combined based on the proportion of each woodland type present. Differences in flood storage numbers between countries largely reflect the different extent of conifer and broadleaf woodland cover present within FRC.

6(a) Bare soil 6(b) Managed grass

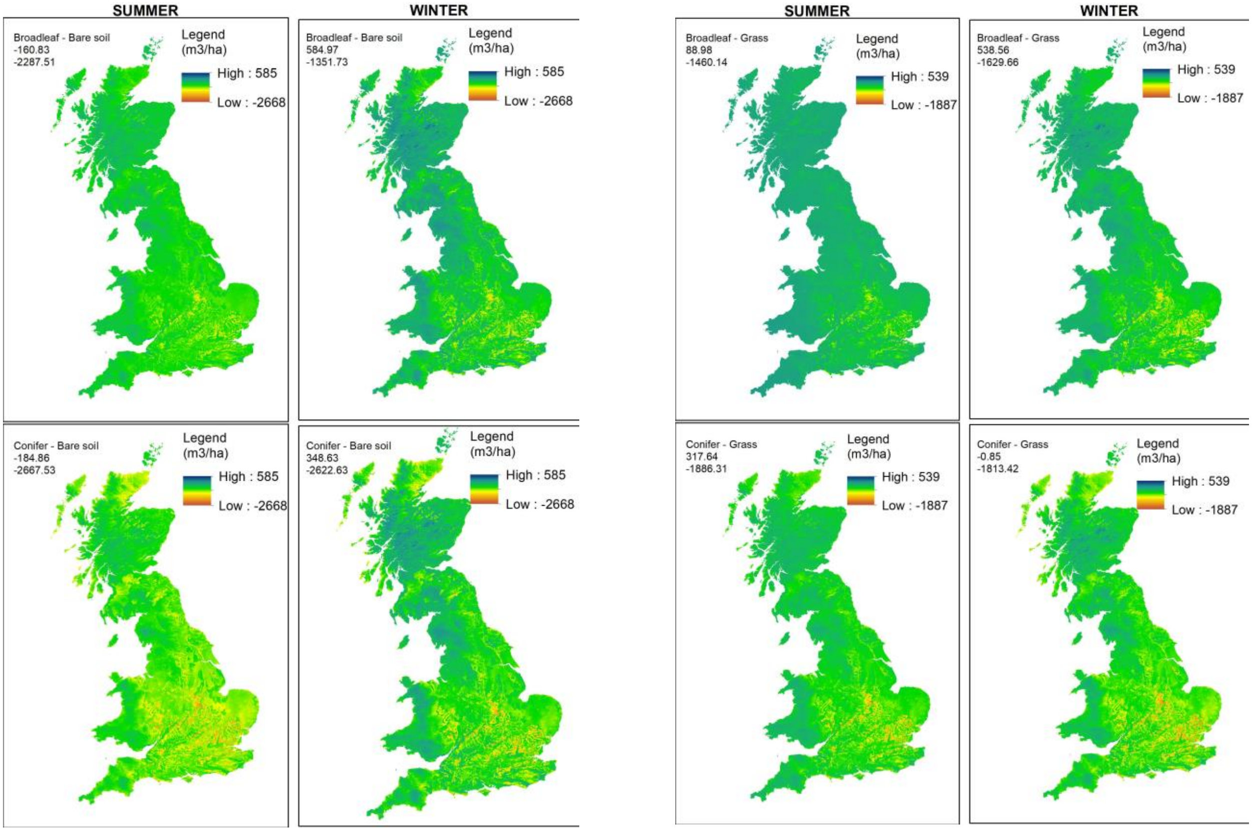

Figure 6 Calculated seasonal potential below ground flood storage in m^3/ha to 3 m depth under broadleaf and conifer compared to (a) bare soil and (b) grass (2005-2016).

(a) Below ground storage vs Bare soil		**England**	**Scotland**	**Wales**	**GB Total**
Combined Woodland	Summer (M m^3)	8810	371	140	1,392
	Winter (M m^3)	707	234	91.3	1,032
Broadleaf woodland	Summer (M m^3)	611	72.2	75.1	758
	Winter (M m^3)	502	42.7	50.5	595
Conifer woodland	Summer (M m^3)	270	299	65.2	634
	Winter (M m^3)	205	191	40.8	437
(b) Below ground storage vs Grass		**England**	**Scotland**	**Wales**	**GB Total**
Combined Woodland	Summer (M m^3)	308	121	31.4	461
	Winter (M m^3)	441	147	50.7	639
Broadleaf woodland	Summer (M m^3)	188	10.8	10.7	210
	Winter (M m^3)	302	21.3	25.1	349
Conifer woodland	Summer (M m^3)	120	110	20.8	251
	Winter (M m^3)	139	125	25.6	290

Table 8. Total below ground flood water storage (Million (M) m^3) for woodland within all FRC compared to (a) bare soil and (b) grassland.

