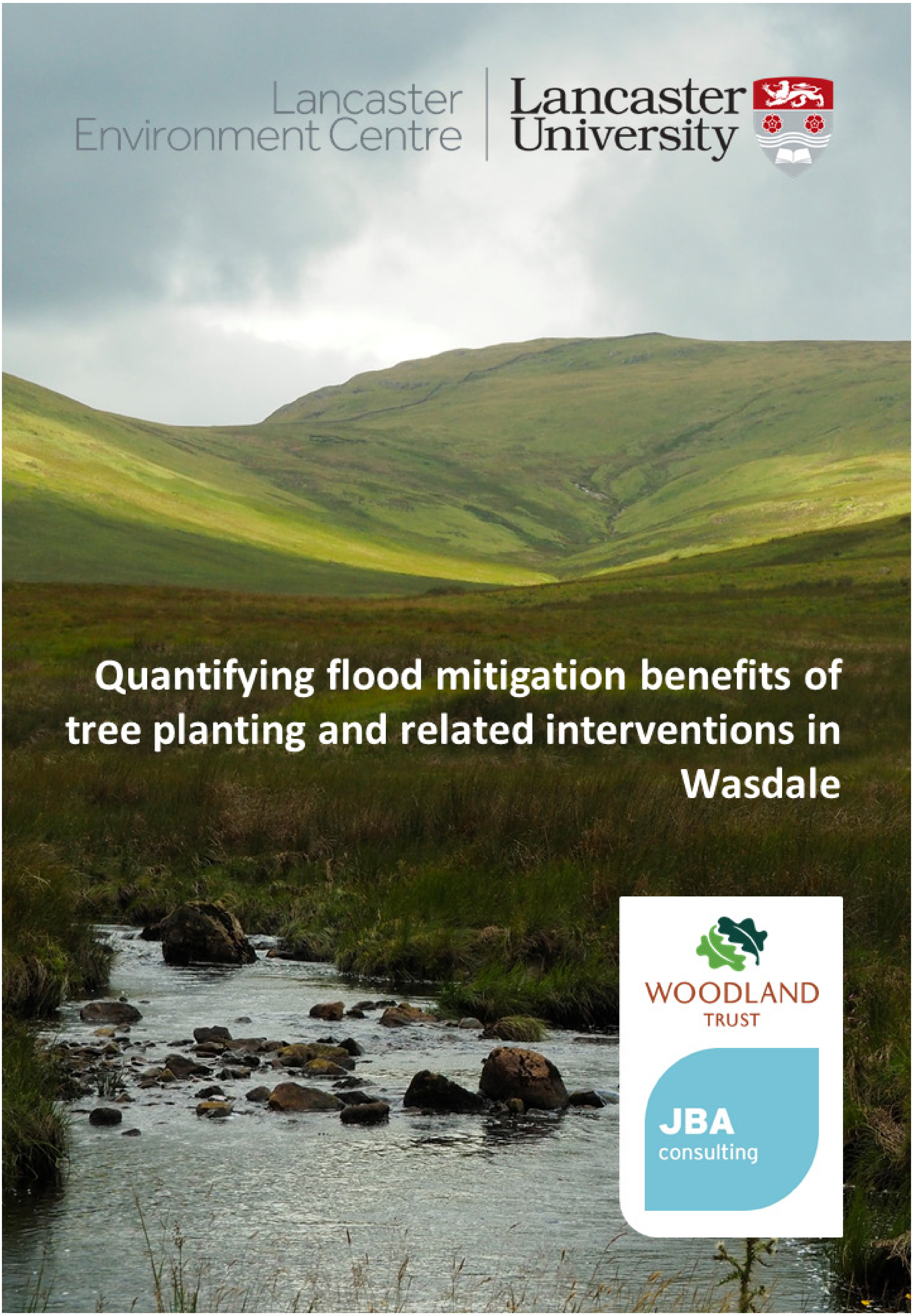

Lancaster Environment Centre | Lancaster University

Quantifying flood mitigation benefits of tree planting and related interventions in Wasdale

WOODLAND TRUST

JBA consulting

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Phase 1

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Funder

The Woodland Trust
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Acknowledgements

We are grateful to David Johnson of the Rivers Trust for incorporating the Woodland Trust planting scenarios in Wasdale within their JFLOW modelling of the whole Lune Catchment and permitting use of the local findings within this study. JBA Consulting carried out the JFLOW modelling in accordance with the changes specified by LEC and Woodland Trust.

Front cover: Photograph of the principal headwater of Wasdale Beck towards Great Yarlside on Shap Fells (Cumbria, United Kingdom)

Executive Summary

This study was commissioned by the Woodland Trust as part of their Uplands Planting Research Programme. This is a pilot study to quantify the potential benefits of tree planting in Wasdale, a source of the River Lune, for reducing the peak discharge of large flood events. The JFLOW model has been used at a national scale to assess surface-water flooding, and the influence of different flood mitigation scenarios on this has been modelled in more recent work for the Rivers Trust. A whole-catchment, 'direct-rainfall and losses approach', combined with the 2 m resolution topographic data was used for Wasdale. The model simulations were based on a tree planting scenario suggested by the Woodland Trust combined with new data on peat extent in the catchment (where tree planting should be avoided due to negative effects on carbon sequestration) and a new synthesis of pertinent hydrological data.

For the 1-in-30 year flood event simulated, planting broadleaf trees on some of the acid grassland in the headwaters of Wasdale, reduced the overland flow peak by approximately 30 % of the current situation. This benefit results largely from the simulated effects of experimental data on additional losses due to the process of 'wet-canopy evaporation' averaged over winter rainstorms. Rates (and resultant flood-mitigation affects) specific to *extreme* rainstorms would be expected to be smaller, but these data have never been collected. Further flood attenuation benefit was achieved by commercial conifer planting in areas outside of the National Park. While peatland restoration and construction of woody dams in small channels were shown to further dampen the flood peaks, their effects were small when compared to the flood mitigation benefits of trees.

Informing the landowners of the likely flood mitigation benefits of a range of management strategies for Wasdale could be undertaken in the future by combining new field investigations with further modelling.

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Rationale for the study

Studies in the UK and internationally are showing the value of local tree planting as a means of helping to reduce flood risk, in addition to its wider commercial, environmental and social benefits. Estimation of the magnitude of the flood mitigation benefits of tree planting at a particular locality is dependent on several factors. These factors include the site characteristics (soils, geology etc.), the type and extent of planting, the quality of available field evidence showing how trees affect flood hydrology, and the abilities of the flood simulation models being used.

Wasdale is one of sources of the River Lune that drains south from Cumbria through Lancashire to the city of Lancaster and thence to Morecambe Bay. Approximately 16 km^2 of Shap Fells is drained by Wasdale Beck, Blea Beck and Trundle Beck in this headwater of the River Lune or 'Lonsdale'. The landscape of Wasdale is currently managed for sheep production with smaller areas of commercial forestry. Shap Pink Quarry, the source of the famous pink decorative granite but also aggregate for new engineered flood defences, is located in the north-eastern corner of the valley. Red deer also have a strong presence in the landscape. The valley is diagonally dissected by the A6 trunk road, and both the M6 motorway and West Coast main railway line cross the downstream areas.

Trees could form a larger component of the management of the Wasdale landscape to deliver a range of commercial, environmental and social benefits for the landowners and wider society. One such benefit could be 'natural flood management' or NFM where trees and other interventions are used to reduce the amount of floodwaters delivered to downstream communities at risk of flooding.

This study aims to quantify the likely magnitude of flood risk reduction (in the overland flow component) produced by a tree planting scenarios recommended by advisors to the Wasdale landowners, notably the Woodland Trust. Tree planting to help mitigate floods is often accompanied by related NFM interventions. The study will also show the additional flood attenuation value arising from blocking artificial drains on peatlands and adding a series of small semi-permeable dams on the tributary streams.

This work is primarily a 'desk study' centred on modelling, rather than involving substantial fieldwork. We are, however, able to incorporate new survey data on peat depths collected by a parallel project undertaken by the Cumbria Wildlife Trust, and also a new synthesis of forest evaporation data considered more pertinent to Wasdale than data currently used in national NFM modelling for the Environment Agency. Undoubtedly, the results of our modelling (or indeed any modelling) would be strengthened with the incorporation of more field measurements locally in Wasdale. We hope that this project forms the first phase of what could become a more detailed research programme with much local experimental data. That said, the modelling that we utilise for this Phase 1 Desk Study is based on a model 'benchmarked' against other 2-dimensional (2D) inundation models (Hunter et al., 2008) and used for national assessments of NFM opportunities in England.

The numerical modelling approach

The 2D overland flow model selected for this Wasdale study is called 'JFLOW'. This model solves Saint-Venant Equations for shallow water-flow on hillslopes and in channels (Lamb et al., 2009; Crossley et al., 2010). We use the model to simulate the routing of overland flow during flood events with losses to infiltration modelled using the procedure of Eckhardt (2005). In addition to the acknowledged scientific basis of JFLOW, it has been used by the Environment Agency for national assessments of: (a) the risk of pluvial flooding using the Risk of Flooding from Surface Water (RoFSW) map (Environment Agency, 2013), and (b) assessment of the optimal locations for the implementation of NFM (e.g., Hankin et al., 2017). JFLOW was set up using a whole catchment implementation of the rainfall with an 'ReFH losses approach' used in the RoFSW, except for three modifications to improve the quality of the process representation more specific to Wasdale.

