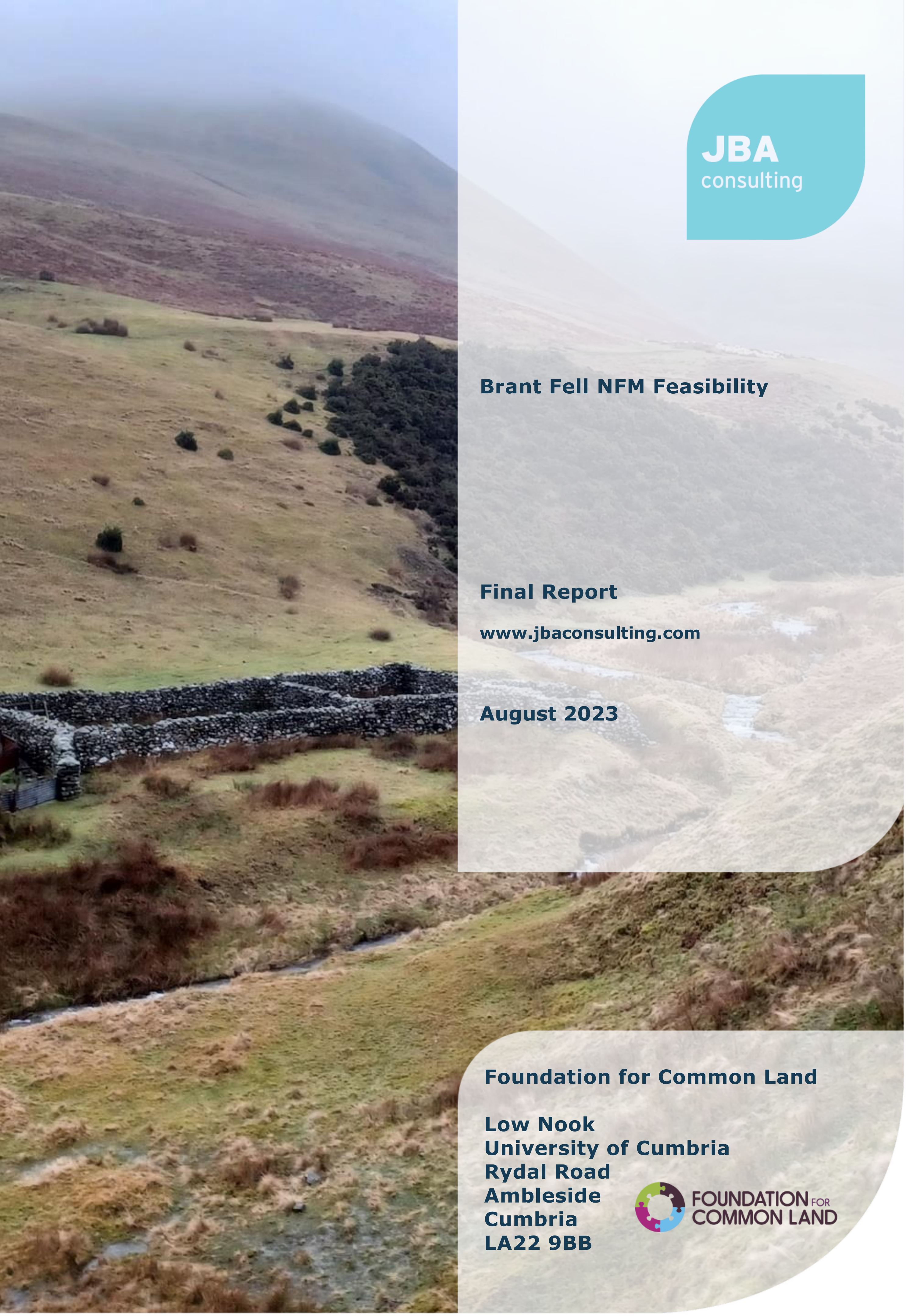

Brant Fell NFM Feasibility

Final Report

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August 2023

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This report describes work commissioned by Claire Hodgson, on behalf of Foundation for Common Land, by an email dated 17/11/2022. Foundation for Common Land's representative for the contract was initially Claire Hodgson and, more recently, Claire Braeburn. Steve Rose, Jenny Broomby, Ethan Wallace and Ryan Jennings 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 Foundation for Common Land.

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Definitions

Within this report, JBA have used the following terms to specify the intervention methods being used on the ground, these include:

- Working with Natural Processes (WwNP)
- Nature Based Solutions (NBS)
- Natural Flood Management (NFM)

Within the report, each of these terms are used. WwNP/NBS focuses on managing, restoring, and emulating a more naturally functioning catchment and river system.

NFM applies the WwNP approach to implement specific features across catchments to intercept, slow and store flood waters.

This report quotes the frequency of a flood in terms of an annual exceedance probability (AEP), which is 100/return period (years). A return period is defined as the average time between years with at least one larger flood. AEPs can be helpful when presenting results to members of the public who may associate the concept of return period with a regular occurrence rather than an average recurrence interval. The table below is provided to enable quick conversion between return periods and annual exceedance probabilities.

Table 1: AEP/Return Period Conversion

Return period (years)	2	5	10	20	25	30	50	75	100	200	1000
AEP	0.5	0.2	0.1	0.05	0.04	0.033	0.02	0.013	0.01	0.005	0.001
AEP (%)	50	20	10	5	4	3.3	2	1.3	1	0.5	0.1

1 Project Introduction

JBA have been commissioned by the Foundation for Common Land (FCL) to provide specialist advice on potential NFM sites across the Brant Fell Common Land. As part of this project, JBA NFM specialists have also undertaken key stakeholder consultations and site walkover surveys. The findings have been quantified through 2D hydraulic modelling to build their (FCL) understanding and help continue the project into the future.

The Howgill Fells are a group of small hills in Cumbria UK confined by Sedbergh to the south, Tebay to the north-west, and Ravenstonedale to the north-east. Brant Fell Common is located at the southern section of the Howgill Fells and stretches from just north of Sedbergh to approximately halfway between Sedbergh and the A685. Brant Fell Common is common land and consists of 2735 hectares of land[1]. Brant Fell is a hill within Brant Fell Common and is located 0.5 km north of Sedbergh. The OS grid reference for Brant Fell is 365740, 495470[2].

The overall aim of the project is to conduct a scoping survey and stakeholder engagement to identify a potential scheme for Natural Flood Management (NFM) measures to be implemented on Brant Fell Common. Brant Fell Common drains into the River Lune, either directly to the west or via the intermediary River Rawthey when draining to the south or east. Sedbergh is situated immediately to the south of Brant Fell Common and slightly to the north of the River Rawthey, with the confluence of the River Rawthey and the River Lune to the south-west of Sedbergh. Watercourses that directly drain into Sedbergh from Brant Fell Common include Settlebeck Gill and several unnamed streams coming from a hill peak known as Winder. NFM measures on Brant Fell Common will primarily aim help to reduce flood risk to Sedbergh and other downstream settlements, as well as provide a range of additional ecosystem services within Brant Fell Common.

The watercourses that have the largest number of high-risk flood receptors (those with a max flood depth exceeding 5cm), and therefore pose the greatest risk of causing significant flooding to properties, are Settlebeck Gill, Ashbeck Gill, and Eller Mire Beck. Settlebeck Gill flows directly into Sedbergh, with Ashbeck Gill flowing joining the River Rawthey just to the east and slightly upstream of Sedbergh.

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[1] https://common-land.com/lands/view/4978

[2] https://getoutside.ordnancesurvey.co.uk/local/brant-fell-south-lakeland-la105hy

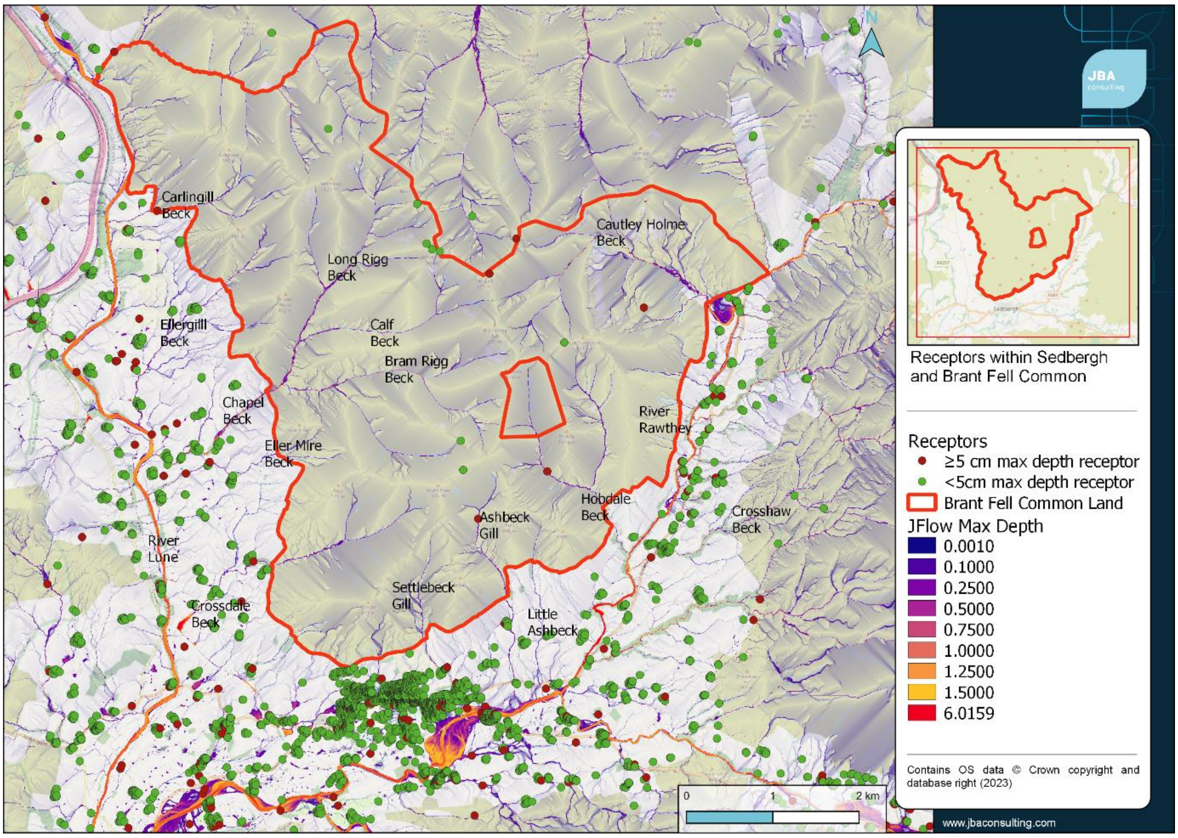

Figure 1-1: The receptors surrounding the Brant Fell area, highlighting those at risk from more than 5 cm of flooding in red.

Table 2: Total number of receptors per watercourse draining from Brant Fell.

Watercourse	Total number of receptors in immediate stream vicinity	<5cm max depth receptor (Low Risk)	≥5cm max depth receptor (High Risk)
Ashbeck Gill	12	8	4
Carlingill Beck	1	0	1
Cautley Holme Beck	0	0	0
Chapel Beck	28	28	0
Crossdale Beck	21	20	1
Eller Mire Beck	25	22	3
Little Ashbeck	6	5	1
Hobdale Beck	1	0	1
Settlebeck Gill	49	43	6

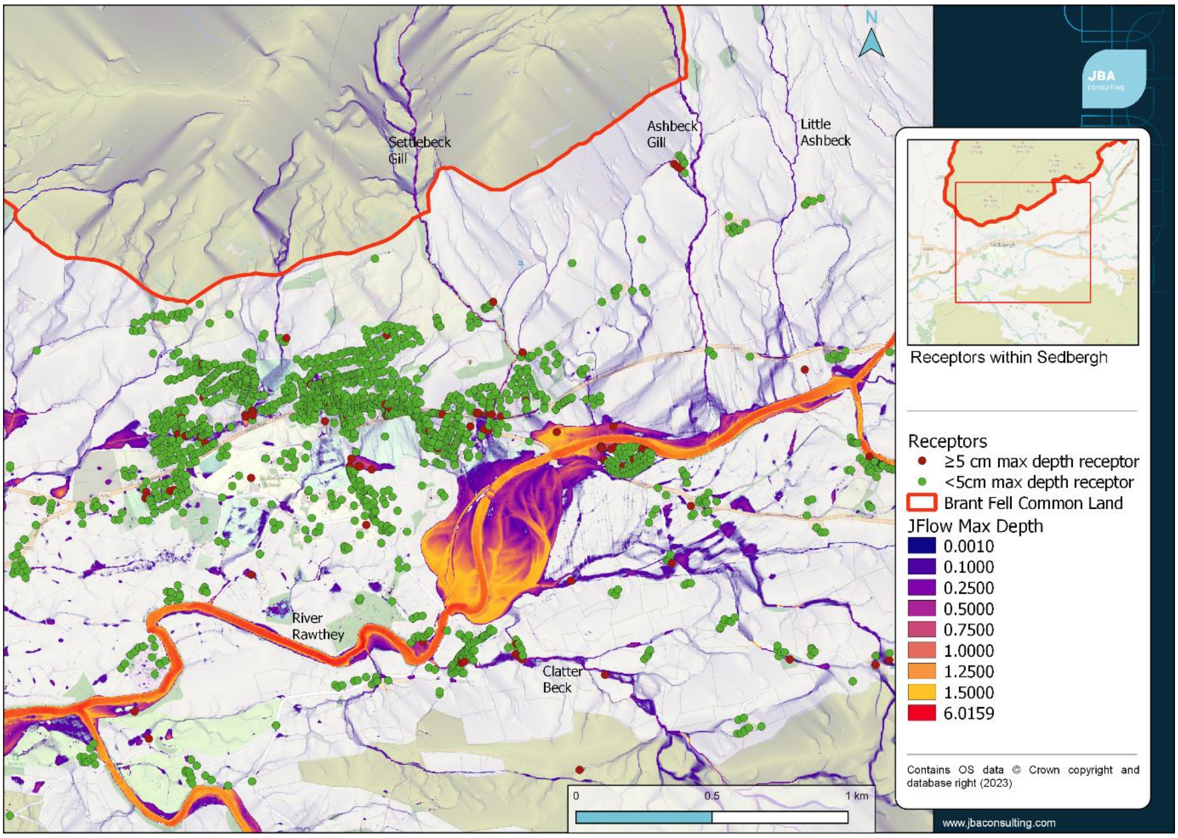

Figure 1-2: The receptors throughout Sedbergh, highlighting those at risk from more than 5 cm of flooding in red.

This report covers the topics of this assessment including the consideration of historic and existing hydrological processes Proposed solutions to restore the hydrology been developed through the application of a natural flood management approach to intercept , slow and store flood waters. Natural Flood Management (NFM) interventions and Working With Natural Processes (WWNP) aim to work with natural processes wherever possible to deliver integrated outcomes including: flood regulation, biodiversity, carbon capture, and water quality benefits.

2 Desk-based Assessment

2.1 Catchment understanding

Brant Fell Common is common land situated at the southern section of the Howgill Fells, with Brant Fell located 0.5 km north of Sedbergh. The major surrounding river systems are the River Lune to the West, and the River Rawthey to the south and east. Broadly, the western sections of Brant Fell Common drain roughly westwards directly into the River Lune, whereas the eastern and southern sections of Brant Fell Common drain eastwards and southwards, respectively, into the River Rawthey. The River Rawthey joins the River Lune around Marthwaite 3.75 km to the south-west of Sedbergh.

Brant Fell Common contains numerous streams. Major streams in the central western sections include Bram Rigg Beck, Swarth Greaves Beck, Long Rigg Beck and Calf Beck, which all drain into Chapel Beck, which then drains into the River Lune approximately 3.5 km to the west of Brant Fell. In the north-western Section of Brant Fell Common Carlingill Beck is a major stream which drains north-west into the River Lune approximately 6.25 km to the north-west of Brant Fell. The south-west sections of

Brant Fell Common are drained by Crossdale Beck which drains south-west into the River Lune approximately 4 km to the south-west of Brant Fell. In the southern section the major stream is Ashbeck Gill which drains south directly into the River Rawthey approximately 3 km to the south of Brant Fell. In the south-east and east of Brant Fell Common the major streams are Hobdale Gill and Long Gill, which combine to form Hobdale Beck which drains south-east directly into the River Rawthey approximately 2.25 km to the south-east of Brant Fell. In the north-east the major stream is Cautley Holme Beck which drains eastwards into the River Rawthey, approximately 3.25 km north-east of Brant Fell. This assessment focuses on these rivers and the surrounding common land, with a focus towards those rivers immediately upstream of Sedbergh, alongside the River Rawthey which flows through Sedbergh.

As a result, Sedbergh is situated within a small catchment (<10km²) which highlight the potential for smaller-scale NFM, in a relatively simple catchment where the receptor is in the vicinity of where the NFM measures would be implemented (Hankin, et al., 2021).

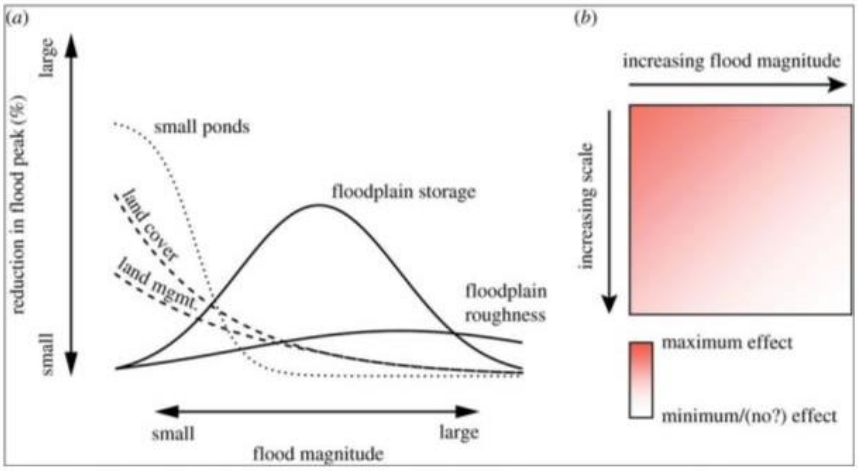

Figure 2-1: Identification of the space on the NFM, Flood Frequency, Risk continuum where the small catchments are targeting.

