Improving river habitats to support wildlife during high and low flows – case studies

Chief Scientist's Group report

March 2024

Version: SC230009/R2

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Published by:

Environment Agency
Horizon House, Deanery Road,
Bristol BS1 5AH

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Keywords:
River restoration, ecological and geomorphological resilience, hydraulic modelling,

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Project number:
SC230009

Citation:
Environment Agency (2023) River Restoration to increase ecological resilience – what works in which rivers. Environment Agency, Bristol.

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Dr Robert Bradburne
Chief Scientist

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Acknowledgements

We would like to thank the following for allowing their projects to be used as case studies: Royal Society for the Protection of Birds (RSPB), National Trust, Wild Trout Trust, Stoke County Council.

1. Introduction

In 2014 the Environment Agency undertook a study to aid understanding of how restoration measures can improve river habitats during lows, (Environment Agency, 2014). The study aimed to help practitioners design suitable schemes by linking restoration measures, river type and restoring natural processes to improve ecological resilience.

Building on the 2014 project, a 2023 investigation aimed to update and further develop the evidence around measures that can be applied to enhance physical habitats during low and high flow conditions, but also to ensure they are effective and sustainable at bank full flows when geomorphic processes are likely to be most active.

The project illustrated the potential habitat benefits at low and high flows of selected interventions through the examination of 10 case studies.

2. Case study locations

The selection of the ten case studies was informed by the evidence gaps and the new restoration techniques. The case studies also needed sufficient available data to enable modelling of the effects under different flow regimes (Figure 1).