The *first modification* relates to the model-specification of the proportion of rainfall that does not deliver overland flow responses during flood events; this is affected by two key components:

> (a) The component of rainfall that recharges the slow river response via infiltration ('baseflow') in national mapping for the Environment Agency utilises spatial patterns in a value called the 'BFIHOST' (see Boorman et al., 1995). New research suggests that this map does not accurately predict areas of impeded recharge when compared with the latest British Geological Survey (BGS) maps showing the location of slowly permeable glacial till (Hankin et al., 2017). As a consequence the Wasdale study does not use the original spatially varying BFIHOST map. Instead, the mean BFIHOST value of 0.26 for the catchment is used to remove 26% of the overland flow by infiltration to a slow flow component (following Eckhardt, 2005).
>
> (b) The component of rainfall that does not produce overland flow because wet-canopy evaporation returns some of the rainfall to the atmosphere (during breaks in a rainfall event) is quantified in this study using a new synthesis of data from pertinent field studies. For deciduous woodland during winter storms this is quantified as 19 % of the storm rainfall, for conifer plantations during days with more than 50 mm of rainfall, a figure of 30 % of the storm rainfall, while grasslands (improved pasture and rough grazing) are quantified as only 5 % of storm rainfall (see justification later). Use of grassland values for heather or bracken covered moorland may slightly under-estimate the true value (see e.g., Calder, 1990).

The *second modification* relates the simulation of a reference 1-in-30 year rainstorm (i.e., an event that has a 1/30 = 0.0333 or 3.3 % chance of being present in any one year), rather than the standard simulation of 1-in-100 year rainstorm (i.e., 1 % chance of being present in any one year). A flood producing event that occurs more frequently has greater relevance to a larger number of big storms.

The *third modification* relates to potential tree planting areas on hillslopes that are either classified as 'high runoff areas' or having 'slowly permeable soils' (Hankin et al., 2017). For Wasdale, this planting strategy is replaced with one devised by the Woodland Trust. The full details of this planting strategy are given below. As part of this strategy, soils newly mapped by the Cumbria Wildlife Trust as having peat deeper than 50 cm (Figure 1) are excluded from the Woodland Trust planting scenario.

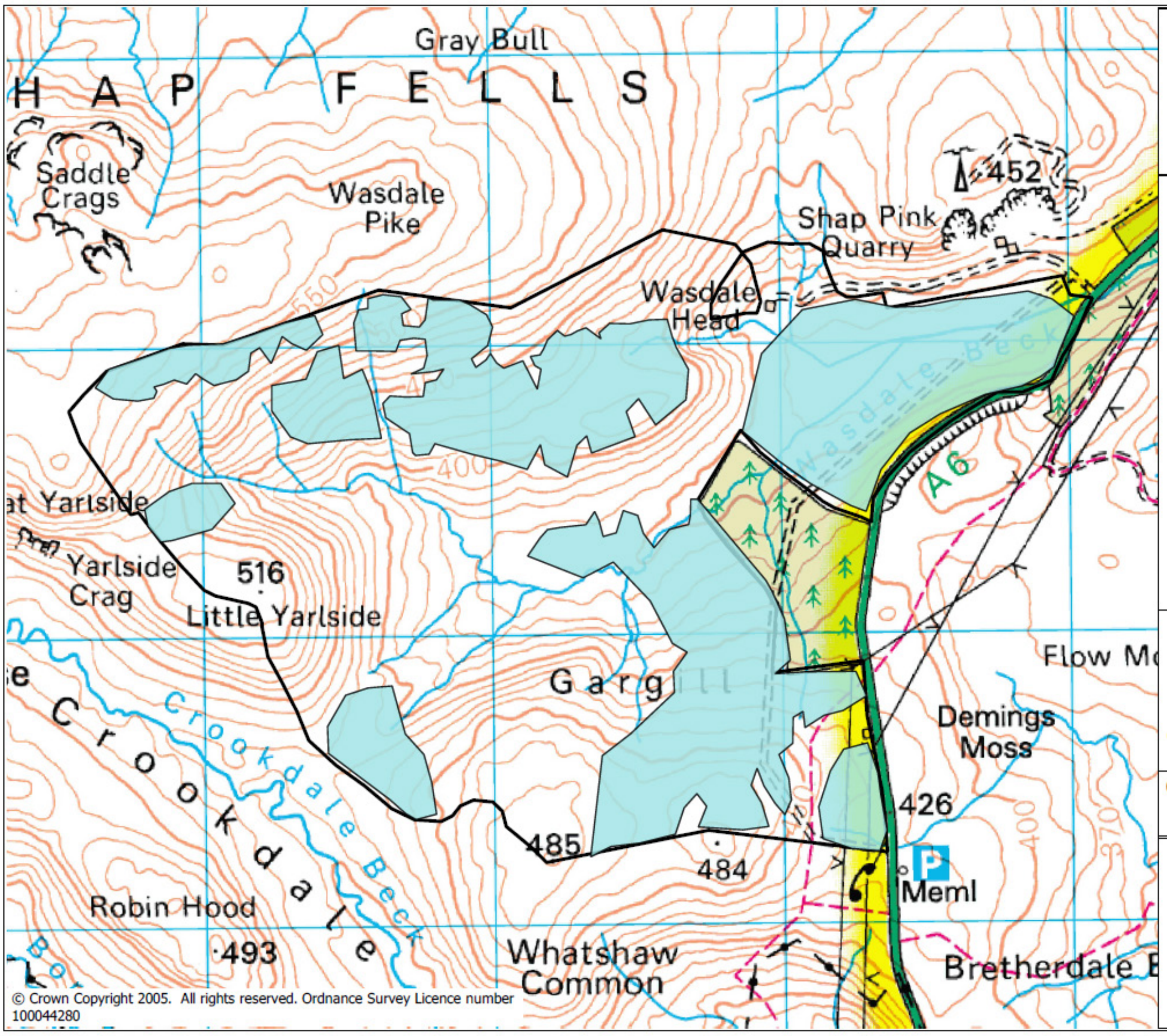

Figure1. Extent of the Wasdale Beck headwater covered by deep peat (i.e., greater than 50 cm) in the first version of the Cumbria Wildlife Trust map.

Incorporating local field evidence on peat depth

Tree planting on deep peat (i.e., soils with organic layers over 50 cm deep) can lead to peat drying and the release of carbon dioxide to the atmosphere (e.g., Byrne and Farrell, 2005), with the potential for negative effects on the global climate. As a consequence of this potential negative impact of tree planting, the planting strategy devised by the Woodland Trust avoids areas with greater than 50 cm deep peat. The map of peat extent developed by Natural England used within national JFLOW simulations does not distinguish between areas with peat in excess of 50 cm depth and those with less, and does not incorporate direct field observations from Wasdale. As a consequence, the Woodland Trust commissioned the Cumbria Wildlife Trust to undertake a detailed survey of peat depth within the headwaters of the Wasdale Beck catchment and produce a map of the areas with greater than 50 cm deep peat (Figure 1). This peat map was used to ensure the suggested deciduous tree planting areas in the Wasdale Beck catchment avoided areas of deep peat (Figure 2).

Incorporating improved field evidence on tree evaporation

A recent modelling study of the Upper Eden, Lower Cocker and Upper Kent catchments in Cumbria undertaken for the Rivers Trust (Hankin et al., 2016) showed that the greater rates of wet-canopy evaporation (also called 'interception loss') based on an uncertainty-weighting of the evidence identified by LEC in Appendix 1, can have beneficial effects on flood peak reduction. The same data has been adapted for Wasdale to model the integrated 'hydrological losses' for trees on overland flow during floods.

It is widely acknowledged (e.g., Roberts, 1999) that conifers in the UK uplands have greater wet-canopy evaporation rates during storms than broadleaf trees (with or without leaves). Locally pertinent evidence for rates of wet-canopy evaporation during winter storms is, therefore, separated into conifer and broadleaf classes. The main problem with the available data on wet-canopy evaporation (E_{WC}) is that it is invariably derived for a contiguous series of rain events, not just a single large event (i.e., events more akin to the 1-in-30 year flood scenarios simulated in this study). Values of E_{WC} are calculated from a canopy water balance, where the average amount of rainfall that reaches the ground surface below plant canopies is subtracted from the amount of rainfall measured either above the canopy or in a large canopy gap over the same time periods. These measurements are typically taken after a week of volumetric water collection, as historically they were only used to assess tree impacts on long-term (i.e., annual or longer) water resources. *Very few data are available on a daily time-step or shorter, where wet-canopy evaporation rates can be associated directly with large daily rainfall totals*. A seminal study on the effects on conifers on rates of wet-canopy evaporation and streamflow changes was undertaken near Stocks Reservoir on Bowland Fells, Lancashire by Mr Frank Law (see e.g., Calder, 1990). Lancaster University hold the original datasheets from Frank Law's experimental facility at Stocks Reservoir, where the wet-canopy evaporation data were collected.

For this Wasdale project, the whole dataset covering July 1955 to December 1970 has been reviewed to find days with large rainfall events (i.e., greater than 50 mm per day) that have both daily rainfall and daily 'throughfall' values. Throughfall is amount of rainfall that penetrates a vegetation canopy rather than be lost back to the atmosphere. Table 1 shows all of the pertinent data found within the 15 year record.