It is therefore likely that NFM in these catchments may have an immediate effect on reducing flood risk.

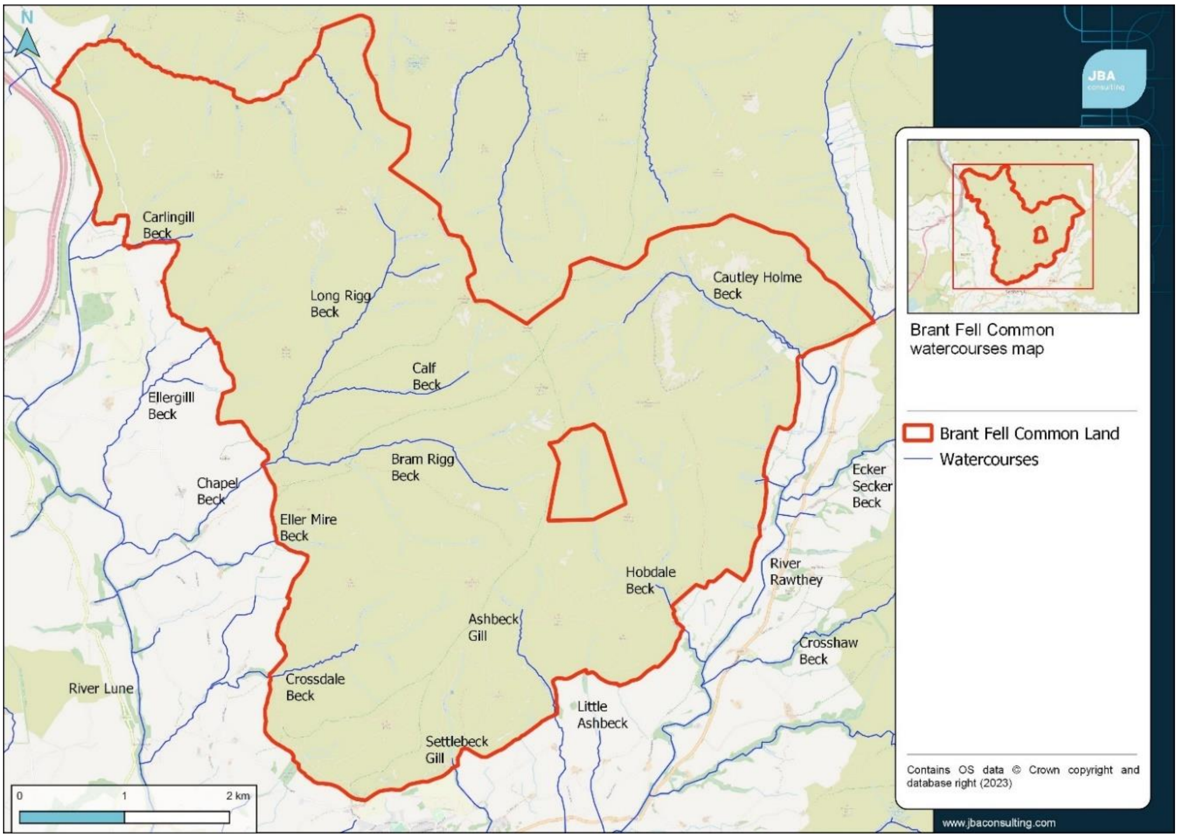

Figure 2-2: The major watercourses throughout Brant Fell Common.

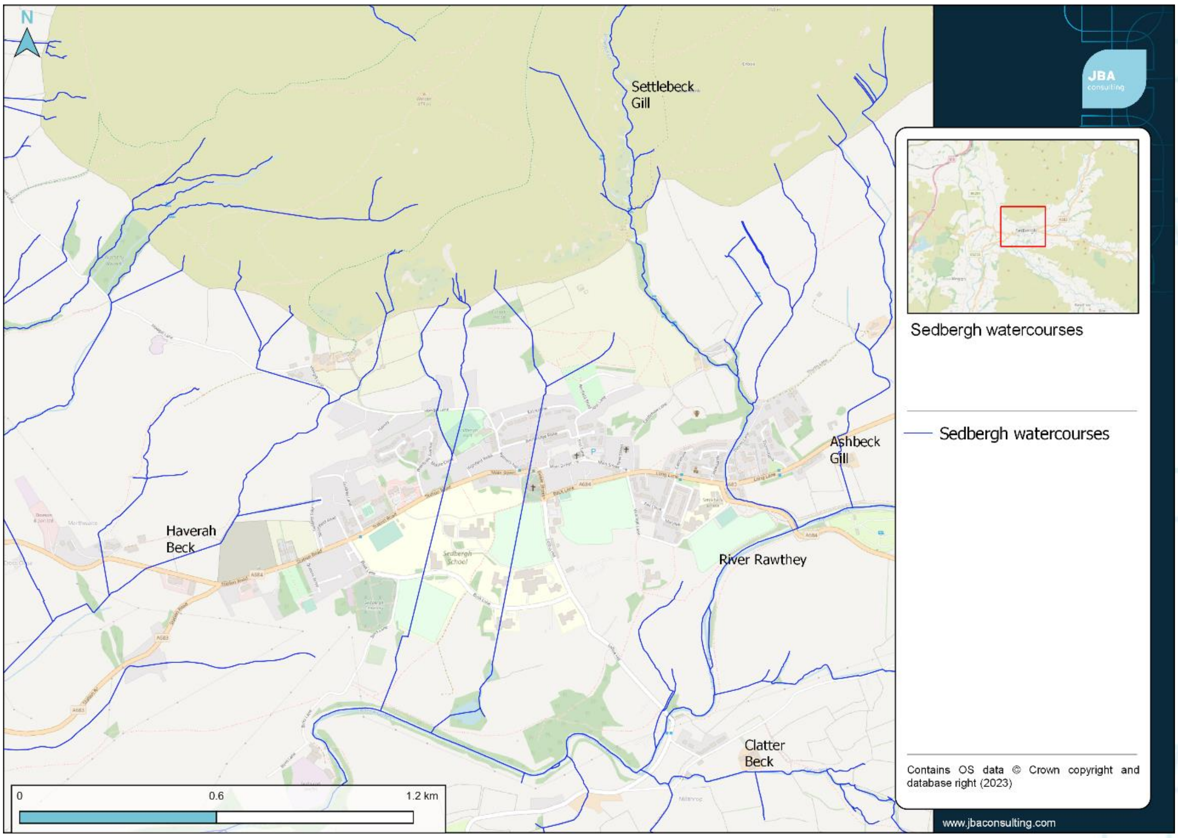

Figure 2-3: The major watercourses throughout Sedbergh*.

It should be noted, there is some differences between the culvert route shown here and the ones in the Flood Investigation Report[4]. The modelling will follow the route of the Report (Figure 2)[4]

2.2 Hydrological understanding

2.2.1 Catchment hydrology and hydrological functioning

Brant Fell Common primarily consists of upland moorlands on fells which are used for rough-grazing by sheep and wild (fell) ponies, with historic grazing rights also present for cattle and geese[1]. The common contains almost no roads, houses or settlements. Brant Fell Common has a number of steep gradients, causing the channels around Brant Fell to be deeply eroded into the landscape and extremely incised. These river networks tend to flow outwards from the centre of the Howgills and from Brant Fell in a loosely radial pattern, likely due to the glacial history of the region. 81% of channels within Brant Fell Common contain a vegetated bed given Sustainable Farming Incentive (SFI) survey information by the local graziers.

The land surface of Brant Fell Common is generally smooth in nature with virtually no tree or hedgerow cover (97% of SFI survey locations contained no tree or scrub cover), although there are notable areas of rough vegetation in places. 42% of the land contained dense moss hummocks, tussocks or bracken, whilst 45% contained sparse moss hummocks, tussocks or bracken, and 13% contained smooth grass, bare ground or carpet moss, all according to the SFI survey. Furthermore, the SFI survey gave 27% of vegetation as below 5cm tall and 37% below 10 cm tall, further amplifying the smooth landscape appearance.

The lack of tree coverage and shrub vegetation in places means that the area is exposed and windswept, likely further inhibiting the growth of vegetation in the area, facilitating the smooth-looking landscape. This lack of tree cover and absence of extensive rough vegetation in places may reduce surface roughness, likely resulting in surface and near-surface hydrological pathways which are less likely to be slowed and/or infiltrated into the ground, causing rapid hydrological responses and elevated flood risk[3].

Areas which lack vegetation, in particular trees, likely have reduced interception and evapotranspiration losses, resulting in increased hydrological inputs through rainfall and resultantly faster and larger hydrological responses and increased flood risk. The lack of trees and vegetation in places also likely decreases localised infiltration capacity and permeability of the soil, further encouraging rapid surface hydrological pathways which increase flood risk and amplify water quality issues, as well as potentially increasing the risk of soil erosion issues. The degree of grazing from both sheep and wild ponies may additionally cause soil compaction of the surface, further reducing permeability and infiltration capacity, and they may also graze any new vegetation before it becomes established. The large number of walkers and mountain bikers in the area will also have contributed to the compaction of track surfaces, causing localised reductions in infiltration-capacity, permeability, and resulting in an increase in the number and distribution of surface hydrological pathways. During the site walkover it was observed that the compacted and eroded paths and tracks tended to act as preferential conduits for rapid surface flow, rather than over heavily grazed areas or areas of rough vegetation. Soils in the area are also likely shallow, and infiltrated rainfall may therefore rapidly come into contact with superficial geology or bedrock geology, and if impermeable, travel laterally along near-surface hydrological pathways which can be fast, thereby contribute towards downstream flood risk.

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[3] Bond S, Kirkby MJ, Johnston J, Crowle A and Holden J. (2020). Seasonal vegetation and management influence overland flow velocity and roughness in upland grasslands. Hydrological Processes. 34(18), pp. 3777-3791

The Brant Fell Common area suffers from landslips, with recent landslips damaging some local archaeology. There are also issues locally with compacted and eroded walking paths and tracks. However, 96% of the land shows no obvious erosion according to the SFI survey, suggesting erosion may be very localised.

The steep gradients on Brant Fell Common, combined with the lack of trees or vegetation in places, shallow soils, and potentially reduced infiltration and permeability of rainfall into the soil, likely means that the area is rapidly responding to rainfall events and amplifies flood risk to downstream areas. This is also intensified as certain areas of Brant Fell Common contain evidence of artificial drainage, meaning that water is rapidly transferred downstream via these artificial pathways such as with drains/gripping of bogs or similar areas. This steep nature of watercourses draining into Sedbergh likely causes them to have very flashy responses and to respond rapidly to heavy rainfall events.

2.2.2 Historical flooding and flood risk

Significant floods have historically occurred on major downstream settlements from Brant Fell Common within the wider Lune catchment. This includes Lancaster, Kirkby Lonsdale, Sedbergh, Caton, and Halton. Examples of such floods include during Storm Desmond in December 2015 and Storm Ciara in February 2020.

Within Sedbergh, properties and/or infrastructure that has historically flooded has occurred in areas including Sedbergh’s People Hall, Rehearsal Hall, Maple Close, Woodside Avenue, Sedbergh Spar, Sedbergh School Medical Centre, Guldrey Terrace, Guldrey Lane, Guldrey Fold, Loftus Hill,

Main Street, and the recreational ground to the south of Howgill Lane. The flooding at these locations is believed to come from channels to the immediate north of Sedbergh which originates to the south of Winder (Fell), as well as to be at least partially due to backwater effects from the channel to the immediate west of Guldrey Fold, as well as from surface water flooding.

The flooding on 5th and 6th December 2015 is believed to be some of, if not the, worst flooding Sedbergh has ever experienced, with five properties directly flooded[4] . During this flood, Sedbergh was affected by several smaller watercourses which ordinarily feed into the main watercourse through the town. Large amounts of debris and sediment were carried within these watercourses during this flood event, and (partially) blocked a culvert upstream of Howgill Lane[4]. This culvert was unable to contain the volume of water within the watercourses and overtopped, causing water to flow across Sedbergh football field towards Maple Close. Rehearsal Hall was flooded as a result as water could not re-enter the culverts, and flood water also built up around the side of the public highway which is elevated in comparison to the Music Hall. Flood water eventually overtopped the public highway embankment and travelled towards the rear of the SPAR supermarket and Sedbergh medical practice, which was amplified by overland flow coming from Howgill Lane. A separate culvert to the back of Nook House was also exceeded, causing flooding on Guldrey Terrace and Guldrey Lane, as well as the nearby tennis courts and car park. No properties were directly flooded on Guldrey Terrace, although properties were flooded on Guldrey Lane. Surface water flooding was also present on 5th -6th December 2015, and has been attributed to the steep nature of the surrounding area[4]. The high gradients of the watercourses in and around Sedbergh mean that the area is at high-risk of flash flooding[4].

2.2.3 Sedbergh flood defence measures

Following the flooding in Sedbergh on 5th -6th December 2015, several actions were recommended to reduce the threat of flooding in the future. This includes: Reviewing

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[4] Sedbergh Flood Investigation Report Flood Event 5th-6th December 2015.

and updating plans to increase the resilience of homes and businesses to flooding, administering flood recovery and resilience grants, reviewing local development plans and strategic flood risk assessments, reviewing the resilience of critical transport, power and utility infrastructure, repairing assets damaged by the flood, reviewing the drainage and sewerage systems, conducting a surface water management plan, increased community engagement, and natural flood management[4].

2.3 DEFRA MAGIC map

The MAGIC website from the Department for Environment, Food and Rural Affairs (Defra) provides geographic information about the natural environment[5]. Analysis of the Brant Fell Common area can provide further useful information on the baseline condition of the catchment.

The MAGIC website provides authoritative national geographic information about the natural environment from across government. The information covers rural, urban, coastal, and marine environments across Great Britain. In summary, the Brant Fell Common area is identified as:

- Within a secondary B bedrock aquifer designation region.
- Containing some secondary undifferentiated superficial drift aquifer designation region around several streams such as Ashbeck Gill, Longrigg Beck, Hobdale Beck, Fairmile Beck and Cautley Holme Beck.
- Within mostly a medium risk groundwater vulnerability zone.
- Consists of grade 5 agricultural land classification, with a Dudley Stamp Land Use Inventory classification of rough-grazing.
- Is partly within the higher-level stewardship target area (The Howgills) for England.
- The southern section and very north-west is partly within a higher-level stewardship theme (Yorkshire and the Humber Region Theme Area) for England.
- Is entirely within a severely disadvantaged less favourable area.
- Is entirely within a former catchment sensitive farming priority area 2011-2015 for catchment partnership.
- Mostly consists of acid, calcareous, or neutral grasslands, with notable sections of fen, marsh and swamp, and minor sections of bracken and dwarf shrub heath.
- Contains some priority habitat for Upland Heathland.
- Containing small amounts of non-priority grass moorland.
- Contains priority species area for Curlew and Lapwing.
- Contains some Grassland Assemblage Farmland bird area, a black grouse area, a curlew area, and lapwing area.
- Is within an Important Birds Area (Breeding Bird Survey (BBS) has been undertaken separately[6]).
- Is within a Woodland Bird Assemblage.
- Contains lower spatial priority for the woodland priority habitat network.

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[5] https://magic.defra.gov.uk/home.htm

[6] Brant Fell Breeding Bird Survey - Haycock and Jay Associates – August 2022

- Contains some red squirrel creation areas, and red squirrel management areas.
- Is entirely within a medium priority area for Countryside Stewardship Water Quality Priority Areas.
- Is entirely within a medium priority area for faecal indicator organism issues.
- Is entirely within a medium priority area for phosphate issues.
- The eastern sections of Brant Fell Common are within sites sensitive to ammonia pollution.
- Contains high priority area for flood risk management in the south and east of the area.
- Contains both higher and lower spatial priority for woodland water quality.
- Contains a large amount of lower spatial priority for woodland flood risk.
- Contains some woodland for water priority catchment in the east of the area.
- Contains some small sections of keeping rivers cool areas.
- Contains mostly medium climate change vulnerability buffer areas, with a small amount of low climate change vulnerability buffer.

The MAGIC analysis highlights Brant Fell Common as being mostly agricultural and unimproved, a rough grazed, grassland moor on severely disadvantaged less favourable land. The area is important for bird and squirrel species. Brant Fell Common has medium priority issues for phosphate issues, faecal indicator organism issues, and for countryside stewardship water quality. Brant Fell Common also has high priority areas for flood risk and woodland water quality.

2.4 Water Framework Directive (WFD) status and pressure

The Environment Agency (EA) catchment data explorer[7] can be used to assess various properties of WFD waterbodies. Brant Fell Common sits on the watershed between the EA water body IDs: River Lune from the confluence with Birk Beck to the confluence with the River Rawthey, River Rawthay (upper) and River Rawthay (lower).

The Rawthay (lower) is not designated as artificial or heavily modified, and has a good ecological status and a failed chemical status due to the presence of priority hazardous substances, specifically mercury and its compounds, and the presence of polybrominated diphenyl ethers (PBDEs). The southern sections of Brant Fell drain into the lower Rawthay such as via Ashbeck Gill.

The Rawthay (upper) is not designated as artificial or heavily modified, and has a good ecological status and a failed chemical status due to the presence of priority hazardous substances, specifically, mercury and its compounds, Perfluorooctane sulphonate (PFOs) and PBDEs. The eastern sections of Brant Fell drain into the upper Rawthay such as Grimes Gill, Hobdale Gill and Hobdale Beck.