3.4 Volume flood water stored by hydraulic roughness

The approach applied in the previous valuation was repeated to calculate the potential flood storage provided by the hydraulic roughness of woodland in the floodplain. The effect of floodplain woodland on flood depth is site and event specific, with water depth varying both temporally and spatially across the width and length of the floodplain. The estimation of the additional aboveground flood storage was based on a review of the results of modelling studies of the effect of native floodplain woodland on water levels within and upstream of the woodland. In this assessment we used the average rise in water depth for a 100-year flood event of 52 mm or 520 m^3/ha. This value was multiplied by the extent of floodplain woodland within Flood Zone 2 to estimate the potential additional flood storage due to woodland hydraulic roughness within each FRC. The results are summed by country and for GB in Table 9. No allowance was made for the relatively small difference in hydraulic roughness between grass and bare soil, and so the same flood storage volumes were applied when comparing the woodland benefit to that provided by both counterfactual land covers.

	England	Scotland	Wales	GB Total
Floodplain woodland flood water storage (M m^3)	41.4	13.3	6.1	60.9

Table 9. Estimated flood water storage (Million (M) m^3) generated by the hydraulic roughness of floodplain woodland within FRC by country and for GB.

3.5 Trees outside of woodland (ToW)

The Forestry Commission reports statistics for the extent of tree cover outside woodland for each region in the National Forest Inventory (FC, 2017). The data were used to estimate the extent of ToW canopy within each FRC assuming all ToW were broadleaf and privately owned. The ratio of ToW area: broadleaved woodland area within each FRC was used to estimate their additional contribution to flood storage for storm day interception and below ground storage (Table 10). The total soil water storage provided by ToW represents around 56% of that provided by NFI broadleaf woodland.

a) Flood storage from ToW vs Bare soil	**England**	**Scotland**	**Wales**	**GB Total**
Total flood storage for ToW (M m^3)	346	16.0	37.9	400
Total storm day interception for ToW (M m^3)	16.2	1.5	2.7	20.4
Total soil water storage for ToW (M m^3)	330	14.5	35.2	380
b) Flood storage from ToW vs Grass	**England**	**Scotland**	**Wales**	**GB Total**
Total flood storage for ToW (M m^3)	159	5.2	12.2	176
Total storm day interception for ToW (M m^3)	13.2	1.2	2.1	16.5
Total soil water storage for ToW (M m^3)	146	4.0	10.0	160

Table 10. Estimated total flood water storage (Million (M) m^3) for ToW due to storm day interception loss and below ground storage vs (a) bare soil and (b) grassland.

3.6 Estimating the economic contribution of existing woodland to flood risk management

The last step was to estimate the economic contribution of existing woodland to flood risk management. The same simple indicative replacement cost approach used in the previous project was adopted, based on the cost of the alternative of constructing a reservoir to provide an equivalent amount of flood storage if the woodland was not present. The calculation drew on a review of the capital costs of 16 flood storage schemes by JBA Consulting for the Environment Agency (Keating et al., 2015).

As before, the assessment was limited to schemes providing similar flood storage volumes to the existing woodland within FRC. Information was available for seven reservoir construction projects (storing between 100k – 1m m^3), resulting in costs ranging from £1.9/m^3 to £23.2/m^3 and a mean of £9.51/m^3. Additional costs were added to reflect initial procurement and enabling work, operation and long-term maintenance, and monitoring and inspection associated with reservoir safety (Keating et al., 2015). They generated revised total costs ranging from £3.34/m^3 to £39.33/m^3 and an average of £14.00/m^3, reflated to 2021 prices. The costs were then annualised based on an assumed 100-year life span for constructed reservoir storage and up-scaled using the calculated flood storage volumes for GB woodland. This gave an estimated annual equivalent cost of £0.47/m^3 and range of £0.11/m^3 to £1.32/m^3. [1]

4 Results

4.1 Bare soil as the counterfactual land cover

The flood storage volumes (m^3) generated by the water use (storm day interception and soil water storage) and hydraulic roughness benefits of woodland compared to bare soil are summed for all FRC within individual countries and for GB in Table 11. For simplicity, the seasonal values for soil water storage were combined to give an annual average. Values are also broken down by the public and private woodland estate in the Appendix, assuming all ToW are privately owned.

4.1.1 Valuation of woodland flood storage compared to bare soil

The calculated flood storage volumes were then multiplied by the cost of providing an equivalent volume of flood storage by constructing flood storage reservoirs. The central estimate of the replacement cost for the flood regulation service provided by existing

[1] NB costs of £0.47/m^3/yr over 100 years are equivalent to present value total costs of £14/m^3. It is computed by dividing the sum over 100 years of annual costs in present value terms (central estimate £14/m^3) by the sum of annual discount factors (29.8) at Treasury Green Book rates.

woodland by country is presented in Table 12. These values reflect the replacement costs for providing equivalent volumes of flood water storage over 100 years and are converted to annualised values in Table 13, representing the mean annual discounted costs. The spilt in values between the public vs private woodland estate is given in the Appendix. Average natural capital asset and annualised equivalent ecosystem service flow values per ha by country and for GB are shown in Table 14.