For the Sitka spruce (*Picea sitchensis* (Bong.) Carr) conifers in this study, the daily E_{WC} rates varied from 17.8 to 40.5 mm/day for individual rain-storms delivering 51 to 90 mm rainfall per day. This very limited number of data gives an average *wet-canopy evaporation rate for this conifer site in the Northwest England uplands of 30 % of the rainfall for events larger than 50 mm/day*, so this value is used for the Wasdale modelling. It is acknowledged that this investigation uses rates based on this specific dataset, and that there are therefore uncertainties, which may be reduced in the upcoming NERC investigations into the effectiveness of Natural Flood Management through additional field data collection.

Table 1. Rates of wet-canopy evaporation (E_{WC}) for large rain-events where daily (or 2-day) rainfall (R) and throughfall (T) available in the July 1955 to December 1970 record for the experimental sites near Stocks Reservoir, Bowland Fells, Northwest England (UK). Note: numbers used in calculations are presented to three decimal places to avoid rounding errors.

Flood event date	Mean of 3 'outside gauges' (inches)	Mean of 10 or 20 'plantation gauges'(inches)	"daily" rain (mm/d) >50mm events	"daily" throughfall (mm/d)	E_{WC} (mm/d)	**E_{WC} (% rain)**
03-Aug-61	2.020	1.660	51.308	42.164	9.144	17.8
8-Dec-64 (incl. 0.997” on 7-Dec-64)	3.537	2.105	89.840	53.454	36.386	40.5
19-Mar-68 (incl. 8.60 mm on 18-Mar-68)			65.400	48.925	16.475	25.2
17-Nov-70 (incl. 5.6 mm on 16-Nov-70)			55.470	39.520	15.950	28.8
			262.018	184.063	77.955	30
			Total R	Total T	R-T	100(E_{WC}/R)

As with conifers, very few data on wet-canopy evaporation pertinent to winter storms are available for broadleaf trees. Appendix 1 does, however, provide a summary of rates observed in winter storms for broadleaf woods in Northern Europe (i.e., when trees were leafless). This new collation of data includes results from Bogle Crag Wood and Meathop Wood in Cumbria. *The values are all based on longer term rates (for winter leafless periods), not daily rates specific to large storms, so are less reliable when applying to 1-in-30 year flood events, but are currently the only data readily available*. The studies report wet-canopy evaporation rates for these periods of 7, 9.9, 10, 10.5, 12, 12.1, 14, 15.1, 15.6, 19.8, 22.6, 31, 36, and 49 % of rainfall. The average of these *wet-canopy evaporation rates from leafless broadleaf trees is 19 % of winter (mostly December) rainstorms*. For reference, a higher 28 % of rainfall was lost to wet-canopy evaporation from these studies for summer periods when trees were in leaf. Consequently, while daily canopy water balance data would be preferable (and needed in future studies), the 19 % of water lost from the storm hydrograph is the experimentally-based estimate used in this desk study.

Wasdale now and a future landscape

The upstream areas of the contributory areas for Wasdale Beck are covered by either semi-natural grassland (heath; acid grassland) or vegetation characteristic of organic soils (blanket bog; mire; see Figure 2) that are grazed by sheep and wild deer. A small plantation block, largely felled, is also present. The upstream areas of Blea Beck have a similar mix of habitats. Further downstream the extent of organic soils reduces and the semi-natural grassland is replaced by improved pasture that is more intensively managed for sheep production.

The Woodland Trust suggest that a significant proportion of the semi-natural grassland area in the headwaters of Wasdale Beck, i.e., upstream of A6 and in the Lake District National Park, could be planted with deciduous woodland to deliver significant NFM benefits and wider environmental and social benefits. This suggested planting area is shown in Figure 3, and would leave large areas of Wasdale for deer grazing.

To demonstrate maximum potential flood mitigation benefit of tree planting within Wasdale *the study simulates the effects of having most of the area outside of the National Park as covered by very extensive, commercial conifer plantation* (Figure 4).

For compatibility with the national modelling of the NFM benefits (by overland flow changes) using trees, the Wasdale simulations also include broadleaf tree planting along 50 m corridors (in areas outside of the nationally mapped zones of organic soils), and all floodplains with a 0.1% chance of flood inundation.

Given that the flood mitigation benefits of peatlands may be improved by incorporating a series of small dams in the drainage grips (Dadson et al., 2017), the modelling of Wasdale also incorporates this intervention, in additional to tree planting. Similarly, tree planting for flood mitigation is often accompanied by the construction of series of small semi-permeable dams (‘leaky barriers’) on the tributary streams to retain flood waters in the headwater channels. Consequently, the effects of these interventions are also assessed.

The complete picture of the intervention simulated is shown in Figure 4, with a more detailed presentation of the upstream areas in Figure 5 and downstream areas in Figure 6.

In addition to delivering flood mitigation benefits for downstream communities, the targeted planting of deciduous trees and restoration of peatlands in the National Park, combined with wider use semi-permeable dams in channels will have the considerable benefit of restoring the wider ecosystem services of the Wasdale landscape.

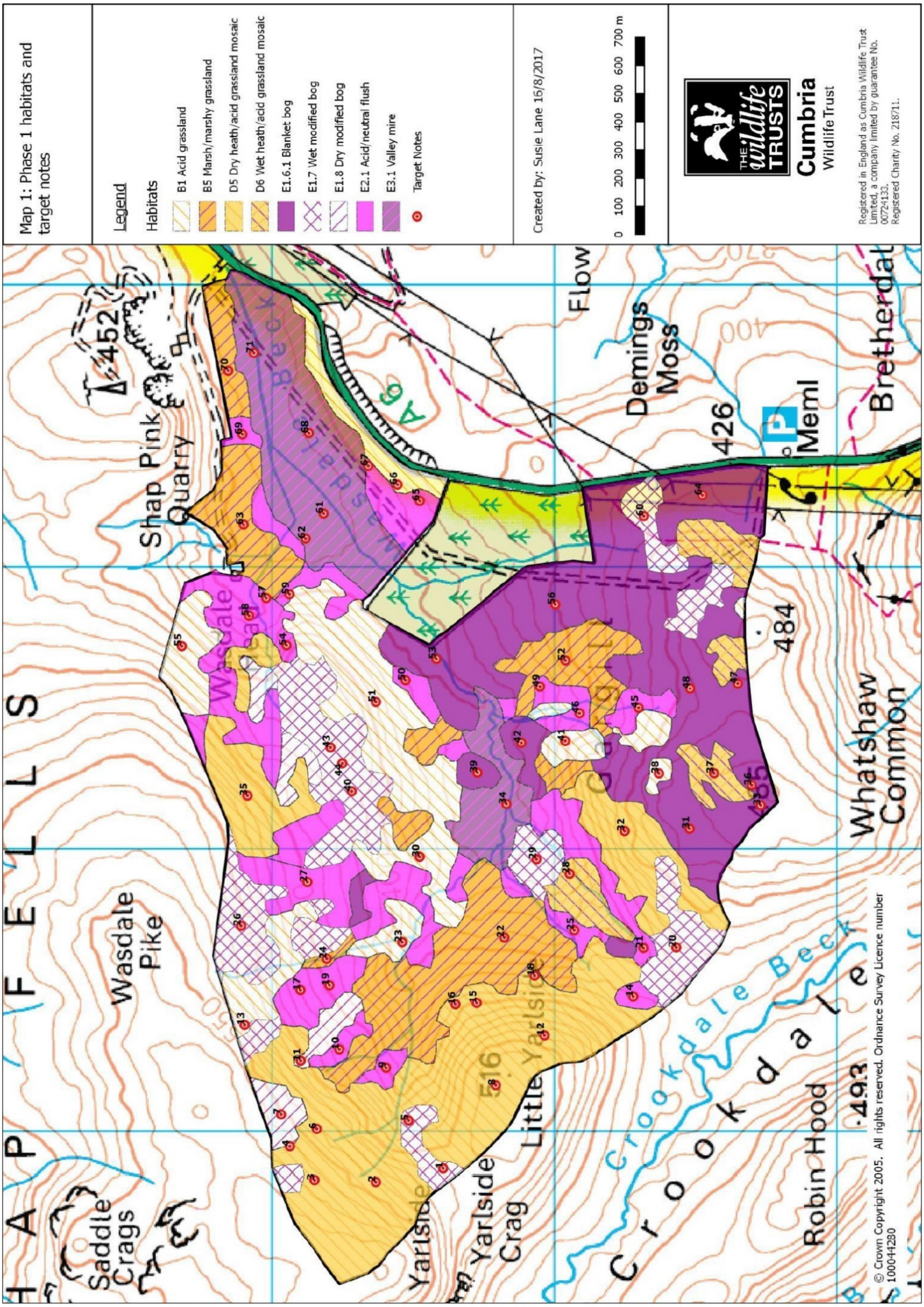

Figure 2. Habitat of the headwaters of Wasdale Beck, adapted from Lane (2017).