The River Lune from the confluence with Birk Beck to the confluence with the River Rawthey is not designated as artificial or heavily modified, and has a good ecological status and a failed chemical status due to the presence of priority hazardous substances, specifically, mercury and its compounds, PFOs and PBDEs. The western sections of Brant Fell drain into the highlighted section of the River Lune such as Bram Rigg Beck, Swarth Greaves Beck, Chapel Beck, Crosdale Beck and Smithy Beck.

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[7] https://environment.data.gov.uk/catchment-planning/ManagementCatchment/3053

It is possible that NFM and WWNP measures may benefit water quality and therefore could help maintain the good ecological status of the rivers. NFM and WWNP also generally maintain or improve biodiversity of an area, and therefore could further improve the ecological status of the area. It is also possible that NFM and WWNP measures may help improve the chemical status of the rivers by slowing rapid hydrological surface pathways which can rapidly transport chemical pollutants into the stream network before they can be captured and/or degraded. Certain NFM features may also help bind soils contaminated with these chemical compounds and slow or stop them from reaching the stream network – potentially improving the chemical water quality status.

2.5 Historic trend analysis

Brant Fell Common looks to have remained largely unchanged even on historic maps dating back to the late 19th century, with the watercourses almost identical to the 1888-1913 map. This is likely due to the remoteness of the region and the difficulty in settling in the area due to the climate, lack of vegetation and the steep surrounding gradients. Artificial drainage is present from site assessment, although the precise dates and locations of this is currently unknown. The number and density of sheep and wild ponies may have changed over time, but this is currently unknown.

2.6 Soils, geology and land use

2.6.1 Soils

Soils on Brant Fell are mostly very acid loamy upland soils with a wet peaty surface and a peat texture. The soil in the wider Brant Fell Common area include slightly acid loamy and clayey soils with impeded drainage, shallow very acid peaty soils over rock, and naturally wet very acid sandy and loamy soils, as well as other areas of very acid loamy upland soils with a wet peaty surface and a peat texture. Soils within the catchment are shallow in many places, having a depth of around 15-20cm according to local landowners, making the soil unfavourable for many tree species. SFI survey data states that 29% of Brant Fell soils are non-peat with a depth shallower than 5cm, and 69% is shallow peat 5cm – 40cm deep.

2.6.2 Superficial Geology

Brant Fell Common consists of sections of superficial deposits of till surrounding many of the river channels such as Bram Rigg Beck, Swarth Greaves Beck, Crosdale Beck, Ashbeck Gill, Hobdale Gill, Grimes Gill and Hobdale Beck. There are small sections of Talus gravel to the east of Brant Fell surrounding Hobdale Gill, and to the south-west, just north of Crosdale Beck. There is a very small amount of alluvium clay on the Crosdale Beck channel. Outside of these areas there is no superficial geology.

2.6.3 Bedrock Geology

The bedrock geology of Brant Fell mostly consists of Coniston Group sandstone, siltstone and mudstone, with notable sections of Screes Gill Formation sandstone and argillaceous rock. There are also thin striations of Coniston Group siltstone. In the western sections of Brant Fell Common and the far north-east, there is Bannisdale Formation siltstone and mudstone, with a smaller amount of Bannisdale Formation sandstone. On the southern border of Brant Fell Common surrounding Sedbergh there is the Sedbergh Conglomerate Formation of conglomerate, as well as Bannisdale Formation siltstone and mudstone, and Bannisdale sandstone. A large number of actively flowing springs are present throughout Brant Fell Common.

2.6.4 Land use

The SFI land-use survey took 277 observations upon Brant Fell. Notable observations were that 12% of the Brant Fell contained more than 50% bracken coverage, whilst 78% contained no bracken cover. 29% of Brant Fell soils are non-peat with a depth of less than 5cm, and 69% is shallow peat 5cm – 40cm deep. 94% of the land does not contain bare peat, and 96% shows no obvious erosion. 42% of the land contained dense moss hummocks, tussocks or bracken, whilst 45% contained sparse moss hummocks, tussocks or bracken, and 13% contained smooth grass, bare ground or carpet moss. 59% of peat areas were dry peat with the opportunity for restoration, 32% were moist peat with opportunities to enhance the peat, and 10% is wet peat. 80% of bog mosses required restoration, and 19% required enhancement. 27% of vegetation was below 5cm tall and 37% of vegetation was below 10cm tall, with 17% over 30 cm tall. 81% of channels had a vegetated base, whereas 19% were bare. 97% of the area did not contain any tree or scrub cover.

2.7 Desk based catchment NFM potential and working with natural processes.

Potential NFM measures (unconstrained) have been identified within the Brant Fell Common area. Riparian tree plantings appear to be an extensive option, with the possibility of riparian planting along the entire length of all of the streams within the Brant Fell Common area, including both minor and major streams. Catchment tree planting also looks to be feasible on considerable sections of Brant Fell Common, especially on areas immediately adjacent to the riparian woodland planting regions. There are also very small sections available for floodplain tree planting, as well as for runoff attenuation features. There is a very small amount of floodplain reconnection possible on the border with the River Lune.

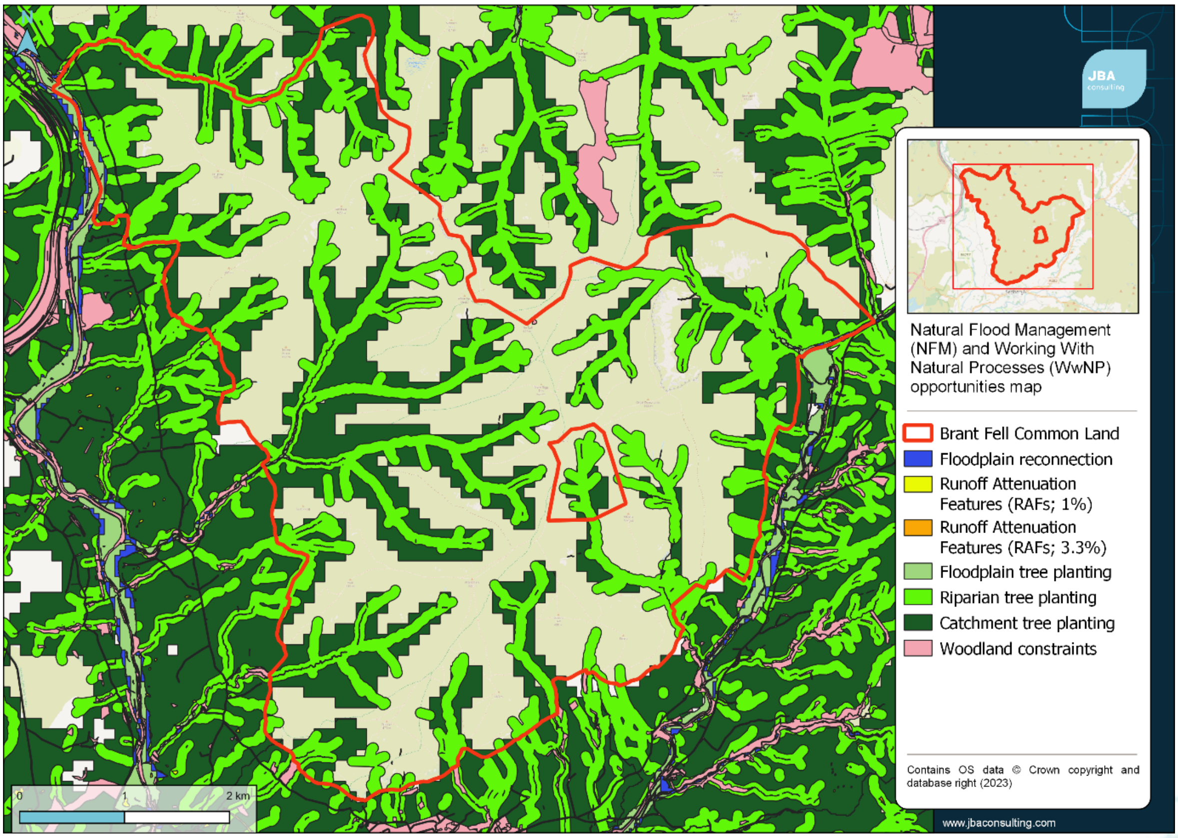

Figure 2-4: The Working With Natural Processes (WWNP) map for Brant Fell Common.

2.8 NFM and WWNP options

There are various NFM and WWNP options in the area that could reduce flood risk and water quality issues in the catchment, alongside providing additional ecosystem services.

Tree planting in the area would likely increase interception, evaporation and transpiration in the catchment, reducing the hydrological inputs reaching the catchment surface and lowering flood risk. Trees would also likely increase the infiltration and permeability of the area, reducing the likelihood and incident of rapid surface hydrological pathways. Trees would additionally provide many co-benefits with ecosystem services. This includes biodiversity as trees could provide food and shelter for a range of species due to the current lack of tree cover – such tree species could be targeted to be especially beneficial to targeted mammal or bird species such as red squirrels (see Section 2.3). Trees would additionally benefit water quality due to the reduction in surface hydrological pathways, and may also help to bind soil and retain nutrients and pollutants, further benefiting water quality, but also reducing soil erosion. The shade and shelter provided by the trees would also benefit livestock welfare in the area, and if planted close to streams could assist in the Keeping Rivers Cool initiative (see Section 2.3). To allow trees to be established in the area, these will almost certainly need to be fenced off to protect them from grazing or placed in 'hard to graze' areas (https://www.nationaltrust.org.uk/visit/wales/carneddau-and-glyderau/thinking-like-a-sheep-to-plant-a-tree), and hardier species should also be prioritised due to the exposed, wind-swept nature of the area. The shallow soils across a considerable proportion of the catchment will also need to be considered, as these will restrict tree growth. It has been noted that there have been numerous attempts to plant trees in the Brant Fell Common area, with the vast majority of trees not surviving (often only the hardier species such as hawthorn/blackthorn surviving), and many of the surviving trees having very stunted growth.

The planting of rough vegetation is another NFM option which should be explored as being suitable for Brant Fell Common. This could involve the planting of vegetation throughout the grassland and moors of Brant Fell Common, but could also involve planting within riparian zones. Rough vegetation will likely increase interception, evapotranspiration, localised permeability and infiltration, as well as elevate surface roughness which could intercept and interrupt surface and near-surface hydrological pathways. This may reduce flood risk if done in problematic areas and/or a considerably large scale. Planting riparian zones with rough vegetation may intercept rapid hydrological pathways before they reach the stream network, reducing flood risk, and likely improving water quality and soil retention. This rough vegetation may also provide additional ecosystem services, such as benefits to carbon capture, biodiversity, etc. If implemented, this rough vegetation may need protecting from grazing by livestock and wild fell ponies, possibly only temporarily while they become established, or if placed in 'hard-to graze' areas. It was noted that there is already a significant amount of dense, rough vegetation on Brant Fell – so such an NFM/WWNP feature is feasible for considerable sections of the area.

Grazing practices could also be modified on Brant Fell to change how the area responds hydrologically. This could involve changing stocking densities, changing grazing strategies e.g., mob grazing, or restricting livestock from accessing certain areas for certain periods. This may reduce the compaction on the soil surface caused by trampling and increase the amount of rough vegetation and trees due to lower grazing pressures, increasing soil infiltration and permeability, and hence reducing flood risk and water quality issues associated with rapid surface and near-surface drainage pathways. This may also have co-benefits to biodiversity and carbon capture due to reduced grazing of certain species, to water quality due to reduced faecal inputs, and to soil erosion rates due to reduced animal traffic.

Channel, riparian zone and floodplain management may be a valid NFM/WWNP option for various sections of Brant Fell Common. This could come in many forms, such as channel fencing, riparian and floodplain planting (mentioned above), leaky barriers, channel reprofiling etc. Channel fencing (possibly achieved in some places, by the repair and/or reinstatment of drystone walls) could aid flood risk and water quality by restricting livestock and wildlife access to certain sections of streams. This will reduce grazing pressure on the local vegetation, possibly increasing tree/vegetation coverage and the amount of rough vegetation and the associated reductions in flood risk, as well as improving water quality by reducing direct faecal inputs.

Leaky barriers may be a valid option on smaller streams within Brant Fell Common. Leaky barriers can pool water behind them during flood periods, if upstream space is available, and/or mechanically slow water reaching downstream locations, potentially reducing flood risk, whilst allowing water and fish to pass unhindered during non-flood conditions. Leaky barriers may therefore encourage water out-of-bank in certain locations, further reducing flood risk. The risk of barrier failure will be crucial to assess around Brant Fell Common due to the steep gradients and likely high water velocities (and possibly volumes) involved.

Channel reprofiling and remeandering is an additional channel measure that could be suitable for Brant Fell Common. This could be used to reduce channel-side slope gradients which could reduce the speed of hydrological inputs, as well as to encourage floodplain reconnection and out-of-bank flow in certain locations. It is very likely that the numerous channel, riparian zone and floodplain management interventions mentioned above can be combined and used concurrently.

Generic moorland management techniques could fall within an NFM/WWNP framework to provide various ecosystem services, including reducing flood risk. Grip (shallow open drain) and gully blocking could reduce flood risk and improve water quality by trapping water, sediment and pollutants behind them. Several materials of various permeabilities can be used for this such as wood, heather, stone, peat, recycled plastic, etc. This has benefits to flood risk management and water quality, but also biodiversity, carbon capture etc. The creation of localised wetlands which have some storage potential for flood events may also be useful, and can benefit flood risk by attenuating flood-peaks due to the storage element, water quality by allowing pollutants to be captured and degraded, and biodiversity due to habitat creation, etc.

3 Stakeholder Engagement

Early stakeholder engagement is vitally important to the success of the scheme given the large number of stakeholders the likelihood of some potentially conflicting views. The finding from the desk- based analysis were used to inform the engagement events. The main purpose of these events was to introduce the project and collect observations and perceived constraints from commoners and graziers. This helps to shape our understanding of local concerns, and how the implementation of a range of NFM could help to address them.

3.1 Co-Design Workshop

The workshop included open discussions and brainstorming activities to allow commoners and graziers to share their ideas, objectives and aspirations for the land. This included discussions with graziers on grazing patterns, hefts and feasible options for NFM measures. Round-table activities with maps and infographics were used to stimulate small group discussions, combined with whole group plenary sessions in order to develop include a draft longlist of potential NFM opportunities, a list of constraints and the identification of any priority spatial areas for NFM implementation were co-created. These were taken forward and used together with technical findings to inform the development of NFM opportunities and recommendations.

Specific mention from a local grazier around the condition of the channel and culverts on Crossdale Beck towards the railway embankment. This section of the watercourse has not been analysed in this project, however it is recommended to review given the local concern.

Figure 3-1: Co Design Workshop group discussions at Sedbergh Peoples Hall.

3.2 Prioritisation Workshop

Following the initial modelling (Section 5 - Natural Flood Management Hydraulic Modelling). A further engagement workshop was held to discuss the initial project findings and prioritise NFM options in collaboration with stakeholders. The event offered the opportunity to keep stakeholders appraised of project progress and to collect opinions on emerging project findings. The event also allowed the identification of any major barriers in terms of lack of support for particular options and conversations around NFM implementation and maintenance requirements.

Although there was in general support for the aspirational long list NFM scenario, the results from the meeting outlined the priority for footpath management options and in particular where this could be combined with local wetland creation for additional storage.

Some of the measures are to be removed from the long list for their limited support, including some sections of woodland planting (implications through Commons Act 2006, Section 38) and leaky barriers.

4 Site Walkover Assessment

Following the Desk Based Analysis and Co-Design Workshop, JBA NFM specialists' ground truthed the potential locations across Brant Fell Common in March 2023. These observations have been collated in Appendix C (Brant Fell NFM Site Walkover Analysis Technical Note).

