Upper Wharfedale Natural Flood Management Feasibility Study

Final Report

April 2018

Yorkshire Dales Rivers Trust

National Trust

Yorkshire Dales National Park Authority

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Revision History

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Draft / October 2017		YDRT, NT, YDNPA
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Contract

This report describes work commissioned by Dan Turner, on behalf of Yorkshire Dales Rivers Trust (YDRT), by a letter dated 9 December 2016. Ryan Jennings and Steve Rose of JBA Consulting carried out this work.

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Purpose

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JBA Consulting has no liability regarding the use of this report except to YDRT, NT & YDNPA.

Acknowledgements

JBA would thank staff at the YDRT, NT and YDNPA for the provision of various datasets for inclusion in this study.

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Executive Summary

JBA Consulting was commissioned by the Yorkshire Dales Rivers Trust (in partnership with the National Trust and the Yorkshire Dales National Park Authority) to undertake a Natural Flood Management (NFM) feasibility study within the Upper Wharfedale catchment down to the southern boundary of the Yorkshire Dales National Park between Bolton Abbey and Addingham.

JBA Consulting's in-house 2D modelling software JFLOW was used to undertake both baseline (current) and post-change NFM scenario modelling across the study area. This broad scale modelling approach enabled the relative changes to the flow (discharge) hydrographs, resulting from the introduction of some NFM measures in the catchment (to slow, intercept and store floodwater), to be predicted and analysed. Distributed NFM measures have been represented in the JFLOW model by modifications to individual model parameters and the underlying model data grids.

JBA have modelled 10 NFM scenarios (for individual NFM options and combinations of NFM options) for 3 rainfall event magnitudes (10 year, 30 year and 100 year return periods) across the catchment, including:

- Runoff Attenuation Features (RAFs)
- Forest Research Woodland for Water (WfW) opportunity areas
- NT/YDNPA new woodland plantings
- Vegetated buffers alongside watercourses
- Flood bank removal along River Wharfe SSSI
- Soil structural improvement to improved/calcareous grasslands

The largest flood attenuation effect at the downstream outlet to the study area was generated by the maximum woodland scenarios which represented the full implementation of the Forest Research Woodland for Water opportunity areas (for catchment woodland, floodplain woodland and riparian woodland), together with any new woodland plantings undertaken by NT/TDNPA (if they located outside of the WfW opportunity areas), and either with or without the application of an associated soil structural improvement under the tree areas. The flood peak across all the 3 rainfall magnitudes was reduced by nearly 40% and delayed by over 4 hours. This is an extremely generous scenario and highly unlikely to be implemented due to a number of constraints which will preclude such extensive woodland plantings.

The second most beneficial flood attenuation effect was generated by the combination scenario incorporating all the NT/YDNPA new tree plantings, the riparian sub-category of the WfW opportunity areas, vegetated buffers on all watercourses, and all the individual RAFs. This scenario was able to reduce the flood peak across the 3 rainfall magnitudes by 6-9% at the catchment outlet and delay it by up to 25 mins. This was followed by the vegetated buffer scenario implemented across all watercourses which reduced the flood peak at the catchment outlet by 2-5% together with a slight delay.

Some scenarios were able to generate localised flood attenuation benefits, especially at lower event magnitudes, that were not then transferred to the larger catchment scale after other catchment contributions and interactions were included. The flood bank removal scenario within the River Wharfe SSSI reach generated a peak flow increase as the shallow floodwater was able to flow quickly over the smooth grassed floodplain surface and short-circuit meander bends. However, if the reconnected floodplain surface was made rougher to reflect a coarser grass sward which might develop as a consequence of more regular flooding then a local flood peak reduction was predicted by the model.

The results from this study have confirmed that significant numbers and/or areas of NFM interventions would need to be implemented in the Upper Wharfedale catchment in order to deliver discernible flood risk management benefits at the catchment outlet, though localised benefits are present at the smaller sub-catchment scale.

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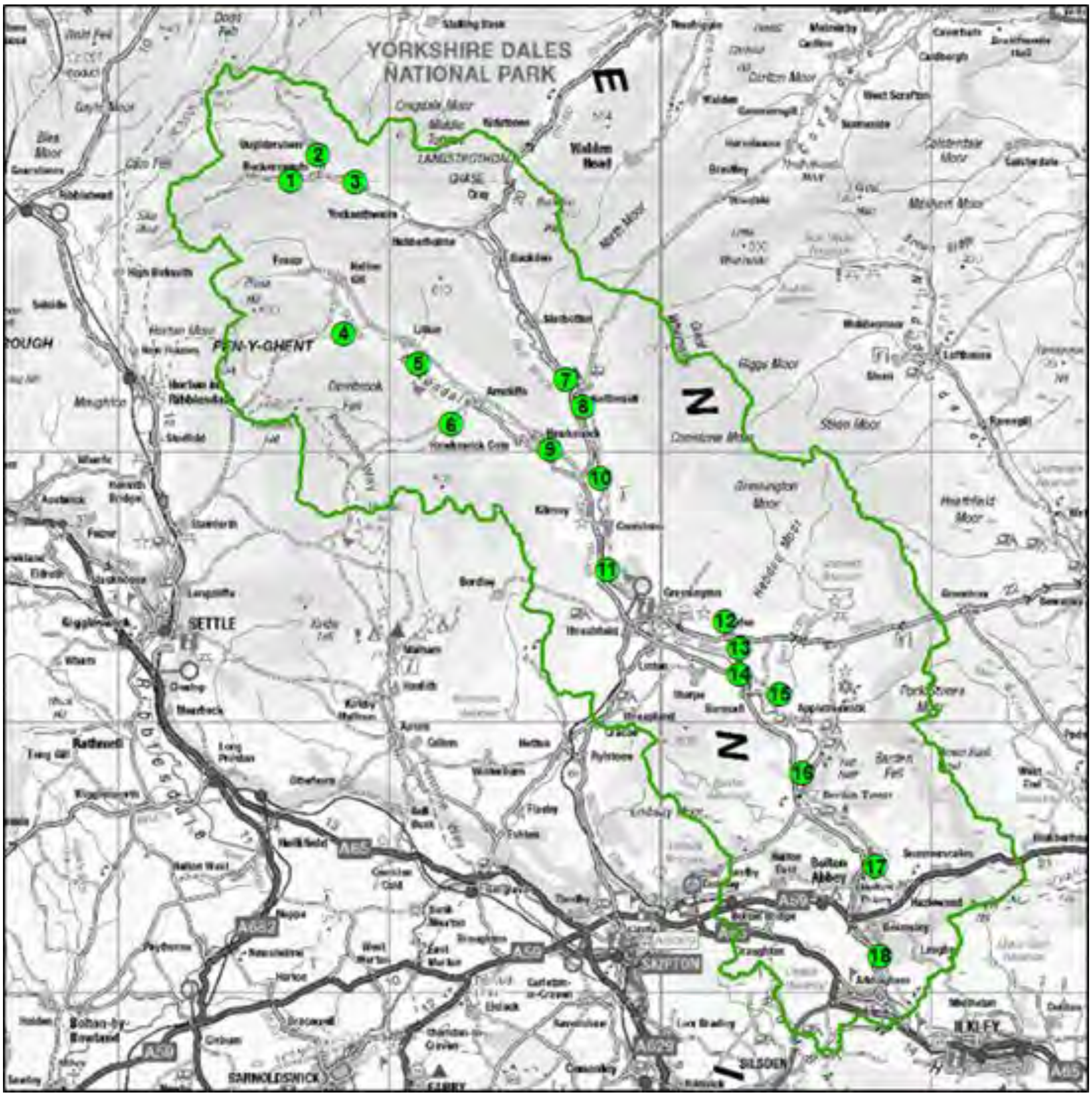
1 Introduction

JBA Consulting was commissioned by the Yorkshire Dales Rivers Trust (in partnership with the National Trust and the Yorkshire Dales National Park Authority) to undertake a Natural Flood Management (NFM) feasibility study within the Upper Wharfedale catchment with a total area about 445km^2 (Figure 1-1) through the application of a hydraulic modelling study. The Upper Wharfedale catchment outlet is the downstream boundary of the YDNPA area between Bolton Abbey and Addingham.

Using JBA Consulting's in-house 2D modelling software JFLOW, both baseline (current) and post-change NFM scenario modelling has been completed for the study area. This modelling enables the relative changes to flood flows (discharge hydrographs), resulting from the introduction of some NFM measures in the catchment (to slow, intercept and store floodwater), to be predicted and analysed.

Figure 1-1. Wharfe River Catchment: modelling extent, detailed study location and discharge (flow) monitoring point location. Contains OS data © Crown copyright and database right 2017.



2 JFLOW modelling

The JFLOW 2D model is able to produce fluvial or surface water (pluvial) flooding outputs, using user inputted grid datasets and hydrological information to solve the St Venant shallow water equations. In this study, a surface water rainfall model is used to produce outputs for in-channel and floodplain areas.

2.1 Hydrology

The model has been run for a 10 year, 30 years and 100-year magnitude rainfall events using three different rainfall hyetographs over a 6-hour period, using a summer storm profile, which is consistent with the approach taken to develop to Environment Agency updated Flood for Surface Water in 2012.

2.2 Input grids

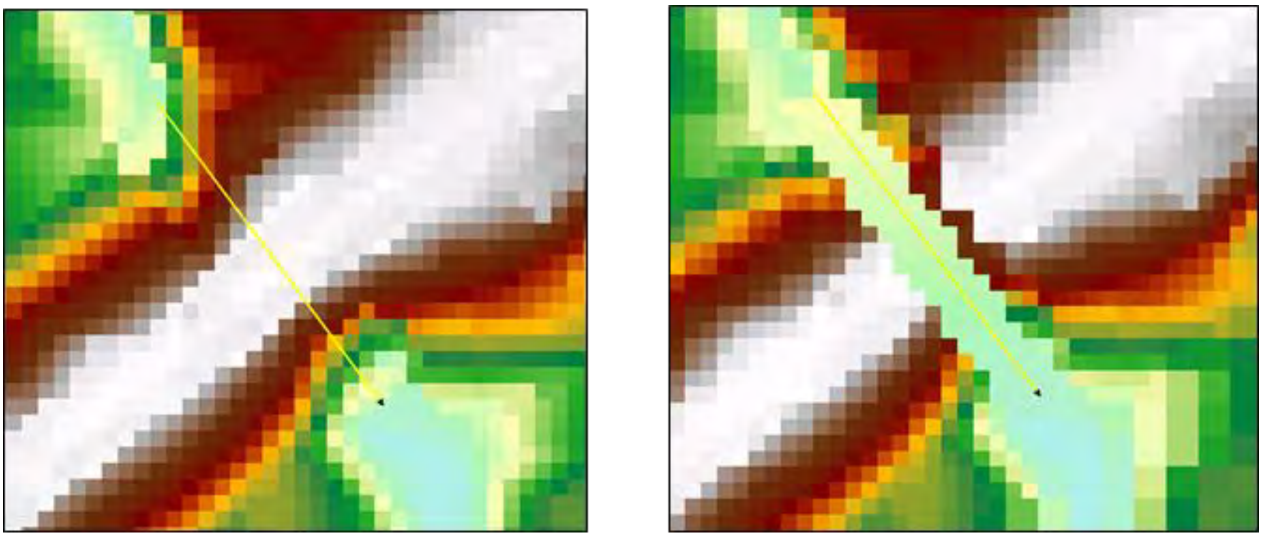
The following grids have been used within the model:

- **Digital Terrain Model (DTM);** continuous 2m grid Environment Agency LiDAR DTM data were made available for this study.
- **Rainfall Mask:** A grid dataset which plots 25km^2 tiles corresponding to differing rainfall hyetographs used across the catchment, supplied by EA.
- **Runoff Mask:** A raster dataset which plots different soil types across the catchment derived from a land soil map supplied by EA. The BFIHOST and PROPWET parameters were calculated and assigned to each different soil type. This enabled the model to calculate and apply the losses within the catchment due to infiltration.
- **Roughness Mask;** A raster dataset which defines ground surface roughness within the catchment derived from a land use map supplied by EA. A ground surface roughness value was then assigned to each land cover type, resulting in a varying resistance to surface runoff across the catchment area.

2.3 DTM Edits

Polyline edits were needed in-channel to allow water to flow through structures (e.g. bridges) and to smooth the channel where the two DTMs have been merged, Example as shown below.

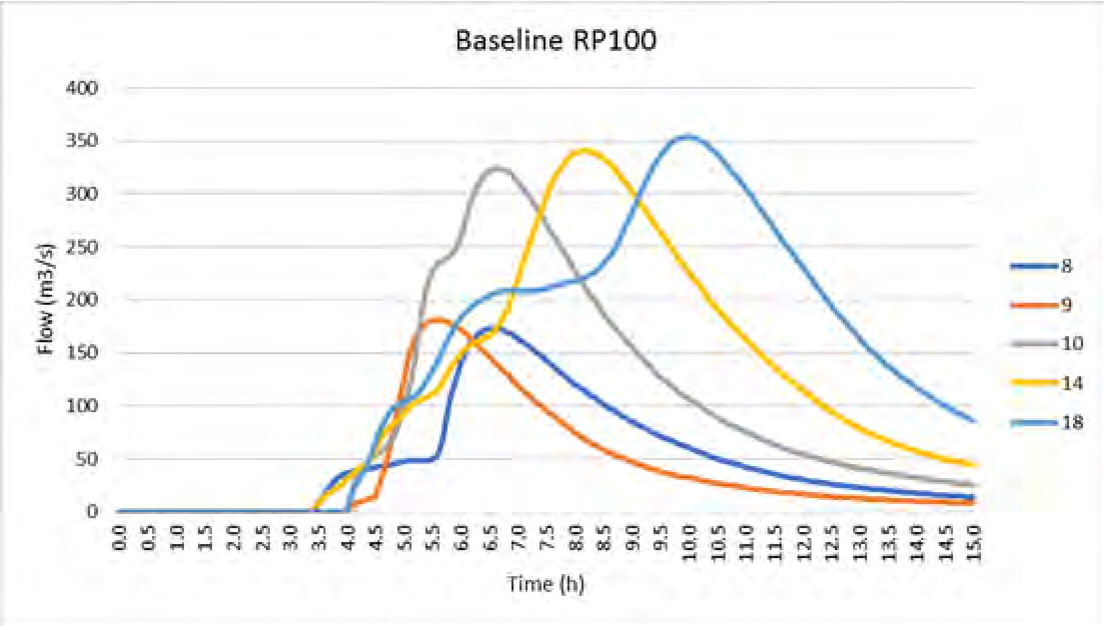
Figure 2-1. Wharfe River: DTM Edit, Before and after edit has been applied.



2.4 Baseline scenario model

A baseline model was run with the above grids to represent the existing (current) scenario within the Wharfe catchment. Figure 2-2 shows the baseline 100 year return period event at various monitoring locations in the catchment. Location 8 is on the Wharfe just downstream of Kettlewell. Location 9 is on the Skirfare downstream of Hawkswick. Location 10 is on the Wharfe just downstream of the confluence with the Skirfare. Location 14 is on the Wharfe upstream of Burnsall. Location 18 is at the catchment outlet just upstream of Addingham.

Figure 2-2. Baseline 100 year flow hydrograph at a selection of monitoring locations in the catchment. The x-axis is model run time in hours.



2.5 NFM scenario model

Several NFM scenario models have been run to see how the addition of different individual NFM measures, or combination of NFM measures, influenced flood attenuation within the catchment.

2.5.1 Runoff Attenuation Features

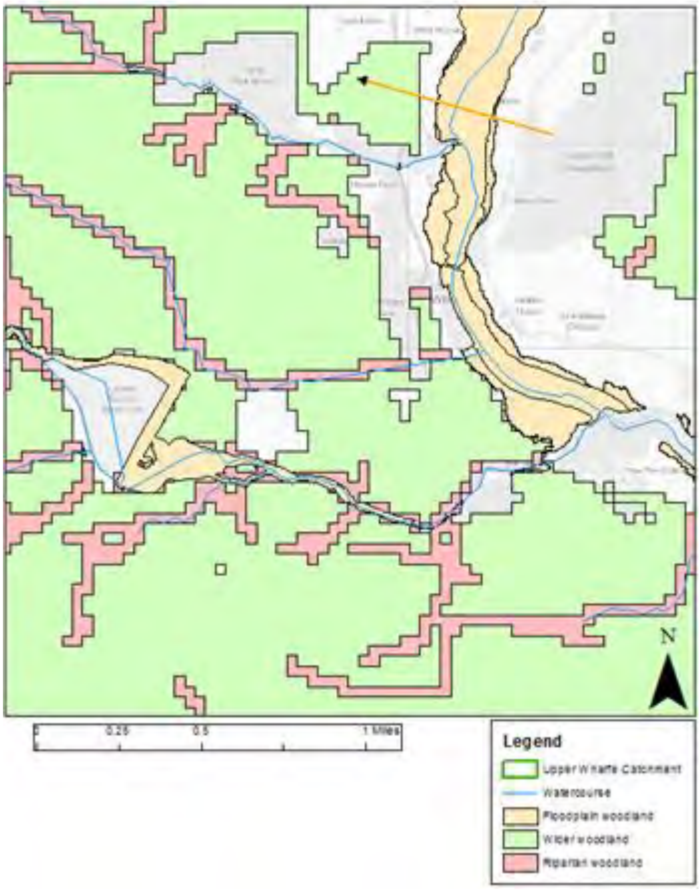
Runoff Attenuation Feature (RAFs), also known as Opportunity Pond Stores, were identified by a spatial analysis of the catchment baseline (current – no change) model results for the different rainfall event magnitudes. This tool identifies areas within the DTM that already store surface floodwater (within the range 100 – 5,000m^2 surface area), which could be modified to temporarily store additional flood water by excavation and/or bunding (Figure 2-3). From the ponded areas, existing pond volumes are calculated based on flood depths and additional pond volumes are calculated based on a theoretical increase in pond depth (by 1m).