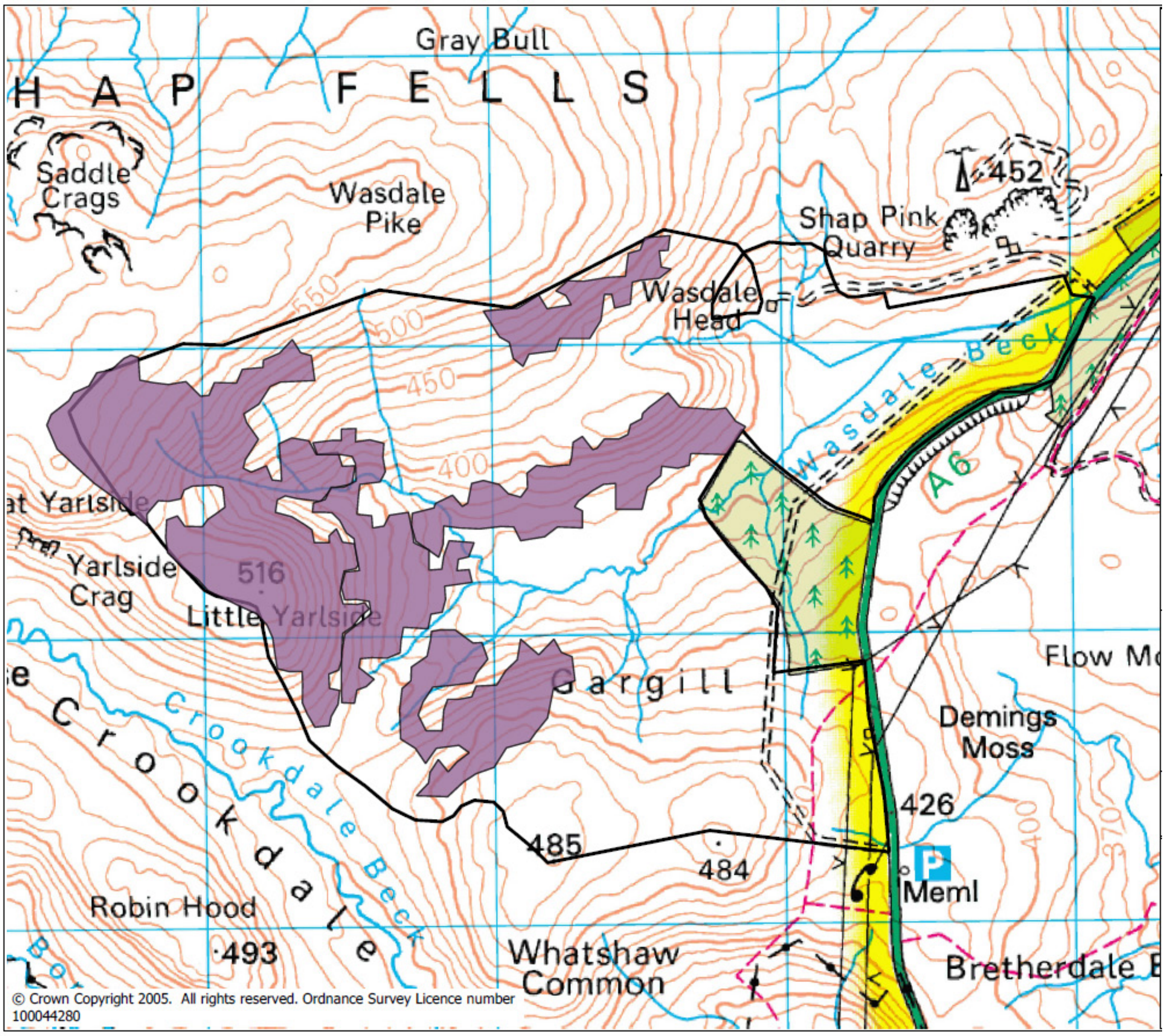

Figure 3. Suggested Woodland Trust strategy for deciduous tree planting in the Wasdale Beck catchment, avoiding areas recently mapped with greater than 50 cm peat (first version of the Cumbria Wildlife Trust map).