ALL WOODLAND	England	Scotland	Wales	GB Total
Total flood storage for all woodland, including ToW (M m^3)	1,233	385	176	1,793
Total flood storage for NFI conifer and broadleaf woodland (M m^3)	887	369	138	1,393
Total flood storage for ToW (M m^3)	346	16.0	37.9	400
Total storm day canopy interception for NFI conifer and broadleaf (M m^3)	51.3	53.3	15.6	120
Total storm day canopy interception for ToW (M m^3)	16.2	1.5	2.7	20.4
Total soil water storage for NFI conifer and broadleaf woodland (M m^3)	794	302	116	1,212
Total soil water storage for ToW (M m^3)	330	14.5	35.2	380
Total floodplain woodland flood storage by hydraulic roughness (M m^3)	41.4	13.3	6.1	60.9

Table 11. Estimated flood water storage (Million (M) m^3) due to woodland water use (split by canopy interception and average soil water storage) and floodplain woodland hydraulic roughness for all woodland, including trees outside of woodland (ToW), by country and for GB, compared to bare soil.

ALL WOODLAND	England	Scotland	Wales	GB Total
Total flood storage for all woodland, including ToW	£17,260m	£5,391m	£2,457m	£25,107m
Total flood storage for NFI conifer and broadleaf woods	£12,414m	£5,167m	£1,926m	£19,508m
Total flood storage for ToW	£4,845m	£223m	£531m	£5,600m
Total storm day canopy interception for NFI conifer and broadleaf woodland	£718m	£746m	£219m	£1,684m
Total storm day canopy interception for ToW	£227m	£21.1m	£37.8m	£286m
Total soil water storage for NFI conifer and broadleaf	£11,116m	£4,234m	£1,621m	£16,972m
Total soil water storage for ToW	£4,618m	£202m	£493m	£5,314m
Total floodplain flood storage by hydraulic roughness	£580m	£187m	£85.7m	£852m

Table 12. Capital value (£million) of the flood regulation service provided by all existing woodland by country and for GB, using a central cost estimate of £14/m^3 at 2021 prices, compared to an alternative landcover of bare soil.

ALL WOODLAND	England	Scotland	Wales	GB Total
Total flood storage for all woodland, including ToW	£579m	£181m	£82.5m	£843m
Total flood storage for NFI conifer and broadleaf woodland	£417m	£173m	£64.7m	£655m
Total flood storage for ToW	£163m	£7.5m	£17.8m	£188m
Total storm day canopy interception for NFI conifer and broadleaf woodland	£24.1m	£25.1m	£7.4m	£56.5m
Total storm day canopy interception for ToW	£7.6m	£0.7m	£1.3m	£9.6m
Total soil water storage for NFI conifer and broadleaf woodland	£373m	£142m	£54.4m	£570m
Total soil water storage for ToW	£155m	£6.8m	£16.6m	£178m
Total floodplain woodland flood storage by hydraulic roughness	£19.5m	£6.3m	£2.9m	£28.6m

Table 13. Annualised value (£million) of the flood regulation service provided by all existing woodland by country and for GB, using a central annualised cost estimate of £0.47/m^3/yr at 2021 prices, compared to an alternative landcover of bare soil.

NATURAL CAPITAL ASSET VALUES:	England	Scotland	Wales	GB Total
Flood storage for all woodland, and ToW	£9,586/ha	£5,660/ha	£6,208/ha	£7,974/ha
Flood storage for woodland only (NFI)	£9,760/ha	£5,763/ha	£6,357/ha	£7,893/ha
Flood storage for ToW	£9,166/ha	£4,012/ha	£5,719/ha	£8,269/ha
Floodplain woodland flood storage by hydraulic roughness	£7,305/ha	£7,280/ha	£7,117/ha	£7,280/ha
ANNUALISED ECOSYSTEM SERVICE FLOW VALUES:				
Flood storage for all woodland, and ToW	£322/ha/yr	£190/ha/yr	£208/ha/yr	£268/ha/yr
Flood storage for woodland only (NFI)	£328/ha/yr	£193/ha/yr	£213/ha/yr	£265/ha/yr
Flood storage for ToW	£308/ha/yr	£135/ha/yr	£192ha/yr	£278/ha/yr
Floodplain woodland flood storage by hydraulic roughness	£245/ha/yr	£244/ha/yr	£239/ha/yr	£244/ha/yr

Table 14. Average natural capital asset and annualised ecosystem service flow values based on a central cost estimate, compared to an alternative land cover of bare soil

4.2 Managed grassland as the counterfactual land cover

The flood storage volumes (m^3) generated by the water use (storm day interception and soil water storage) and hydraulic roughness benefits of woodland cover compared to managed grass are summed for all FRC within individual countries and then for GB in Table 15. For simplicity, the seasonal values for soil water storage were combined to give an annual average. Values are also broken down by the public and private woodland estate in the Appendix, assuming that all trees outside of woodland are privately owned.