Figure 2-3. Example model output showing RAFs.

2.5.2 Woodlands for Water

Potential woodland planting areas have been identified within the catchment based on the Forest Research Woodlands for Water Opportunity Maps. Three areas of woodland were identified within these opportunity maps, namely: wider catchment woodland, floodplain woodland, and riparian woodland. To model these areas the land surface roughness (Manning's n value) has been altered to an appropriate mature woodland value (0.1), together with improved soil infiltration (by increasing the BFIHOST parameter of the soils under the new woodland areas by 5%).

Figure 2-4. Example of highlighted potential woodland areas within the Wharfe catchment. Contains OS data © Crown copyright and database right 2017.



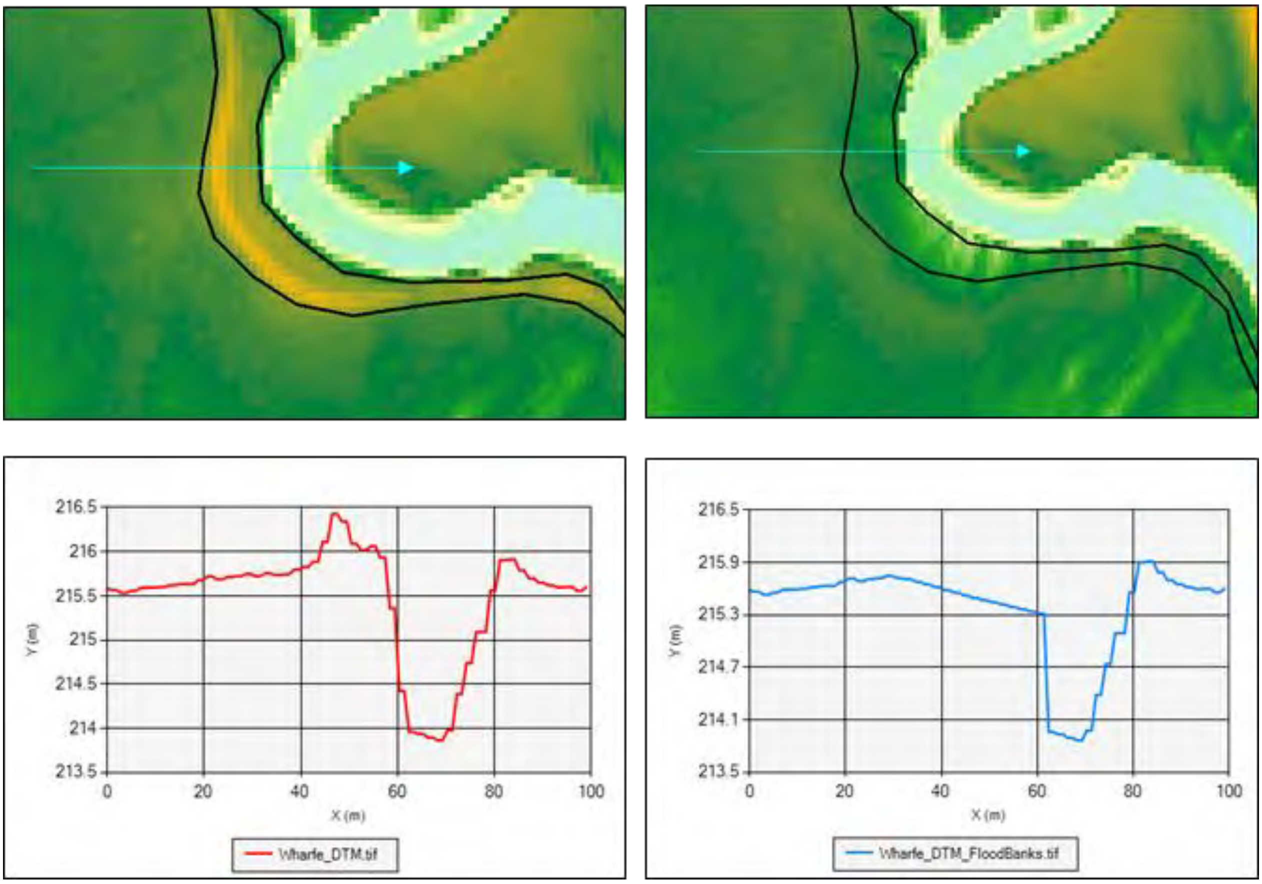
2.5.3 New woodland plantings

The boundaries of areas of new woodland plantings within the Upper Wharfe catchment have been supplied by the National Trust and Yorkshire Dales National Park Authority. Both organisations would like to quantify the likely flood attenuation benefits from the planting of these new woodlands. To model these new areas the land surface roughness (Manning's n value) has been altered to an appropriate mature woodland value (0.1), together with an improved soil infiltration condition (by increasing the BFIHOST parameter of the soils under the new tree areas by 5%).

2.5.4 Flood bank removal

Removal of the flood banks lining the section of the Wharfe from Hubberholme to Skirfare has also been explored. The River Wharfe is a nationally important river designated as a Site of Special Scientific Interest (SSSI) for its contrasting upland and lowland character which is important for its wildlife and habitat. The SSSI status covers the river channel and small areas of adjacent floodplain between Buckden and upstream of the River Skirfare confluence near Kettlewell. All identified flood banks within this area have been removed from the DTM allowing the river to flood more naturally over the adjacent floodplain (Figure 2-5). One of the model options also explored a rougher floodplain surface as a consequence of the flood bank removal.

Figure 2-5. Example flood bank within the SSSI from Hubberholme to Skirfare: DTM flood bank removal, before and after the edit has been applied.



2.5.5 Vegetated buffers

Vegetated buffers have been represented have an increased hydraulic roughness (a typical rough grass) to a 3m wide buffer along both sides of all watercourses (main and ordinary) in Upper Wharfedale. We have only applied the rough grass Manning's n value to those buffer areas that are not already covered by a rougher vegetation type (e.g. trees). The Manning's n value applied to the vegetated buffers was 0.05.

2.5.6 Soil structural improvement

Grassland fields (comprising 'improved grassland' and 'calcareous grassland') in the catchment have been identified using Land Cover Map 2007. This scenario assumes that there has been a degradation of soil structure across all grass fields in rural catchments (i.e. compaction due to livestock trampling and/or use of heavy machinery on land during inappropriate soil wetness conditions). In reality, there will be a wide range of actual in-field soil structural condition (from good to bad) across the catchment but its real spatial distribution is unknown. To represent a soil structural improvement within these areas the BFIHOST parameter has been increased by 10% thereby promoting greater infiltration of water in to the soil profile which is then then not available for rapid surface runoff.

3 Results

Several post-change models have been run for the flood event scenarios. The results of these model runs are presented alongside the baseline (current – no change) model results. NB. It should be noted that the exact peak flow values derived from the modelled flood hydrographs at the downstream monitoring station cannot be directly compared to flood hydrograph derived from a standard Flood Estimation Handbook method for the same location due to different calculation methods. All references to time in this section refer to the model run time.

3.1 RAFs

3.1.1 Flood Mapping

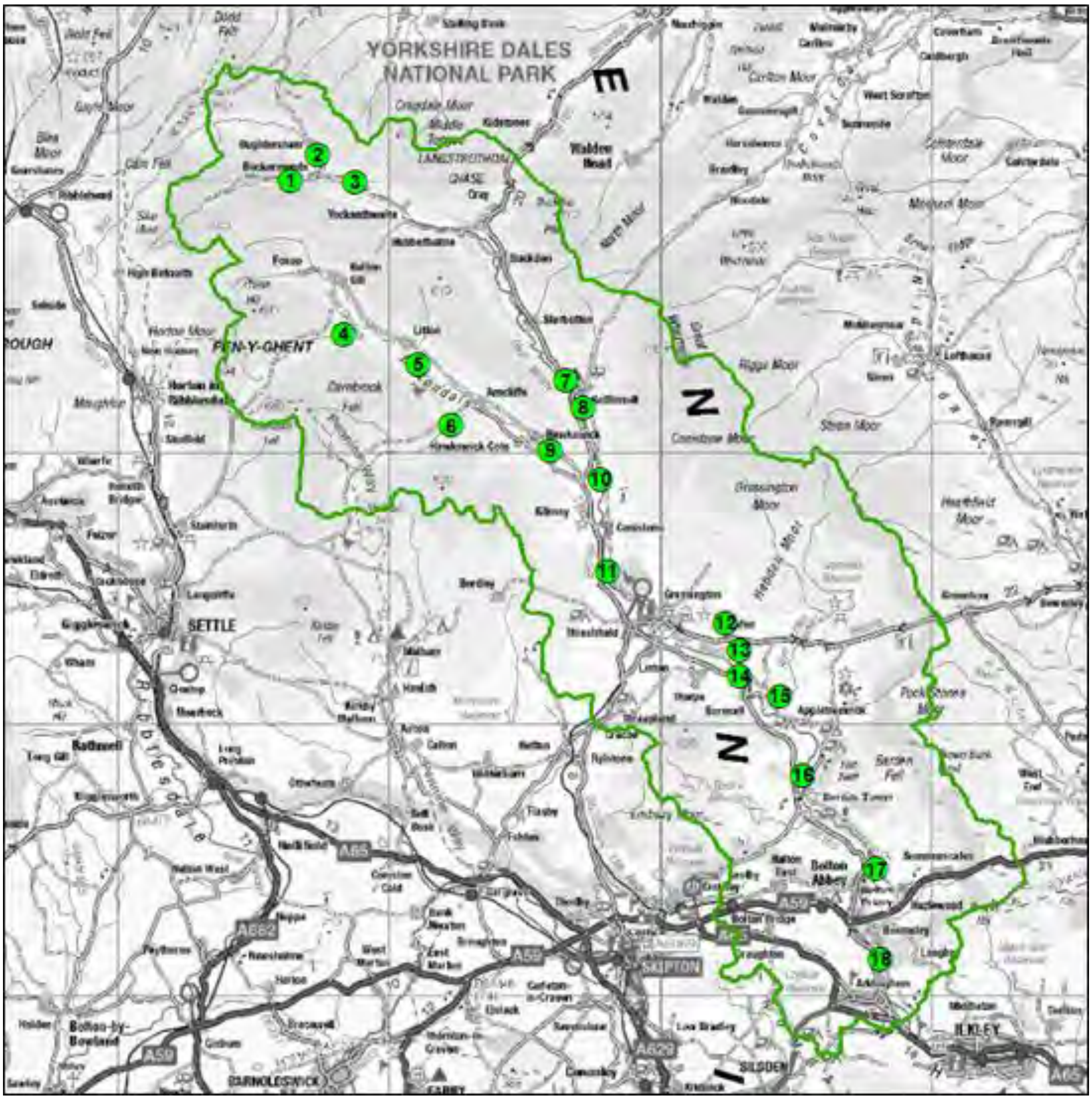
This scenario involves modelling all of the 1,046 individual RAFs identified in section 2.5.1 above. The RAFs are distributed throughout the Wharfe catchment. By adding RAFs into the catchment, additional pooling water surrounding the ponded areas results in a change to both the flood extent and flood depths. These measures can also provide a delay in the timing of surface runoff reaching the arterial drainage network.

3.1.2 Hydrographs and peak flow

Using designated flow monitoring points, the model can extract hydrological data at any defined location within the model domain; including the complete flow (discharge) hydrograph. This allows the baseline and post-change models to be compared for the flood event. Key monitoring locations have been selected to identify local and wider scenario results.

For this scenario, monitoring locations 8 (Kettlewell), 9 (Hawkswick) and 10 (just downstream of Skirfare and Wharfe confluence) have been selected to identify the changes to each of the main upstream tributaries (Figure 3-1). Location 18 has also been selected to identify the whole catchment changes to the southern boundary of the National Park between Bolton Abbey and Addingham.

Figure 3-1. Wharfe monitoring locations, contains OS data © Crown copyright and database right 2017.



3.1.3 Kettlewell RAFs (8)

Situated just downstream of the village of Kettlewell, RAFs have been distributed within the River Wharfe sub-catchment. The results from this location show the RAFs produce a small reduction in the peak flow with no delay to the timing of the peak flow. For the 10-year flood event the peak flow was reduced by 0.5m3/s (1%). This scenario has a similar impact during the 30 and 100-year flood event, with a reduction of 1%.

Figure 3-2. 100-year flow hydrograph for Kettlewell monitoring location (8). Baseline compared to the Wharfe RAFs scenario.

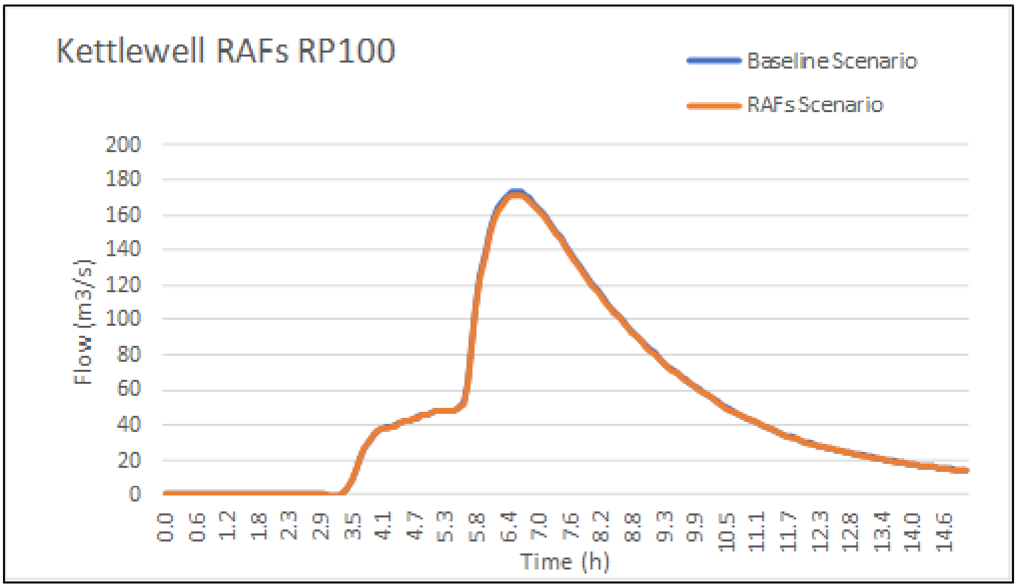


Table 3-1: Details of 100-year rainfall event peak flow and time of the flood peak data for the RAFs scenario at Kettlewell monitoring location (8).

Scenario	Peak flow (m3/s)	Peak flow reduction (%)	Time to peak (hours)	Time to peak (minutes)	Delay in flood peak (minutes)
Baseline	173.2	n/a	6.6	395	n/a
RAFs	171.5	1%	6.6	395	0

3.1.4 Hawkswick RAFs (9)

Situated just downstream of the village of Hawkswick, RAFs have been distributed within the River Skirfare sub-catchment. The results from this location show the RAFs produce a small reduction in the peak flow with no delay to the timing of the peak flow. For the 10-year flood event the peak flow reduces by 0.3m3/s (1%). This scenario has a similar impact during the 30 and 100-year flood event, with a reduction of 1%.

Table 3-2: Details of 100-year rainfall event peak flow and time of the flood peak data for the RAFs scenario at Hawkswick monitoring location (9).

Scenario	Peak flow (m3/s)	Peak flow reduction (%)	Time to peak (hours)	Time to peak (minutes)	Delay in flood peak (minutes)
Baseline	181.3	n/a	5.6	335	n/a
RAFs	180.0	1%	5.6	335	0

3.1.5 Conistone RAFs (10)

Situated just upstream of the village of Conistone, just downstream of the Skirfare and Wharfe confluence. RAFs have been distributed up both sub-catchments. The results from this location show the RAFs slightly reduced the peak flow with no delay in the timing of the peak flow. For the 10-year flood event the peak flow reduces by 1.0m3/s (1%). This scenario has a similar impact during the 30 and 100-year flood event, with a reduction of 1%

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Figure 3-3. 100-year flow hydrograph for Conistone monitoring location (10). Baseline compared to the Wharfe RAFs scenario.