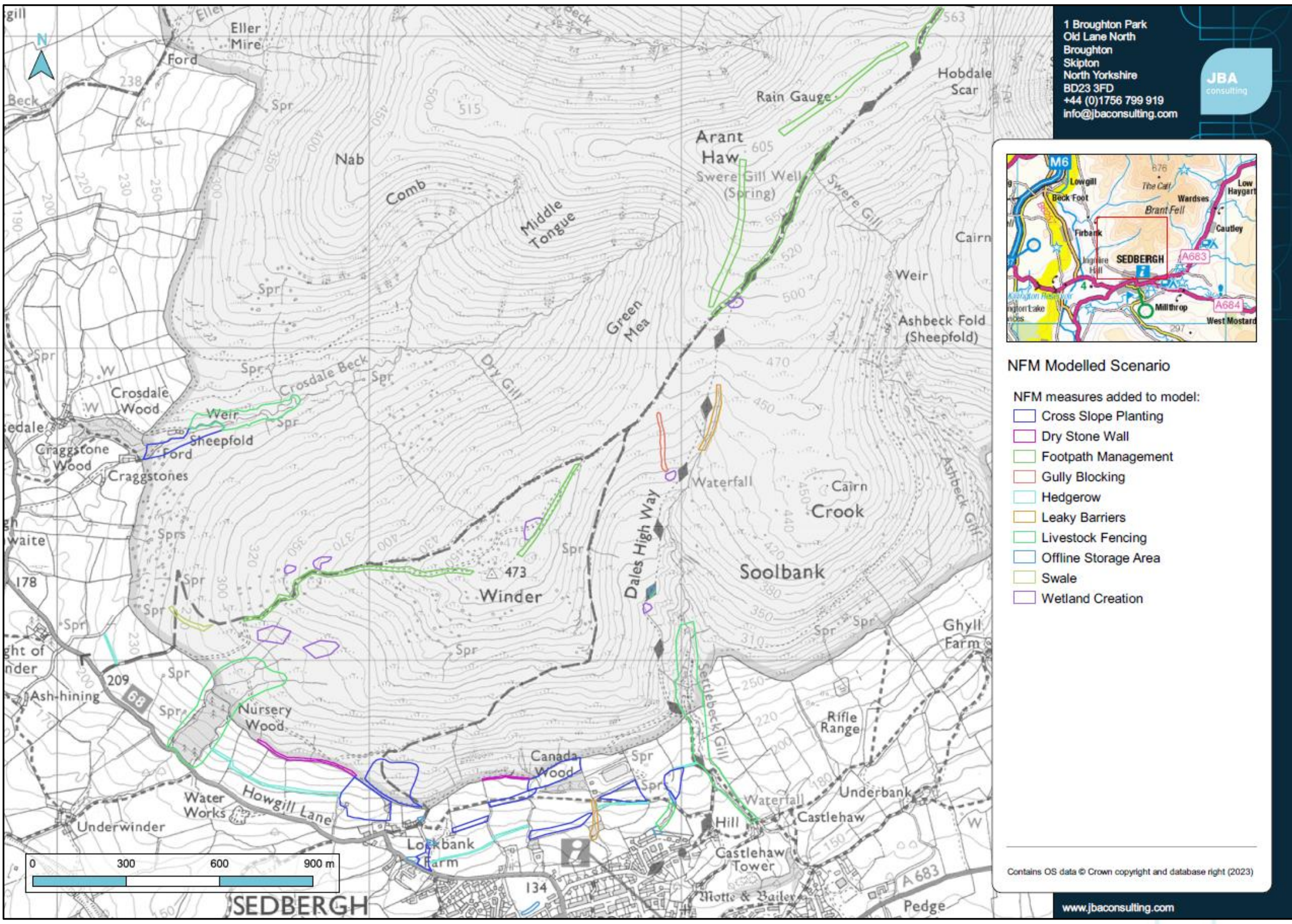

Figure 4-1: Potential Long List (Aspirational) NFM Options as per site walkover and workshop priorities.

5 Natural Flood Management Hydraulic Modelling

A JFlow® 2D rainfall runoff hydraulic model has been developed for the Brant Fell common land with particular focus on the Settlebeck Gill, Ashbeck Gill, and Eller Mire Beck given these have the largest number of high-risk receptors (those with a max flood depth exceeding 5cm), and therefore pose the greatest risk of causing significant flooding to properties. Settlebeck Gill flows directly into Sedbergh, with Ashbeck Gill flowing joining the River Rawthey just to the east and slightly upstream of Sedbergh (Section 2).

The surface water flood model will be used to produce outputs for the in-channel, floodplain and wider landscape environment, as defined by a continuous 1m resolution Digital Terrain Model (DTM) of the entire Settlebeck Gill, Ashbeck Gill, and Eller Mire Beck catchments. All the sub catchments within the domain will be explored for potential NFM interventions.

The FEH13 DDF rainfall model will be used within ReFH2 (Appendix A - Hydrology Technical Note) to determine appropriate total (i.e. before losses) design rainfall based on the 20%, 3.3%, 1% AEP. This will be directly applied across the whole catchment as total catchment (lumped) average rainfall. JFlow® adjusts the total rainfall to calculate the effective (net) rainfall which is then added to the model (Appendix B - JFlow® Technical Note).

5.1 Baseline JFlow® hydrographs

Analysis of the JFlow® hydrographs from the 5-year and 30-year return period events at the Canada Wood flume from the JFlow® monitoring lines shows a more similar shape to observed event 3 (although admittedly different timings and scales) than the ReFH hydrographs. The JFlow® hydrographs compared to other observed events also show very broadly similar hydrograph shapes, although the observed events contain substantial degrees of noise and disinformation as mentioned above.

Comparison of JFlow® hydrographs with ReFH hydrographs for the 30-year return period event shows a relatively similar peak discharge, although the response within JFlow® appears to be notably flashier. There is also a substantially higher total volume of water associated with the ReFH hydrograph than the JFlow® hydrograph for the 30-year return period event.

Comparison of JFlow® hydrographs with ReFH hydrographs for the 5-year return period event shows ReFH to have a higher peak discharge of approximately 50% more than JFlow, although the response within JFlow® appears to be notably flashier. There is a substantially higher total volume of water associated with the ReFH hydrograph than the JFlow® hydrograph in a similar sense to the 30-year ReFH values. The peak discharge associated with the 5-year return period event of JFlow® is much more aligned with the 2-year return period event for ReFH.

Comparison of JFlow® hydrographs with ReFH hydrographs for the 100-year return period event reveal very similar peak discharge estimates, although the response within JFlow® appears to be notably flashier. There is a substantially higher total volume of water associated with the ReFH hydrograph than the JFlow® hydrograph in a similar sense to the 5-year and 30-year ReFH values.

5.2 Baseline JFlow® depth grids

Analysis of the JFlow® max depth grids demonstrates that the RP-5, RP-30 and RP-100 events show very similar outputs. All maximum flood depth grids concur that the vast majority of Sedbergh does not become inundated during such events. The RP-5 max depth grids shows some flooding in Sedbergh on Loftus Hill, as well as at the Woodside Avenue and Maple Close area, Bainbridge Road, Winfield Road, Sedbergh medical centre, Guldrey Lane and Guldrey Fold, around Sedbergh School, Maryfell, Queens Drive, Castlegarth, and the area where the A683 joins the A684. The RP-30 and RP-100 events agree essentially entirely with these areas, with slightly increased flood extents and depths, respectively. RP-5, RP-30 and RP-100 max depth grids align very strongly with the receptors at risk mentioned above, as well as with the Section 19 flood investigation report, also mentioned above.

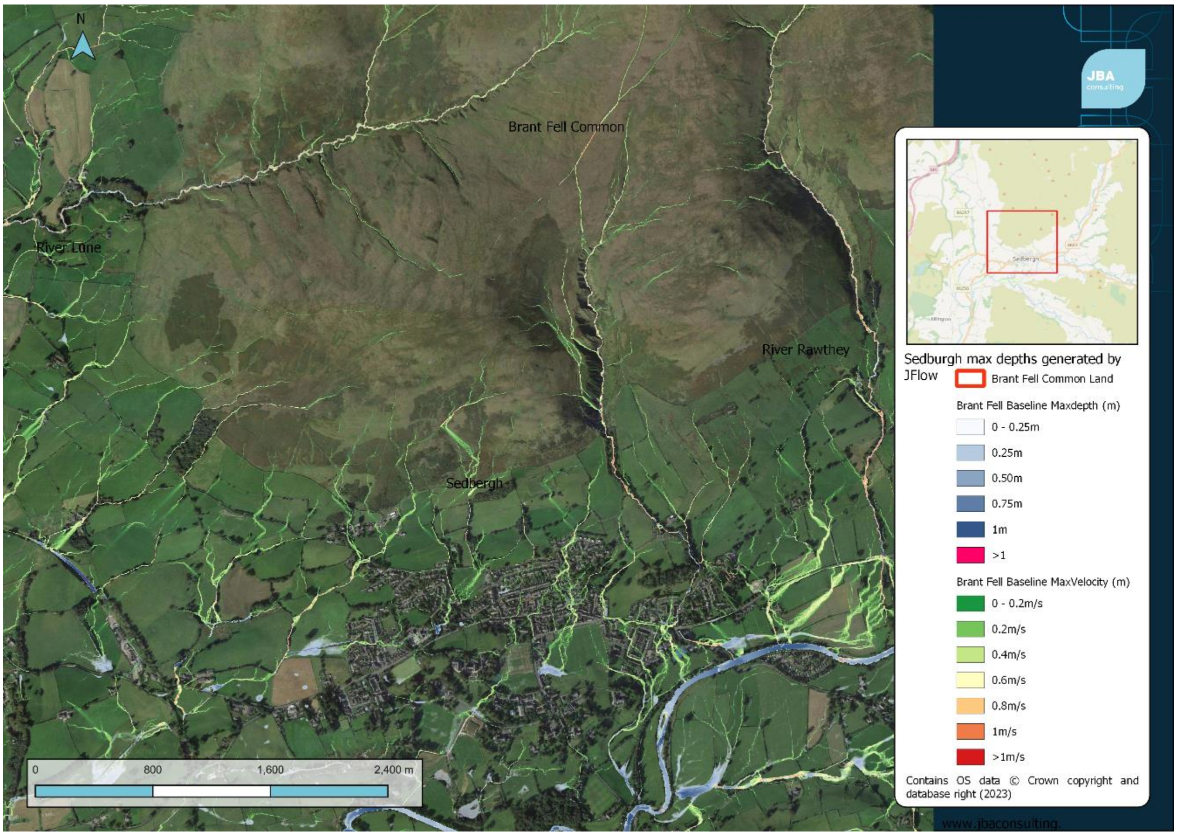

Figure 5-1: The max flood depth grid for the 5-year return period event around Sedbergh.

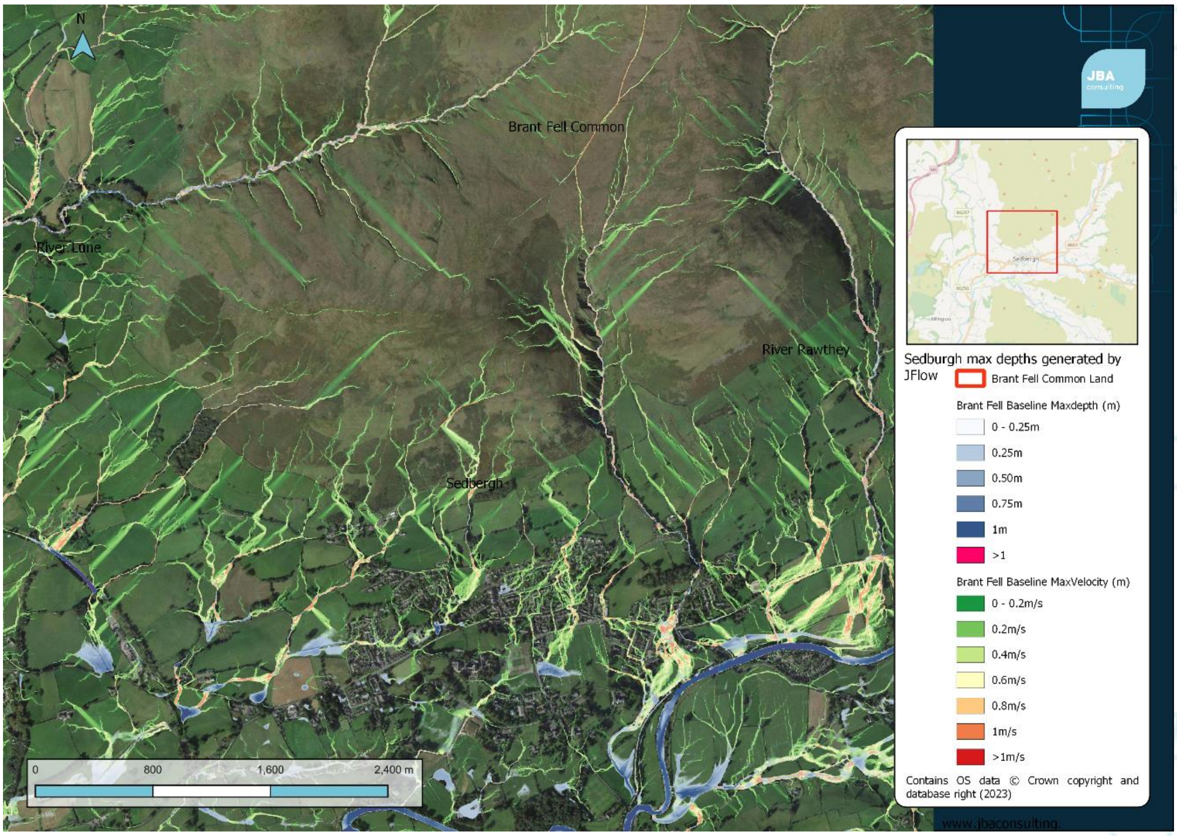

Figure 5-2: The max flood depth grid for the 100-year return period event around Sedbergh.

5.3 NFM Scenario (Long List)

The NFM Long List opportunities were compared against the baseline (pre-NFM interventions) results through the use of designated flow monitoring lines. Flow monitoring lines can be used to 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 each modelled flood event.

This type of modelling enables relative changes to peak flood flows and timing of the peak flow resulting from the introduction of NFM measures in the catchment to be predicted and analysed. The results from this scenario are best used in a comparative way (e.g. baseline condition versus changed condition) rather than using the absolute discharge values.

It should be noted that on the resulting flood maps any flood water depths of below 0.05m have been excluded from the dataset used to highlight the main flow pathways.

The maximum NFM scenarios show that the max depth grids for the 5-year return-period event reveal significant reductions in maximum flood depth throughout Sedbergh in comparison the baseline (Table 3; Figure 5-3). Under the maximum NFM scenario there is still some flooding around Maple Close, Woodside Avenue, Sedbergh medical centre, and the SPAR, although this is somewhat reduced. There remains a small amount of flooding to the East of Loftus Hill, as well as a minor amount of flooding on Bainbridge road, and very minor flooding on Queens Drive and at Sedbergh School, although all of these locations are somewhat reduced in their flood extents and depths in comparison to the baseline scenario. The remaining areas of Sedbergh are no longer inundated under this maximum NFM scenario. There are notable reductions in maximum flooding depth between the two scenario in the following locations: the Maple Close, Woodside Avenue, Sedbergh Medical Centre, Guldrey Lane area; the Bainbridge Road, Winfield Road, Joss Lane, Fairholme and Lowlangstaffe area; the Maryfell, Sedbergh Primary School, Castlegarth and A6683/A684 area; the Loftus Hill area; and the Queens Drive area. The largest notable reductions in extent of flooding and maximum flood depth between the baseline and maximum NFM scenario for the 5-year return period event are at the Guldrey Lane and Guldrey Fold area, Sedbergh medical centre and Sedbergh SPAR, Woodside Avenue, Maple Close, Winfield Road, and to the East of Loftus Hill.

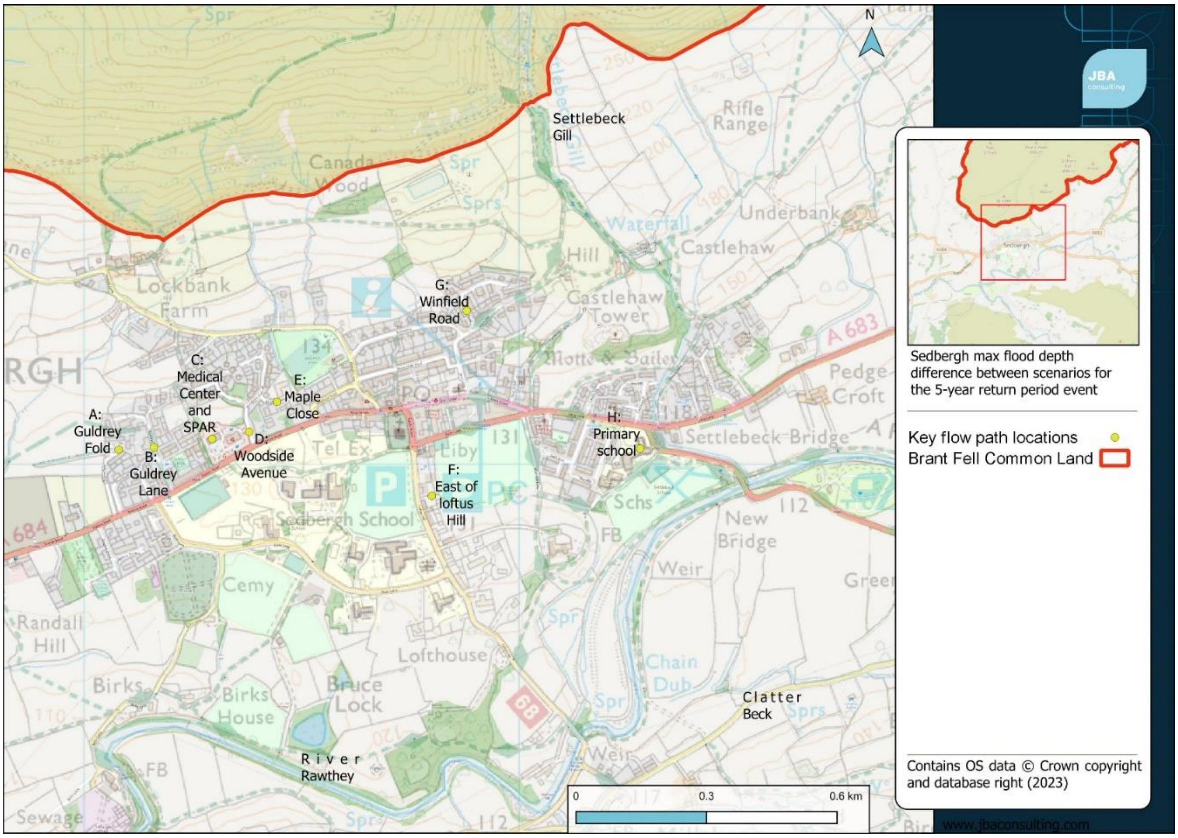

Figure 5-3: The locations of key flow paths throughout Sedbergh.