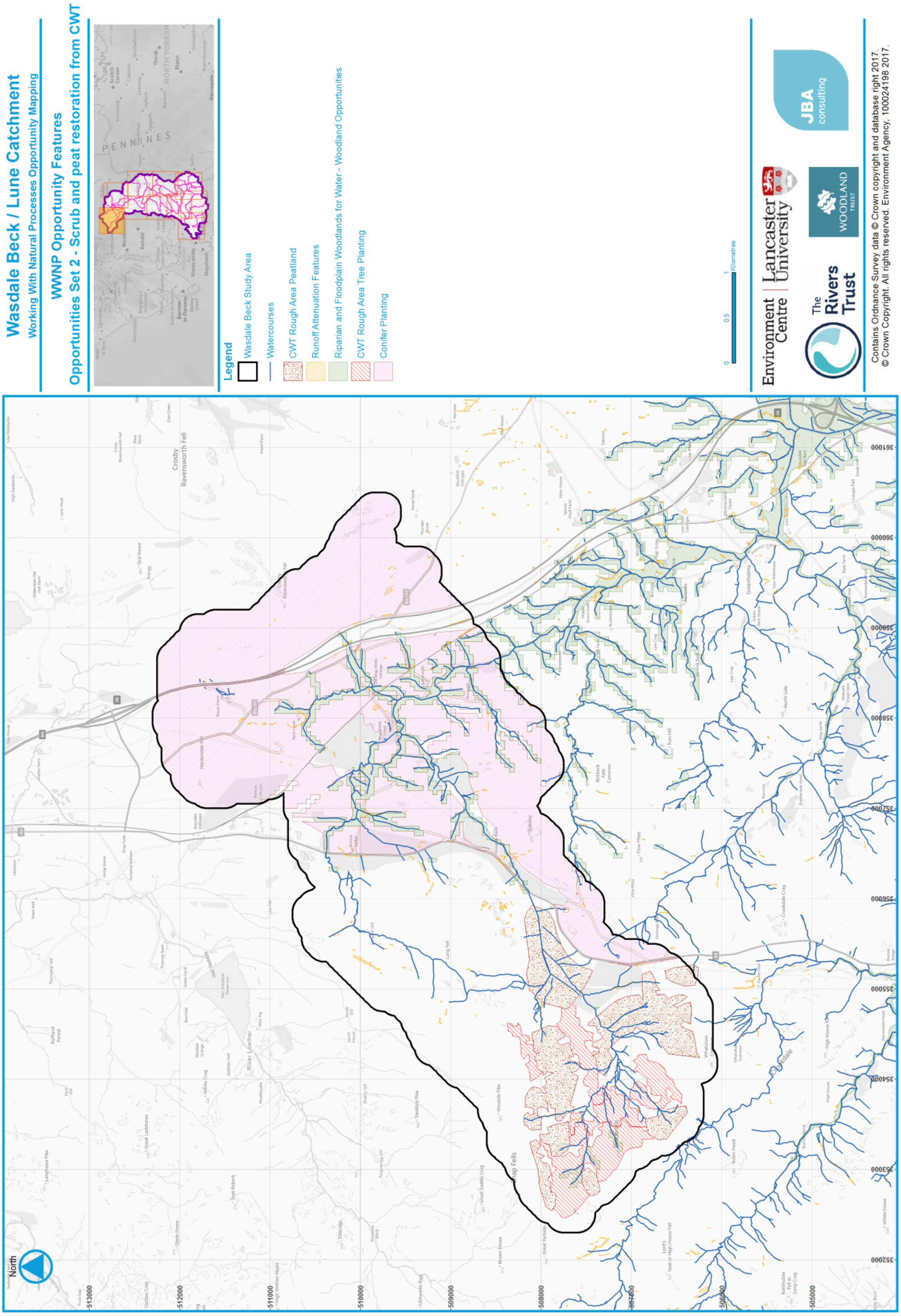

Figure 4. Map of the complete set of interventions simulated for Wasdale

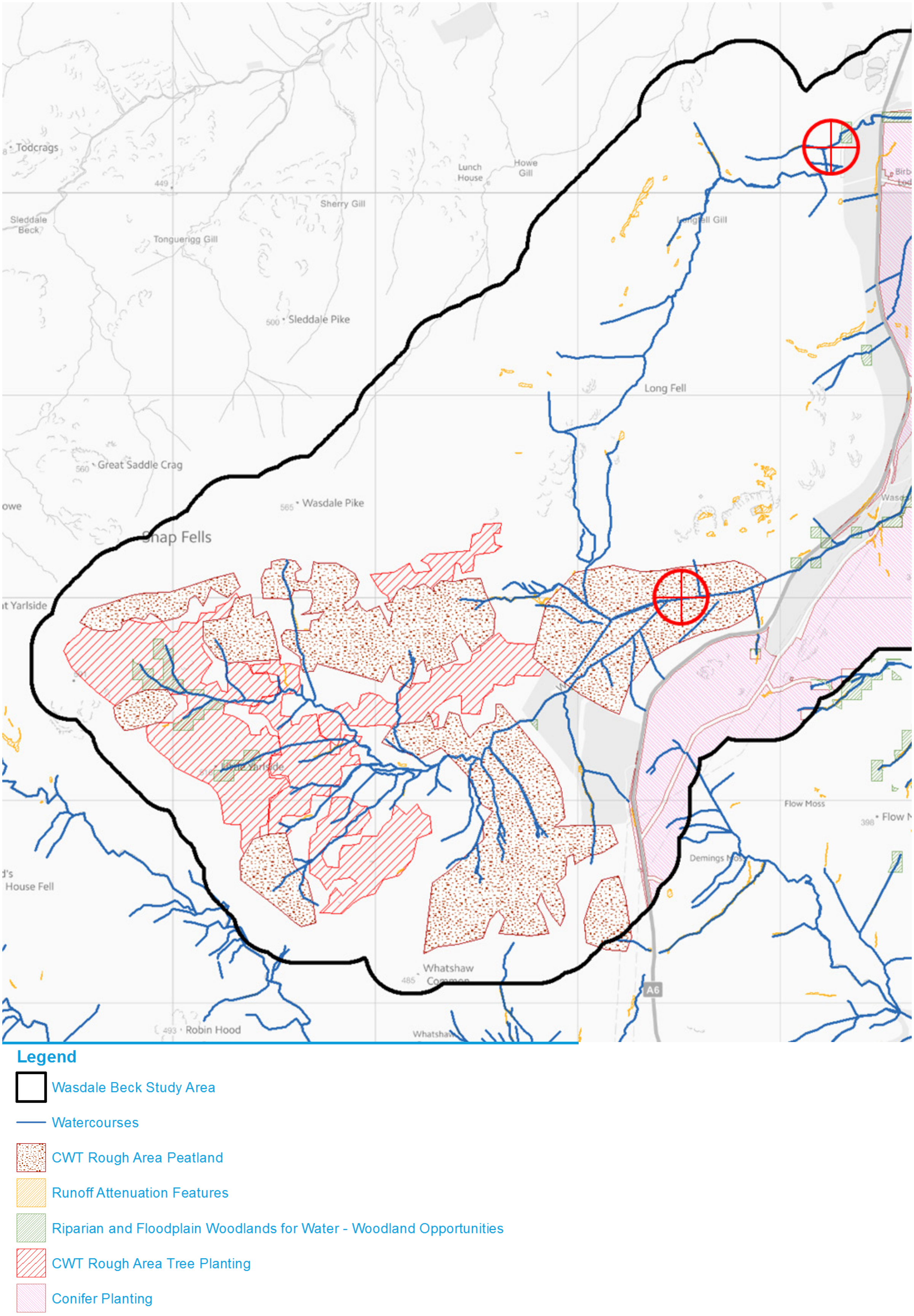

Figure 5. Detailed map of the complete set of interventions simulated for the Wasdale headwaters. The lower crosshair shows the location of the 'virtual gauging station' on Wasdale Beck, and upper crosshair on Blea Beck.

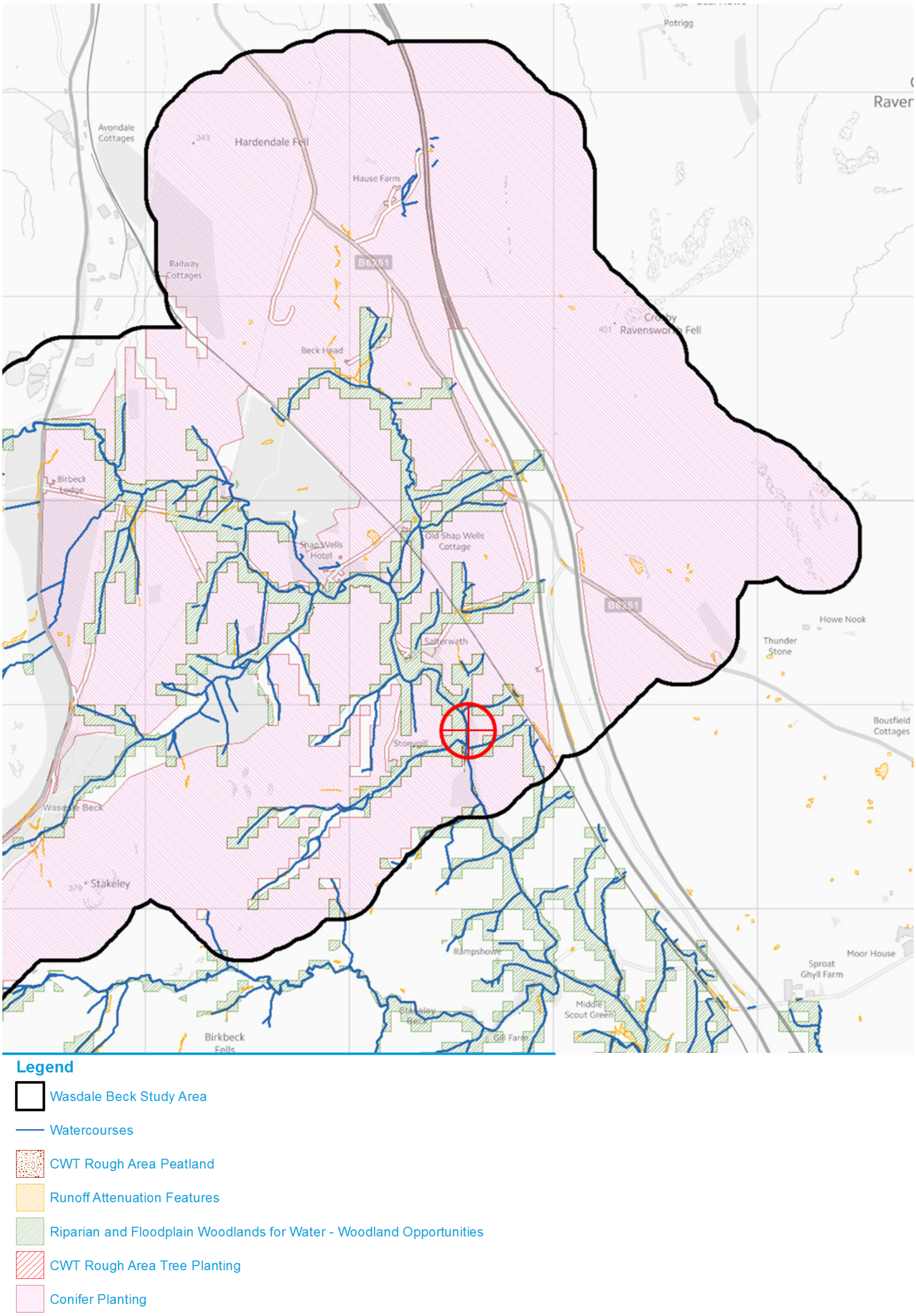

Figure 6. Detailed map of the complete set of interventions simulated for the downstream areas of Wasdale. The crosshair shows the location of the virtual gauging station on Birk Beck.

Results of baseline simulations of overland flow in a 1-in-30 year flood

Baseline flood simulations are undertaken prior to the simulation of the effects of tree planting (and additional effects of 'leaky dams' on small channels and peatland restoration). These simulations are based on the landscape classifications and JFLOW-model used in the Environment Agency's national surface-water flooding maps (e.g., Hankin et al., 2017), but with the adjustments highlighted above.

Figure 7 shows the overland flow flood hydrograph for a 1-in-30 year extreme event.

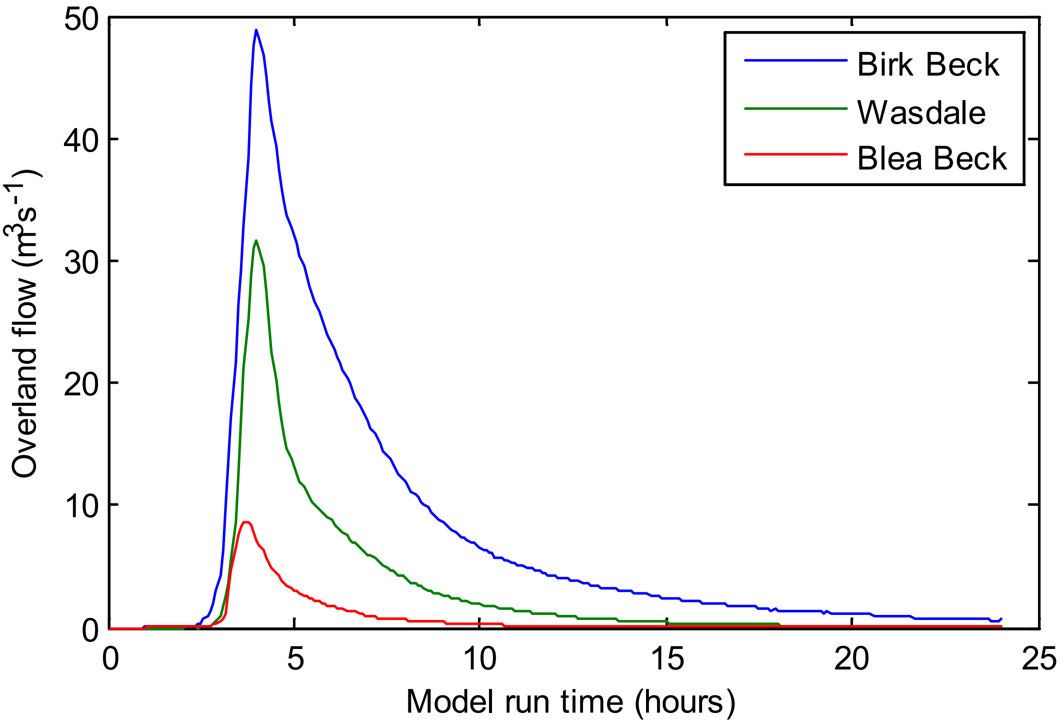

Figure 7. Baseline overland flow simulations of Birk Beck, Wasdale Beck headwater and Longfell Gill headwater (of Blea Beck) for a flood event with a 1-in-30 year recurrence interval (ref: flow_separation4.m).