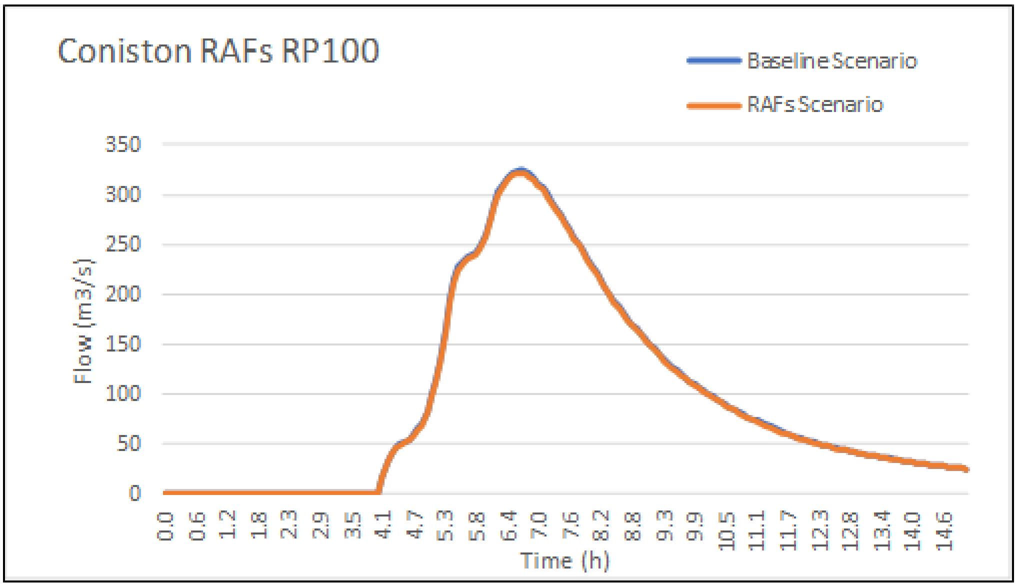

Table 3-3: Details of 100-year rainfall event peak flow and time of the flood peak data for the RAFs scenario at Conistone monitoring location (10).

Scenario	Peak flow (m3/s)	Peak flow reduction (%)	Time to peak (hours)	Time to peak (minutes)	Delay in flood peak (minutes)
Baseline	324.3	n/a	6.7	400	n/a
RAFs	321.4	1%	6.7	400	0

3.1.6 Addingham RAFs (18)

Situated just upstream of the town of Addingham, RAFs have been distributed up the entire catchment. The results from this location show the barriers reduce the peak flow but with no delay in the timing of the flood peak. For the 100-year flood event the peak flow reduces by 3.0m3/s (1%).

Table 3-4: Details of 100-year rainfall event peak flow and time of the flood peak data for the RAFs scenario at Addingham monitoring location (18).

Scenario	Peak flow (m3/s)	Peak flow reduction (%)	Time to peak (hours)	Time to peak (minutes)	Delay in flood peak (minutes)
Baseline	353.9	n/a	10.0	600	n/a
RAFs	351.0	1%	10.0	600	0

3.2 Maximum woodland opportunities

3.2.1 Flood Mapping

This extreme scenario involved modelling all of the Forest Research Woodland for Water (WfW) opportunity areas (catchment woodland, floodplain woodland, riparian woodland), together with any new woodland plantings undertaken by NT/TDNPA (if they located outside of the WfW opportunity areas). This scenario was applied to a 115km^2 area (or about 25% of the entire catchment). Modelling a greater woodland coverage increases the surface roughness (as represented by the

Manning's n coefficient) thereby creating a flood attenuation benefit. These measures also provide a delay in the timing of surface runoff reaching the arterial drainage network.

3.2.2 Hydrographs and peak flow

Using designated flow monitoring points, the model can extract hydrological data at any defined location within the model domain; including the complete flow (discharge) hydrograph. This allows the baseline and post-change models to be compared for the flood event.

For this scenario, monitoring location 8, 9, and 10 have been selected to identify the changes to each of the main upstream tributaries (Figure 3-1). Location 18 has been selected to identify the whole catchment changes.

3.2.3 Kettlewell max woodland (8)

Situated just downstream of the village of Kettlewell, woodland plantings have been distributed up the River Wharfe sub-catchment. The results from this location show the maximum woodland plantings significantly reduced the peak flow and delayed the timing of the flood peak. For the 10-year flood event the peak flow significantly reduces by 12m3/s (30%) as well as delaying the peak by 165 minutes. This scenario has a similar impact during the 30-year flood event with a reduction of 29% and a delay of 125 minutes. The 100-year flood event shows a reduction of 27% and a delay of 95 minutes.

Figure 3-4. 100-year flow hydrograph for Kettlewell monitoring location (8). Baseline compared to the maximum woodland scenario.

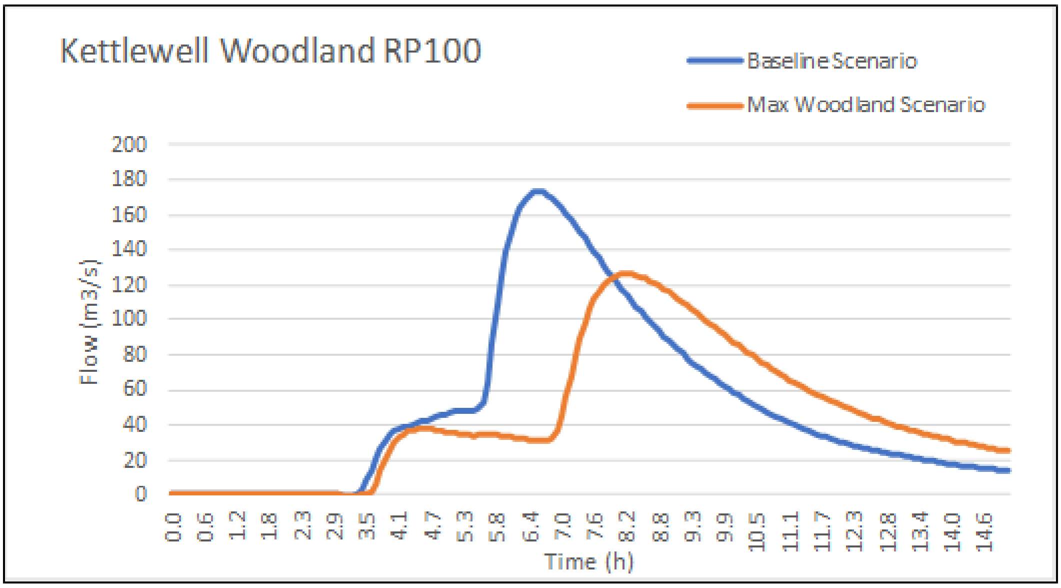

Table 3-5: Details of 100-year rainfall event peak flow and time of the flood peak data for the maximum woodland scenario at Kettlewell monitoring location (8).

Scenario	Peak flow (m3/s)	Peak flow reduction (%)	Time to peak (hours)	Time to peak (minutes)	Delay in flood peak (minutes)
Baseline	173.2	n/a	6.6	395	n/a
Maximum Woodland	126.4	27%	8.2	490	95

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3.2.4 Hawkswick max woodland (9)

Situated just downstream of the village of Hawkswick, woodland plantings have been distributed up the River Skirfare sub-catchment. The results from this location show the maximum woodland plantings reduce the peak flow and delay the timing of the flood peak. For the 10-year flood event the peak flow significantly reduces by 5m3/s (11%) as well as delaying the peak by 95 minutes. This scenario has a similar impact during the 30-year flood event with a reduction of 11% and a delay of 80 minutes. The 100-year flood event shows a reduction of 11% and a delay of 60 minutes.

Table 3-6: Details of 100-year rainfall event peak flow and time of the flood peak data for the maximum woodland scenario at Hawkswick monitoring location (9).

Scenario	Peak flow (m3/s)	Peak flow reduction (%)	Time to peak (hours)	Time to peak (minutes)	Delay in flood peak (minutes)
Baseline	181.3	n/a	5.6	335	n/a
Maximum Woodland	162.1	11%	6.6	395	60

3.2.5 Conistone max woodland (10)

Situated just upstream of the village of Conistone, just downstream of the Skirfare and Wharfe confluence. Woodland plantings have been distributed up both sub-catchments. The results from this location show the maximum woodland plantings significantly reduced the peak flow and delayed the timing of the peak flow. For the 10-year flood event the peak flow significantly reduces by 24m3/s (32%) as well as delaying the peak by 170 minutes. This scenario has a similar impact during the 30-year flood event with a reduction of 31% and a delay of 145 minutes. The 100-year flood event shows a reduction of 95m3/s (29%) and a delay of 110 minutes.

Table 3-7: Details of 100-year rainfall event peak flow and time of the flood peak data for the maximum woodland scenario at Conistone monitoring location (10).

Scenario	Peak flow (m3/s)	Peak flow reduction (%)	Time to peak (hours)	Time to peak (minutes)	Delay in flood peak (minutes)
Baseline	324.3	n/a	6.7	400	n/a
Maximum Woodland	228.8	29%	8.5	510	110

3.2.6 Addingham max woodland (18)

Situated just upstream of the town of Addingham, woodland plantings have been distributed across the entire Upper Wharfe catchment. The results from this location show the maximum woodland plantings significantly reduced the peak flow and delayed the timing of the flood peak. For the 10-year flood event the peak flow significantly reduces by 15m3/s (32%) as well as delaying the peak by 160 minutes. This scenario has a greater impact during the 30-year flood event with a reduction of 37% and a delay of 350 minutes. The 100-year flood event shows a reduction of 130m3/s (37%) and a delay of 275 minutes.

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Figure 3-5. 100-year flow hydrograph for Addingham monitoring location (18). Baseline compared to the max woodland scenario.

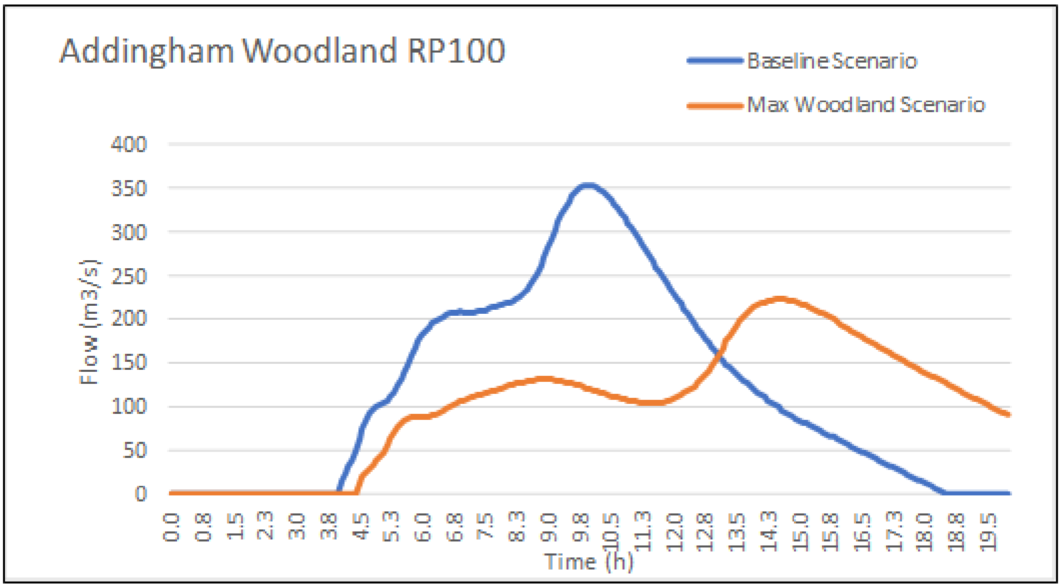


Table 3-8: Details of 100-year rainfall event peak flow and time of the flood peak data for the max woodland scenario at Addingham monitoring location (18).

Scenario	Peak flow (m3/s)	Peak flow reduction (%)	Time to peak (hours)	Time to peak (minutes)	Delay in flood peak (minutes)
Baseline	353.9	n/a	10.0	600	n/a
Max Woodland	223.0	37%	14.6	875	275

3.3 NT/YDNPA new tree plantings

3.3.1 Flood Mapping

This scenario involves modelling only the NT/YDNPA new tree plantings, covering an area of about 6km^2 (or about 1.5% of the total catchment area). By modelling the increased woodland, the result is increased surface roughness thereby creating a flood attenuation benefit. These measures also provide a delay in the timing of surface runoff reaching the arterial drainage network.

3.3.2 Hydrographs and peak flow

For this scenario, monitoring location 7, 9, 10 have been selected to identify the changes to each of the main upstream tributaries (Figure 3-1). Location 18 has also been selected to identify the whole catchment changes.

3.3.3 Kettlewell max woodland (7)

Situated just downstream of the village of Kettlewell, new woodland plantings have been distributed up the Upper Wharfe sub-catchment. The results from this location show the new woodland plantings slightly reduced the peak flow. For the 10-year flood event the peak flow reduces by 0.6m^3/s (2%) as well as delaying the peak by 5 minutes. This scenario has slightly less of an impact during the 30-year flood event with a reduction of 1%. The 100-year flood event also shows a reduction of 1%.

Table 3-9: Details of 100-year rainfall event peak flow and time of the flood peak data for the new woodland scenario at Kettlewell monitoring location (7).

Scenario	Peak flow (m3/s)	Peak flow reduction (%)	Time to peak (hours)	Time to peak (minutes)	Delay in flood peak (minutes)
Baseline	160.1	n/a	6.5	390	n/a
New Woodland	158.8	1%	6.5	390	0

3.3.4 Hawkswick new woodland (9)

Situated just downstream of the village of Hawkswick, new woodland plantings have been distributed up the River Skirfare sub-catchment. The results from this location show the new woodland plantings reduce the peak flow. For the 10-year flood event the peak flow reduces by less than 1%. There are similar results for the 30 and 100-year flood events with a reduction of less than 1% for both.

3.3.5 Conistone new woodland (10)

Situated just upstream of the village of Conistone, below the River Skirfare and Upper Wharfe confluence. Woodland plantings have been distributed up both sub-catchments. The results from this location show the new woodland plantings slightly reduced the peak flow. For the 10-year flood event the peak flow reduced by 1.4m3/s (2%) as well as delaying the peak by 5 minutes. This scenario has slightly less of an impact during the 30-year flood event with a reduction of 1% and a delay of 5 minutes. The 100-year flood event shows a reduction of 1%.

Table 3-10: Details of 100-year rainfall event peak flow and time of the flood peak data for the new woodland scenario at Conistone monitoring location (10).

Scenario	Peak flow (m3/s)	Peak flow reduction (%)	Time to peak (hours)	Time to peak (minutes)	Delay in flood peak (minutes)
Baseline	324.3	n/a	6.7	400	n/a
New Woodland	321.8	1%	6.7	400	0

3.3.6 Addingham new woodland (18)

Situated just upstream of the town of Addingham, new woodland plantings have been distributed up the catchment. The results from this location show the new woodland plantings reduce the peak flow. For the 100-year flood event the peak flow reduces by 3.7m3/s (1%).

Figure 3-6. 100-year flow hydrograph for Addingham monitoring location (18). Baseline compared to the new woodland scenario.

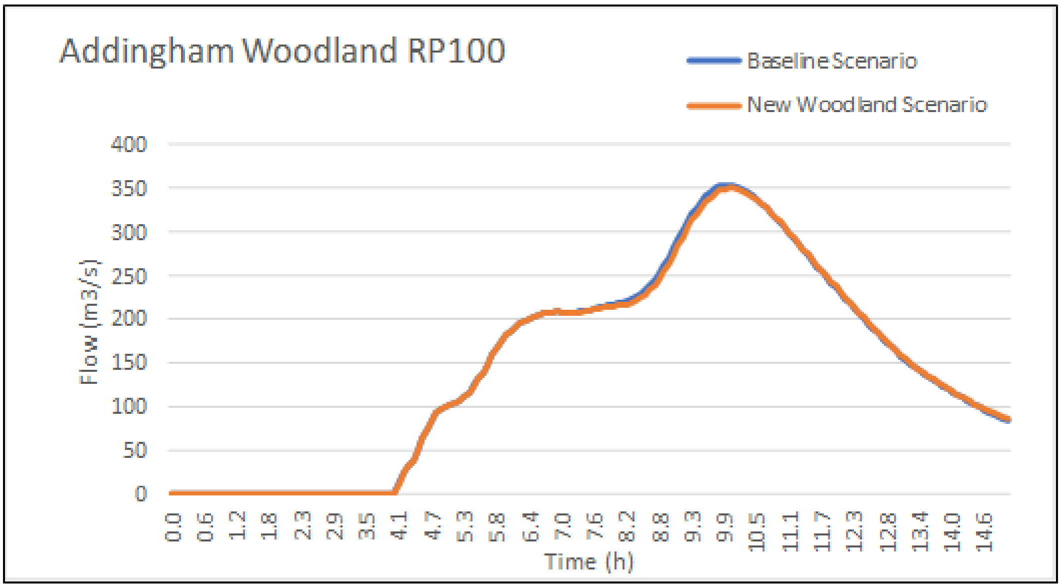


Table 3-11: Details of 100-year rainfall event peak flow and time of the flood peak data for the new woodland scenario at Addingham monitoring location (18).