ALL WOODLAND	England	Scotland	Wales	GB Total
Total flood storage for all woodland, including ToW (M m^3)	619	201	73.2	893
Total flood storage for NFI conifer and broadleaf woodland (M m^3)	460	196	61.0	717
Total flood storage for ToW (M m^3)	159	5.2	12.2	176
Total storm day canopy interception for NFI conifer and broadleaf woodland (M m^3)	43.9	48.6	13.8	106
Total storm day interception for ToW (M m^3)	13.2	1.2	2.1	16.5
Total soil water storage for NFI conifer and broadleaf woodland (M m^3)	375	134	41.1	550
Total soil water storage for ToW (M m^3)	146	4.0	10.0	160
Total floodplain woodland flood storage by hydraulic roughness (M m^3)	41.4	13.3	6.1	60.9

Table 15. Estimated flood water storage (Million (M) m^3) due to woodland water use (split by canopy interception and average soil water storage) and floodplain woodland hydraulic roughness for all woodland, including ToW, by country and for GB, compared to an alternative managed grassland landcover.

4.2.1 Valuation of woodland flood storage benefit compared to managed grassland

The calculated flood storage volumes were then multiplied by the cost of providing an equivalent volume of flood storage by constructing flood storage reservoirs. The central estimate of the replacement cost for the flood regulation service provided by existing woodland by country is presented in Table 16. These values reflect the replacement costs for providing equivalent volumes of flood water storage over 100 years and are converted to annualised values in Table 17, representing the mean annual discounted costs. The spilt in natural capital asset and annualised values between the public vs private woodland estate is given in the Appendix. Average natural capital asset and annualised ecosystem service values per ha by country and GB are shown in Table 18.

ALL WOODLAND	England	Scotland	Wales	GB Total
Total flood storage for all woodland, including ToW	£8,661m	£2,816m	£1,025m	£12,502m
Total flood storage for woodland only (NFI)	£6,439m	£2,742m	£854m	£10,036m
Total flood storage for ToW	£2,222m	£73.4m	£170m	£2,466m
Total storm day interception for woodland only: NFI	£614m	£680m	£194m	£1,488m
Total storm day canopy interception for ToW	£184m	£16.9m	£30.0m	£231m
Total soil water storage for NFI conifer and broadleaf woodland	£5,245m	£1,876m	£575m	£7,696m
Total soil water storage for ToW	£2,038m	£56.4m	£140m	£2,235m
Total floodplain woodland storage by roughness	£580m	£187m	£85.7m	£852m

Table 16. Capital values (£million) for the additional flood regulation service provided by all existing woodland, by country and for GB, using a central cost estimate of £14/m^3 at 2021 prices, compared to an alternative managed grassland landcover.

ALL WOODLAND	England	Scotland	Wales	GB Total
Total flood storage for all woodland, including ToW	£291m	£94.5m	£34.4m	£420m
Total flood storage for NFI conifer and broadleaf woodland	£216m	£92.1m	£28.7m	£337m
Total flood storage for ToW	£74.6m	£2.5m	£5.7m	£82.8m
Total storm day canopy interception for NFI conifer and broadleaf woodland	£20.6m	£22.8m	£6.5m	£50.0m
Total storm day canopy interception for ToW	£6.2m	£0.6m	£1.0m	£7.8m
Total soil water storage for NFI conifer and broadleaf woodland	£176m	£63.0m	£19.3m	£258m
Total soil water storage for ToW	£68.4m	£1.9m	£4.7m	£75.0m
Total floodplain woodland flood storage by hydraulic roughness	£19.5m	£6.3m	£2.9m	£28.6m

Table 17. Annualised values (£million) for the additional flood regulation service provided by all existing woodland by country and for GB, using a central annualised cost estimate of £0.47/m^3/yr at 2021 prices, compared to an alternative managed grassland landcover.

NATURAL CAPITAL ASSET VALUES:	England	Scotland	Wales	GB Total
Flood storage for all woodland, and ToW	£4,810/ha	£2,957/ha	£2,589/ha	£3,970/ha
Flood storage for woodland only (NFI)	£5,063/ha	£3,058/ha	£2,820/ha	£4,061/ha
Flood storage for ToW	£4,204/ha	£1,317/ha	£1,835/ha	£3,641/ha
Floodplain woodland flood storage by hydraulic roughness	£7,305/ha	£7,280/ha	£7,117/ha	£7,280/ha
ANNUALISED ECOSYSTEM SERVICE FLOW VALUES:				
Flood storage for all woodland, and ToW	£161/ha/yr	£99/ha/yr	£87/ha/yr	£133/ha/yr
Flood storage for woodland only (NFI)	£170/ha/yr	£103/ha/yr	£95/ha/yr	£136/ha/yr
Flood storage for ToW	£141/ha/yr	£44/ha/yr	£62/ha/yr	£122/ha/yr
Floodplain woodland flood storage by hydraulic roughness	£245/ha/yr	£244/ha/yr	£239/ha/yr	£244/ha/yr

Table 18. Estimated average natural capital asset and annualised ecosystem service flow values based on a central cost estimate, compared to an alternative managed grassland landcover

5 Discussion

Of the assessed woodland processes, the direct contribution of storm day interception remains the smallest at between 8-11% of total woodland flood storage, although greater than that estimated in the previous assessment (2-5%; Broadmeadow et al. (2018)). Conifer interception was around two to three times that of broadleaves but still small in overall terms, equating to a loss of between 6-8 mm per storm day compared to bare soil or grass. This remains at the lower end of the range of observed values from plot studies (1.5 to 39.4 mm/d; Page et al., 2020).