The largest peak in overland flow is for a point downstream of Wasdale Beck where the stream is now called 'Birk Beck' after joining with Blea Beck. The 'virtual monitoring station' (i.e., it is virtual as there are no streamflow monitoring stations on the streams within or just outside of Wasdale) is just upstream of the tributary input from Stoneygill Beck (near Stoneygill Farm). This point on Birk Beck is shown with a crosshair on Figure 6. This approximately 16 km^2 basin includes the main tributary of Wasdale Beck, but also that of Blea Beck (fed by Longfell Gill) and minor drainage around the corridor of the M6 and railway line, notably Trundle Beck. A further 'virtual monitoring station' is located in the headwaters of Wasdale Beck, 500 m upstream of the A6 (Figure 5). This river location has a slightly more flashy overland flow flood hydrograph to that produced at Birk Beck downstream, with a flood peak that is as much as 65 % of that the large basin, while the overland flow hydrograph contains 40 % less water. The larger flood peak per unit basin area is probably due the steeper slopes in this area, when compared with other parts of the basin, such as Longfell Gill in the Blea Beck headwater (also shown in Figure 5) or compared with the eastern area of the corridor of the M6 and railway line. The difference in amount of water delivered is as expected, given that the 'virtual monitoring station' in the Wasdale headwaters gauges 40 % of the area (i.e., approximately 6 km^2) of larger basin.

The observation that the Wasdale headwaters: (a) occupy a significant proportion of Wasdale, and (b) have a slightly flashier response than the catchment as a whole means that it is an optimal location to deploy flood mitigation interventions involving trees etc.

Results of tree planting effects on overland flow in a 1-in-30 year flood

In accordance with the NFM strategies contained within the Environment Agency and Forest Research 'Woodland for Water' layer, there are three types of location in the landscape where hypothetical tree planting scenarios have been evaluated. The first locations are areas of river floodplain (with a likelihood of flooding more than 0.1 % probability in any year, i.e., Environment Agency 'Flood Zone 2'). The second locations are 50 m wide corridors containing all permanent stream channels; though such locations are excluded where the national map shows presence of organic-rich soils. In other simulations of JFLOW, the third location for tree planting (outside of the first two areas) has been areas mapped nationally as having a higher likelihood of generating fast flowing surface-flow on slopes. This has been predicted using the spatial dataset of 'SPR>50% index' values (see Boorman et al. 1995; Broadmeadow et al., 2014). Recently, Hankin et al. (2017) have shown that areas of slowly permeable soils are better predicted at the sub-catchment scale using geological data (e.g., maps of glacial till location).

With the assessment of the potential value of tree planting in Wasdale, the following planting locations are covered:

(1) The effect of deciduous tree planting on floodplains (e.g., in the central section of Wasdale Beck; see Figure 5);

(2) Planting of all streambanks (except those in areas of peat) with a 50 m wide corridor of deciduous trees (see Figure 5 and 6). The map (embedded within the "Woodlands-for-Water or WfW" GIS layer that we use in our modelling: Broadmeadow et al., 2014) shows peat around most channels in the headwaters of Wasdale and so this type of planting is excluded in the Wasdale headwaters, but much more extensive downstream (Figure 6). Strictly only in areas (including streambanks) where peat depth exceeds 50 cm, should tree planting be excluded (Broadmeadow et al., 2014). A parallel field survey of Wasdale by the Cumbria Wildlife Trust has mapped areas of peat exceeding 50 cm depth. This work shows that many of the channels in the headwaters of Wasdale Beck do not have such depths of peat (see Figure 1). We are, therefore, slightly underestimating the potential role of deciduous tree planting in the Wasdale Beck headwaters (see Figure 3 and 5), because these streambanks are unnecessarily excluded from the modelling;

(3) Fenced areas with planting at a density of 400-650 deciduous trees per hectare are included in the headwaters of Wasdale Beck upstream of the A6 and so inside the Lake District National Park. The location and size of these areas (see Figures 3 and 5) were determined by the Woodland Trust, and excluded areas mapped by the Cumbria Wildlife Trust as having deep peat (Figure 1);

(4) All areas of Wasdale (gauged 'virtually' downstream on Birk Beck) that are outside of the Lake District National Park (i.e., all areas east of the A6 trunk road) are projected to be planted with commercial conifers in the requested Woodland Trust scenario (see Figures 5 and 6). This would be a major expansion of conifer planting to cover half of Wasdale. Only the poorly accessible area between the railway line and M6 motorway is excluded from this conifer planting; and

(5) To focus attention on the effects of the Woodland Trust strategy for deciduous tree planting in the headwaters, additional tree planting in areas of glacial till (or areas with SPR>50% index values) in the upper catchments of Wasdale Beck or Blea Beck are not included within Wasdale tree planting scenario.

For all areas planted with either deciduous trees or conifers, the ground-surface roughness against the passage of overland flow down slopes was increased from the baseline of 0.100 to 0.125 (dimensionless), as within the Environment Agency RoFSW maps. Additionally, the proportional losses were increased from 0.05 to 0.19 (expressed as 'BFIHOST value' and used to estimate the maximum soil moisture storage in the 'ReFH losses model' of JFLOW) for all areas with deciduous planting, and increased from 0.05 to 0.30 for conifer planting, to represent the increase in wet-canopy evaporation from 5 % of rainfall to 19 % and 30 %, respectively, from such planting areas. For all scenarios an additional 26 % of the resultant overland flow is lost to slow flow via infiltration (in line with the national BFIHOST map).

For the Wasdale Beck headwater (i.e., upstream of 'virtual monitoring station' shown in Figure 5), almost all of the tree planting is associated with the "Woodland Trust planting areas" (i.e., 'planting location 3' above), with a small area of conifer planting on Packhorse Hill, and smaller areas of floodplain planting and riparian planting along the upper 200-400 m of the headwater channels dominated by mineral soils (Figure 5).

Figure 8 shows the visual change in: (i) the magnitude of the overland flow peak and (ii) its timing, and (iii) the amount of overland flow between the baseline and tree planting scenario in the Wasdale Beck headwater (i.e., upstream of 'virtual river monitoring station' in the lower part of Figure 5). A clear reduction in the peak of the 1-in-30 year flood discharge can be seen as a result of the tree planting. The peak after tree planting is only 70 % that of the baseline simulation (i.e., the peak has reduced by 30 %). Comparison of the total amount of water rapidly discharged during the event (i.e., area under the curves in Figure 8), tree planting to the extent described above has reduced the overland flow by 15 percent. Almost all of this effect is due to the enhanced wet-canopy evaporation in planted areas, but there is also a very small additional amount of water retained in the planted areas due to roughening the ground surface (i.e., 'detention storage'). The greater roughness in the fenced and planted areas also has a small effect on the timing of the flood peak. The time-to-peak for the headwater basin reduces by 10 minutes (i.e., two modelling time-steps) from 4.000 to 4.167 hours following tree planting. Such a small effect of roughness change on time-to-peak of flood hydrographs is typical of other catchment-scale modelling studies in the region (e.g., Hankin et al., 2016). Additional changes to infiltration by trees are not covered in this study due to a lack of local measurements.

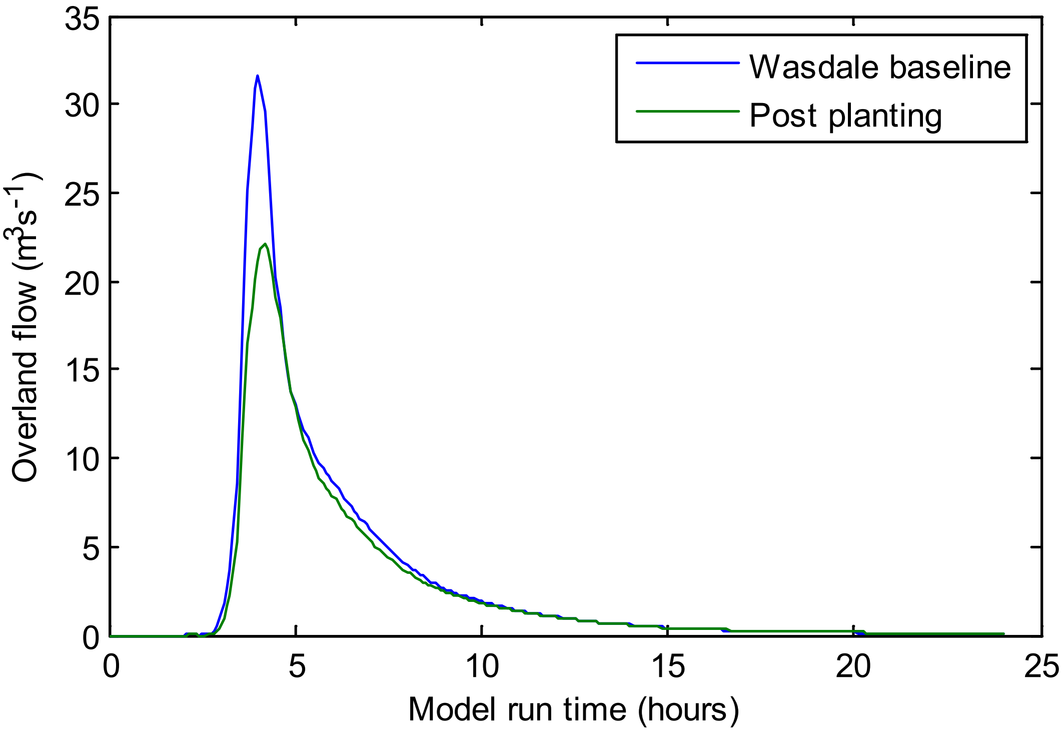

Figure 8. Results of the simulation of a 1-in-30 year overland flow flood event with current conditions ('Baseline') and post planting at the 'virtual monitoring river station' in the Wasdale Beck headwaters (see Figure 5).