Scenario	Peak flow (m3/s)	Peak flow reduction (%)	Time to peak (hours)	Time to peak (minutes)	Delay in flood peak (minutes)
Baseline	353.9	n/a	10.0	600	n/a
New Woodland	350.1	1%	10.0	600	0

3.4 Vegetated buffers

3.4.1 Flood Mapping

This scenario involves modelling a 3m wide vegetated buffer of increased hydraulic roughness represented by typical rough grass along all watercourses (unless a rougher cover, e.g. trees, already existed). The result is increased surface roughness thereby creating a flood attenuation benefit. These measures also provide a delay in the timing of surface runoff reaching the arterial drainage network.

3.4.2 Hydrographs and peak flow

Using designated flow monitoring points, the model can extract hydrological data at any defined location within the model domain; including the complete flow (discharge) hydrograph. This allows the baseline and post-change models to be compared for the flood event.

For this scenario, monitoring location 8, 9, and 10 have been selected to identify the changes to each of the main upstream tributaries. Location 18 has been selected to identify the whole catchment changes.

3.4.3 Kettlewell Vegetated Buffers (8)

Situated just downstream of the village of Kettlewell, the buffer strips have been modelled either side of all watercourses up the Upper Wharfe sub-catchment. The results from this location show the buffer strips reduced the peak flow. For the 10-year flood event the peak flow reduces by 1m3/s (2%) as well as delaying the peak flow by 10 minutes. This scenario has a similar impact during the 30 and 100-year flood event, with a reduction of 1% and a time delay of 5 minutes.

Figure 3-7. 100-year flow hydrograph for Kettlewell monitoring location (8). Baseline compared to the vegetated buffer scenario.

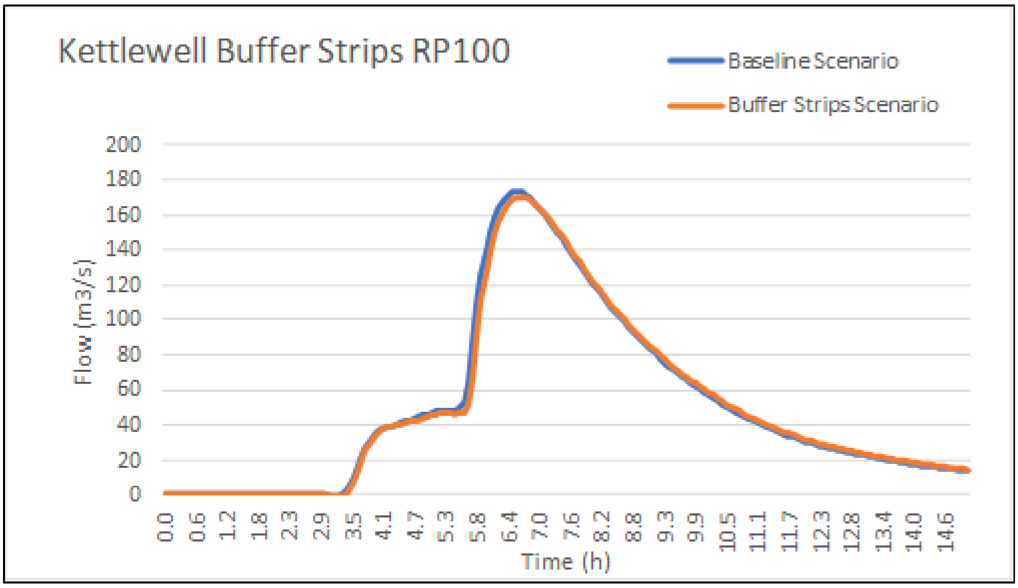


Table 3-12: Details of 100-year rainfall event peak flow and time of the flood peak data for the buffer strips scenario at Kettlewell monitoring location (8).

Scenario	Peak flow (m3/s)	Peak flow reduction (%)	Time to peak (hours)	Time to peak (minutes)	Delay in flood peak (minutes)
Baseline	173.2	n/a	6.6	395	n/a
Buffer Strips	170.0	2%	6.7	400	5

3.4.4 Hawkswick Vegetated Buffers (9)

Situated just downstream of the village of Hawkswick, the buffer strips have been modelled either side of all watercourses up the River Skirfare sub-catchment. The results from this location show the buffer strips delayed the peak flow. For the 10 and 30-year flood event the peak flow reduces by less than 1%, however, the peak has been delayed by 5 minutes. This scenario has a similar impact during the 100-year flood event, with a reduction of less than 1%.

Table 3-13: Details of 100-year rainfall event peak flow and time of the flood peak data for the buffer strips scenario at Hawkswick monitoring location (9).

Scenario	Peak flow (m3/s)	Peak flow reduction (%)	Time to peak (hours)	Time to peak (minutes)	Delay in flood peak (minutes)
Baseline	181.3	n/a	5.6	335	n/a
Buffer Strips	181.1	0%	5.6	335	0

3.4.5 Conistone Vegetated Buffers (10)

Situated just upstream of the village of Conistone, below the River Skirfare and Upper Wharfe confluence. The buffer strips have been modelled either side of all watercourses up both sub-catchments. The results from this location show the buffer strips have slightly reduced the peak flow. For the 10-year flood event the peak flow reduces by 2.0m^3/s (2%) as well as a delay to the flood peak of 10 minutes. This scenario has a similar impact during the 30-year flood event with a reduction of 2% and a delay of 5 minutes. The 100-year flood event, shows a reduction of 6m^3/s (2%).

Figure 3-8. 100-year flow hydrograph for Conistone monitoring location (10). Baseline compared to the vegetated buffer scenario.

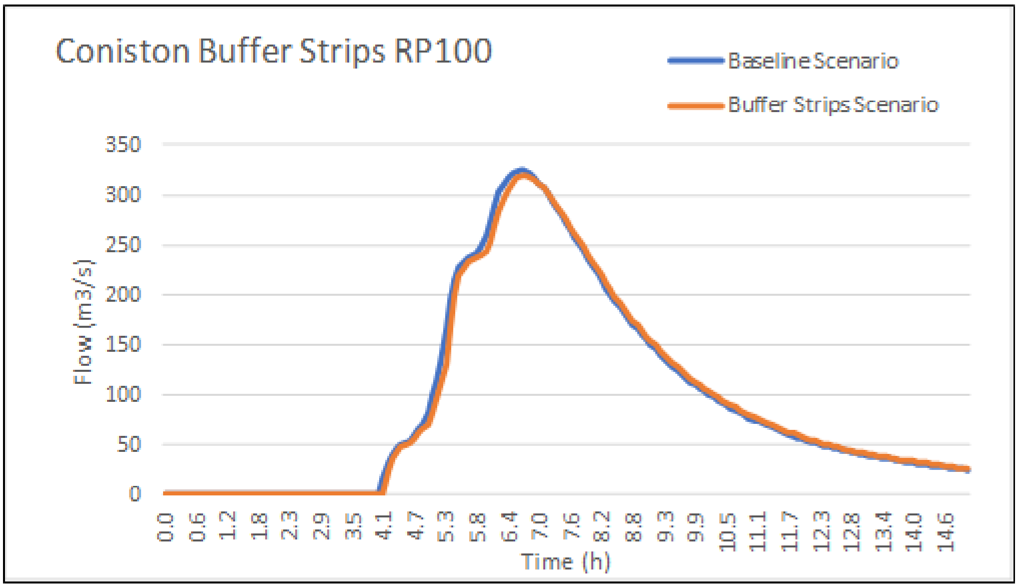


Table 3-14: Details of 100-year rainfall event peak flow and time of the flood peak data for the buffer strips scenario at Conistone monitoring location (10).

Scenario	Peak flow (m3/s)	Peak flow reduction (%)	Time to peak (hours)	Time to peak (minutes)	Delay in flood peak (minutes)
Baseline	324.3	n/a	6.7	400	n/a
Buffer Strips	318.4	2%	6.7	400	0

3.4.6 Addingham Vegetated Buffers (18)

Situated just upstream of the town of Addingham, the buffer strips have been modelled either side of all watercourses up the River Wharfe. The results from this location show the buffer strips have slightly reduced the peak flow. For the 10-year flood event the peak flow reduces by 4m^3/s (5%) as well as delaying the peak by 20 minutes. The 30-year flood event has a lower impact with a reduction of 2% and a delay of 15 minutes. Similarly, the 100-year event shows a reduction of 2% and a delay of 5 minutes.

Figure 3-9. 100-year flow hydrograph for Addingham monitoring location (18). Baseline compared to the vegetated buffer scenario.

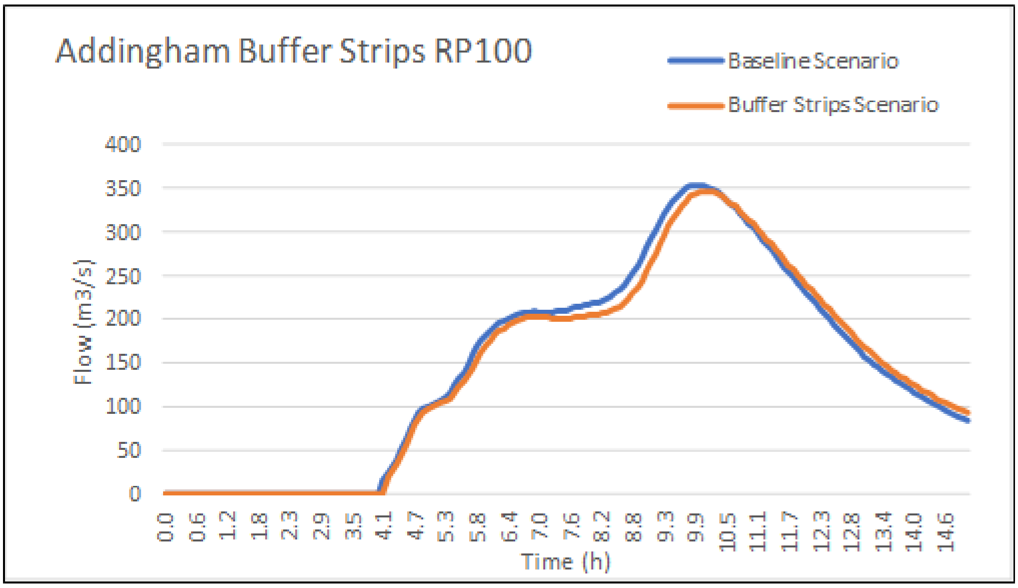


Table 3-15: Details of 100-year rainfall event peak flow and time of the flood peak data for the buffer strips scenario at Addingham monitoring location (18).

Scenario	Peak flow (m3/s)	Peak flow reduction (%)	Time to peak (hours)	Time to peak (minutes)	Delay in flood peak (minutes)
Baseline	353.9	n/a	10.0	600	n/a
Buffer Strips	346.9	2%	10.1	605	5

3.5 SSSI flood bank removal

3.5.1 Flood Mapping

This scenario involves modelling the removal of the existing flood banks (representing a length of 7.5km) within the SSSI area. By modelling the flood bank removal, the Wharfe can flood more naturally over the adjacent floodplain (modelled with rougher vegetation) rather than being confined within the embanked river channel. These measures also provide a delay in the timing of surface runoff reaching the arterial drainage network.

3.5.2 Hydrographs and peak flow

This scenario is based around the SSSI area from Hubberholme to Skirfare. All monitoring locations upstream of urban areas (and downstream of the SSSI) have been selected to identify the changes in flow. These locations include 7 (upstream of Kettlewell), 10 (upstream of Kilnsey and Conistone), 11 (upstream of Grassington), 14 (upstream of Burnsall) and 18 (upstream of Addingham).

3.5.3 Kettlewell flood bank removal (7)

Situated just upstream of the village of Kettlewell. The results from this location show the flood bank removal increases the peak flow. For the 10-year flood event the peak flow actually increases by 2m^3/s (5%) as well as resulting in an earlier peak by 20 minutes. The 30-year flood event also increases the peak by 1% peaking 10 minutes earlier. Similarly, the 100-year event shows an increase in the peak by 1% peaking 10 minutes earlier.

Figure 3-10. 100-year flow hydrograph for Kettlewell (upstream) monitoring location (7). Baseline compared to the flood bank removal scenario.

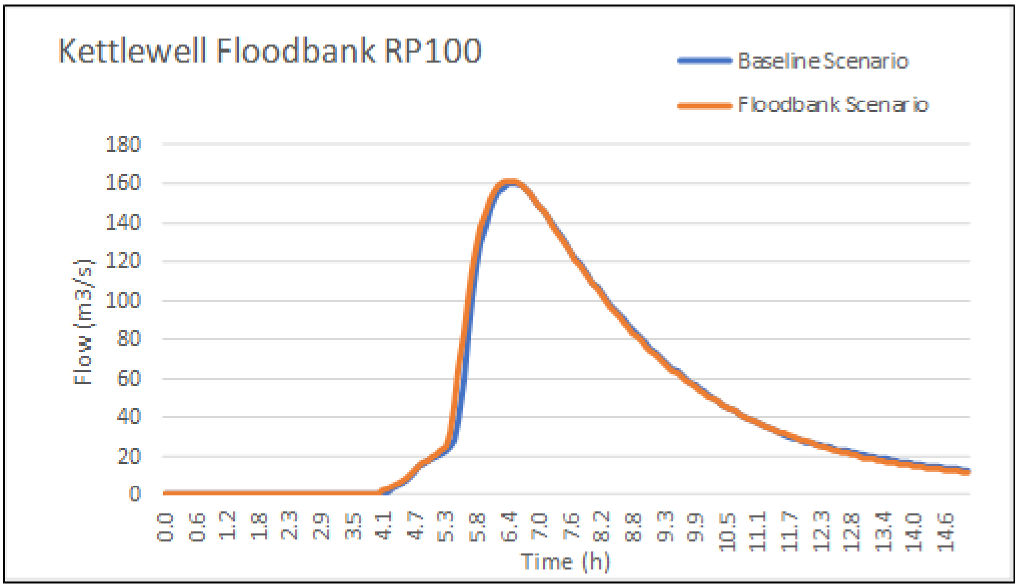


Table 3-16: Details of 100-year rainfall event peak flow and time of the flood peak data for the flood bank removal scenario at Kettlewell (upstream) monitoring location (7).

Scenario	Peak flow (m3/s)	Peak flow reduction (%)	Time to peak (hours)	Time to peak (minutes)	Delay in flood peak (minutes)
Baseline	160.1	n/a	6.5	390	n/a
Floodbank	161.5	-1%	6.4	385	-5

3.5.4 Conistone flood bank removal (10)

Situated just upstream of the village of Conistone. The results from this location show the flood bank removal increases the peak flow locally. For the 10-year flood event the peak flow increases by 5m^3/s (7%) as well as resulting in an earlier peak by 30 minutes. The 30-year flood event also increases the peak by 3% peaking 10 minutes earlier. Similarly, the 100-year event shows an increase in the peak by 2% peaking 5 minutes earlier. This could be due to the floodwater being able to flow more directly across the floodplain rather than around all the meanders. Further exploration of this result is required.

Table 3-17: Details of 100-year rainfall event peak flow and time of the flood peak data for the flood bank removal scenario at Conistone monitoring location (10).

Scenario	Peak flow (m3/s)	Peak flow reduction (%)	Time to peak (hours)	Time to peak (minutes)	Delay in flood peak (minutes)
Baseline	324.3	n/a	6.7	400	n/a
Floodbank	329.4	-2%	6.6	395	-5

3.5.5 Grassington flood bank removal (11)

Situated just upstream of the town of Grassington. The results from this location show the flood bank removal increases the peak flow. For the 10-year flood event the peak flow increases by 2.5m^3/s (4%) as well as resulting in an earlier peak by 20 minutes. The 30-year flood event also increases the peak by 3% peaking 10 minutes earlier. Similarly, the 100-year event shows an increase in the peak by 2% peaking 5 minutes earlier.

Table 3-18: Details of 100-year rainfall event peak flow and time of the flood peak data for the flood bank removal scenario at Grassington monitoring location (11).

Scenario	Peak flow (m3/s)	Peak flow reduction (%)	Time to peak (hours)	Time to peak (minutes)	Delay in flood peak (minutes)
Baseline	326.0	n/a	7.3	435	n/a
Floodbank	331.3	-2%	7.2	430	-5

3.5.6 Burnsall flood bank removal (14)

Situated just upstream of the village of Burnsall. The results from this location show the flood bank removal increases the peak flow. For the 10-year flood event the peak flow increases by 3.5m3/s (4%) as well as resulting in an earlier peak by 15 minutes. The 30-year flood event also increases the peak by 3% peaking 10 minutes earlier. Similarly, the 100-year event shows an increase in the peak by 2% peaking 5 minutes earlier.