Once again, the drier soil conditions beneath woodland, which are mainly due to the accumulated interception loss during the year, exerted the largest influence, providing an average daily additional below ground flood water storage of 51 mm vs bare soil and 22 mm vs grassland (compared to 16.5 mm previously). This amounted to between 81-89% of the total woodland flood water storage potential. Conifer woodland provided an average daily additional storage of 5-10 mm compared to broadleaves.

The hydraulic roughness created by floodplain woodland was the most effective contribution at 52 mm of additional above ground flood water storage per unit area, although the effect is highly constrained by the relatively small spatial footprint of floodplain woodland within FRC. This averaged out at 2 mm across all GB woodland and 4-7% of total woodland flood storage.

A simple aggregation of the three components of woodland flood water storage gives a GB average daily combined volume of 57 mm vs bare soil and 28 mm vs grass.

Differences in potential flood storage volumes between countries mainly reflect the different levels of woodland cover present in FRC and often in the order of England>Scotland>Wales for each storage component. A similar pattern occurs in the values across the public vs private woodland estate. The storage volumes for the private woodland exceed the public forest estate due to the greater extent of woodland cover, including the additional contribution from ToW (see Appendix).

Estimating the replacement cost of flood water storage by GB woodland based on the costs of constructing reservoir storage (range of £3.34/m^3 to £39.33/m^3 and mean of £14.00/m^3, at 2021 prices) generates large numbers for the value of the potential woodland contribution to flood risk management (Tables 12 and 16). Compared to bare soil, the combination of flood storage by interception loss, additional soil water storage and the hydraulic roughness of floodplain woodland, equates to a total value of £25.1 billion (£6.0 - £70.5 billion) for all GB trees and woodland. This is double the equivalent value for the comparison with managed grassland, which totalled £12.5 billion (£3.0 - £35.1 billion) for all GB woodland. The latter value is almost twice the previous estimate of £6.5 billion (Broadmeadow et al., 2018), although this did not include the contribution of ToW, which adds £2.5 billion to the GB total.

The breakdown by country and between public and private forest estate reflects differences in woodland area (see Appendix), although with some variation in scale due to climate and other factors (such as variation in amounts of conifer and broadleaf canopy between the countries).

Averaging these natural capital asset values per hectare of woodland generates a central estimate for all GB woodland of £7,974/ha (Table 14), comprising £626/ha for storm day interception loss, £7,078/ha for below ground storage and £7,280/ha for above ground storage created by hydraulic roughness by floodplain woodland (at 2021 prices), compared to bare soil. The equivalent GB average values for a comparison with managed grass are £3,970/ha for all woodland (Table 18), comprising £546/ha for storm day interception loss, £3,154/ha for below ground storage and £7,280/ha for above ground storage by floodplain woodland (at 2021 prices).

Expressing the numbers as annualised values per hectare of woodland generates a central estimate of £268/ha/yr for all GB woodland (Table 14), comprising £21/ha/yr for storm day interception loss, £238/ha/yr for below ground storage and £244/ha/yr for above ground storage by floodplain woodland (at 2021 prices), compared to bare soil. The equivalent annualised numbers for the comparison with managed grass are £133/ha/yr for all woodland (Table 18), comprising £18/ha/y for storm day interception loss, £106/ha/yr for below ground storage and £244 for above ground storage by floodplain woodland (at 2021 prices).

These numbers compare well with those derived from catchment specific studies using an alternative approach to valuation based on avoided costs of flood damage. Nisbet et al. (2015) estimated the value of the flood regulation service provided by storm-day interception plus soil water storage generated by planting riparian broadleaved woodland at Pickering in North Yorkshire to range from £20-£129/ha/yr, with a central estimate of £126/ha/yr (at 2015 prices). Calculating the benefit-cost ratio for a combination of riparian woodland planting plus installing a network of leaky woody structures within wooded streams gave values of 1.5 to 3.0 for the flood regulation benefit.

In a second study, Scott et al. (2017) conducted an economic appraisal of the impact of woodland creation on flood risk for the community of Southwell in Nottinghamshire. They assessed the effect of planting 150 ha of conifer woodland across the 5.9 km^2 catchment of the Potwell Dyke and 2.2 km^2 catchment of Halam Hill. The establishment of mature woodland was predicted to protect between 9 and 16 properties in the former catchment and between 4 and 9 in the latter for medium-sized flood events (25 to 75-year return periods). This equated to an annual benefit of around £250/ha/yr and a flood benefit-cost range of 1.0 to 8.3 (at 2016 prices).

6. Limitations of Method

While the revised method has addressed some of the weaknesses identified by Broadmeadow et al. (2018), a number of limitations remain that would benefit from further work. These include:

- The parameterization of woodland storm day canopy interception within the JULES model continues to underestimate observed values based on the work of Page et al. (2020). The present version of JULES cannot be adjusted any further without becoming unstable, necessitating structural changes to the model to achieve a better fit.

- The spatial resolution of soils data in the JULES model is not ideal as it relies on the open source, free to use FAO Harmonized World Soil Database. This means that UK soils are simply ascribed to four main soil types.