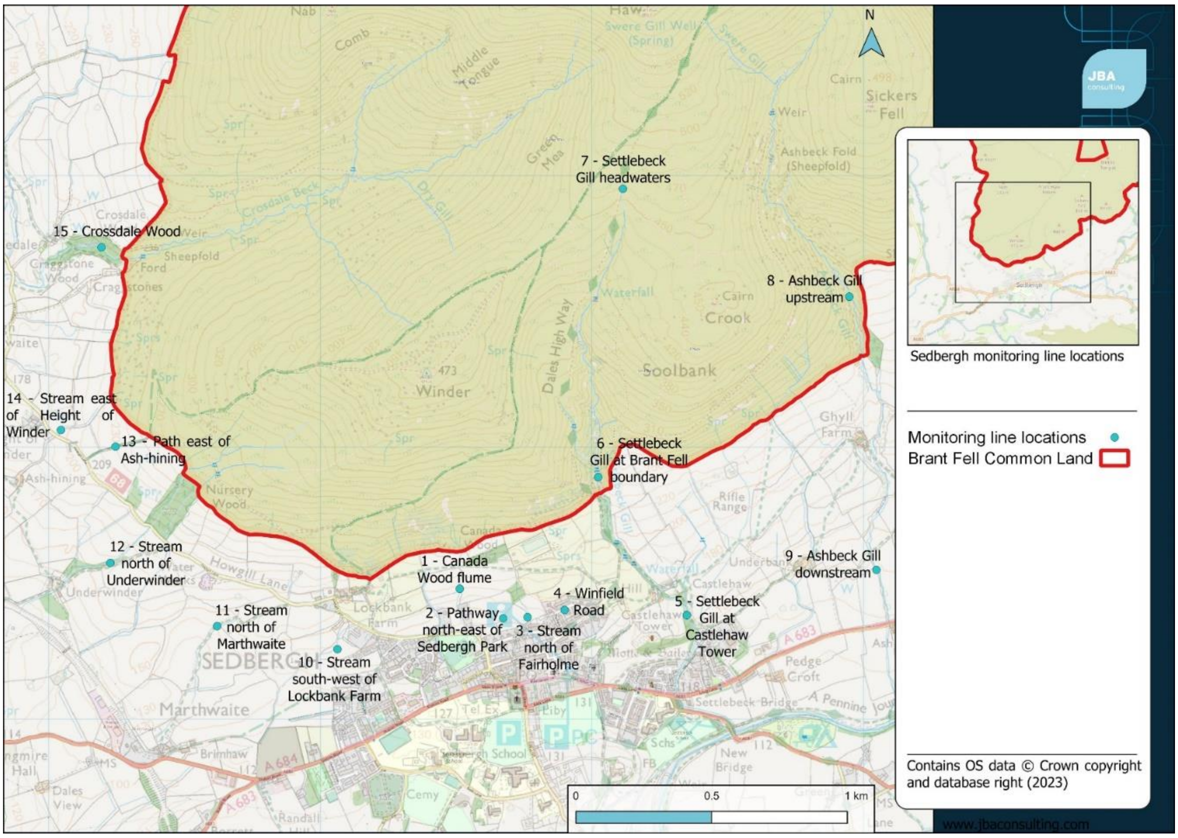

Figure 5-4: The monitoring line locations located throughout Sedbergh and the surrounding areas.

Table 3: The hydrograph peaks and time to peak for baseline and the maximum NFM scenarios for the 1-in-5-year event.

Location	Baseline hydrograph peak (m³/s)	NFM MAX hydrograph peak (m³/s)	Absolute difference in hydrograph peak (m³/s)	Percentage difference in hydrograph peak (%)	Hydrograph peak delay (mins)
1 – Canada Wood flume	0.16	0.15	-0.007	4.6%	5
2 – Pathway north-east of Sedbergh park	0.02	0.02	0.00	0.0%	-5
3 – Stream north of Fairholme	0.08	0.15	0.07	-86.5%*	20
4 – Winfield Road	0.12	0.01	-0.10	87%	-10
5 – Settlebeck Gill at Castlehaw Tower	0.75	0.69	-0.06	8.7%	-5

6 – Settlebeck Gill at Brant Fell Boundary	0.61	0.59	-0.01	1.8%	-5
7 – Settlebeck Gill Headwaters	0.04	0.04	-0.002	5.3%	0
8 – Ashbeck Gill upstream	0.74	0.76	0.02	-2.5%	0
9 – Ashbeck Gill downstream	0.99	0.97	-0.02	2.2%	5
10 – Stream south-west of Lockbank Farm	0.26	0.24	-0.02	6.6%	10
11 – Stream north of Marthwaite	0.15	0.12	-0.03	19.1%	5
12 – Stream of Underwinder	0.11	0.10	-0.01	8.8%	0
13 – Path east of Ash-hining	0.02	0.01	-0.008	44%	-20
14 – Stream east of Height of Winder	0.13	0.12	-0.004	3.0%	0
15 – Crossdale Wood	1.25	1.25	0.00	0%	0

*Overall decrease with Monitoring Line 4 included.

Table 4: The maximum flood depths for locations throughout Sedbergh for the baseline and maximum NFM scenario, and the difference between them for the 5-year return period event.

Location	Max flood depth in meters (baseline)	Max flood depth in metres (NFM)	Difference in max flood depth in metres	Percentage Difference
A – Guldrey Fold	0.55	0.54	-0.01	-2%
B – Guldrey Lane	0.16	0.16	-0.00	0%
C – Sedbergh SPAR and medical centre	0.20	0.20	-0.00	0%
D – Woodside Avenue	0.93	0.92	-0.01	-1%
E – Maple Close	0.33	0.30	-0.03	-9%
F – East of Loftus Hill	0.40	0.30	-0.10	-25%
G – Winfield Road	0.06	0.02	-0.04	-66%
H – Sedbergh Primary School	0.14	0.13	-0.01	-7%

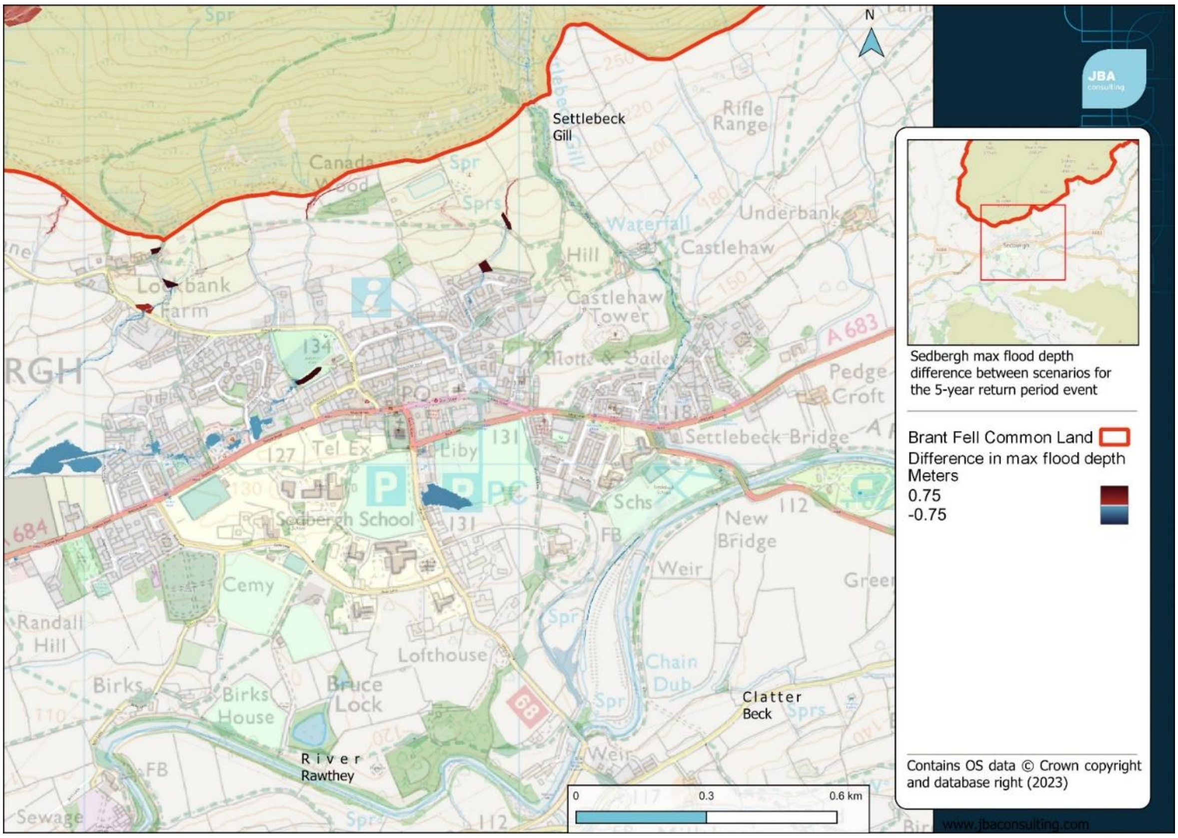

Figure 5-5: The difference in maximum flood depth between the baseline and maximum NFM scenario, for the 5-year RP event.

The maximum NFM scenarios show that the max depth grids for the 30-year return-period event reveal significant reductions in maximum flood depth throughout Sedbergh in comparison to the baseline (Table 4). The 30-year return-period event with the NFM scenario reveals identical flooding locations as the 5-year return-period event with the NFM scenario, although flooding extents are increased, and a small amount of flooding is now present on Guldrey Lane, Sedbergh police station, Castlegarth, and on the A683.

When comparing the 30-year return period event between the baseline scenario and the maximum NFM scenario, flood extents are considerably reduced throughout Sedbergh under the maximum NFM scenario (Table 4). The largest notable reductions in extent of flooding and maximum flood depth between the baseline and maximum NFM scenario for the 30-year return period event are at the Guldrey Lane and Guldrey Fold area, Sedbergh medical centre and Sedbergh SPAR, Woodside Avenue, Maple Close, Winfield Road, and to the East of Loftus Hill.

Table 5: The hydrograph peaks and time to peak for baseline and the maximum NFM scenarios for the 1-in-30-year event.

Location	Baseline hydrograph peak (m³/s)	NFM MAX hydrograph peak (m³/s)	Absolute difference in hydrograph peak (m³/s)	Percentage difference in hydrograph peak (%)	Hydrograph peak delay (mins)

1 – Canada Wood flume	0.38	0.37	0.00	-1%	0
2 – Pathway north-east of Sedbergh park	0.04	0.09	0.05	-126%	5
3 – Stream north of Fairholme	0.15	0.03	0.12	78.5%	0
4 – Winfield Road	0.26	0.03	-0.23	90.5%	-5
5 – Settlebeck Gill at Castlehaw Tower	1.74	1.30	-0.44	25%	-5
6 – Settlebeck Gill at Brant Fell Boundary	1.42	1.00	-0.42	31%	0
7 – Settlebeck Gill Headwaters	0.08	0.08	0.00	1%	0
8 – Ashbeck Gill upstream	1.78	1.71	-0.07	4.5%	5
9 – Ashbeck Gill downstream	2.30	2.29	-0.01	0.5%	0
10 – Stream south-west of Lockbank Farm	0.68	0.17	-0.51	75%	-15
11 – Stream north of Marthwaite	0.34	0.34	0.00	-2.5	0
12 – Stream of Underwinder	0.56	0.57	-0.07	25.5%	-20
13 – Path east of Ash-hining	0.08	0.02	-0.03	54.5%	-10
14 – Stream east of Height of Winder	0.24	0.24	0.00	1.5%	5
15 – Crossdale Wood	2.97	2.95	-0.02	0.5%	5

The 100-year return-period event with the NFM scenario reveals identical flooding locations as the 30-year return-period event with the NFM scenario, although flooding extents are increased. Notable increases in flood depths between the 30-year and 100-year NFM scenarios are at Queens Drive and Guldrey Lane (both still very minor), Bainbridge Road, Castlegarth, the A683, and to the East of Loftus Hill. New areas of notable flooding include Long Lane.

When comparing the 100-year return period event between the baseline scenario and the maximum NFM scenario (Table 5), flood extents and maximum flood depths are considerably reduced throughout Sedbergh under the maximum NFM scenario. The largest notable reductions in extent of flooding and maximum flood depth between the baseline and maximum NFM scenario for the 100-year return period event are at the Guldrey Lane and Guldrey Fold area, Sedbergh medical centre and Sedbergh SPAR, Woodside Avenue, Maple Close, Winfield Road, to the East of Loftus Hill, Castlegarth, and at Sedbergh primary school.

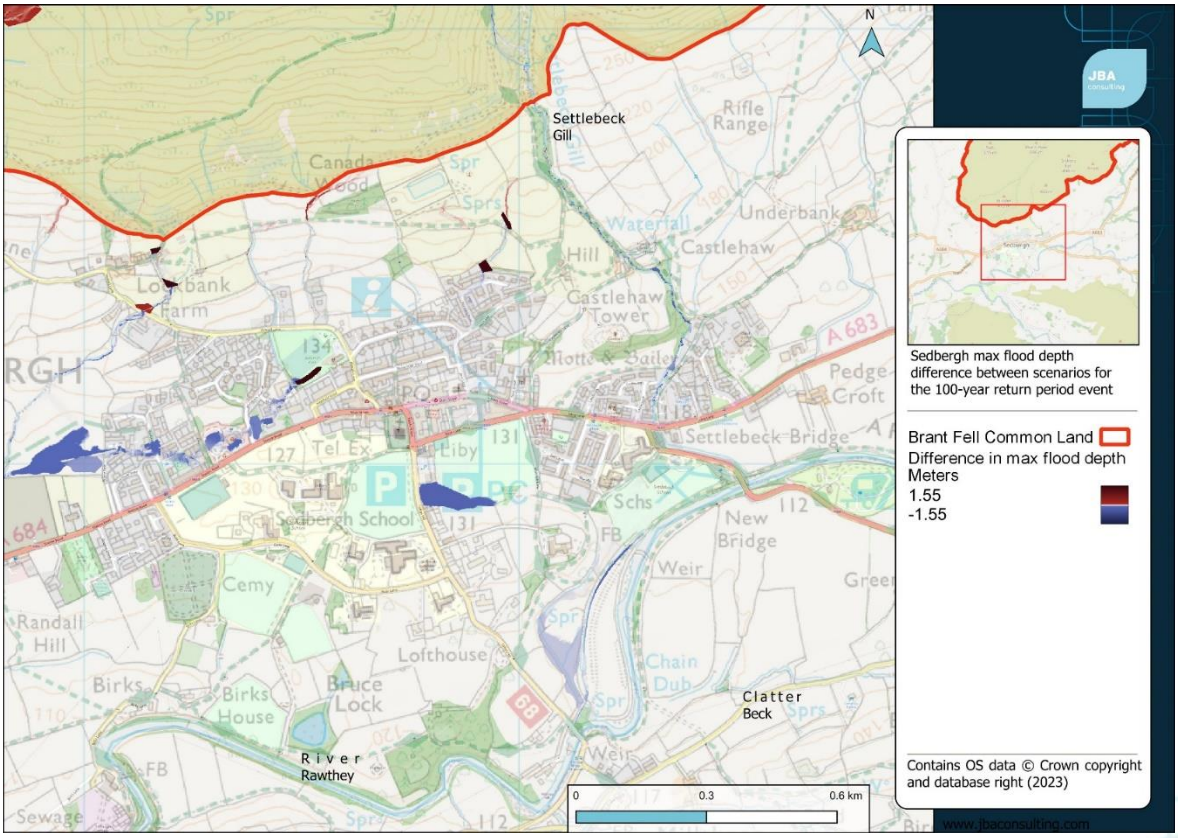

Figure 5-6: The difference in maximum flood depth between the baseline and maximum NFM scenario, for the 100 year RP event.

Table 6: The hydrograph peaks and time to peak for baseline and the maximum NFM scenarios for the 1-in-100-year event.

Location	Baseline hydrograph peak (m^3/s)	NFM MAX hydrograph peak (m^3/s)	Absolute difference in hydrograph peak (m^3/s)	Percentage difference in hydrograph peak (%)	Hydrograph peak delay (mins)
1 – Canada Wood flume	0.61	0.52	-0.06	9.5%	-10
2 – Pathway north-east of Sedbergh park	0.05	0.05	0.00	-0.5	-5
3 – Stream north of Fairholme	0.21	0.48	0.27	-125	10
4 – Winfield Road	0.43	0.08	-0.34	81%	10

5 – Settlebeck Gill at Castlehaw Tower	2.93	2.70	-0.20	7.5%	0
6 – Settlebeck Gill at Brant Fell Boundary	2.42	2.17	-0.25	10.5%	5
7 – Settlebeck Gill Headwaters	0.14	0.13	-0.02	10.5%	0
8 – Ashbeck Gill upstream	2.81	2.80	-0.01	0.5%	0
9 – Ashbeck Gill downstream	3.72	3.70	-0.01	0.5%	5
10 – Stream south-west of Lockbank Farm	0.95	0.89	-0.05	5.5%	0
11 – Stream north of Marthwaite	0.57	0.56	-0.01	2.0%	0
12 – Stream of Underwinder	0.56	0.57	0.01	-2.5	10
13 – Path east of Ash-hining	0.08	0.03	-0.05	58%	5
14 – Stream east of Height of Winder	0.37	0.39	0.02	-5.5	10
15 – Crossdale Wood	5.02	5.02	0.00	-0.2	0

Table 7: The maximum flood depths for locations throughout Sedbergh for the baseline and maximum NFM scenarios, and the difference between them for the 100-year return period event.

Location	Max flood depth in meters (baseline)	Max flood depth in metres (NFM)	Difference in max flood depth in metres	Percentage Difference
A – Guldrey Fold	0.78	0.77	-0.01	-1.2%
B – Guldrey Lane	0.16	0.16	-0.00	0%
C – Sedbergh SPAR and medical centre	0.23	0.22	-0.01	-4%
D – Woodside Avenue	0.16	0.08	-0.08	-50%
E – Maple Close	1.18	1.17	-0.07	-1%
F – East of Loftus Hill	0.74	0.56	-0.19	-24%
G – Winfield Road	0.10	0.04	-0.06	-60%

H – Sedbergh Primary School	0.25	0.24	-0.02	-4%

5.1 NFM Scenario (Short List)

Following the Landowner Engagement (Section 3.2 - Prioritisation Workshop) the NFM short list has been prioritised on Footpath Management, Wetland Creation and Hedgerow Planting.