Table 3-19: Details of 100-year rainfall event peak flow and time of the flood peak data for the flood bank removal scenario at Burnsall monitoring location (14).

Scenario	Peak flow (m3/s)	Peak flow reduction (%)	Time to peak (hours)	Time to peak (minutes)	Delay in flood peak (minutes)
Baseline	340.9	n/a	8.2	490	n/a
Floodbank	347.0	-2%	8.1	485	-5

3.5.7 Addingham flood bank removal (18)

The results from this location show the flood bank removal increases the peak flow. For the 10-year flood event the peak flow increases by 3.5m^3/s (4%) as well as resulting in an earlier peak by 5 minutes. The 30-year flood event also increases the peak by 3% peaking 10 minutes earlier. Similarly, the 100-year event shows an increase in the peak by 2% peaking 5 minutes earlier.

Figure 3-11. 100-year flow hydrograph for Addingham monitoring location (18). Baseline compared to the flood bank removal scenario.

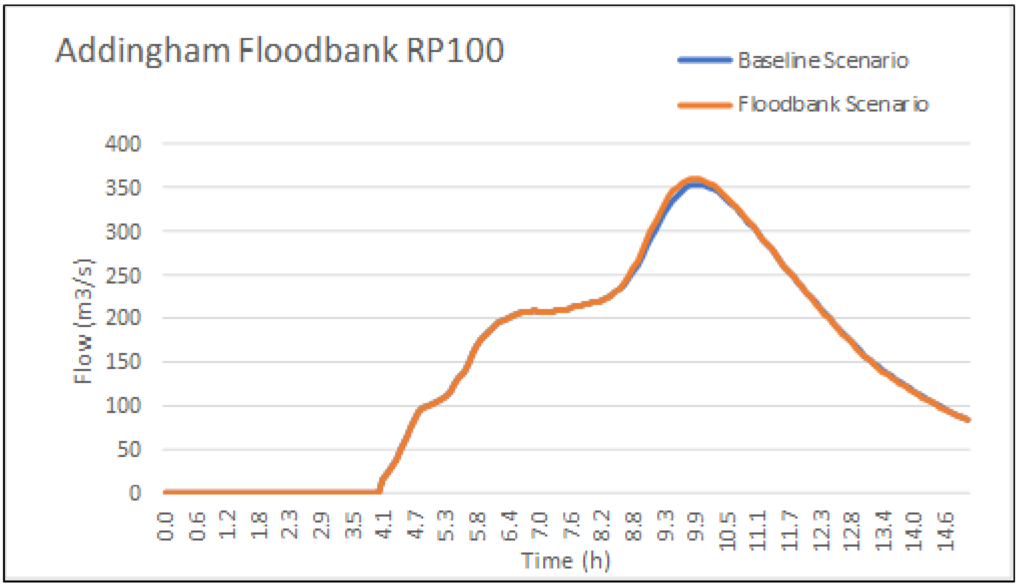


Table 3-20: Details of 100-year rainfall event peak flow and time of the flood peak data for the flood bank removal scenario at Addingham monitoring location (18).

Scenario	Peak flow (m3/s)	Peak flow reduction (%)	Time to peak (hours)	Time to peak (minutes)	Delay in flood peak (minutes)
Baseline	353.9	n/a	10.0	600	n/a
Floodbank	360.2	-2%	9.9	595	-5

3.6 Soil structural improvement

3.6.1 Flood Mapping

This represents significant soil structural improvement across ‘improved’ grass fields in the Upper Wharfe catchments (classified as 'improved grassland' and 'calcareous grassland' in the CEH Land Cover Map 2007), covering an area of nearly 150km^2 (or about 33% of the whole catchment). This scenario assumes there has been a degradation of soil structure across all the improved grassland and calcareous grassland fields in the catchment (e.g. due to soil compaction from livestock trampling and/or heavy machinery trafficking in wet conditions). By improving the soil structural condition in these areas, additional infiltration and lower surface water runoff generation will help to reduce both the flood extent and flood depths. These measures also provide a delay in the timing of surface runoff reaching the arterial drainage network.

3.6.2 Hydrographs and peak flow

Using designated flow monitoring points, the model can extract hydrological data at any defined location within the model domain; including the complete flow (discharge) hydrograph. This allows the baseline and post-change models to be compared for the flood event. Key monitoring locations have been selected to identify local and wider scenario results.

For this scenario, monitoring location 8, 9, and 10 have been selected to identify the changes to each of the main upstream tributaries (Figure 3-1). Location 18 has been selected to identify the whole catchment changes.

3.6.3 Kettlewell soil structural improvement (8)

Situated just downstream of the village of Kettlewell, several of the improved grass fields are distributed up the River Wharfe sub-catchment. The results from this location show the improved fields reduced the peak flow. For the 10-year flood event the peak flow reduces by 0.2m^3/s (>1%). This scenario has a similar impact during the 30-year flood event with a reduction of 2%. The 100-year flood event shows a reduction of 1%.

Table 3-21: Details of 100-year rainfall event peak flow and time of the flood peak data for the soil improvement scenario at Kettlewell monitoring location (8).

Scenario	Peak flow (m3/s)	Peak flow reduction (%)	Time to peak (hours)	Time to peak (minutes)	Delay in flood peak (minutes)
Baseline	173.2	n/a	6.6	395	n/a
Soil Improvement	172.4	1%	6.6	395	0

3.6.4 Hawkswick soil structural improvement (9)

Situated just downstream of the village of Hawkswick, several of the improved grass fields are distributed up the River Skirfare sub-catchment. The results from this location show the improved fields reduced the peak flow. For the 10-year flood event the peak flow reduces by 0.8m^3/s (2%) as well as delaying the flood peak by 5 minutes. This scenario has a similar impact during the 30-year flood event with a reduction of >1%. The 100-year flood event shows a reduction of 2%.

Table 3-22: Details of 100-year rainfall event peak flow and time of the flood peak data for the soil improvement scenario at Hawkswick monitoring location (9).

Scenario	Peak flow (m3/s)	Peak flow reduction (%)	Time to peak (hours)	Time to peak (minutes)	Delay in flood peak (minutes)
Baseline	181.3	n/a	5.6	335	n/a
Soil Improvement	178.5	2%	5.6	335	0

3.6.5 Conistone soil structural improvement (10)

Situated just upstream of the village of Conistone, just downstream of the Skirfare and Wharfe confluence. Several of the improved grass fields are distributed up both sub-catchments. The results from this location show the improved fields reduced the peak flow. For the 10-year flood event the peak flow reduces by 0.6m3/s (1%). This scenario has a similar impact during the 30 and 100-year flood events with reductions of 1%.

Table 3-23: Details of 100-year rainfall event peak flow and time of the flood peak data for the soil improvement scenario at Conistone monitoring location (10).

Scenario	Peak flow (m3/s)	Peak flow reduction (%)	Time to peak (hours)	Time to peak (minutes)	Delay in flood peak (minutes)
Baseline	324.3	n/a	6.7	400	n/a
Soil Improvement	320.6	1%	6.7	400	0

3.6.6 Addingham soil improvement (18)

Situated just upstream of the town of Addingham, several of the improved grass fields are distributed across the entire Upper Wharfe catchment. The results from this location show the improved fields reduced the peak flow. For the 10-year flood event the peak flow reduces by 0.7m^3/s (1%). This scenario has a similar impact during the 30 and 100-year flood events with reductions of 1%.

Figure 3-12. 100-year flow hydrograph for Addingham monitoring location (18). Baseline compared to the soil improvement scenario.

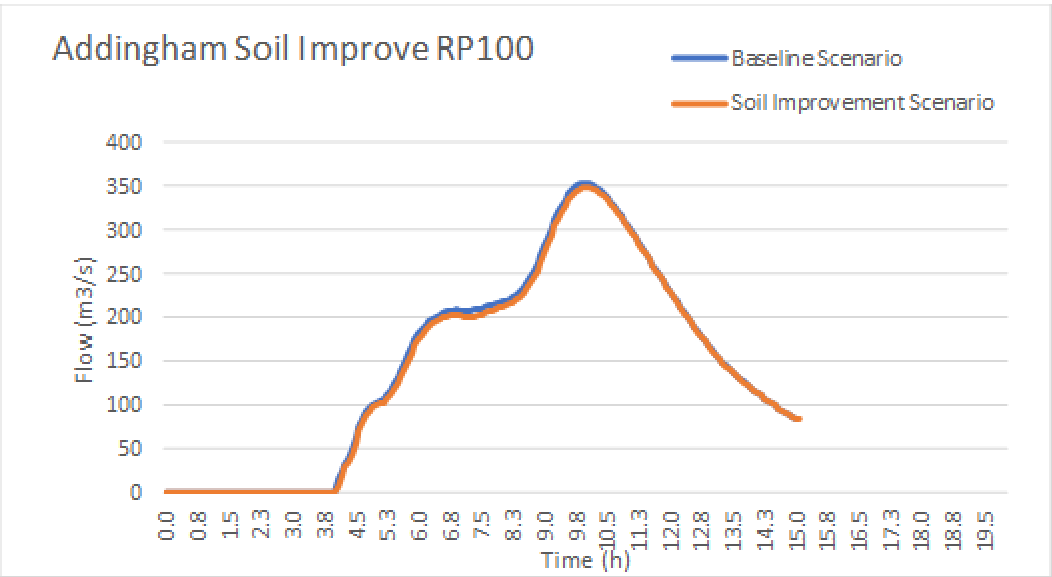


Table 3-24: Details of 100-year rainfall event peak flow and time of the flood peak data for the soil improvement scenario at Addingham monitoring location (18).

Scenario	Peak flow (m3/s)	Peak flow reduction (%)	Time to peak (hours)	Time to peak (minutes)	Delay in flood peak (minutes)
Baseline	353.9	n/a	10.0	600	n/a
Soil Improvement	349.3	1%	10.0	600	0

3.7 SSSI flood bank removal with increased floodplain surface roughness

3.7.1 Flood Mapping

This scenario involves modelling the removal of the existing flood banks (representing a length of 7.5km) within the SSSI area. By modelling the flood bank removal, the Wharfe can flood more naturally over the adjacent floodplain rather than being confined within the embanked river channel. The roughness of the adjacent floodplain areas have been increased from 0.03 to 0.04 (Manning's N value) to represent coarser grasses. These measures also provide a delay in the timing of surface runoff reaching the arterial drainage network.

3.7.2 Hydrographs and peak flow

This scenario is focussed around the SSSI area from Hubberholme to Skirfare.

3.7.3 Kettlewell flood bank removal (7)

Situated just upstream of the village of Kettlewell. The results from this location show the increased roughness decreases the increased effect of the peak flow for the flood bank removal scenario. For the 10-year flood event the peak flow still increases by 1m^3/s (2%). However, this increase has been reduced from (5%) for the flood bank removal scenario as well as the earlier flood peak being eradicated. The 30-year flood event shows a reduction to the peak by 1% as well as a delay of 5 minutes. Similarly, the 100-year event shows a reduction in the peak by 2% as well as a delay of 20 minutes. Both the 30 and 100-year flood events originally showed an increase of 1% in the flood peaks before the increased roughness was implemented.

Figure 3-13. 100-year flow hydrograph for Kettlewell (upstream) monitoring location (7). Baseline compared to the flood bank removal increased roughness scenario.

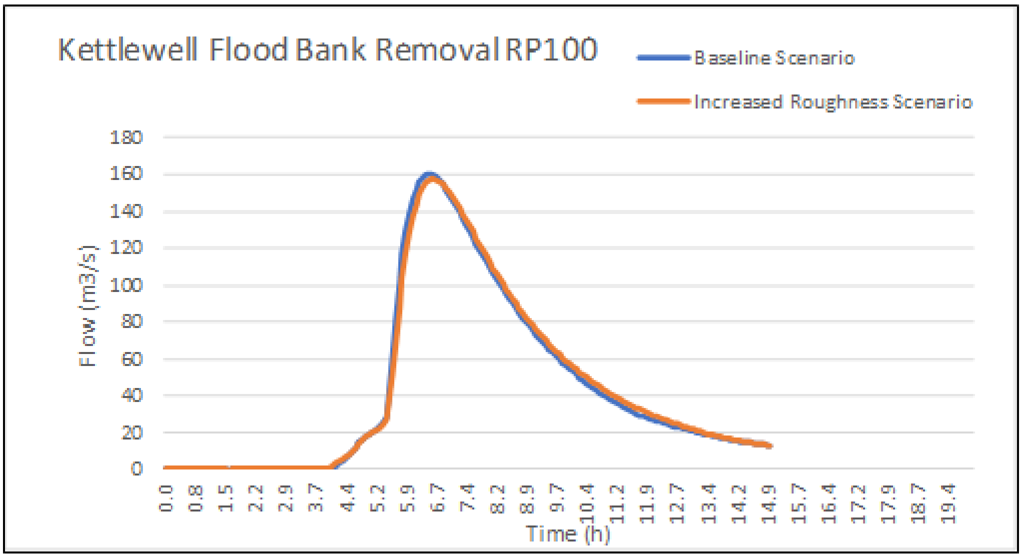


Table 3-25: Details of 100-year rainfall event peak flow and time of the flood peak data for the flood bank removal increased roughness scenario at Kettlewell monitoring location (7).

Scenario	Peak flow (m3/s)	Peak flow reduction (%)	Time to peak (hours)	Time to peak (minutes)	Delay in flood peak (minutes)
Baseline	160.1	n/a	4.2	251	n/a
Flood Bank Removal	161.5	-1%	4.0	242	-9
(Increased Roughness)	157.5	2%	4.5	272	21

3.8 Additional NT/YDNPA new tree plantings

3.8.1 Flood Mapping

2km^2 of additional NT tree plantings have been added to the model upstream of Kettlewell following the supply of some additional woodland data from NT/YDNPA. Therefore, the NT/YDNPA new tree plantings area has increased to about 8km^2 (or about 1.8% of the total catchment area). The increased woodland is represented by increased surface roughness (for mature trees) thereby creating a flood attenuation benefit, together with enhanced soil infiltration. These measures also provide a delay in the timing of surface runoff reaching the arterial drainage network.

3.8.2 Hydrographs and peak flow

This scenario is focussed around the SSSI area from Hubberholme to Skirfare.

3.8.3 Kettlewell flood bank removal (7)

The results from this location show the new woodland plantings slightly reduced the peak flow. For the 10-year flood event the peak flow reduces by 0.7m^3/s (2%) as well as delaying the peak by 10 minutes. This scenario has slightly less of an impact during the 30-year flood event with a reduction of 1%. The 100-year flood event shows a reduction of 1%. The additional 2km2 of woodland does show an increased reduction when compared to the original tree planting area, however this reduction is minimal. The 100 year flood event however, does show a delay to the flood peak by 5 minutes.

Table 3-26: Details of 100-year rainfall event peak flow and time of the flood peak data for the additional NT/YDNPA new tree plantings scenario at Kettlewell (upstream) monitoring location (7).

Scenario	Peak flow (m3/s)	Peak flow reduction (%)	Time to peak (hours)	Time to peak (minutes)	Delay in flood peak (minutes)
Baseline	160.1	n/a	6.5	390	n/a
NT/YDNPA Plantings	158.8	1%	6.5	390	0
Additional NT/YDNPA Plantings	158.7	1%	6.6	395	5

3.9 Maximum woodland opportunities with soil structural improvement

3.9.1 Flood Mapping

This extreme scenario involved modelling all of the Forest Research Woodland for Water (WfW) opportunity areas, together with any new woodland plantings undertaken by NT/TDNPA (if they located outside of the WfW opportunity areas). A 5% improvement in the BFIHOST value has been applied to the soil surrounding the 115km^2 area of woodland (or about 25% of the entire catchment). Modelling a greater woodland coverage increases the surface roughness (as represented by the Manning's n coefficient) thereby creating a flood attenuation benefit. By improving the soil structural condition in these areas, additional infiltration and lower incidence surface water runoff generation will help to reduce both the flood extent and flood depths. These measures also provide a delay in the timing of surface runoff reaching the arterial drainage network.

3.9.2 Hydrographs and peak flow

Using designated flow monitoring points, the model can extract hydrological data at any defined location within the model domain; including the complete flow (discharge) hydrograph. This allows the baseline and post-change models to be compared for the flood event. Key monitoring locations have been selected to identify local and wider scenario results.

For this scenario, monitoring location 8, 9, and 10 have been selected to identify the changes to each of the main upstream tributaries (Figure 3-1). Location 18 has been selected to identify the whole catchment changes.

3.9.3 Kettlewell max woodland soil improvement (8)

Situated just downstream of the village of Kettlewell, woodland plantings have been distributed up the River Wharfe sub-catchment. The results from this location show the maximum woodland plantings significantly reduced the peak flow and delayed the timing of the flood peak. For the 10-year flood event the peak flow significantly reduces by 13m3/s (31%) as well as delaying the peak by 165 minutes. The soil improvement shows an extra 1% decrease for the 10-year flood event. This scenario has a similar impact during the 30-year flood event with a reduction of 30% and a delay of 125 minutes. The 100-year flood event shows a reduction of 28% and a delay of 95 minutes. These flood events show an extra 1% reduction when compared to the maximum woodland without soil improvement.