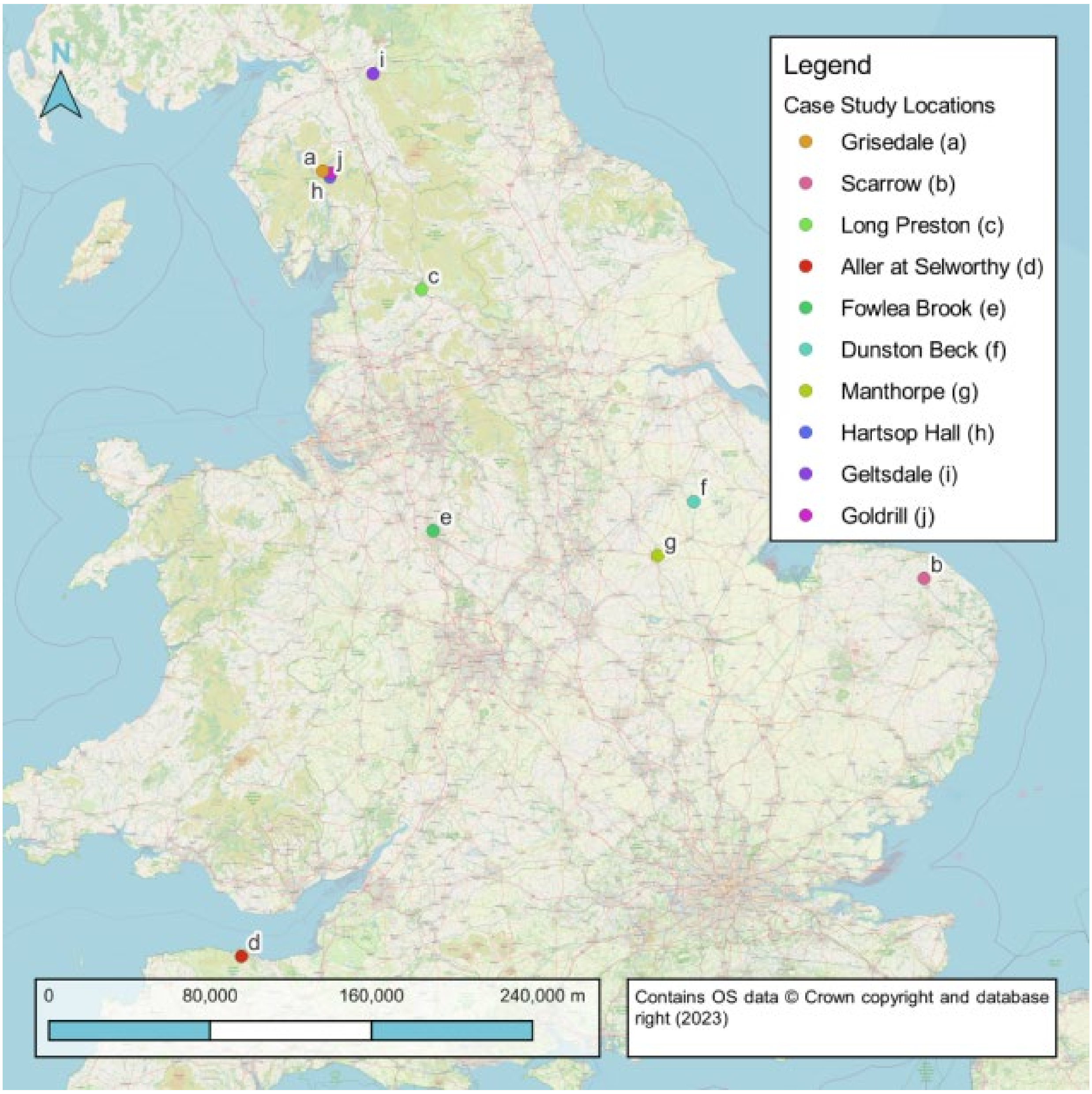


Figure 1. Case study locations.

3. Modelling Methodology

3.1. Hydraulic modelling

Hydraulic habitat mapping was performed using a simulation of low flow and bankfull conditions to assess the composition and distribution of biotopes, shear stress and habitat. A 2-dimensional fixed bed hydrodynamic model (HecRas) was applied to a DEM and used to assess the presence of different hydraulic biotopes. Using a fixed bed hydraulic model was deemed appropriate since the hydraulic habitat mapping used a simulation of low flow conditions where the hydraulic forces operating are generally insufficient to cause bed or bank erosion or to transport gravel and cobble sized sediment. The approach is also consistent with modelling undertaken in the previous study (Environment Agency 2014). The modelling of shear stress values was used to provide an indication of the restoration of riverine processes and the potential for future channel adjustment at high flows.

Three flows were modelled to provide an indication of measure performance:

- Q95 – Representing a summer flow identifying hydraulic biotopes and habitat conditions at low flows (including low flow refuge)
- Q10 - Representing a winter flow, identifying hydraulic biotopes and habitat conditions during moderately high flows (including high flow refuge)
- QMed – the median annual flood, identifying hydraulic biotopes and refuge availability during a flood which would occur relatively frequently.

As established above, the presence of refuge is considered essential for ecological resilience (see, for example, Lake 2000, Lake 2007, Boulton and Lake 2008). The choice of the above three flows allows an understanding to be developed of the performance of the restoration measures in terms of hydraulic and ecological resilience across the range of flows which could be expected to occur relatively frequently.

For each case study, a comparison of the reach where the morphological measure had been applied was made to pre-restoration conditions. This gave an indication of how the biotope habitat composition had changed as a result of the scheme.

The constraints associated with this approach include the following.

- The hydraulic model is not a dynamic sediment model and therefore changes to the channel form over time will not be quantified. For example, the impacts of fine sediment management may be better demonstrated in a dynamic sediment model where sediment supply and loads can be quantified.
- The modelling process is dependent on the availability of suitable data to adequately model the restoration measure. The data available and the limitations associated with each case study are provided in each of the detailed Appendices.
- The fixed bed model approach assumes that no morphological change will occur during low flow conditions. This is not unreasonable as the hydraulic forces operating are generally insufficient to cause bed or bank erosion. However, it is recognised that the restoration measures will be subject to higher flows, which may alter the channel

form and low flow hydraulics over time (see, for example: Newson et al. 2002, Gilvear et al. 2013).

3.2. Analysis

3.2.1. Hydraulic biotope

The assignment of different hydraulic ranges to define physical habitats (biotopes) is a widely accepted approach to assessment (see, for example, Kemp et al. 2000, Harvey et al. 2008, Harvey and Clifford 2008, Heritage et al. 2009). Mapping of the biotopes allows quantification of habitat area, diversity and patchiness – all of which are important aspects of defining ecological quality, diversity and resilience.