- It was not feasible to assess the soil infiltration benefit of existing woodland or the contribution from reduced sediment delivery to watercourses, and thus our calculation of the flood regulation service provided by existing woodland is likely to be a lower bound estimate.

- The additional below ground flood water storage under woodland is a daily average and will vary greatly during the year, often reaching a peak in late summer. It can also be filled during a very wet period and may be slow to regenerate, especially in the winter under broadleaved woodland with its relatively low interception loss compared to conifer. The alternative method of basing this calculation on the soil water storage available on the day prior to a storm day, as adopted by Fitch et al. (2022), partly addresses this issue, although was found to generate drier soil values compared to using the daily average (much will depend on the timing and nature of the actual flood event).

- The potential flood storage contribution from riparian woodland has not been fully accounted for. Canopy interception and soil water storage is included in the assessment but no allowance has been made for the contribution to hydraulic roughness, including by the presence of leaky woody dams. Broadmeadow et al (2018) used a case study to demonstrate that riparian woodland has the potential to create a significant additional volume of flood storage but data are lacking to upscale this assessment to all FRC. It would not be appropriate to adopt a simple scaling factor to the hydraulic roughness effect of floodplain woodland due to the very variable nature of riparian woodland and management of leaky woody dams.

- The calculated flood storage volumes are not directly related to a specific level of flood protection or flood risk for vulnerable communities within FRC. There is a possibility that the number of FRC is underestimated, particularly in Scotland and Wales), due to the forest flood regulation service providing existing protection, although this is unlikely in view of the nature of the flood risk.

- In the absence of evidence for each FRC confirming both that building a reservoir is the least cost alternative and that the flood protection benefits equal or exceed the construction costs, the replacement cost approach adopted to estimating the economic contribution of existing woodlands for flood risk mitigation represents a first approximation. In most cases there is insufficient evidence available at present to determine whether the net present value of annualised benefits of the level of flood protection provided by existing woodlands would exceed the initial costs of building a reservoir. It might be expected that the benefits would exceed the costs in some, with costs exceeding the benefits in others. Were both effects taken into account, the net effect on the aggregate estimates of the economic contribution of existing woodlands to flood risk mitigation is difficult to determine. Undertaking a benefit cost test on a selected proportion of FRC would help to demonstrate whether the simple use of replacement costs is justified.

- The replacement costs are based on a limited number (seven) of reservoir storage schemes and some elements of the costs involved draw on general estimates rather than actual values, which are often difficult to obtain.

- The calculated values for the flood regulation service draw on data from different time periods. In particular, the interception loss and soil water storage estimates use meteorological data for the ten-year period 2006-2015, while the forest cover data are based on the 2018 National Forest Inventory (NFI). In principle, some of these numbers could be updated on an annual basis (e.g. meteorological data, although would require re-running models) but with a lag of one to two years for release of meteorological data due to quality control, while the NFI data are only reviewed on a five yearly basis. Since all countries support woodland creation the capital value of the flood regulation service can be expected to progressively increase over time, albeit by a relatively small degree in the short medium term in relation to the extent of the existing woodland cover. The largest annual change is likely to be in terms of the contribution of below ground flood water storage as soil water content and the forest water use effect respond to the variation in seasonal rainfall and evaporation between years. This would generate significant ‘noise’ in an annual valuation record and thus updates would be better suited to a five or ten-year moving average aligned to NFI repeat surveys. The number of FRC is unlikely to change significantly over time since much of the country is already included. Flood damages can be expected to rise with population and economic growth, as well as with climate change, for which the replacement cost methodology could be adjusted to take into account.

7. Conclusions

This updated study uses an improved set of parameter values for the Joint UK Land Environment Simulator (JULES) model and expert judgement from floodplain modelling to revise the flood regulation service provided by GB woodland (conifer and broadleaf), including trees outside of woodland but not felled or recently replanted land, compared to alternative land covers of bare soil and managed grassland. As before, the assessment was limited to 'Flood Risk Catchments (FRC)' defined as areas draining to downstream communities impacted by flooding. Calculated volumes are expressed in m^3/ha and considered to be equivalent to effective flood water storage that would have to be provided if the woodland cover was absent.

The value of this woodland flood water storage was estimated based on the average cost per m^3 for providing the same volume by constructing and operating a flood storage reservoir. A central estimate of £14/m^3 at 2021 prices was obtained from seven reservoir storage schemes (of equivalent volume) and used to estimate the replacement cost of flood storage provided by existing woodland by country and for the public and private woodland estates (based on discounted costs applying the Treasury Green Book discount rates to costs incurred in future years). These replacement costs were annualised assuming a 100-year life span for the constructed reservoir storage and gave a central estimate of £0.47/m^3/yr.

Although the woodland water use effect varies during the year, especially in terms of below ground water storage, flood events can occur at any time during the year and therefore valuation of the woodland benefit was limited to annual daily average soil water storage. The capital value of the estimated flood regulation service provided by existing GB woodland, including trees outside woodland, within FRC was estimated at £25.1 billion (£7,974/ha) compared to bare soil and £12.5 billion (£3,970/ha) compared to managed grass. Expressing the flood regulation service as an annualised central estimate gave values of £843 million/yr (£268/ha/yr) and £420 million/yr (£133/ha/yr) compared to bare soil and managed grass, respectively.