Table 3-27: Details of 100-year rainfall event peak flow and time of the flood peak data for the maximum woodland with soil improvement scenario at Kettlewell monitoring location (8).

Scenario	Peak flow (m3/s)	Peak flow reduction (%)	Time to peak (hours)	Time to peak (minutes)	Delay in flood peak (minutes)
Baseline	173.2	n/a	6.6	395	n/a
Max Woodland Scenario	126.4	27%	8.2	490	95
Woodland with Soil Imp Scenario	124.5	28%	8.2	490	95

3.9.4 Hawkswick max woodland soil improvement (9)

Situated just downstream of the village of Hawkswick, woodland plantings have been distributed up the River Skirfare sub-catchment. The results from this location show the maximum woodland plantings reduce the peak flow and delay the timing of the flood peak. For the 10-year flood event the peak flow significantly reduces by 5m3/s (12%) as well as delaying the peak by 100 minutes. The soil improvement shows an extra 1% decrease for the 10-year flood event as well as an extra 5-minute delay to the flood peak. This scenario has a similar impact during the 30-year flood event with a reduction of 12% and a delay of 85 minutes. The 100-year flood event shows a reduction of 12% and a delay of 60 minutes. These flood events show an extra 1% reduction when compared to the maximum woodland without soil improvement.

Table 3-28: Details of 100-year rainfall event peak flow and time of the flood peak data for the maximum woodland with soil improvement scenario at Hawkswick monitoring location (9).

Scenario	Peak flow (m3/s)	Peak flow reduction (%)	Time to peak (hours)	Time to peak (minutes)	Delay in flood peak (minutes)
Baseline	181.3	n/a	5.6	335	n/a
Max Woodland Scenario	162.1	11%	6.6	395	60
Woodland with Soil Imp Scenario	160.1	12%	6.6	395	60

3.9.5 Conistone max woodland soil improvement (10)

Situated just upstream of the village of Conistone, just downstream of the Skirfare and Wharfe confluence. Woodland plantings have been distributed up both sub-catchments. The results from this location show the maximum woodland plantings significantly reduced the peak flow and delayed the timing of the peak flow. For the 10-year flood event the peak flow significantly reduces by 25m3/s (33%) as well as delaying the peak by 170 minutes. The soil improvement shows an extra 1% decrease for the 10-year flood event. This scenario has a similar impact during the 30-year flood event with a reduction of 32% and a delay of 150 minutes. The 100-year flood event shows a reduction of 31% and a delay of 100 minutes. These flood events show an extra 1-2% reduction when compared to the maximum woodland without soil improvement.

Table 3-29: Details of 100-year rainfall event peak flow and time of the flood peak data for the maximum woodland with soil improvement scenario at Conistone monitoring location (10).

Scenario	Peak flow (m3/s)	Peak flow reduction (%)	Time to peak (hours)	Time to peak (minutes)	Delay in flood peak (minutes)
Baseline	324.3	n/a	5.0	300	n/a
Max Woodland Scenario	228.8	29%	6.7	400	100
Woodland with Soil Imp Scenario	225.3	31%	6.7	400	100

3.9.6 Addingham max woodland soil improvement (18)

Situated just upstream of the town of Addingham, woodland plantings have been distributed across the entire Upper Wharfe catchment. The results from this location show the maximum woodland plantings significantly reduced the peak flow and delayed the timing of the flood peak. For the 10-year flood event the peak flow significantly reduces by 25m3/s (38%) as well as delaying the peak by 425 minutes. The soil improvement shows an extra 1% decrease for the 10-year flood event. This scenario has a similar impact during the 30-year flood event with a reduction of 38% and a delay of 350 minutes. The 100-year flood event shows a reduction of 38% and a delay of 275 minutes. These flood events show an extra 1% reduction when compared to the maximum woodland without soil improvement.

Figure 3-14. 100-year flow hydrograph for Addingham monitoring location (18). Baseline compared to the max woodland with soil improvement scenario.

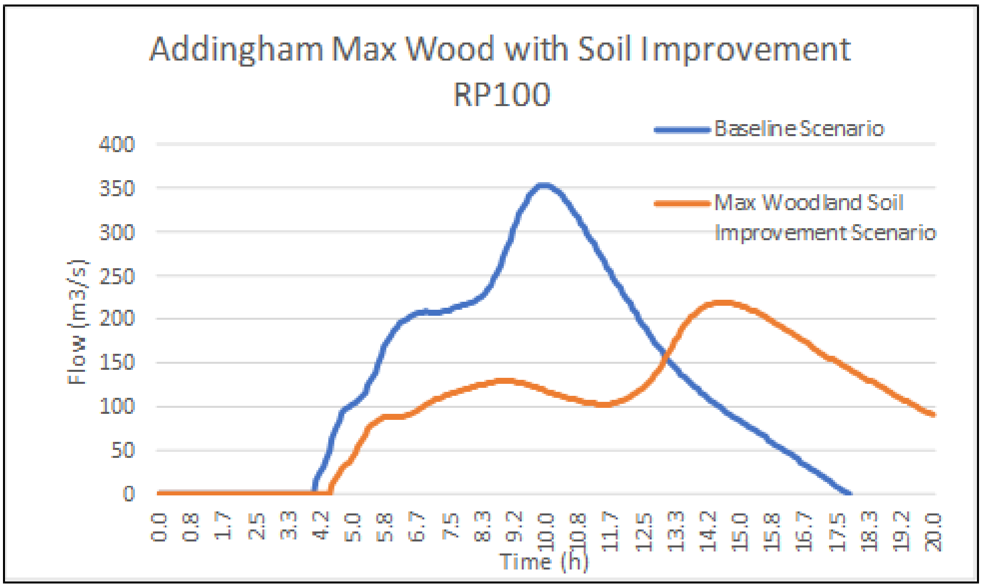


Table 3-30: Details of 100-year rainfall event peak flow and time of the flood peak data for the max woodland with soil improvement scenario at Addingham monitoring location (18).

Scenario	Peak flow (m3/s)	Peak flow reduction (%)	Time to peak (hours)	Time to peak (minutes)	Delay in flood peak (minutes)
Baseline	353.9	n/a	10.0	600	n/a
Max Woodland Scenario	223.0	37%	14.6	875	275
Woodland with Soil Imp Scenario	219.8	38%	14.6	875	275

3.10 Combination scenario

3.10.1 Flood Mapping

This scenario involved modelling a combination of different NFM measures to see their combined effect across the Upper Wharfe catchment. The combination of measures was; (i) all NT/YDNPA new tree plantings, (ii) riparian sub category of the Woodland for Water (WfW) opportunity areas, (iii) 3m wide vegetated buffers on all watercourses, and (iv) all the individual RAFs.

3.10.2 Hydrographs and peak flow

Using designated flow monitoring points, the model can extract hydrological data at any defined location within the model domain; including the complete flow (discharge) hydrograph. This allows the baseline and post-change models to be compared for the flood event.

For this scenario, monitoring location 8, 9, and 10 have been selected to identify the changes to each of the main upstream tributaries (Figure 3-1). Location 18 has been selected to identify the whole catchment changes.

3.10.3 Kettlewell Combination (8)

Situated just downstream of the village of Kettlewell. The results from this location show the combined scenario reduced the peak flow. For the 10-year flood event the peak flow reduces by 3.5m^3/s (8%) as well as a delay to the flood peak of 30 minutes. This scenario has a similar impact during the 30-year flood event with a reduction of 8% and delay of 20 minutes. The 100-year flood event shows a reduction of 7% and a delay of 15 minutes to the flood peak.

Table 3-31: Details of 100-year rainfall event peak flow and time of the flood peak data for the combined scenario at Kettlewell monitoring location (8).

Scenario	Peak flow (m3/s)	Peak flow reduction (%)	Time to peak (hours)	Time to peak (minutes)	Delay in flood peak (minutes)
Baseline	173.2	n/a	6.6	395	n/a
Combined	161.0	7%	6.8	410	15

3.10.4 Hawkswick Combination (9)

Situated just downstream of the village of Hawkswick. The results from this location show the combined scenario reduced the peak flow. For the 10-year flood event the peak flow reduces by 0.5m^3/s (1%) as well as a delay to the flood peak of 5 minutes. This scenario has a similar impact during the 30-year flood event with a reduction of 1% and delay of 5 minutes. The 100-year flood event shows a reduction of 1% and a delay of 5 minutes to the flood peak.

Table 3-32: Details of 100-year rainfall event peak flow and time of the flood peak data for the combined scenario at Hawkswick monitoring location (9).

Scenario	Peak flow (m3/s)	Peak flow reduction (%)	Time to peak (hours)	Time to peak (minutes)	Delay in flood peak (minutes)
Baseline	181.3	n/a	5.6	335	n/a
Combined	179.8	1%	5.7	340	5

3.10.5 Conistone Combination (10)

Situated just upstream of the village of Conistone, just downstream of the Skirfare and Wharfe confluence. The results from this location show the combined scenario reduced the peak flow. For the 10-year flood event the peak flow reduces by 7m3/s (9%) as well as a delay to the flood peak of 25 minutes. This scenario has a similar impact during the 30-year flood event with a reduction of 8% and delay of 20 minutes. The 100-year flood event shows a reduction of 7% and a delay of 10 minutes to the flood peak.

Table 3-33: Details of 100-year rainfall event peak flow and time of the flood peak data for the combined scenario at Conistone monitoring location (10).

Scenario	Peak flow (m3/s)	Peak flow reduction (%)	Time to peak (hours)	Time to peak (minutes)	Delay in flood peak (minutes)
Baseline	324.3	n/a	6.7	400	n/a
Combined	301.4	7%	6.8	410	10

3.10.6 Addingham Combination (18)

Situated just upstream of the town of Addingham, the results from this location show the combined scenario reduced the peak flow. For the 10-year flood event the peak flow reduces by 8m^3/s (9%). This scenario has a similar impact during the 30-year flood event with a reduction of 8% and delay of 25 minutes. The 100-year flood event shows a reduction of 6% and a delay of 15 minutes to the flood peak.

Figure 3-15. 100-year flow hydrograph for Addingham monitoring location (18). Baseline compared to the combination scenario.

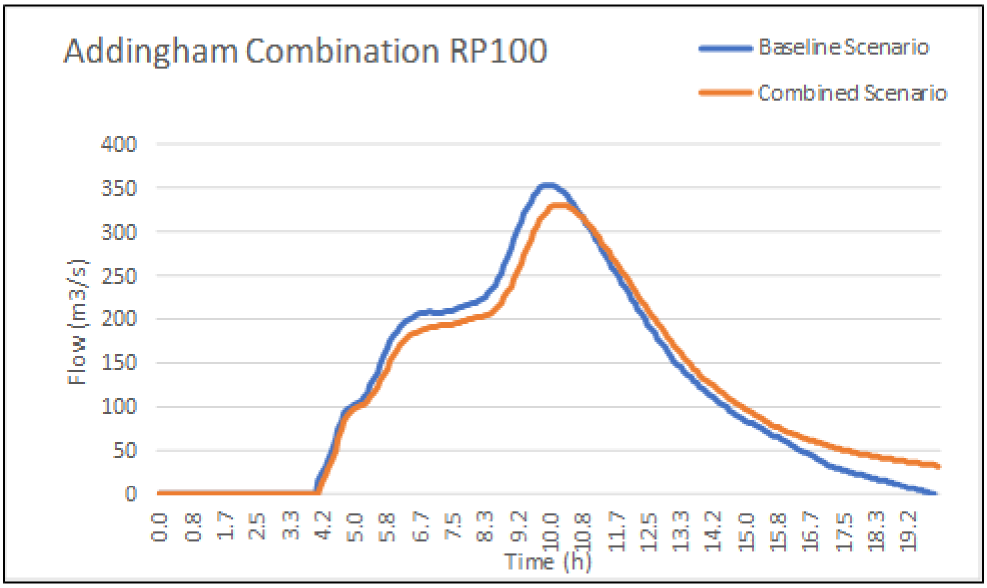


Table 3-34: Details of 100-year rainfall event peak flow and time of the flood peak data for the combined scenario at Addingham monitoring location (18).

Scenario	Peak flow (m3/s)	Peak flow reduction (%)	Time to peak (hours)	Time to peak (minutes)	Delay in flood peak (minutes)
Baseline	353.9	n/a	10.0	600	n/a
Combined	331.7	6%	10.3	615	15

4 Results Summary

The full set of modelling results is described in the tables below for a number of target locations in the catchment.

Figure 4-1: JFLOW flow monitoring locations

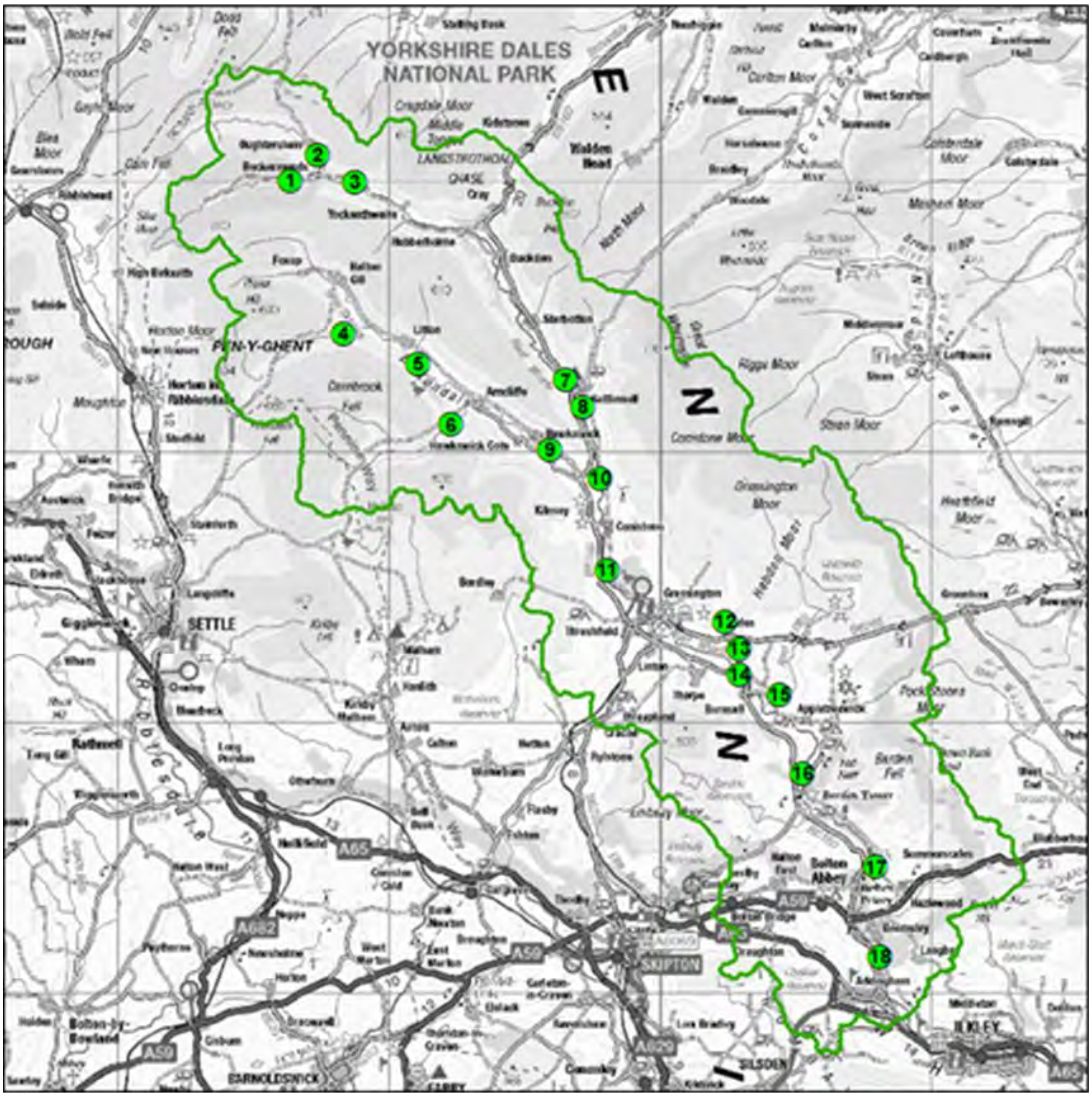


Table 4-1: Summary table of modelled results of 10-year return period for all NFM scenarios