The habitat maps were used to identify the presence and coverage of faster flowing areas during low flow conditions (low flow refuge) and slower flowing or slack areas during higher (bankfull) flows (high flow refuge). The hydraulic biotopes were defined by the variation of the Froude number (the ratio of inertial to accelerational forces) (see Gordon et al. 1994). The Froude number has been found to be a reliable hydraulic variable to distinguish between different biotopes (see, for example, Wadeson 1994, Kemp et al. 2000, Heritage et al. 2009). The Froude number is calculated as follows:

$$Fr = \frac{v}{\sqrt{gd}}$$

where *v* is flow velocity, *g* is gravitational acceleration and *d* is hydraulic depth.

The thresholds for the different hydraulic biotopes are presented in Figure 2.

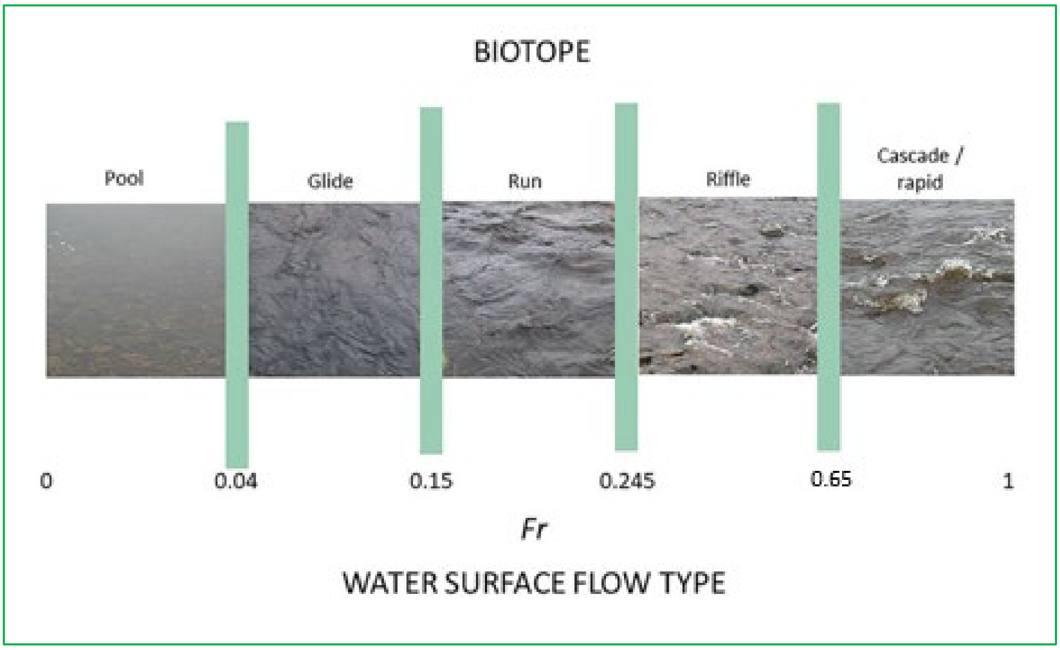


Figure 2. Hydraulic biotope thresholds used.

3.2.2. Fuzzy logic

Where the modelling, restoration measure and data were appropriate, a fuzzy logic habitat model (JHAB) was used to assess habitat suitability for fish. This approach was used to review the habitat suitability for different life stages of fish species of interest (depends on the fish present in the river) and refuge at high flows.

The habitat suitability for trout was based on available literature for trout (Heggenes 1989, de Crispin de Billy and Usseglio-Polatera 2002, Armstrong et al. 2003). For cyprinid fish, only one life stage was investigated since there is less published information and the adults are often found in a wider range of habitats (Environment Agency 2013c). The 0+ life stage is considered important as the primary control on the year class strength (see, for example: Mann 1995). Refuge assessment at high flows used a general rule based on research on fish swimming speed (Clough and Turnpenny 2001).