The values for woodland compared to grass are significantly greater than those generated by the previous assessment, reflecting the improved modelling of these land covers that now includes the contribution of conifer woodland, as well as the increased woodland cover due to incorporating trees outside of woodland. While these numbers provide better estimates than those of Broadmeadow et al. (2018), a number of significant caveats remain that would benefit from further work. The parameterisation of the JULES model continues to pose an issue but addressing this would require structural changes to the model.

8. References

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11. Appendix

(a) PUBLIC FOREST ESTATE	England	Scotland	Wales	GB Total
Total flood storage for conifer and broadleaf woodland (M m^3)	145	112	52.5	310
Total storm day interception for conifer and broadleaf woodland (M m^3)	10.9	17.2	7.4	35.6
Total soil water storage for conifer and broadleaf woodland (M m^3)	133	93.4	44.6	271
Total floodplain woodland flood storage by hydraulic roughness (M m^3)	1.4	1.5	0.5	3.4

(b) PRIVATE WOODLAND	England	Scotland	Wales	GB Total
Total flood storage for all woodland, including ToW (M m^3)	1,088	273	123	1,484
Total flood storage for conifer and broadleaf woodland (M m^3)	741	257	85.2	1,084
Total flood storage for ToW (M m^3)	346	16.0	37.9	400
Total storm day interception for conifer and broadleaf woodland (M m^3)	40.4	36.1	8.2	84.7
Total storm day canopy interception for ToW (M m^3)	16.2	1.5	2.7	20.4
Total soil water storage for conifer and broadleaf woodland (M m^3)	661	209	71.2	941
Total soil water storage for ToW (M m^3)	330	14.5	35.2	380
Total floodplain woodland flood storage by hydraulic roughness (M m^3)	39.8	11.8	5.8	57.5

Table 19. Estimated flood water storage (Million (M) m^3) due to woodland water use (split by canopy interception and average soil water storage) and floodplain woodland hydraulic roughness for (a) the public forest estate and (b) privately owned trees and woodland, including trees outside woodland (ToW), by country and for GB, compared to bare soil.

(a) PUBLIC FOREST ESTATE	England	Scotland	Wales	GB Total
Total flood storage for conifer and broadleaf woodland	£2,032m	£1,570m	£734m	£4,337m
Total storm day canopy interception for conifer and broadleaf woodland	£153m	£241m	£104m	£498m
Total soil water storage for conifer and broadleaf woodland	£1,859m	£1,308m	£624m	£3,791m
Total floodplain woodland flood storage by hydraulic roughness	£20.1m	£20.9m	£6.5m	£47.5m

(b) PRIVATE WOODLAND	England	Scotland	Wales	GB Total
Total flood storage for all woodland, including ToW	£15,226m	£3,820m	£1,725m	£20,771m
Total flood storage for conifer and broadleaf woodland	£10,381m	£3,597m	£1,193m	£15,171m
Total flood storage for ToW	£4,845m	£223m	£531m	£5,600m
Total storm day canopy interception for conifer and broadleaf woodland	£566m	£505m	£115m	£1,186m
Total storm day canopy interception for ToW	£227m	£21m	£37.8m	£286m
Total soil water storage for conifer and broadleaf woodland	£9,258m	£2,926m	£997m	£13,181m
Total soil water storage for ToW	£4,618m	£202m	£493m	£5,314m
Total floodplain woodland flood storage by hydraulic roughness	£558m	£166m	£81.2m	£805m

Table 20. Capital value (£million) of the flood regulation service provided by (a) the public forest estate and (b) private woodland and ToW, by country and for GB, using a central cost estimate of £14/m^3 at 2021 prices, compared to an alternative landcover of bare soil.

(a) PUBLIC FOREST ESTATE	England	Scotland	Wales	GB Total
Total flood storage for conifer and broadleaf woodland	£68.2m	£52.7m	£24.7m	£146m
Total storm day canopy interception for conifer and broadleaf woodland	£5.1m	£8.1m	£3.5m	£16.7m
Total soil water storage for conifer and broadleaf woodland	£62.4m	£43.9m	£21.0m	£127m
Total floodplain woodland flood storage by hydraulic roughness	£0.7m	£0.7m	£0.2m	£1.6m

(b) PRIVATE WOODLAND	England	Scotland	Wales	GB Total
Total flood storage for all woodland, including ToW	£511m	£128m	£57.9m	£697m
Total flood storage for conifer and broadleaf woodland	£348m	£121m	£40.1m	£509m
Total flood storage for ToW	£163m	£7.5m	£17.8m	£188m
Total storm day canopy interception for conifer and broadleaf woodland	£19.0m	£17.0m	£3.9m	£39.8m
Total storm day canopy interception for ToW	£7.6m	£0.7m	£1.3m	£9.6m
Total soil water storage for conifer and broadleaf woodland	£311m	£98.2m	£33.5m	£442m
Total soil water storage for ToW	£155m	£6.8m	£16.6m	£178m
Total floodplain woodland flood storage by hydraulic roughness	£18.7m	£5.6m	£2.7m	£27.0m

Table 21. Annualised value (£million) of the flood regulation service provided by (a) the public forest estate and (b) private woodland and ToW, by country and for GB, using a central annualised cost estimate of £0.47/m^3/yr at 2021 prices, compared to an alternative landcover of bare soil.