The NFM Short List opportunities were compared against the baseline (pre-NFM interventions) results through the use of designated flow monitoring lines as per the Long List analysis. This allows the baseline and post-change models to be compared for each modelled flood event.

Location	RP5 Peak Flow Reduction (%)	RP5 Delay (Minutes)	RP30 Peak Flow Reduction (%)	RP100 Peak Flow Reduction (%)	RP100 Delay (Minutes)
1 – Canada Wood flume	15%	15	8%	9%	-10
2 – Pathway north-east of Sedbergh park	0%	0	0%	0%	0
3 – Stream north of Fairholme	4.5%	20	2.5%	2%	0
4 – Winfield Road	0%	0	0.5%	2.5%	0
5 – Settlebeck Gill at Castlehaw Tower	8.5%	-10	2.5%	4%	0
6 – Settlebeck Gill at Brant Fell Boundary	7.5%	5	2.5%	5%	0
7 – Settlebeck Gill Headwaters	5.5%	0	7.5%	10.5%	0
8 – Ashbeck Gill upstream	0%	-5	4.5%	0%	0
9 – Ashbeck Gill downstream	0%	0	0%	0.5%	0
10 – Stream south-west of Lockbank Farm	3.5%	0	-1%	0%	0
11 – Stream north of Marthwaite	11%	5	4.5%	-1%	-5
12 – Stream of Underwinder	12%	-5	-3.5%	10.5%	10
13 – Path east of Ash-hining	44%	-20	54.5%	58.5%	-5
14 – Stream east of Height of Winder	3%	0	-1.5%	-5.5%	10

15 – Crossdale Wood	0%	0	0%	0%	0

5.2 Total Volume Reduction

Further Analysis on the Short List NFM Measures also show a total reduction in flow volume in some key locations on the rising limb and peak of the hydrograph. This is a significant benefit to the existing culverts under Sedbergh and the capacity to transfer flow through them without exceedance.

At Canada Wood the volume for the RP5 flood event has reduced by 5.5% and 6% for the RP100. On Settlebeck Gill a 6% reduction in total volume is shown for the RP5 and 4% for the RP100.

For the RP100 NFM Max total volume reduction at Canada Wood increases to 160m³ or 9%. It increases to 600m³ on Settlebeck which is equivalent to 7% reduction.

5.3 Sediment Risk

Within the JFlow2D Outputs Maximum Velocity has been compared against the baseline (pre-NFM interventions) results. Erosion of sediment across this location given the slope and quantity of flood water has significant implication on water quality and flood risk in Sedbergh. The majority of Sedbergh's watercourses are piped underground and the blockage of these pipes is a key flood risk implication.

The comparisons show that even the decreased short listed NFM scenario reduces the maximum velocity in these watercourses. This therefore reduces the risk of erosion and sediment transportation towards the culverted watercourses. Further reduction of livestock poaching would also have significant benefits for reducing the sediment load.

Location	Baseline Max Velocity RP100 (m/s)	NFM SL Max Velocity RP100 (m/s)	Reduction (%)
1 – Canada Wood flume	3.18	3.12	2%
2 – Pathway north-east of Sedbergh park	0.82	0.80	2.5%
3 – Stream north of Fairholme	0.50	0.50	0%
4 – Winfield Road	0.93	0.90	3%
5 – Settlebeck Gill at Castlehaw Tower	3.04	2.97	2.5%
6 – Settlebeck Gill at Brant Fell Boundary	3.63	3.57	1.5%

5.4 Wildfire Risk

The NFM measure identified in this work will aid further wetting of the moorland on Brant Fell and help hold water in the landscape. This could significantly aid wildfire risk on the moorland in drought conditions.

6 Implementation cost estimates

This section will discuss cost estimates for each the different NFM features proposed. Feature costs were obtained using the cost estimation for land use and run-off - summary of evidence report published by the Environment Agency (Pettit et al., 2015). The report includes cost estimates for different land and run-off management techniques, obtained from a number of UK based case studies. It should be noted that these costs are indicative, with the exact cost of feature implementation dependent upon site specific characteristics, with factors such as scale, stakeholder acceptance, together with physical and technical constraints, all known to impact upon implementation costs.

The costs used and the sources from which they were obtained are detailed in Table 8 below. The table includes an estimate of the total cost of each feature under the long listed NFM scenario. The total cost estimates shown represent the average (mean) of the upper and lower cost estimates, which were calculated by multiplying the lower and upper cost per unit/per given area by the total number of units/total area proposed for each feature type.

In addition to the construction costs the following additional costs have been assumed:

- Design and enabling costs – 5%
- Annual operation and maintenance costs – 0.5% discounted over the 100-year appraisal.
- Optimism Bias on total costs – 25%

Optimism Bias has been considered using a risk components assessment. Risks for NFM options are lower than standard FCERM projects due to the following aspects:

- Measures are implemented in the upper catchment with few site constraints.
- Measures can be implemented using volunteer organisations with lower costs.
- Options and approaches can attract multiple funding sources.
- Environmental impacts will be low or provide environmental opportunities.
- Landowner disputes may be applicable but can be mitigated through early engagement.
- Options are low risk in terms of design and implementation.
- Unit rates for certain aspects are well understood with little scope for significant cost increase.

Table 8: Indicative NFM Construction Costs (Long List)

Feature	Cost (£)	Original sources from which cost estimates were obtained	Total Area of Feature	Total Estimated Measure Cost (Average £)
Ponds/Runoff Attenuation Features	£15 per m^3 (Online storage)	Bellfields Farm, Staffordshire WT & Nafferton Farm (Pettit et al., 2015)[8]	2,861m^3 at 1m deep	42,915
Wetland Creation (Excavation of soil)	2.10-20 per m^3 (Excavation of soil)	Bellfields Farm, Staffordshire WT & Nafferton Farm (Pettit et al., 2015)	17,662m^3 at 1m deep	38,856

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[8] Pettit, A., Keating, K., Rose, S. (2015). Cost estimation for land use and runoff - summary of evidence. SC080039/R12, Environment Agency, Bristol, UK. [Online]. Available from: https://assets.publishing.service.gov.uk/media/6034eefdd3bf7f264e517436/Cost_estimation_for_land_use_and_run-off.pdf

		9		
Leaky barriers (where only reach length is known, count has been estimated using 20m spacing per barrier)	50-600 per barrier – mean value 315 per barrier	Quinn et al., (2013)[10]	540m = 27 barriers at 20m spacing.	8,505
Hedgerow planting and fencing	22.97/m 8.00/m	Countryside Stewardship Mid Tier, Higher Tier and Capital Grant 2021	1,136m	35,188
Riparian Buffer – Fencing with natural recovery	8.00/m for fencing both sides of buffer	Somerset County Council, (N.D) [11]	3,579m	28,632
Woodland planting	2500-5200 per hectare	Nisbet & Thomas (2008) [12]	106,000m^2 / 10.6ha	42,400
Swale	2.10-20 per m^3 (Excavation of soil)	Bellfields Farm, Staffordshire WT & Nafferton Farm (Pettit et al., 2015)	900m^3 at 0.5m deep	1,935
Dry Stone Wall	£35/m	Countryside Stewardship Mid Tier, Higher Tier and Capital Grant 2021	300m	10,500
Footpath Management	£750.26 per drain.	Countryside Stewardship Mid Tier, Higher Tier and Capital Grant 2021	3776m = 76 barriers at 50m spacing.	57,019
Long List Sub Total				265,950
Design and enabling costs			5%	13,298
Annual operation and maintenance costs			0.5%	1,330
Long List Sub Total				280,578
Optimism Bias on total costs			25%	70,145
Long List Total				350,723
Short List Total (Green and Yellow)				236,775
Short List Total (Green)				189,152

7 Summary/Recommendations

The land surface of Brant Fell Common is generally pretty smooth in character with virtually no tree cover (97% of SFI survey locations contained no tree or scrub cover), although there are notable areas of rough vegetation (incl. bracken) in places. The area suffers from landslips, with recent landslips damaging some local archaeology.

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[9] Pettit, A., Keating, K., Rose, S. (2015). Cost estimation for land use and runoff - summary of evidence. SC080039/R12, Environment Agency, Bristol, UK. [Online]. Available from: https://assets.publishing.service.gov.uk/media/6034eefdd3bf7f264e517436/Cost_estimation_for_land_use_and_run-off.pdf

[10] Quinn, P., O'Donnell, G., Nicholson, A., Wilkinson, M., Owen, G., Jonczyk, J., Barber, N., Hardwick, M., Davies, G. (2013). NFM RAF Report - Potential Use of Runoff Attenuation Features in Small Rural Catchments for Flood Mitigation. Newcastle University Environment Agency.

[11] Somerset County Council, (N.D). Final Report. Woodland and Flood Management [provided by Stephen Dury].

[12] Nisbet, T.R., Thomas, H. (2008). Restoring Floodplain Woodland for Flood Alleviation. Final Report. Defra FCERM Innovation Fund Project SLD2316. London: Department for Environment, Food and Rural Affairs.

There are also issues locally with compacted and eroded walking paths and tracks. This was evident at the time of the site walkover, with the main footpaths acting as surface flow routes across the common.

This lack of tree cover and absence of extensive rough vegetation in places may reduce surface roughness, likely resulting in surface and near-surface hydrological pathways which are less likely to infiltrate into the ground, causing rapid hydrological responses and elevated flood risk.

Wider desk understanding of the catchment highlights the area is important for bird and squirrel species. Brant Fell Common has medium priority issues for phosphate issues, faecal indicator organism issues, and for countryside stewardship water quality. Brant Fell Common also has high priority areas for flood risk and woodland water quality.

Across this project, local stakeholder engagement has been undertaken with the active graziers of the common. This was to capture key local understanding and constraints. Although there was in general support for the aspiration long list NFM scenario. The results from the engagement outlined the priority for footpath management options and in particular where this could be combined with wetland creation for additional local flood storage. Some of the measures were removed from the long list for their limited support, including some sections of woodland planting and leaky barriers.

A JFlow® 2D rainfall runoff hydraulic model has been developed for the Brant Fell common land with particular focus on the Settlebeck Gill, Ashbeck Gill, and Eller Mire Beck given these have the largest number of high-risk receptors (those with a max flood depth exceeding 5cm), and therefore pose the greatest risk of causing significant flooding to properties. The NFM simulations were compared back to the Baseline (pre NFM) scenario. This type of modelling enables relative changes to peak flood flows and timing of the peak flow resulting from the introduction of NFM measures in the catchment to be predicted and analysed. ***The results from this scenario are best used in a comparative way (e.g. baseline condition versus changed condition) rather than using the absolute discharge values.*** No modelling work has been undertaken on the known groundwater discharges or potential increased risk for greater infiltration from the NFM measures on Brant Fell. It is assumed any increased infiltration will transfer flow through the sub surface geology slower than the overland peak runoff and therefore benefit flood risk by increasing lag time as a minimum.

The NFM measure identified in this work will aid further wetting of the moorland on Brant Fell and help hold water in the landscape. This could significantly aid wildfire risk on the moorland in drought conditions.

The results showed that the NFM Long List simulations reduced peak flow across the catchment draining to Sedbergh. For the RP5 event the results showed reductions of 1-20% and delays to the peak of 0-20minutes. Similar results were shown for the RP30 event (0.5% - 30%), with a lower delay of 0-5 minutes. There were reduced results for the RP100 as expected with 0.5% -10% peak reduction and delay 0-10 minutes.

Similar results were shown for the revised NFM short list with reduced peak flow reductions given the total reduction of NFM measures in the catchment. Further Analysis on the Short List NFM Measures also show a total reduction in flow volume in some key locations on the rising limb and peak of the hydrograph. This is a significant benefit to the culverts under Sedbergh and the capacity to transfer flow through them.

Erosion of sediment across this location given the slope and quantity of flood water has significant implication on water quality and flood risk in Sedbergh. The majority of Sedbergh’s watercourses are culverted underground and the blockage of these culverts is a key flood risk implication. The comparisons show that even the decreased short listed NFM scenario reduces the maximum velocity in these watercourses. This therefore reduces the risk of erosion and sediment transportation towards the culverted watercourses. Further reduction of livestock poaching would also have significant benefits for reducing the sediment load.

7.1 Recommendations for Future Work

- Undertake consent applications for preferred short list of NFM measures given the simulated benefit and grazier agreement.
- Continue the valuable stakeholder engagement and branch out to local council/Environment Agency to combine plans for the area/funding sources.
- Detailed Design will likely be required for wetland design given the catchment conditions (slope/ground investigations).

A Hydrology Technical Note

A.1 Flume at Canada Wood

A FRPB style fibreglass flume is present adjacent to Canada Wood to the north of Sedbergh at latitude 54.326722 and longitude -2.5318484 (WGS 1984), and GB OS grid reference SD 65508 92480. This flume collects the stream to the west of Canada Wood which flows south directly towards the Recreational Ground and into Sedbergh, which flooded in December 2015. There is also a raingauge immediately adjacent to the flume to collect localised rainfall data.

The flume site is mostly surrounded by pastoral fields, as well as some sections of woodland such as Canada Wood. In the upper sections of the catchment there is moorland, and this also includes sections of Winder (a local hill peak). These upper sections of the catchment contain many steep gradients. The vast majority of the bedrock geology upstream of the flume within the catchment is Screes Gill Formation consisting of sandstone and argillaceous rocks. Surrounding the flume and in smaller sections of the catchment there is Coniston Group sandstone, siltstone and mudstone, and Coniston Group siltstone. There is largely no superficial geology within the catchment – connecting the surface to the bedrock geology. The soils surrounding the flume are freely draining slightly acid loamy soils. There is also some shallow very acid peaty soils over rock.

Upstream of the flume there are four woody debris dumps within the channel. These woody debris dumps are believed capable of capturing sediment, although the influence of these upon stormflow is less well established. It is known that the leaky barriers in this location have failed since their installation due to high flows down the channel.

Randomly selecting rainfall-runoff events showed that there was approximately a 62-minute lag time from peak rainfall from the flume raingauge to peak discharge within the flume – highlighting a relatively flashy response within the catchment. The flume and rainfall data additionally showed that there were multiple periods of misinformative data, i.e. when rainfall was observed and no clear hydrograph response was observed, and also periods of hydrological response in the absence of rainfall – underlining that there is spatially distributed rainfall within the catchment, and that the stream responds to an area much wider than purely the area immediately surrounding the flume. As a result, often the rainfall data and hydrograph data did not appear to be closely linked, and observing clearly defined hydrograph responses from clearly defined precipitation events was not always possible.

Figure 7-1: The Canada Wood flume to the North of Sedbergh.

Analysis of ten random rainfall-runoff events with clear hydrograph responses from the Canada Wood flume and rain-gauge, showed that the average lag time from peak rainfall to peak hydrograph response was 62 minutes (Table 9). Using ReFH, the lag time between peak rainfall and peak discharge is 42 minutes, corresponding relatively well with observed results, although is slightly flashier than observed.

Table 9: The event dates with the respective event duration, total event rainfall, peak water level, peak rainfall intensity, and lag time between peak rainfall intensity and peak water level.

Event	Event Date	Event duration (min)	Total event precipitation (mm)	Peak Water level (cm)	Peak precipitation intensity (mm 5 min -1)	Lag time between peaks (minutes)
1	5th Feb 22	330	22	9.23	2.2	50
2	20th Feb 22	375	25.8	18.75	2.4	165
3	9th May 22	260	5.6	58.05	0.4	90
4	30th April 22	710	9.2	4.85	0.2	20
5	6th July 22	30	0.6	30.08	0.4	10
6	23rd May 22	10	0.4	29.03	0.2	30
7	1st July 22	65	7	16.11	1.6	105

8	22nd May 22	105	4.6	26.06	0.6	-10
9	16th May 22	145	3.4	30.58	0.4	120
10	25th June 22	80	7	17.67	2.8	40
Arithmetic mean		211	8.56	24.04	1.12	62

Event duration was the time between the first and last observed 5-minute period recording precipitation during the event, with several consecutive 0mm precipitation periods denoting the end of the event. Total event precipitation was the summation of precipitation during the event period. Peak water level was the maximum height of water observed within the flume within the 5-minute period during the event, and peak precipitation was the maximum amount of precipitation observed within a 5-minute period during the storm event. The lag time was the difference in time between the peak water level, and the peak precipitation intensity. Negative lag times indicate that the precipitation intensity peaked after the hydrograph.

A.2 ReFH2

A ReFH2 model was created with baseline parameters for 2, 5, 10, 20, 30, 50, 60, 75, 100, 200 and 1000-year return period events (hydrographs given below). The ReFH 2 analysis and subsequent hydrographs were updated by increasing the lag time from 42-minutes to 62-minutes, an increase of approximately 50%, to be more aligned with observed average lag times from peak precipitation to peak discharge, although the large variation in lag times (-10 minutes to 165 minutes) for each individual event was noted (Table 9). The 62-minute lag-time is most similar to observed events 1 and 10.

Results from lag analysis have been used as the arithmetic average LAG values for the catchment.

$$Tp(0)_{Obs} = 0.879 LAG^{0.951}$$

LAG = 62/60 = 1.033

TP Estimate: 0.879 * (1.033 ^ 0.851) = 0.904

The alternative (unused in this case) method for calculating TP is given below.

$$Tp(0)_{CDs} = 4.27 DPSBAR^{-0.35} PROPWET^{-0.8} DPLBAR^{0.54} (1 + URBEXT)^{-5.77} (2.10)$$

Tp(0)= 4.270*(218.1^-0.35)*(0.71^-0.80)*(0.86^0.54)*((1+0)^-5.77)

Tp(0) = 0.786

Within the ReFH2 model, the TP was changed from the baseline of 1, to 0.904 to match observed results. The ReFH2 model states that values below 1 should be used with caution.