	Flow monitoring cross-section	Peak flow (m3/s)	% reduction in peak flow	Model time of peak flow (hrs)	Model time to peak (mins)	Delay in time of peak (mins)
10 year						
Baseline	2	12.6	n/a	5	300	n/a
	7	40.5	n/a	8.6	520	n/a
	8	43.5	n/a	8.75	525	n/a
	9	42.9	n/a	7	420	n/a
	10	77.0	n/a	9	535	n/a
	14	78.9	n/a	10.25	615	n/a
	15	5.6	n/a	5.5	325	n/a
	16	82.7	n/a	11	655	n/a
	18	86.4	n/a	12.5	750	n/a
All RAFs	2	12.1	4%	5.1	305	5
	8	42.9	1.5%	8.75	525	0
	9	43	0%	6.75	405	-15
	10	75.9	1.5%	9	540	5
	14	78.3	1%	10.25	615	0
	15	5.5	2%	5.5	330	5
	16	82.1	1%	11	660	5
	18	85.7	1%	12.5	750	0
Veg Buffers	2	12.5	1%	5	300	0
	8	42.4	2.5%	9	535	10
	9	43.2	-1%	7	410	-10
	10	75.1	2.5%	9	545	10
	14	75.4	4.4%	10.5	625	10
	15	5.9	-5.5%	5.5	325	0
	16	78.9	4.6%	11.25	675	20
	18	82.5	4.5%	12.5	740	-10
Soil structural improvement	2	12.6	0%	5	300	0
	8	43.2	1%	8.75	525	0
	9	42.5	1%	6.75	405	-15
	10	76.4	1%	9	535	0
	14	78.5	0.5%	10.5	620	5
	15	5.3	5.5%	5.5	325	0
	16	82.2	0.5%	11	660	5
	18	85.7	1%	12	725	-25
SSSI Floodbanks Removal	7	42.5	-5%	8.3	500	-20

	9	43.4	-1.2%	6.5	400	-20
	10	82.2	-7%	8.5	505	-20
	14	82.4	-4.5%	10	600	-15
	15	5.6	0%	5.5	325	0
	16	86.1	-4%	11	650	-5
	18	89.9	-4%	12	715	-35
SSSI Floodbanks Removal (incl. floodplain roughness Increase)	7	41.2	-2%	8.7	520	0
NT/YDNPA Woodland	2	12.5	1%	4.9	295	-5
	7	39.9	2%	8.8	525	5
	9	43.4	-1%	6.75	405	-15
	10	75.6	2%	9	540	5
	14	76.5	3%	10.5	620	5
	15	5.6	0%	5.5	325	0
	16	80.3	3%	11	660	5
	18	83.9	3%	12	725	-25
Additional NT/YDNPA Woodland	7	39.8	2%	8.8	525	5
WFW	2	12.3	2.5%	5.25	315	15
	8	30.1	31%	11.5	690	165
	9	37.9	12%	8.5	505	85
	10	51.5	33%	11.75	705	170
	14	51.2	35%	15.5	925	310
	15	5.3	5.5%	5.5	330	5
	16	52.3	37%	17	1015	360
	18	53.2	38.5%	19	1145	395
Combination	2	11.8	6%	5.33	320	20
	8	39.9	8.5%	9.25	555	20
	9	42.9	0%	6.833	410	-10
	10	70.1	9%	9.333	560	25
	14	71.5	9.5%	10.917	655	40
	15	5.4	3.5%	5.583	335	10
	16	74.8	9.5%	11.5	690	35
	18	78.6	9%	11.75	705	-45

Table 4-2: Summary table of modelled results of 30-year return period for all NFM scenarios

	Flow monitoring cross-section	Peak flow (m3/s)	% reduction in peak flow	Model time of peak flow (hrs)	Model time to peak (mins)	Delay in time of peak (mins)
30 year						
Baseline	2	23.0	n/a	4.6	275	n/a
	7	78.8	n/a	7.5	450	n/a
	8	84.8	n/a	7.5	455	n/a
	9	85.9	n/a	6	370	n/a
	10	156.8	n/a	7.5	455	n/a
	14	165.1	n/a	9.5	570	n/a
	15	11.2	n/a	4.75	285	n/a
	16	167.9	n/a	10	610	n/a
	18	173.3	n/a	11.25	675	n/a
All RAFs	2	22.0	4%	4.75	285	10
	8	83.9	1%	7.5	455	0
	9	85.1	1%	6	370	0
	10	154.7	1.5%	7.5	455	0
	14	163.1	1%	9.5	570	0
	15	11.1	1%	5	290	5
	16	165.9	1%	10	610	0
	18	171.2	1%	11.25	675	0
Veg Buffers	2	22.8	1%	4.66	280	5
	8	82.9	2%	7.5	460	5
	9	85.7	0%	6.25	375	5
	10	153.4	2%	7.5	460	5
	14	161.2	2.5%	9.5	580	10
	15	11.1	1%	4.75	285	0
	16	164.1	2.5%	10.5	620	10
	18	168.9	2.5%	11.5	690	15
Soil structural improvement	2	23.0	0%	4.5	270	-5
	8	78.0	8%	8	475	20
	9	85.1	1%	6.25	375	5
	10	144.7	8%	8	475	20
	14	152.7	7.5%	10	590	20
	15	10.9	2.5%	5	290	5
	16	155.2	7.5%	10.5	635	25
	18	160.3	7.5%	11.5	700	15
SSSI Floodbanks Removal	7	79.7	-1%	7.3	440	-10

	9	85.9	0%	6.	370	0
	10	160.9	-2.5%	7.5	445	-10
	14	170.1	-3%	9.5	560	-10
	15	11.2	0%	4.75	285	0
	16	173.4	-3.5%	10	600	-10
	18	178.6	-3%	11	665	-10
SSSI Floodbanks Removal (incl. floodplain roughness Increase)	7	77.7	1%	8.7	455	5
NT/YDNPA Woodland	2	22.8	0.5%	4.33	260	-15
	7	77.8	1%	7.5	450	0
	9	86.1	0%	6	370	0
	10	155.3	1%	7.5	460	5
	14	163.2	1%	9.5	570	0
	15	11.2	0%	4.75	285	0
	16	166	1%	10	610	0
	18	171.3	1%	11.25	675	0
Additional NT/YDNPA Woodland	7	77.7	1%	7.5	450	0
WFW	2	22.5	2.5%	4.8	290	15
	8	59.6	29.5%	9.5	580	125
	9	75.3	12.5%	7.5	455	85
	10	106	32.5%	10	605	150
	14	107.8	34.5%	13.5	800	230
	15	10.7	4.5%	4.75	285	0
	16	107.1	36%	14.75	890	280
	18	107.5	38%	17	1025	350
Combination	2	21.7	5.5%	4.9	295	20
	8	78	8%	8	475	20
	9	85.1	1%	6.25	375	5
	10	144.7	7.5%	8	475	20
	14	152.7	7.5%	9.75	590	20
	15	10.9	2.5%	4.75	290	5
	16	155.2	7.5%	10.5	635	25
	18	160.3	7.5%	11.5	700	25

Table 4-3: Summary table of modelled results of 100-year return period for all NFM scenarios

	Flow monitoring cross-section	Peak flow (m3/s)	% reduction in peak flow	Model time of peak flow (hrs)	Model time to peak (mins)	Delay in time of peak (mins)
100 year						
Baseline	2	43.2	n/a	4.3	260	n/a
	7	160.1	n/a	6.5	390	n/a
	8	173.2	n/a	6.5	395	n/a
	9	181.3	n/a	5.5	335	n/a
	10	324.3	n/a	6.5	400	n/a
	14	340.9	n/a	8.	490	n/a
	15	23.4	n/a	4.5	260	n/a
	16	346.6	n/a	8.75	530	n/a
	18	353.9	n/a	10	600	n/a
All RAFs	2	41.7	3.5%	4.15	250	-10
	8	171.5	1%	6.583	395	0
	9	179.9	1%	5.583	335	0
	10	321.4	1%	6.667	400	0
	14	338.3	1%	8.167	490	0
	15	23.3	0.5%	4.417	265	5
	16	343.8	1%	8.833	530	0
	18	350.9	1%	10	600	0
Veg Buffer	2	43.0	0.5%	4.25	265	5
	8	170	2%	6.5	400	5
	9	181.1	0%	5.5	335	0
	10	318.4	2%	6.5	400	0
	14	334.2	2%	8.25	495	5
	15	23.2	1%	4.5	275	15
	16	339.7	2%	9	535	5
	18	346.9	2%	10	605	5
Soil structural improvement	2	43.2	0%	4.1	245	-15
	8	172.4	0.5%	6.5	395	0
	9	178.5	1.5%	5.5	335	0
	10	320.6	1.1%	6.75	400	0
	14	336.8	1.2%	8	490	0
	15	22.5	3.8%	4.25	260	0
	16	342.1	1.3%	8.75	530	0
	18	349.3	1.3%	10	600	0
SSSI Floodbanks Removal	7	161.5	-1%	6.4	385	-5

	9	181.3	0%	5.5	335	0
	10	329.4	-1.5%	6.5	395	-5
	14	347	-2%	8	485	-5
	15	23.363	0%	4.25	260	0
	16	352.9	-2%	8.75	525	-5
	18	360.2	-2%	10	595	-5
SSSI Floodbanks Removal (incl. floodplain roughness Increase	7	157.5	2%	6.6	395	5
NT/YDNPA Woodland	2	43.0	0.5%	4	245	-15
	7	158.8	1%	6.5	390	0
	9	181.8	0%	5.5	335	0
	10	321.8	1%	6.5	400	0
	14	337.6	1%	8.25	495	5
	15	22.6	3.5%	4.5	260	0
	16	342.9	1%	9	535	5
	18	350.1	1%	10	600	0
Additional NT/YDNPA Woodland	7	158.7	1%	6.6	395	5
WFW	2	42.2	2%	4.4	265	5
	8	124.5	28%	8	490	95
	9	160.1	11.5%	6.5	395	60
	10	225.3	30.5%	8.5	510	110
	14	224.3	34%	11	665	175
	15	22.5	4%	4.5	265	5
	16	222.4	36%	12.5	745	215
	18	219.8	38%	14.5	875	275
Combination	2	40.9	5%	4.4	265	5
	8	161	7%	6.75	410	15
	9	179.8	1%	5.5	340	5
	10	301.4	7%	6.75	410	10
	14	318.9	6.5%	8.5	505	10
	15	23.1	1.5%	4.5	265	5
	16	324.4	6.5%	9	545	10
	18	331.7	6.5%	10.25	615	15

5 Discussion

A slightly greater amount of flow is generated from the River Skirfare sub-catchment compared to the Upper Wharfe sub-catchment (upstream of Kettlewell). The Skirfare catchment is affected most by the maximum woodland planting scenario. This extreme scenario generates a 11% reduction to peak flow. The catchment responds the least to the buffer strips scenario, with reductions of below 1%. There are similar results for the Upper Wharfe sub-catchment with the maximum woodland planting scenario generating a 27% reduction to peak flow. In this catchment, it is the RAFs scenario that has the lowest reduction of 1%. At the downstream monitoring location, (just upstream of Addingham) the max woodland scenario has the greatest impact with a reduction of 37% to peak flow and a delay of over 4.5 hours to the timing of the flood peak. The RAFs scenario has the least impact with only a 1% reduction.

The RAFs scenario generates a small 1% reduction across the whole catchment. The results show that even with the maximum number of RAFs implemented into the catchment, the effect to peak flow is minimal. This may be due to the high levels of flow within the River Wharfe and RAFs at a depth of 1m cannot store a sufficient amount of surface water to affect the peak flow. Similarly, the soil structural improvement scenario across the ‘improved’ grassland areas only reduced the flood peak at the catchment outlet by 1%.

The vegetated buffer strip scenario has a slightly greater effect on the peak flow. This scenario has a 2% reduction in peak flow down the main River Wharfe and Upper Wharfe sub-catchment. However, the buffer strips have no influence on the Skirfare River tributary. When comparing the two tributaries, it is noticed that the Upper Wharfe drainage network is denser and therefore has more buffer strips applied to the catchment.

The results from the flood bank removal scenario suggests that by removing the banks the flow throughout the River Wharfe downstream of the SSSI actually increases slightly, in particular, a 2% increase upstream of the built-up areas of Conistone, Grassington, Burnsall and Addingham. There is also a 1% increase immediately downstream of the SSSI, just above Kettlewell. In this situation, by removing the flood banks, the flooded water which has reached the floodplain can travel rapidly over the floodplain and re-enter the river further downstream. This means that a very small amount of flood water is being stored on the floodplain when compared to the baseline. As the floodplain surface becomes rougher, it provides a delay in the timing of surface runoff reaching the arterial drainage network. The results show that upstream of Kettlewell, the peak flow has been reduced by 2% as well as delayed by 20 minutes. This compares to the 1% increase in peak flow at this location for the scenario without increased floodplain roughness.

The new woodland plantings have influenced the overall flow hydrograph. Like in the RAFs scenario the new woodland areas have slightly reduced the peak flow by 1% up the Wharfe and Upper Wharfe catchments. The new woods on the River Skirfare has hardly any impact due to the low number of new woodland areas within this sub-catchment. The additional NT woodland planting which was added to the model, did provide further reduction to peak flow, however this further reduction was less than 1%.

The maximum woodland scenario is further improved by adding an associated soil structural improvement to the land under the tree areas. The results from this scenario showed a further 1% reduction for the Kettlewell and Skirfare sub-catchments. This also created a 2% overall reduction downstream of the confluence.

The combination option of all NT/YDNPA new tree plantings, riparian sub category of the Woodland for Water (WfW) opportunity areas, 3m wide vegetated buffers and all the individual RAFs, showed a significant effect throughout the catchment. The Kettlewell sub-catchment was affected the greatest with a 7% overall reduction in peak flow. The Skirfare sub-catchment only showed a 1% reduction. Downstream of the confluence the peak flow reduced by 6-7% as well as showing delays of 15 minutes.

The results from this study has confirmed that significant numbers and/or areas of NFM interventions would be needed in the Upper Wharfe to deliver discernible flood risk management benefits at the catchment outlet. However, greater flood risk management benefits are identifiable at the local scale for some of the NFM options.

Appendices

A NFM Scenario Locations

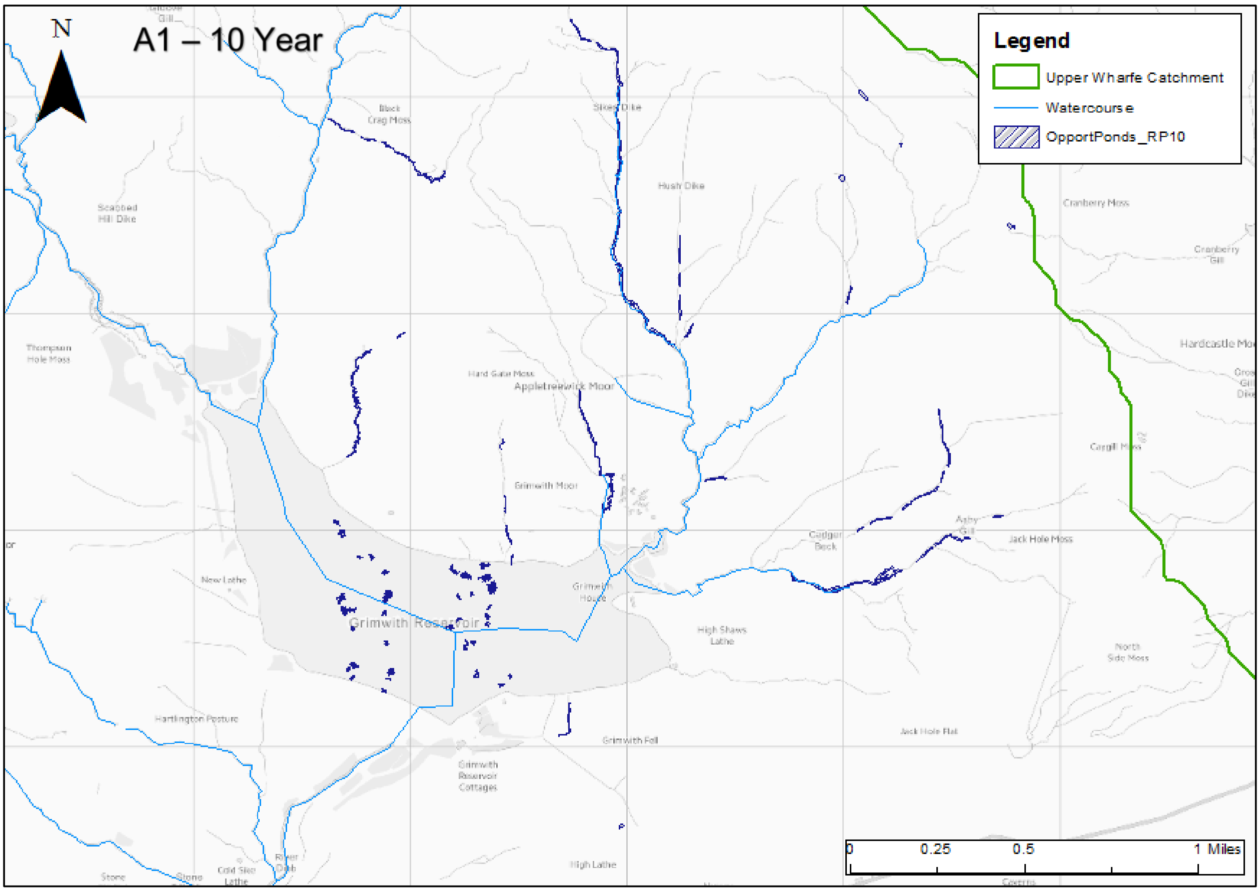
A.1 Example RAF (opportunity pond) locations for Wharfe catchment (RP10). Contains OS data © Crown copyright and database right 2017.