For the whole Wasdale catchment (for 'virtual monitoring station' in Figure 6), almost all of the downstream half the catchment is planted with conifers in the simulation scenario, and so considerably larger effects on overland flow flood peaks are expected. Figure 9 shows the visual change between the baseline and tree planting scenario for the whole Wasdale catchment.

The tree planting scenario at the whole catchment scale gives a peak-flow that is only 40 % that of the baseline simulation (i.e., the peak has reduced by 59 %). The total amount of water rapidly discharged during the event has also reduced by 40 % of that seen before the planting. The large reduction in the amount overland flow is due primarily to the very extensive nature of the conifer planting (about half of the whole catchment) and the change in the wet-canopy evaporation in this extensive area from 5 % to 30 % of rainfall shortly after it falls. The time-to-peak reduces by 45 minutes (i.e., 9 simulation time-steps each 5 minutes in duration) from 4.000 to 4.750 hours following the extensive conifer planting. This effect is primarily due to the wet-canopy evaporation being lost on the rising stage of the flood hydrograph during gaps in the rainfall pulses. There is also a small effect of the increased ground roughness over such a large area. A slightly more complex flood hydrograph is produced from such extensive interventions in only one half of the catchment.

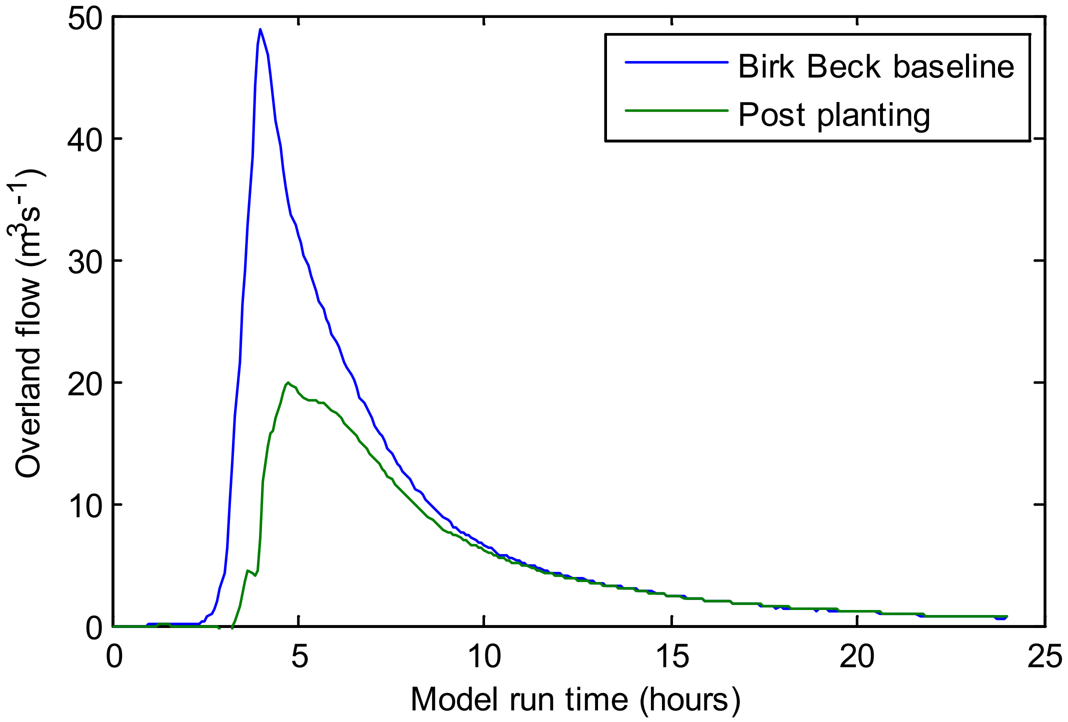

Figure 9. Results of the simulation of a 1-in-30 year overland flow flood event with current conditions (‘Baseline’) and post planting at the ‘virtual river monitoring station’ downstream on Birk Beck (see Figure 6).

Results of additional benefits from peatland restoration and leaky dams on overland flow in a 1-in-30 year flood

Separate simulation scenarios were undertaken to show the effects, added to those of tree planting, of restoring deep peats and adding ‘leaky dams’ on tributary channels. A significant proportion of the deep peat in the Wasdale headwater, as mapped by the Cumbria Wildlife Trust, has been drained (Orr and Carling, 2006). If numerous small dams are placed in these drainage channels, the effective roughness of the peat surface may be increased to slow the overland flows in peat areas. Temporary water storage within incised sections of small natural channels may be increased if semi-permeable dams (made from natural materials) are added into reaches of these channels. They are often called ‘leaky dams’ and allow low-flows to pass the dams with little effect, but hold back high-flows during large flood events. Leaky dams can be introduced at key channel locations within JFLOW simulations using automated routines. Within the Environment Agency opportunity mapping, the numerous small dams added hypothetically to peatland drains may be introduced by changing from a baseline roughness of 0.100 (for drained peat) to 0.125 (for undrained or restored peatland); we utilise these values in this desk study for Wasdale.

Figure 10 shows the visual change in the flood hydrograph for the Wasdale Beck headwater for the baseline scenario, following tree planting alone (shown in Figure 8) and after adding peatland restoration and 'leaky dams' to the tree planting scenario.

By supplementing the tree planting with these peatland restoration and 'leaky dams' the peak-flows for the 1-in-30 year reduce only by a further 3 % of the original baseline overland peak-flows for the Wasdale Beck headwater. Similarly, the total volume of fast flow only reduces by a further 0.9 % of the baseline relative to the tree planting scenario. Roughness reduces by a further 5 minutes (i.e., one additional simulation time-step). The additional peak-flow reductions come from the rougher peatland slopes following drain management combined with storage behind leaky dams filling on the rising stage of the flood hydrograph. The additional removal of water from the overland flow pathways to the outlet comes from detention storage caused by the surface roughening and storage behind the leaky dams. Critically, it is clear that the effects of peatland restoration and 'leaky dams' in the Wasdale Beck headwater is, however, much smaller than the effect of tree planting, even though the area of potential peatland restoration (Figure 1) is comparable in area to the slope planting areas suggested by the Woodland Trust (Figure 3).

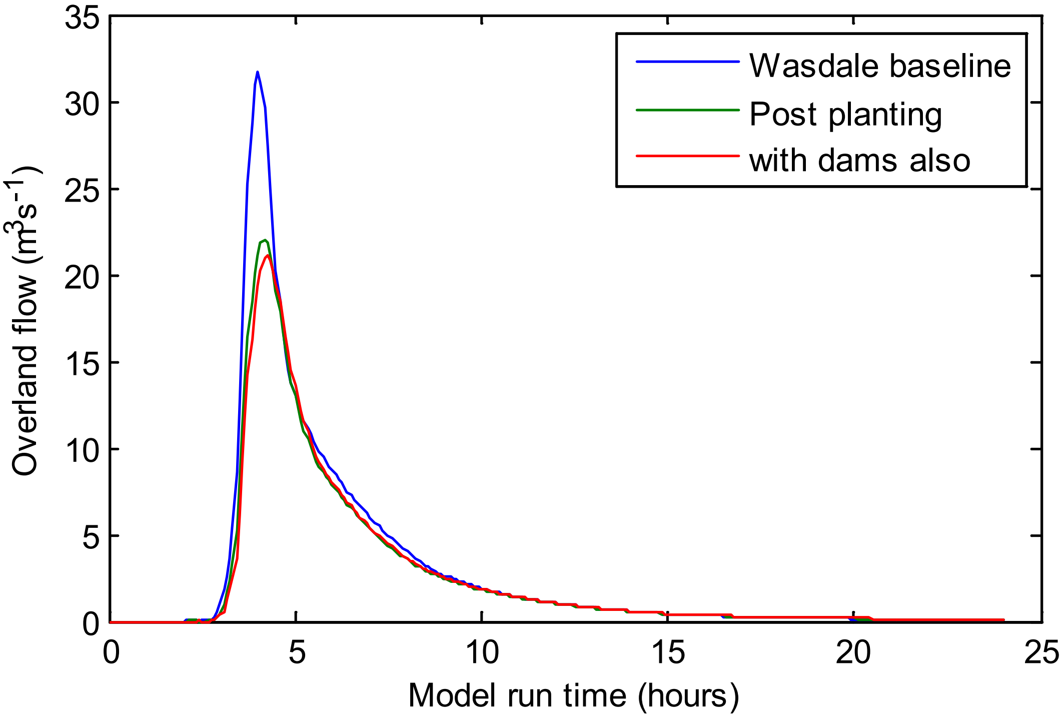

Figure 10. Results of the simulation of a 1-in-30 year flood event with current conditions ('Baseline overland flow') and post planting with additional effects of peatland restoration and 'leaky dams' at the 'virtual river monitoring station' in the Wasdale Beck headwaters (see Figure 5).