Using the recommended formula that calculates the estimated critical duration from Tp and SAAR gave a value of 2.16 hours. The time to peak was updated from the baseline of 2 hours 18 minutes - 2.3 (hrs), to 2 hours 9 minutes - 2.15 (hrs), for a winter storm, accordingly.

$$D = Tp\ (1 + \frac{SAAR}{1000})$$

D = 0.904(1 + 1390/1000) = 2.16

Note: *This table is for recording the ReFH2 results from catchment descriptor for a lumped catchment.*

Table 10: The flood peak for 2, 5, 10, 20, 30, 50, 60, 75, 100, 200 and 1000 year return period events from ReFH2.

Site code	Flood peak (m^3/s) for the following return periods (in years)										
	2	5	10	20	30	50	60	75	100	200	1000
Brant Fell	0.22	0.30	0.36	0.42	0.46	0.51	0.53	0.56	0.59	0.68	1.04

The hydrographs generated through the ReFH2 method are considerably less noisy than the observed data series, as should be expected from simulated as opposed to actual data. Given the misinformative information associated with the observed precipitation and discharge – the hydrographs from the ReFH2 method display a clearly defined rainfall-runoff response which is seldom observed with the actual observations. The hydrographs shapes from both ReFH2 and observed hydrographs appear broadly similar given the noise and disinformation mentioned, although certain observed events show a flashier hydrograph response than the ReFH simulated response e.g., Events 1, 2, 3 and 9.

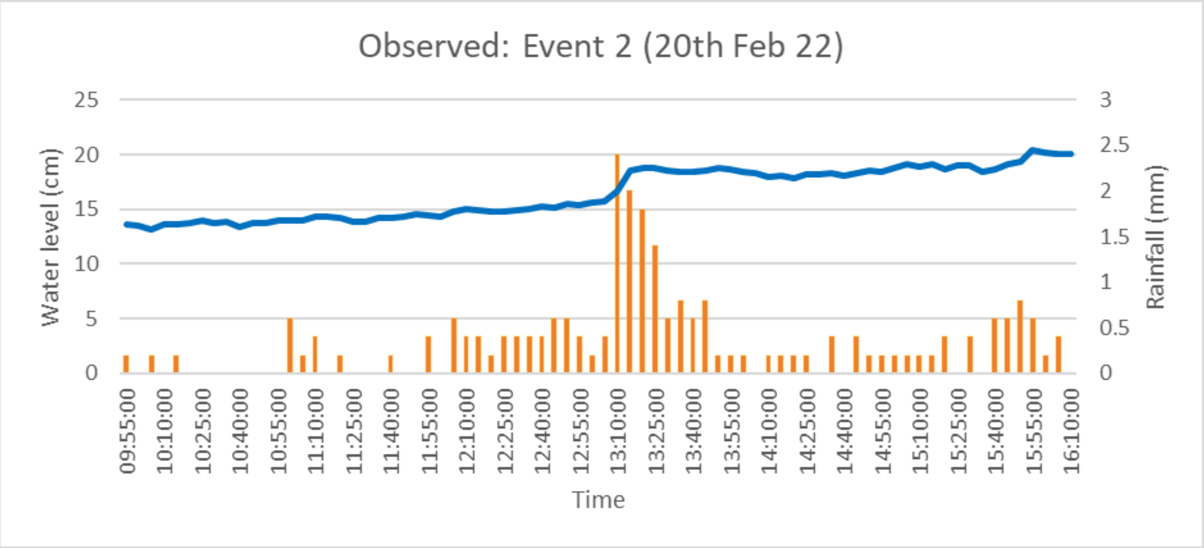


Figure 7-2: Observed rainfall and water level for event number 2 for the Canada Wood flume.

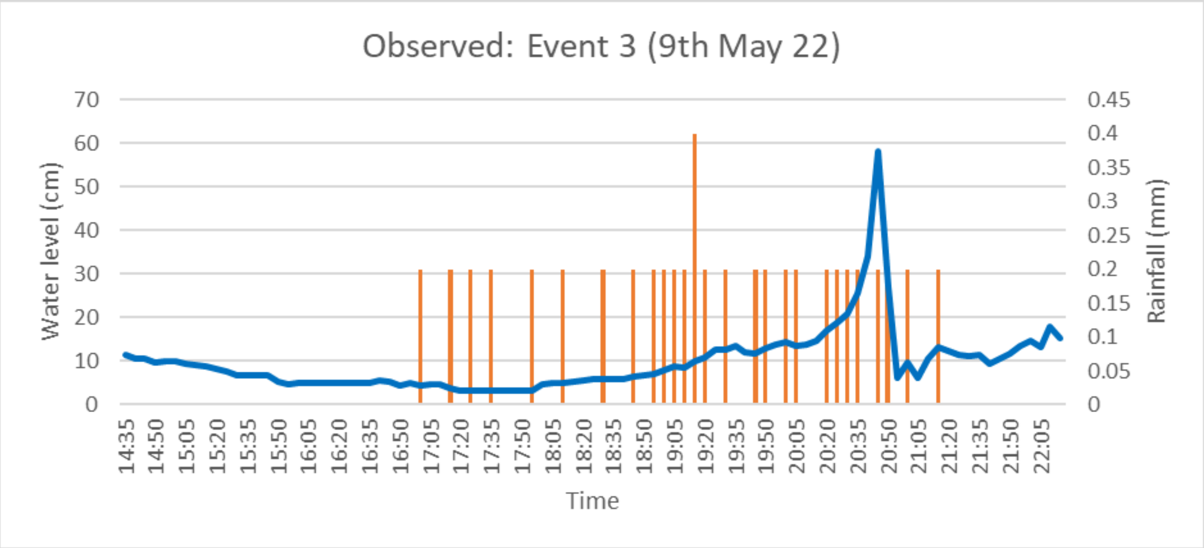


Figure 7-3: Observed rainfall and water level for event number 3 for the Canada Wood flume.

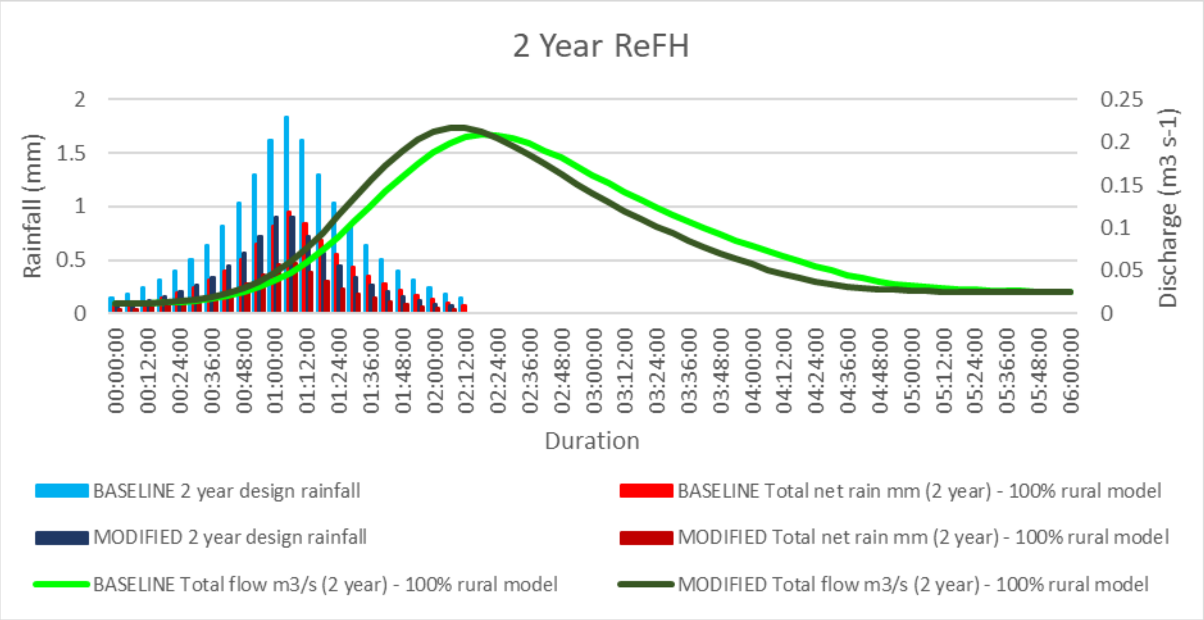


Figure 7-4: Rainfall and discharge for the 2-year return period event for the Canada Wood flume, generated by baseline ReFH, and with the modified parameters influenced by the observations. Modified parameter values cause minor changes in the 2-year hydrograph.

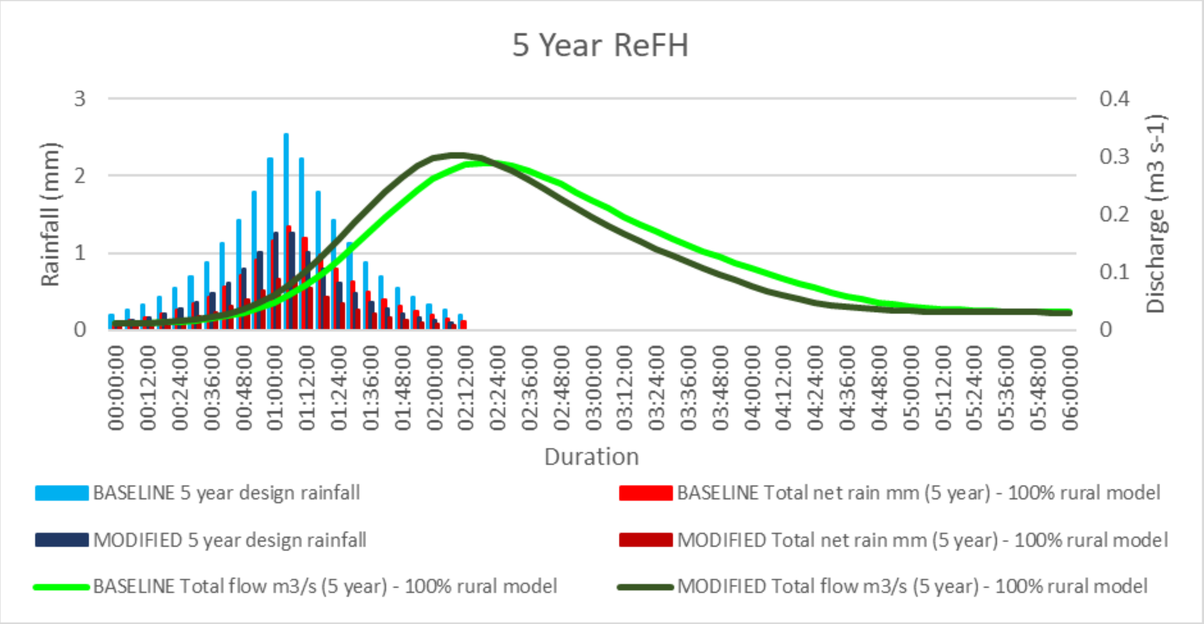


Figure 7-5: Rainfall and discharge for the 5-year return period event for the Canada Wood flume, generated by baseline ReFH, and with the modified parameters influenced by the observations. Modified parameter values cause minor changes in the 5-year hydrograph.

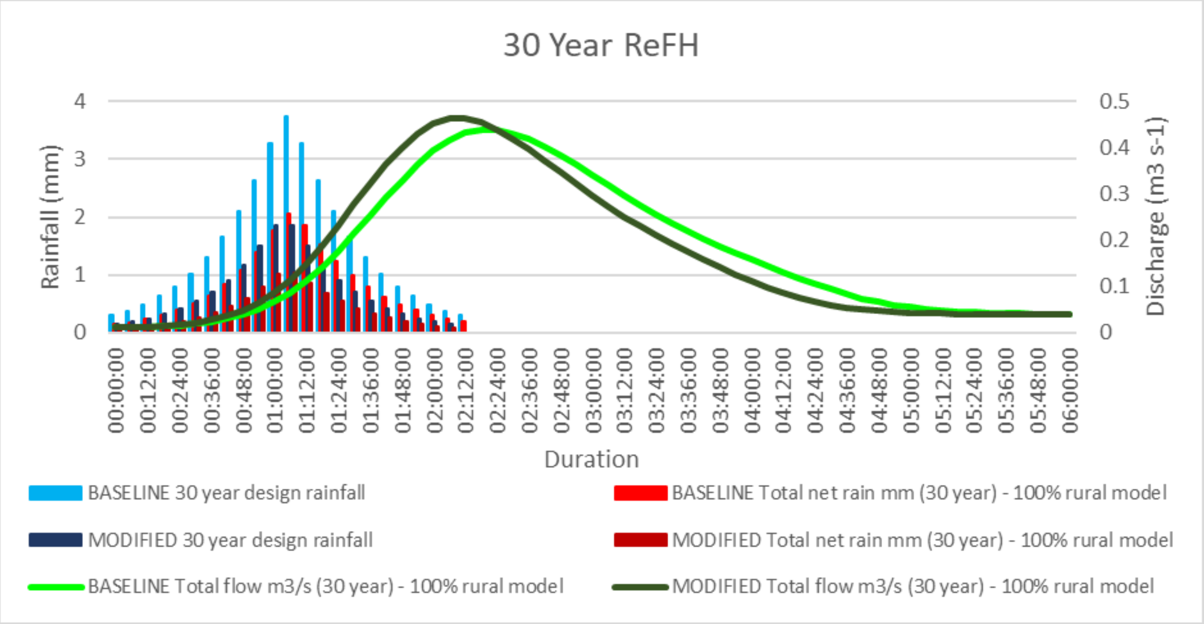


Figure 7-6: Rainfall and discharge for the 30-year return period event for the Canada Wood flume, generated by baseline ReFH, and with the modified parameters influenced by the observations. Modified parameter values cause minor changes in the 30-year hydrograph.

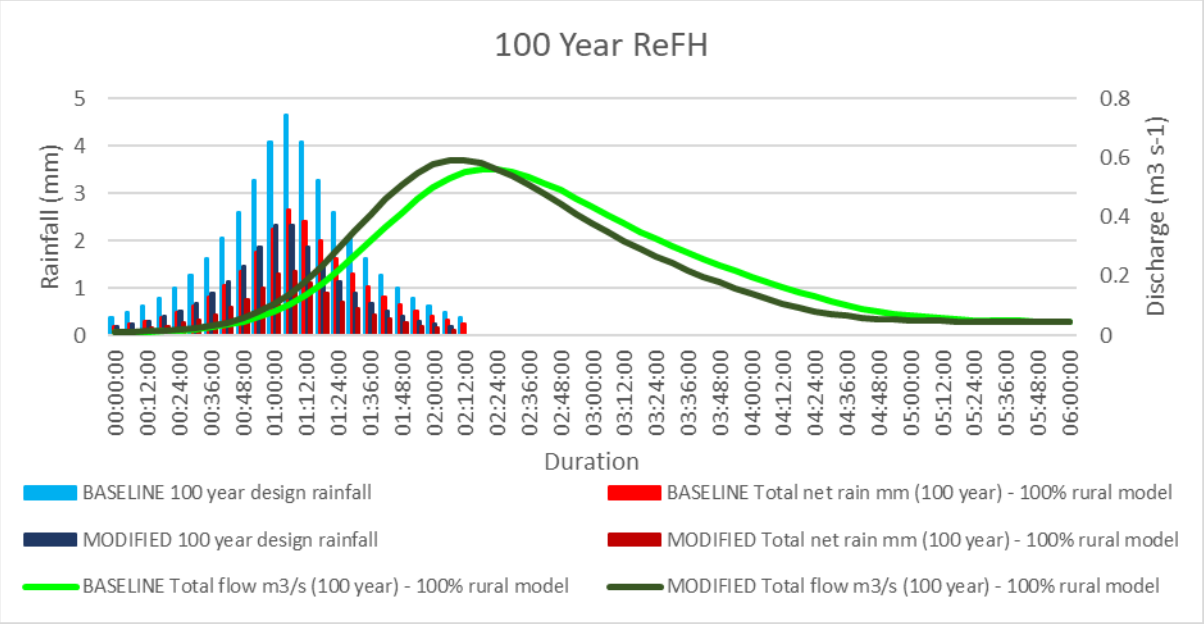


Figure 7-7: Rainfall and discharge for the 100-year return period event for the Canada Wood flume, generated by baseline ReFH, and with the modified parameters influenced by the observations. Modified parameter values cause minor changes in the 100-year hydrograph.

The modified parameters for the ReFH2 models show very minor shifts in the hydrograph compared to the baseline ReFH2 model hydrographs.