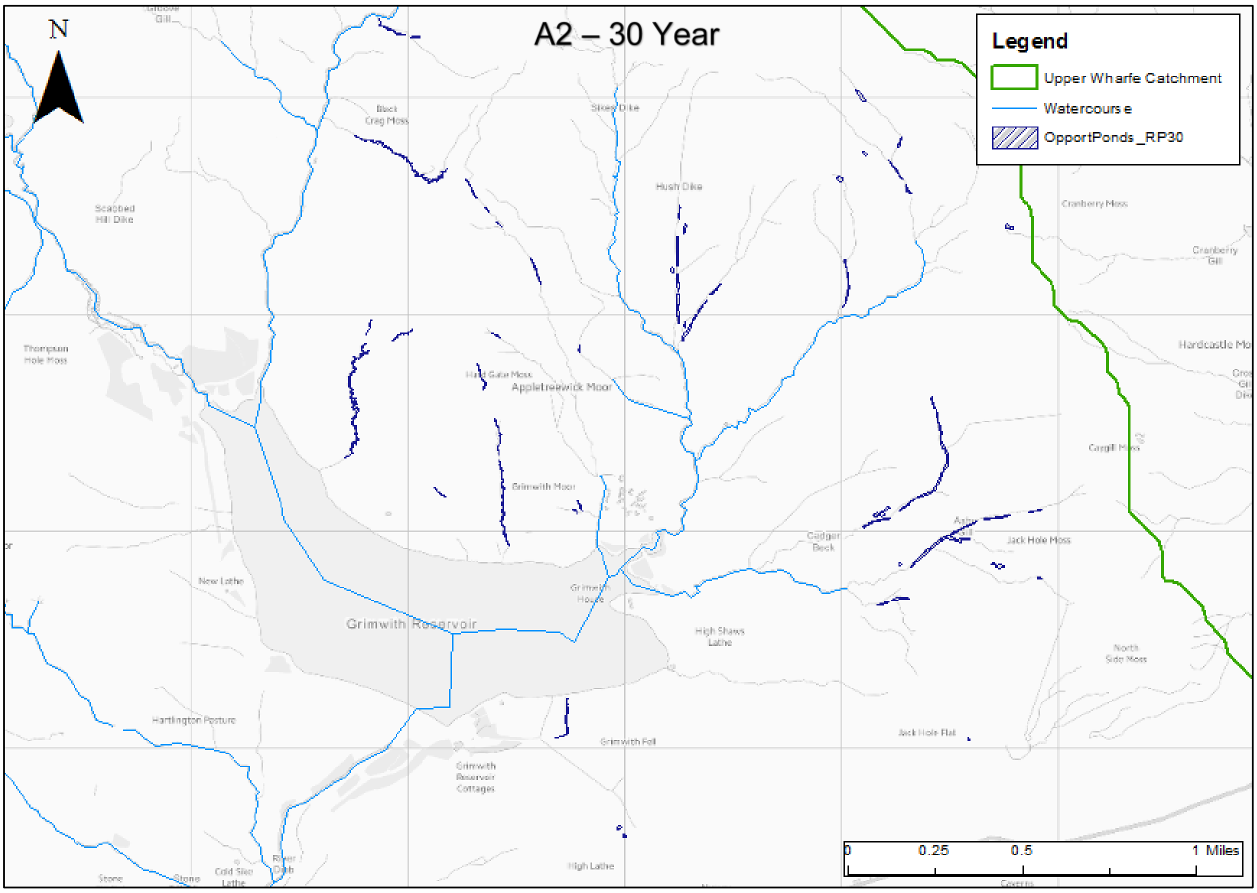
A.2 Example RAF (opportunity pond) locations for Wharfe catchment (RP30). Contains OS data © Crown copyright and database right 2017.

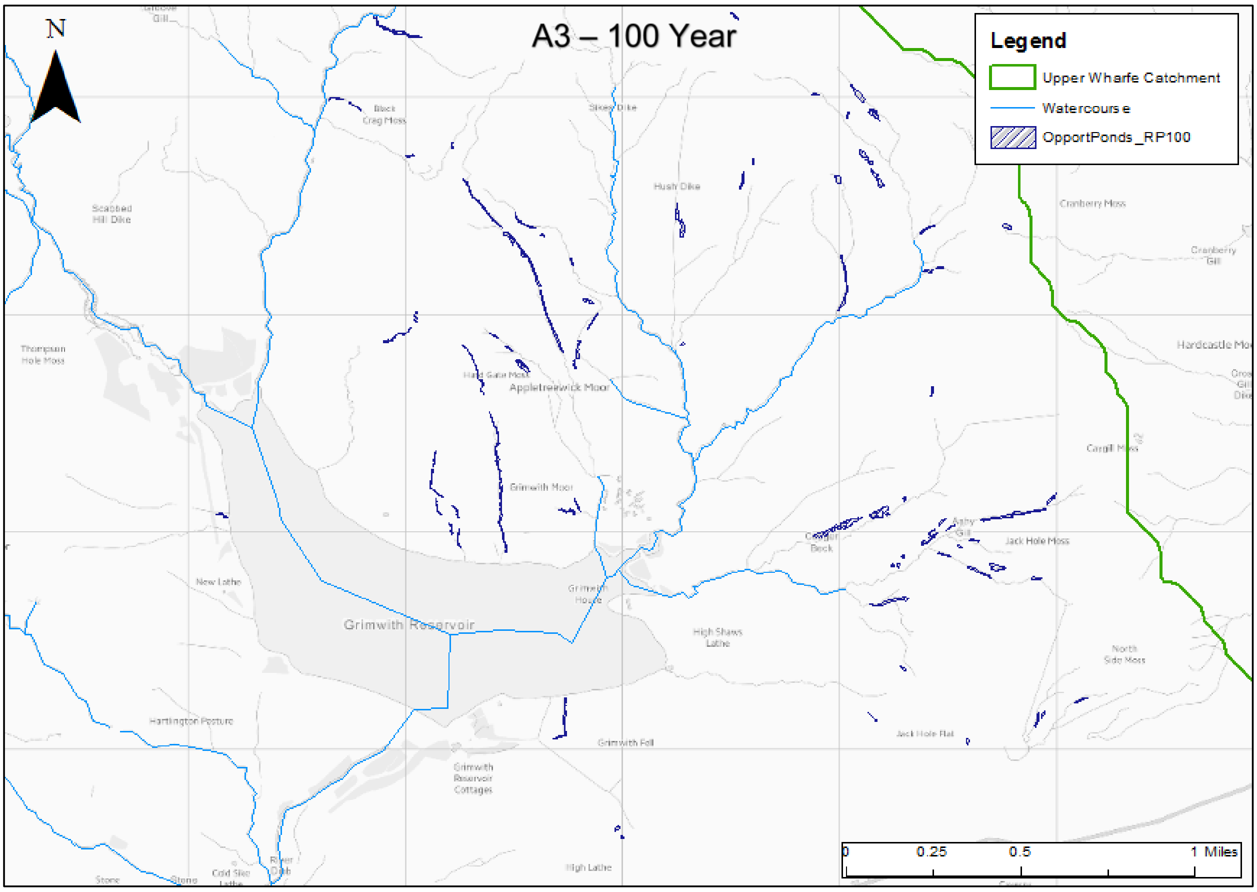
A.3 Example RAF (opportunity pond) locations for Wharfe catchment (RP100). Contains OS data © Crown copyright and database right 2017.

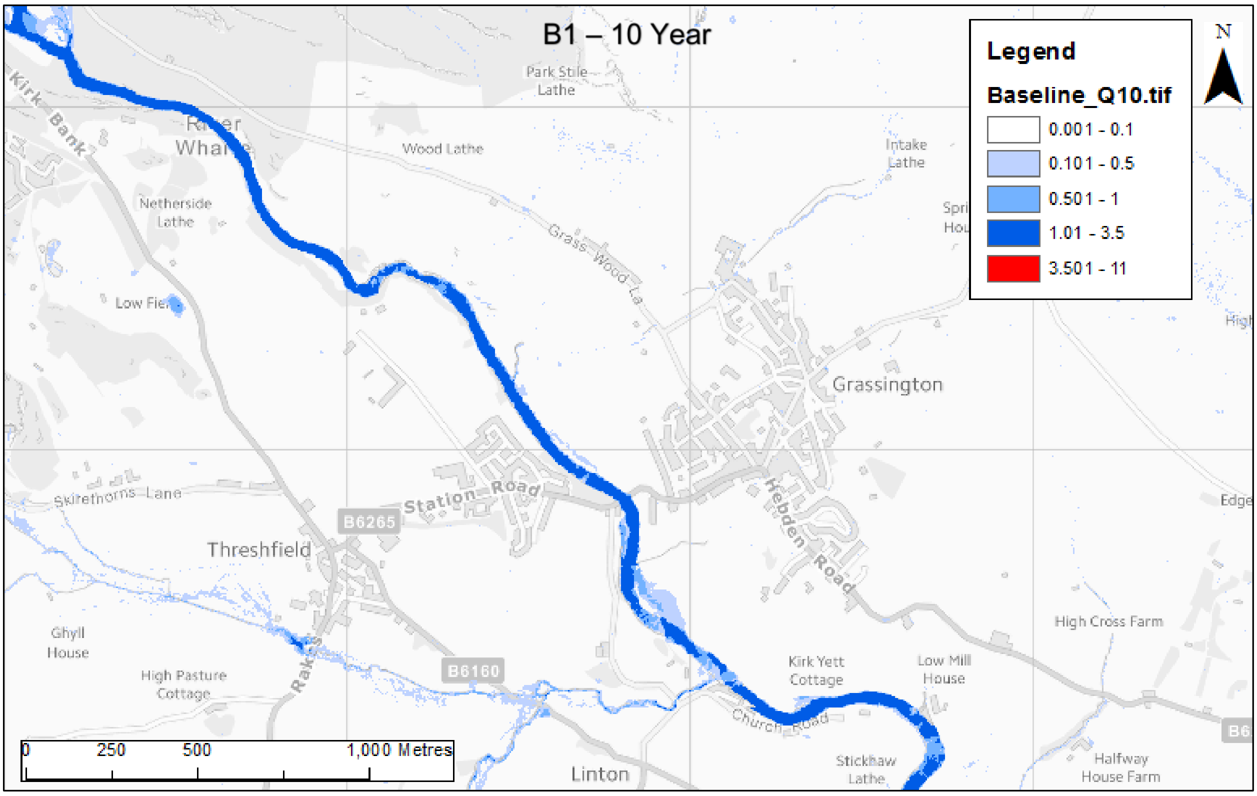
B Flood Mapping

B.1 Flood depth maps for Baseline (current) scenario for all three flood events. Flood depths shown in metres above ground level. Contains OS data © Crown copyright and database right 2017.

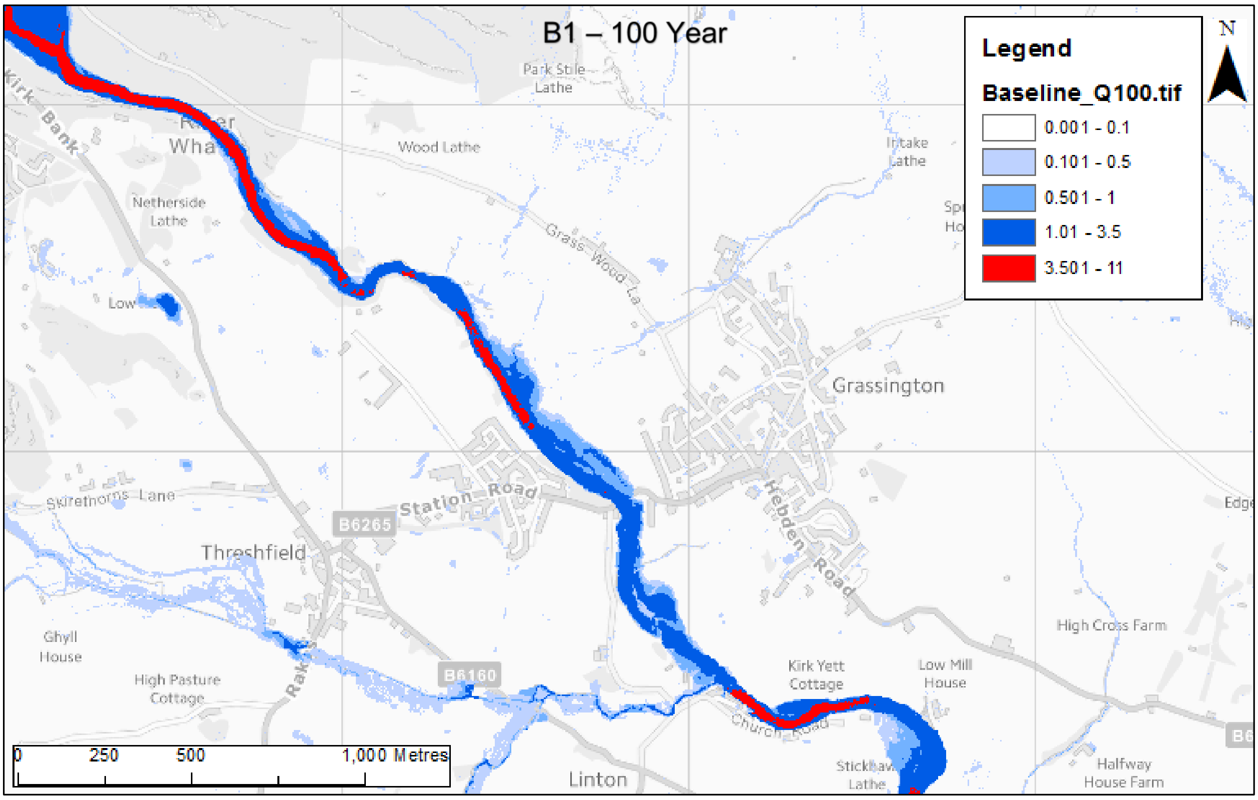

N
A1 – 10 Year
Legend
Upper Wharfe Catchment
Watercourse
OpportPonds_RP10
Grimwith Reservoir
Appletreewick Moor
Grimwith Moor
Hardcastle Moor
Cranberry Moss
Jack Hole Moss
High Shaws Lathe
New Lathe
Hartlington Pasture
Grimwith Fell
Grimwith Reservoir Cottages
High Lathe
Jack Hole Flat
North Side Moss
0
0.25
0.5
1 Miles


A2 – 30 Year
N
Legend
Upper Wharfe Catchment
Watercourse
OpportPonds_RP30
Grimwith Reservoir
Appletreewick Moor
0
0.25
0.5
1 Miles


A3 – 100 Year
N
Legend
Upper Wharfe Catchment
Watercourse
OpportPonds_RP100
Grimwith Reservoir
Appletreewick Moor
Grimwith Moor
Hartlington Pasture
Grimwith Fell
High Shaws Lathe
Jack Hole Moss
Cranberry Moss
Hardcastle Moor
0 0.25 0.5 1 Miles



B1 – 10 Year
Legend
Baseline_Q10.tif
0.001 - 0.1
0.101 - 0.5
0.501 - 1
1.01 - 3.5
3.501 - 11
N
0 250 500 1,000 Metres
Park Stile Lathe
Wood Lathe
Intake Lathe
Netherside Lathe
Grass Wood La
Grassington
Skirethorns Lane
Station Road
B6265
Threshfield
Hebden Road
High Cross Farm
Ghyll House
High Pasture Cottage
B6160
Kirk Yett Cottage
Low Mill House
Church Road
Linton
Stickhaw Lathe
Halfway House Farm
Kirk Bank
Edge


B1 – 100 Year
Legend
Baseline_Q100.tif
0.001 - 0.1
0.101 - 0.5
0.501 - 1
1.01 - 3.5
3.501 - 11
N
0
250
500
1,000 Metres
Grassington
Threshfield
Linton
Park Stile Lathe
Wood Lathe
Netherside Lathe
Grass Wood La
Station Road
Hebden Road
B6265
B6160
Skirethorns Lane
Ghyll House
High Pasture Cottage
Kirk Yett Cottage
Low Mill House
High Cross Farm
Halfway House Farm
Church Road

Offices at
Coleshill
Doncaster
Dublin
Edinburgh
Exeter
Glasgow
Haywards Heath
Isle of Man
Limerick
Newcastle upon Tyne
Newport
Peterborough
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