The modelling provided a spatial assessment of the channel through the calculation of a Habitat Suitability Index (HSI) for each flow and species/life stage of interest. This was used to assess:

- quantity of available habitat – Total Habitat Suitability Index (THSI)
- quality of the habitat – Habitat Quality Index (HQI)

The HQI is derived by dividing the THSI by the number of wet cells in the model for that scenario. Visual assessments were made for the presence of hydraulic refuge at high and low flows, habitat connectivity and patchiness.

3.2.3. Vegetation classification

For a selection of the case studies, floodplain habitat creation has been classified and mapped to demonstrate the overall floodplain habitat gains and likely development linked to the proposed restoration scheme. Table 1 summarises the wetting thresholds used to map the floodplain habitat. Mapped extents of each habitat in the case studies show the optimal vegetation development over time based on the new hydrological regime at the site. This may differ in reality due to species competition and other factors, but these provide a template for anticipated development. The summer (Q95), autumn (Q30), winter (Q10) and spring (Q50) inundation area has been extrapolated to predict water table levels across the wider floodplain for the study sites assessed based on the restored scenario.

Table 1. Summer, winter, spring, autumn wetting threshold for each habitat

Habitat Type	Habitat Code	Water table depth below FP surface (negative numbers indicated flooded ground)			
		Winter	Spring	Summer	Autumn
Wet Grassland	MG13	0.1-0.25	0.03-0.45	0.2-0.8	0.1-1
	MG4	0.1-0.6	0.25-0.7	0.4-1.0	0.25-1
	MG8	0.03-0.3	0.03-0.35	0.15-0.5	0.1-0.4
Fen Mire	M24	--	--	0.249-0.533	--
	M13	--	--	0.096-0.386	--
	S24	--	--	0.167-0.784	--
	S2	0-(0.4)	--	<0.15	--
Ditch Swamp	S4	0-(1.5)	0.25-(1.25)	0.8-(0.5)	1-(0.75)
	S5	0.3-(0.9)	0.6-(0.7)	0.8-(0.8)	0.6-(0.8)

4. Grisedale Beck

4.1. Background

Grisedale Beck is a heavily modified, rural, single-thread, gravel-bed river draining the predominantly rural elevated land within Grisedale. The nearby Grisedale Tarn also has some control of the hydrology within the beck. The channel has been artificially straightened and there is a strong coarse sediment supply with frequent bar and riffle / rapid type features. Levels of diffuse fine sediment input do not seem high. It eventually discharges into the Goldrill Beck at Patterdale.

There are distinct palaeo-channels along the right-hand bank of the study reach that appear to be well connected to the current main channel at the upstream end of the reach. The main channel has clearly been straightened and aligned to the left-hand side of the valley, leaving it slightly perched above the true valley bottom, with several other palaeo-channels evident over the right-hand bank. The likely former course of the main river to the right of the floodplain is now occupied by a small cut tributary, which has begun to naturalise.

Drainage across the valley floor is extensive but is less maintained than in the past and wet areas are now dominated by soft rush.

A restoration design that would improve the channel and floodplain form and function for the study reach of the Grisedale Beck at Grisedale was requested.

The restoration design included the following measures:

- riffle-rapids,
- point bars,
- bank lowering,
- floodplain reconnection.

The Grisedale Beck supports populations of migratory salmonid fishes including brown trout (*Salmo trutta*) and Atlantic salmon (*Salmo salar*). The connection to the sea is via Ullswater Reservoir and eventually the River Eden Special Area of Conservation (SAC). The Grisedale Beck also supports European eel (*Anguilla anguilla*), however populations in these areas are likely to be small owing to the upland setting. Other fish species present include the stone loach (*Barbatula barbatula*), bullhead (*Cottus gobio*) and minnow (*Phoxinus phoxinus*).