(a) PUBLIC FOREST ESTATE	England	Scotland	Wales	GB Total
Total flood storage for conifer and broadleaf woodland (M m^3)	78.3	60.5	24.7	163
Total storm day interception for conifer and broadleaf woodland (M m^3)	9.7	15.8	6.7	32.2
Total soil water storage for conifer and broadleaf woodland (M m^3)	67.2	43.2	17.5	128
Total floodplain woodland flood storage by hydraulic roughness (M m^3)	1.4	1.5	0.5	3.4

(b) PRIVATE WOODLAND	England	Scotland	Wales	GB Total
Total flood storage for all woodland, including ToW (M m^3)	540	141	48.7	729
Total flood storage for conifer and broadleaf woodland (M m^3)	381	135	36.5	553
Total flood storage for ToW (M m^3)	159	5.2	12.2	176
Total storm day interception for conifer and broadleaf woodland (M m^3)	34.2	32.7	7.1	74.1
Total storm day canopy interception for ToW (M m^3)	13.2	1.2	2.1	16.5
Total soil water storage for conifer and broadleaf woodland (M m^3)	307	90.8	23.6	422
Total soil water storage for ToW (M m^3)	146	4.0	10.0	160
Total floodplain woodland flood storage by hydraulic roughness (M m^3)	39.8	11.8	5.8	57.5

Table 22 Estimated flood water storage (Million (M) m^3) due to woodland water use (split by canopy interception and average soil water storage) and floodplain woodland hydraulic roughness for (a) the public forest estate and (b) privately owned trees and woodland, including ToW, by country and for GB, compared to an alternative managed grassland landcover.

(a) PUBLIC FOREST ESTATE	England	Scotland	Wales	GB Total
Total flood storage for conifer and broadleaf woodland	£1,097m	£847m	£345m	£2,289m
Total storm day canopy interception for conifer and broadleaf woodland	£135m	£222m	£94m	£451m
Total soil water storage for conifer and broadleaf woodland	£941m	£604m	£245m	£1,790m
Total floodplain woodland flood storage by hydraulic roughness	£20.1m	£20.9m	£6.5m	£47.5m

(b) PRIVATE WOODLAND	England	Scotland	Wales	GB Total
Total flood storage for all woodland, including ToW	£7,562m	£1,969m	£681m	£10,213m
Total flood storage for conifer and broadleaf woodland	£5,340m	£1,896m	£511m	£7,747m
Total flood storage for ToW	£2,222m	£73.4m	£170m	£2,466m
Total storm day canopy interception for conifer and broadleaf woodland	£479m	£458m	£99.5m	£1,037m
Total storm day canopy interception for ToW	£184m	£16.9m	£30.0m	£231m
Total soil water storage for conifer and broadleaf woodland	£4,303m	£1,271m	£330m	£5,905m
Total soil water storage for ToW	£2,038m	£56.4m	£140m	£2,235m
Total floodplain woodland flood storage by hydraulic roughness	£558m	£166m	£81.2m	£805m

Table 23. Capital values (£million) for the additional flood regulation service provided by (a) the public forest estate and (b) private woodland and ToW, by country and for GB, using a central cost estimate of £14/m^3 at 2021 prices, compared to an alternative managed grassland landcover.

a) PUBLIC FOREST ESTATE	England	Scotland	Wales	GB Total
Total flood storage for conifer and broadleaf woodland	£36.8m	£28.4m	£11.6m	£76.8m
Total storm day canopy interception for conifer and broadleaf woodland	£4.5m	£7.4m	£3.2m	£15.1m
Total soil water storage for conifer and broadleaf woodland	£31.6m	£20.3m	£8.2m	£60.1m
Total floodplain woodland flood storage by hydraulic roughness	£0.7m	£0.7m	£0.2m	£1.6m

(b) PRIVATE WOODLAND	England	Scotland	Wales	GB Total
Total flood storage for all woodland, including ToW	£254m	£66.1m	£22.9m	£343m
Total flood storage for conifer and broadleaf woodland	£179m	£63.6m	£17.2m	£260m
Total flood storage for ToW	£74.6m	£2.5m	£5.7m	£82.8m
Total storm day canopy interception for conifer and broadleaf woodland	£16.1m	£15.4m	£3.3m	£34.8m
Total storm day canopy interception for ToW	£6.2m	£0.6m	£1.0m	£7.8m
Total soil water storage for conifer and broadleaf woodland	£144m	£42.7m	£11.1m	£198m
Total soil water storage for ToW	£68.4m	£1.9m	£4.7m	£75.0m
Total floodplain woodland flood storage by hydraulic roughness	£18.7m	£5.6m	£2.7m	£27.0m

Table 24. Annualised values (£million) for the additional flood regulation service provided by (a) the public forest estate and (b) private woodland and ToW, by country and for GB, using a central annualised cost estimate of £0.47/m^3/yr at 2021 prices, compared to an alternative managed grassland landcover.