Figure 10 shows the visual change in the flood hydrograph for the whole of Wasdale for the baseline scenario, following tree planting alone (shown in Figure 9) and after adding peatland restoration and 'leaky dams' to the tree planting scenario.

The additional interventions have reduced the peak-flows in Birk Beck by an additional 5 % of the baseline simulation, slowed time-to-peak by an additional 15 minutes (i.e., one additional time-step), and reduced the overland flow volume by an additional 3.8 %. The deep peats within the simulations are all located in the Wasdale Beck headwaters, so the slightly greater additional benefits observed further downstream must relate to the addition of many leaky dams on the small channels in the downstream half of Wasdale.

As in the headwaters, most of the flood mitigation benefits come from the tree planting rather than deploying so called 'Runoff Attenuation Features', RAFs, in natural channels or peatland drains. This tree-related benefit is mostly attributable to the wet-canopy evaporation role of trees in removing storm rainfall before it reaches the ground.

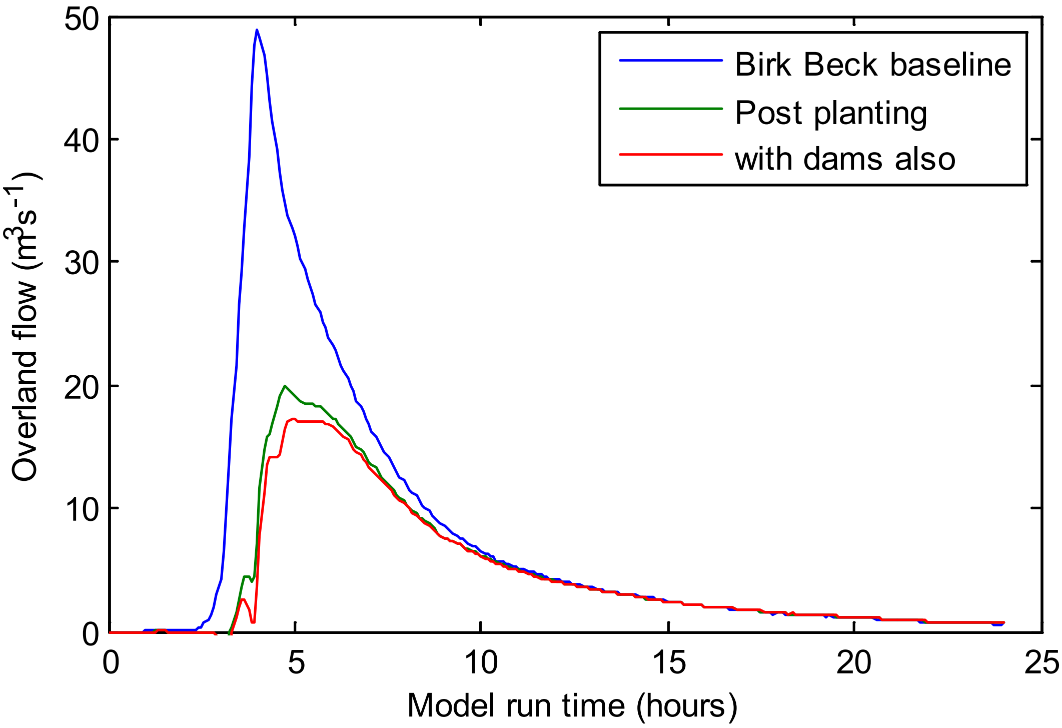

Figure 11. Results of the simulation of a 1-in-30 year flood event with current conditions ('Baseline overland flow') and post planting with additional effects of peatland restoration and 'leaky dams' at the 'virtual river monitoring station' downstream on Birk Beck (see Figure 6).

Limitations and potential for future work

This study has utilised the simulation model selected by the Environment Agency to quantify the flood mitigation benefits of trees and wider interventions at a national scale. Further, its implementation to Wasdale has been further improved with the incorporation of data locally more pertinent than the national dataset. There are, however, limitations to this modelling work and the data currently available, that need to be highlighted, so that further work may address these issues:

1/ The model focuses on routing storm rainfall towards stream channels according the detailed topographic setting and a physics-based description of the water-flow. There is a lack of locally verified data on the rates of recharge of deep water pathways (that maintain “baseflow” between storms), so spatial variations in this process are not explicitly simulated. Along the main channel of Birk Beck below the main confluence of Wasdale Beck and Blea Beck, slowly permeable glacial till is absent and the solid geology comprises of relatively permeable sandstone. If field data were available, explicit modelling of recharge or discharge of groundwater from the solid geology in this area to the river would locally improve the accuracy of the simulations.

2/ This study seeks to quantify the maximum potential benefit of tree planting (and related interventions) on overland flow within Wasdale. The maximum benefit arising from enhanced wet-canopy evaporation following tree planting on acid grassland or improved pasture, is not delivered as soon as trees are planted. For example, with conifers the maximum benefit is only delivered after canopy closure that may take a decade (depending on site conditions: e.g., Hudson et al., 1997). With a programme of local measurements of wet-canopy evaporation from stands of trees of different ages (and species), the time-varying effects of woods/plantations may be quantified and incorporated into model simulations. Equally the effects of forest management (e.g., encouragement of ground-cover vegetation, tree thinning, clear-felling, continuous-cover forestry) could be quantified locally (i.e., in the upper Lune or adjacent catchments) and then simulated. In terms of providing continuity of the flood mitigation benefits of trees, utilising continuous-cover forestry rather than clear-felling of large proportions of catchment, would be preferable.

Constructing numerous small dams in peatland grips or semi-permeable dams in small streams (so called ‘leaky dams’) will deliver maximum benefit as soon as they are present. Use of such interventions in the UK is new, so it is not known if the structural integrity of these features deteriorates over time (with sedimentation or collapse), and hence if their flood mitigation benefits reduce without maintenance or re-construction. With such field experimental information, non-optimal performance of such semi-natural dams may be simulated.

3/ This study has demonstrated the importance of pertinent wet-canopy evaporation data to the results of simulations tree effects on flood mitigation. The study has sourced and incorporated more pertinent data to simulations specifically of flood conditions. As noted earlier there is a fundamental lack of experimental data on the daily balance between rainfall and throughfall (combined with stemflow) beneath tree canopies. With the availability of such data collected locally (or nationally) at a daily or better time resolution, more reliable rates of wet-canopy evaporation specific to *very* large storms may be incorporated in the modelling. This is important, as the rates of wet canopy evaporation used here for conifers are based on large rainstorms delivering 51-90 mm of rainfall (Table 1). **Rainfall events larger than 90 mm (where throughfall data is currently not available at a sub-daily resolution) would be expected to provide smaller opportunities for wet-canopy evaporation, and so the beneficial effect of this water removal process to resultant overland flow flood peaks would be smaller.** Given the potential importance of this effect for extreme floods, the lack of observations of throughfall (and related stemflow) specific to *extreme* rain-events is a research gap of national importance.

4/ With JFLOW, the rapid delivery of water from slopes to streams during flood events is simulated as an overland flow pathway. If locally observed data on overland flow, then explicitly simulating this pathway would produce more accurate assessments of the impacts of tree planting on flood response.

5/ There are no river gauging stations within Wasdale. If a river gauging station were to be installed, even in the Wasdale Beck headwaters, the properties of the model could be adjusted ('calibrated') to produce accurate simulations of *observed flood events*. Such baseline simulations would be more accurate than those undertaken where no observed streamflow data are available. This would similarly improve the accuracy of the simulations of the interventions that build on the baseline simulations.

6/ The current study has simulated NFM effects through a 1-in-30 year rainstorm (i.e., an event that has 3.3 % chance of being present in any one year) of 6 hours duration. With improved observations of the local hydrological processes during large flood events, simulations of a range of much larger flood events would become more realistic and so included in future modelling studies.

7/ The issues above demonstrate that new field observations are needed to significantly improve our assessments of the value of trees and related interventions in the mitigation of overland flow flood peaks. A more comprehensive modelling study building on extensive field data should reflect the uncertainties inherent in the experimental data and the model simplifications that result from data gaps. To demonstrate the effect of the uncertainties on the simulation of flood peaks (with or without interventions) requires that many thousands of model runs are undertaken to sample the range in uncertainty present in the data and model structural components. Such simulations are possible with the latest parallel computing (Crossley et al., 2010; Hankin et al., 2016).

Summary of findings

This desk study utilising a whole-catchment 'direct-rainfall and losses' modelling approach at 2 m resolution, has demonstrated that tree planting in Wasdale has the potential to make significant reductions in the overland flow component of flood peaks. For the 1-in-30 year flood event simulated, planting broadleaf trees on some of the acid grassland areas of the Wasdale headwaters may reduce the overland flow component of flood peaks by 30 % of the current situation (based on average winter wet-canopy evaporation rates; needed rates for *extreme* storms with a recurrence interval of 1-in-30 years or less have never been collected). As expected, further flood mitigation would be achieved by introducing extensive conifer plantations further downstream outside of the National Park. While peatland restoration and construction of woody dams in small channels would further dampen the overland flow flood peaks, their effects are small when compared to the flood mitigation benefits of trees. Field investigations within Wasdale would be needed to justify more detailed modelling results. Such new field investigations, combined with further modelling, would place the Wasdale landowners at the forefront of estates making evidence-based assessments of how best to manage land for combined commercial, environmental and social benefit.

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Appendix 1

Wet canopy evaporation loss of storm rainfall from deciduous trees during winter storms