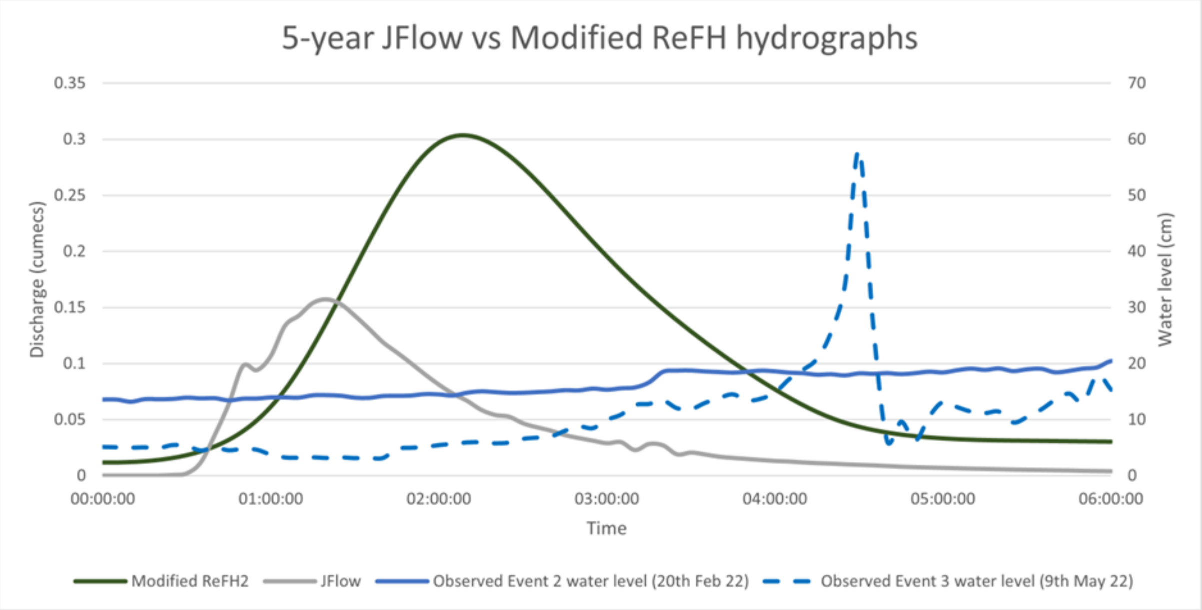


Figure 7-8: A comparison of the ReFH2 with modified parameter values and JFlow® hydrographs for the 5-year return period event at the Canada Wood flume. Peak discharge between the methods is similar, although the volume is much larger for the ReFH2 method. The water level from observed event 2 (20th Feb 22) and 3 (9th May 22) is overlaid to assess modelled response to observed response.

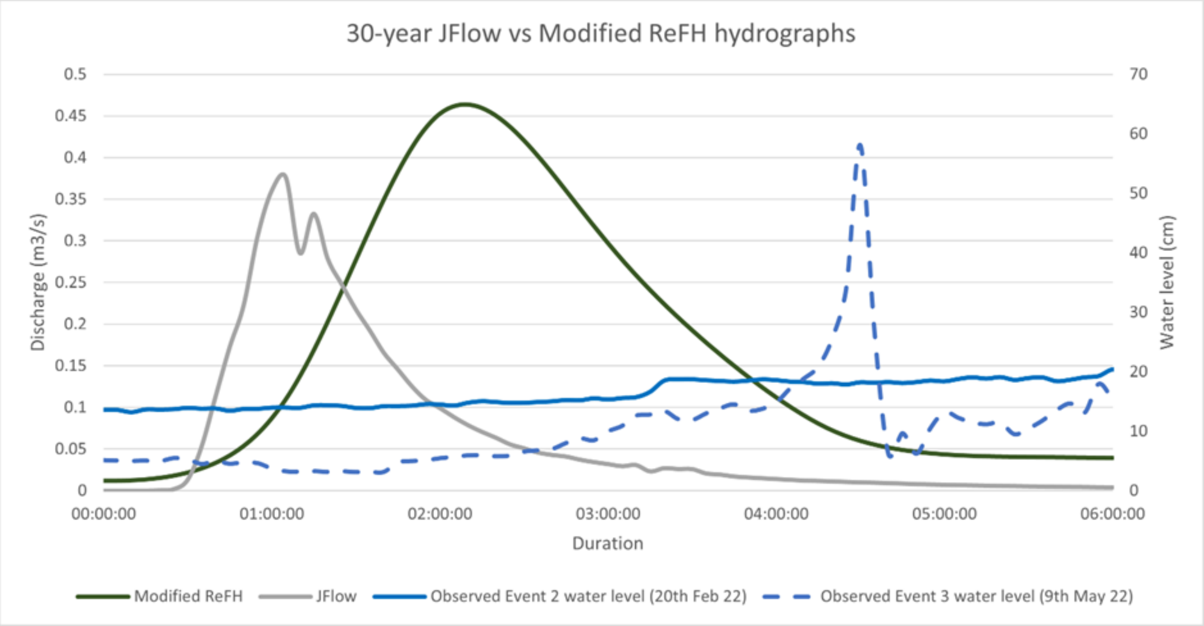


Figure 7-9: A comparison of the ReFH2 with modified parameter values and JFlow® hydrographs for the 30-year return period event at the Canada Wood flume. Peak discharge between the methods is similar, although the volume is much larger for the ReFH2 method. The water level from observed event 2 (20th Feb 22) and 3 (9th May 22) is overlaid to assess modelled response to observed response.

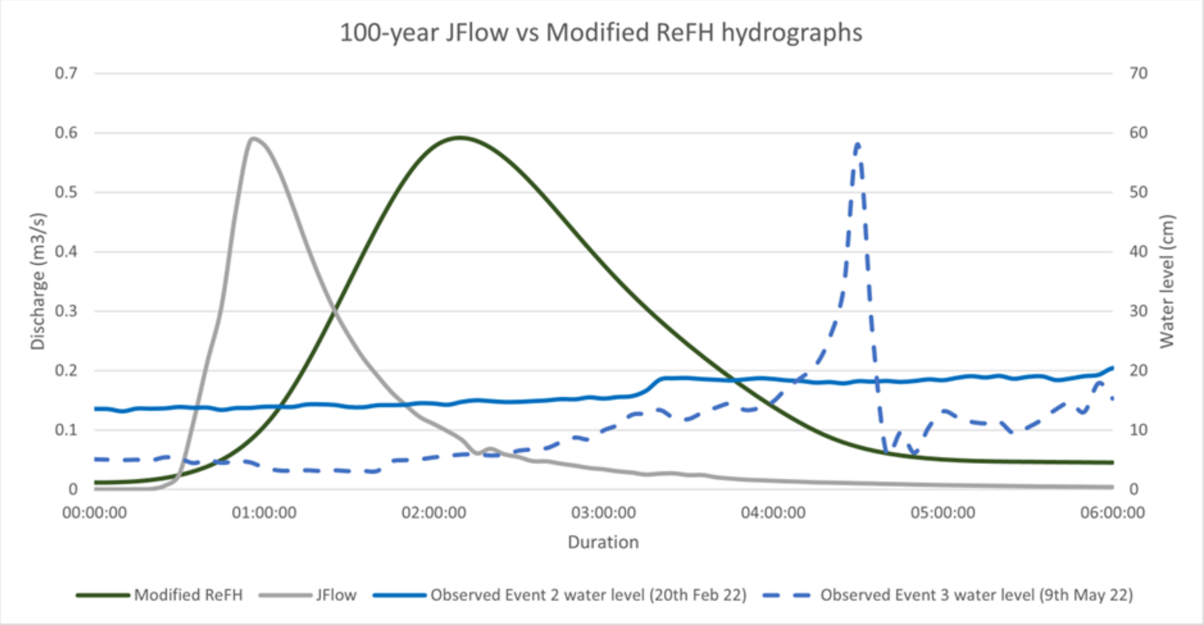


Figure 7-10: A comparison of the ReFH2 with modified parameter values and JFlow® hydrographs for the 100-year return period event. Peak discharge between the methods is similar, although the volume is much larger for the ReFH2 method. The water level from observed event 2 (20th Feb 22) and 3 (9th May 22) is overlaid to assess modelled response to observed response.

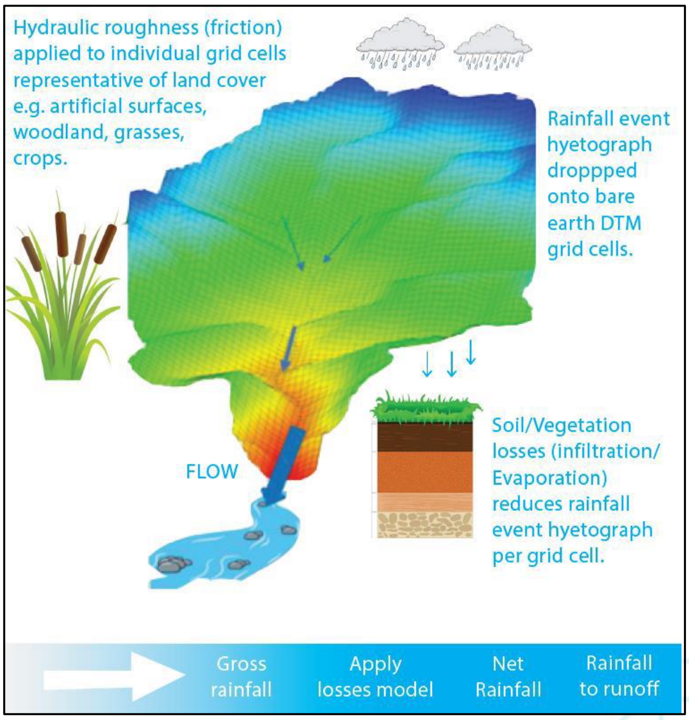
B JFlow® Technical Note

B.1 JFlow® Runoff and Losses

JFlow® adjusts the total rainfall to calculate effective (net) rainfall which is then added to the model. The method used for this is based on the uFMfSW, where across the UK, hydraulic losses were calculated based on whether areas were classed as “urban” or “rural”.

“Urban” areas were defined based on Ordnance Survey MasterMap information for grid squares 250m by 250m. Where more than 50% of the grid square consists of manmade land uses (including all buildings, roads, paths and other hard standing). If the square was determined as "urban" (in summer 2013, when the uFMfSW project was progressed) then urban runoff rules were applied. All other squares were defined as "rural" and the ReFH1 rainfall-runoff methods were used. More information is provided in the uFMfSW report10.

In the ReFH rainfall runoff models, the losses component calculates the runoff volume based on a single parameter, Cmax (maximum soil moisture capacity) and an initial condition, Cini (initial soil moisture). For the design floods, a representative value of Cini will be automatically estimated from catchment descriptors.



B.1.1 Adjustments in urban areas

Within these urban areas, rainfall is reduced to 70% to represent greater surface runoff on paved areas, roofs and other similar hard surfaces, then a rainfall reduction of 12mm/hr is applied to represent the effects of a typical urban drainage system.

The runoff coefficient of 70% was chosen for urban areas as this was a good average runoff coefficient for built-up areas including gardens and green verges and a mix of city centre and more suburban land uses, (in summer 2013). The FEH catchment descriptor method also assumes a 70% percentage runoff coefficient for urban areas. The losses model from the ReFH1 rainfall-runoff method that was used for the rural areas was also applied for calculation of runoff within the green portions of the urban areas.

Urban drainage systems vary in nature between catchments, those built at different times and using different techniques. Their effectiveness in different storm events is linked to very local characteristics such as the arrangement and capacity of road gullies and whether drainage is via combined or separate sewerage systems. Previous national studies have carried out analysis of the sewer capacity to derive a nationally representative figure, from the following factors:

- service level (or standard of protection from flooding) for drainage systems (between 1 in 5 and 1 in 30 years, centred around 1 in 10 years)
- estimates of critical storm duration (0.5 to 2 hours)
- estimates of percentage impermeable area (30% to 80%)

- estimates of DDF rainfall parameters

For the uFMfSW the calculated range of sewer capacities was in the range between 5mm/hr and 54mm/hr; with a typical drainage removal rate of 12mm/hr across catchments in England and Wales. Independent validation carried out as part of these earlier studies confirms that 12mm/hr is a suitable 'typical' value to represent the effects of urban drainage, and there was no new information available that contradicts this assumption.

A drainage removal rate of 12mm/hr has therefore been adopted in the nationally produced mapping unless otherwise specified by LLFAs. In areas of known low or high drainage capacity, LLFAs could substitute alternative values of 6mm/hr or 20mm/hr.

B.1.2 Adjustments in rural areas

The approach used in the uFMfSW for calculating runoff in rural areas used the rainfall losses model from ReFH and parameters from the National Soil Resources Institute (NSRI) 'SERIES Hydrology' data.

The losses in the model are controlled by the maximum soil moisture storage capacity. The model calculates the volume of runoff at each time step as a function of the current soil moisture content, so that the percentage runoff increases as the rainfall continues. This increase is minor for short duration storm events. BFIHOST and PROPWET parameters were assigned across the UK "Rural" areas (defined in Summer 2013) represent these hydraulic losses.

$$C_{max} = 596.7\ \mathrm{BFIHOST}^{0.95}\ \mathrm{PROPWET}^{-0.24}$$

B.2 JFlow® Groundwater inputs

In catchments with low and medium permeability bedrock, most of the fluvial inflow volume during a flood event comes from the 'direct runoff' component of the hydrograph. Due to the medium permeability of the Brant Fell catchment, the JFlow® will not directly represent the accurate baseflow contributions within the model.

This method could be significantly improved if the model was used to focus on either groundwater, or fluvial flooding but, as this project's focus is on surface water flooding then this estimated method is appropriate. The JFlow® 2D catchment model is focused only surface water flooding from high intensity rainfall events.

B.3 NFM Representation

The different types of measures identified in the scenarios were implemented into the model in the same way, as summarised in (Table 11).

Table 11: Method of implementing NFM opportunities within the JFlow® model

Measure	JFlow® implementation
Reach of leaky barriers	Increase in hydraulic roughness (Manning's n = 0.16 and 0.10[13]), this has been used for reaches with high densities of leaky barriers depending on location.
Leaky barriers acting as deflectors	DEM modification of a set height to cause blockage in the channel, with a culvert placed through the blockage to allow free passage of baseflow. Culverts set as 1m wide and 0.2m in height.
Wetland Creation	Excavation into the terrain represented as a DEM modification of a set height (-1m from baseline elevation).

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[13] Based on the latest NFM research in (Addy & Wilkinson, 2019) - Representing natural and artificial in-channel large wood in numerical hydraulic and hydrological models.

Measure	JFlow® implementation
Woodland/Hedgerow planting	Increase in hydraulic roughness (Manning's n = 0.15). Only simulated the slowing of runoff in these locations due to the addition of woodland, rather than the smoother baseline surface. Does not take into account increased infiltration, evaporation, transpiration or interception[14]. Woodland values are for fully mature woodland stands. We appreciate that overland flow velocity can significantly vary across a catchment and seasonally, Bond et al. (2020)[3].
Cross Drains	DTM modification at the proposed height of the drains across the paths.
Footpath management	Increase in hydraulic roughness back to value of surrounding common land (Manning's n = 0.05). Rather than the eroded smoother surface (0.02)
Livestock Fencing	Increase in hydraulic roughness (Manning's n = 0.07). Only simulated the slowing of runoff in these locations due to the addition of increased vegetation, rather than the smoother baseline surface. Does not take into account increased infiltration, evaporation, transpiration or interception[14]

B.4 JFlow® Baseline Verification/Sensitivity

Direct rainfall modelling of this sort must be approached with caution, since the models used make assumptions which are not always true, and they may not adequately represent the hydrological processes which control runoff.

This type of modelling is currently the subject of academic research into the best and most appropriate methods for different types of catchments (Hankin, et al., 2021). Detailed uncertainty analysis, both for model parameters and how the NFM features are changed, will be necessary to narrow down the impact on peak flows which is most robust if available for this project.

JBA expected a difference in hydrograph shape due to the JFlow® simulation of the designed rainfall, compared to the ReFH/statistical lumped estimation used within the downstream existing models. Due to the uncertainties around the hydrograph shape of the ReFH estimation, it is assumed that the JFlow® generated hydrograph shape is a better representation of the river catchment.

Because of this change in hydrograph shape the peak flow from the JFlow® results is also likely to vary. This could be due to some of the flow volume being stored within the DTM (in natural depressions) of the model.

Due to the ReFH2 replication of the two observed events it is highly likely that the estimations will be underestimated. We expect the JFlow® results to produce higher flows as a result. Further uncertainty in the project includes:

- Assumptions within the ReFH software used to estimate these inputs for the model.
- Modification to the critical storm duration within the hydrological estimates
- At some locations within the catchment the DTM resolution cannot pick up the smaller surface flow paths and therefore the model accuracy in these locations deteriorate.

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[14] Wood Wise • Tree and woodland conservation 2022 The Woodland Trust - Page, T., Chappell, N.A., Beven, K.J., Hankin, B., and Kretzschmar, A. (2020) Assessing the significance of wet-canopy evaporation from forests during extreme rainfall events for flood mitigation in mountainous regions of the United Kingdom. Hydrological Processes, 34: 4740–4754.

- The JFlow® model does not represent groundwater interactions which will be showing an effect on the REFH estimates. The baseflow component of the hydrograph is not fully represented within the JFlow® hydrographs due to it's focus on surface water interactions.
- Estimation of flood frequency for return periods longer than 100 years is highly uncertain across all flood estimation methods.
- The ReFH method is affected by uncertainty in the catchment descriptor values, but there is no broadly accepted method of quantifying uncertainty in the ReFH methodology. However, these uncertainties are small, compared to the ReFH model structure, parameters and composition of the design flood event.
- Rainfall losses to infiltration and evaporation, specific to this catchment, have been assumed to conform to the generalised ReFH1 losses model. There is no way to understand whether the net rainfall calculated, which will be applied to the catchment grid, is representative of the catchment or not. The JFlow® model also assumes a dry catchment for the initial conditions and therefore the depressions in the DTM used within the JFlow® model take time to fill up before water can flow overland. This explains why there is no flow at the start of the JFlow® hydrograph. This can cause added delays to the hydrographs.
- JBA have also found that for multiple events like shown above that the 2d model response is highly variable. In addition, the initial state of the model represents a dry soil condition and dry storage areas. In reality, the soils would remain wet and stores would only partially empty prior to the later events. Iteration with Cini can aid this situation.
- Also, the difference between the DTM data, resolution of the DTM used in the model, and telemetry data used by the gauge can cause differences in the results.

Further calibration of the initial conditions and potential Cini calibration within JFlow® may produce a closer representation of the flood events if required. JBA as a result has increased confidence that the JFlow® simulation of runoff across the catchment is representative of the catchment conditions and therefore reliable to test distributed NFM measures.

The result should be used in a comparative way rather than using the absolute discharge values of the modelling.

C Brant Fell NFM Site Walkover Analysis Technical Note

Supplied as separate PDF.

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