4.2. Site Specific Methodology

4.2.1. Model schematisation

A HEC-RAS 2D model of the study area was developed for pre and post scheme representation. The pre-restoration model used a DTM created using the EA 2021 LiDAR dataset, and the post-restoration model used DTM generated using 25cm photogrammetric drone-based survey data. A mesh resolution of 2m by 2m was predominantly used, however this was refined in places. Additionally, the sub-grid scale feature in HEC-RAS 2D computes storage-level and conveyance-level relationships for each cell face from the underlying DTM. As the conveyance tables are across cell faces, in areas where there is significant topographic level change, a break-line along the face ensures flow is unable to progress until the topographic crest level is overtopped. Break-lines have been included along the river channel to ensure the flows are perpendicular to the cell faces in direction of greatest flow.

The model covered a 1km reach of the Grisdale Beck, with the model boundary positioned as far upstream as possible to ensure restoration measures are captured, and minimise the risk of the upstream and downstream boundary of the model influencing results in the study area (Figure 4.1).

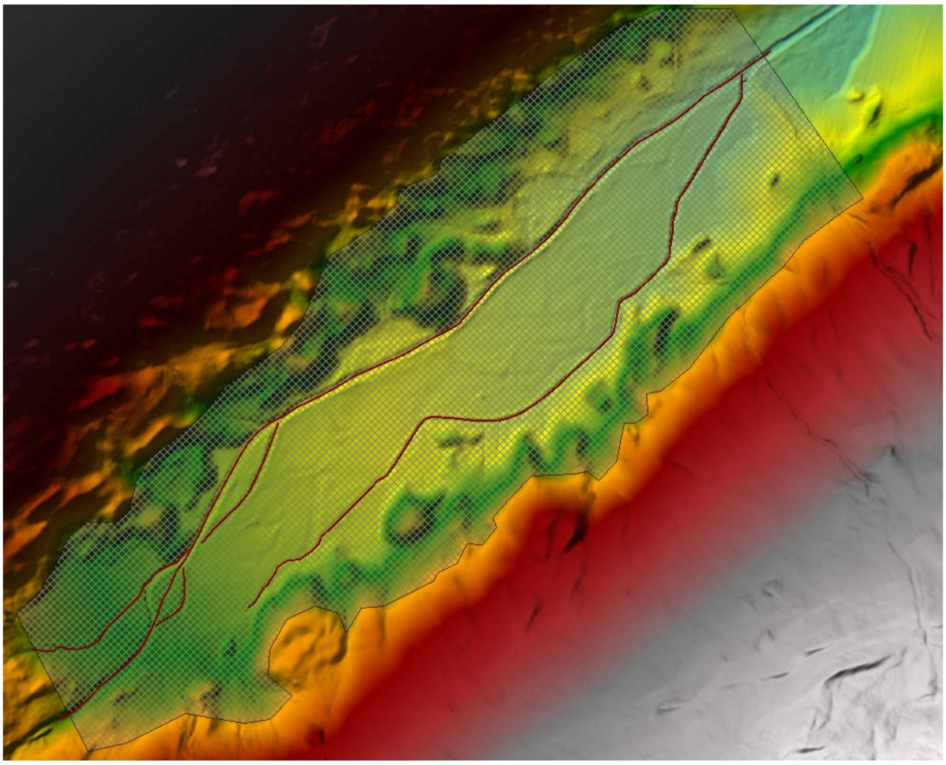


Figure 4.1. HEC-RAS 2D – baseline grid set-up of the study site at Grisdale Beck.

Inflows

The flows used in the modelling are shown in Table 4.1 below. The low flows for Q95, Q50, and Q10 were derived using Low Flows 2 software. The 2-year return period flows were calculated using Flow Estimation Handbook (FEH) techniques.

Table 4.1. Inflows to the model.

Scenario	Flow (m^3/s)
Q95 (summer flow)	0.05
Q10 (winter flow)	0.65
2-year return period flood	5.05

Manning's roughness

Satellite imagery was used to inform the choice of Manning's n values used within the hydraulic model (Figure 4.2).

Figure 4.2: Satellite imagery of Grisdale Beck used to inform Manning's n values used within the hydraulic model.

The spatial distribution of each land cover type is shown in Figure 4.3, with the values assigned to each land cover type shown in Table 4.2. These values have also been cross-checked against values listed in Chow, 1959[1].

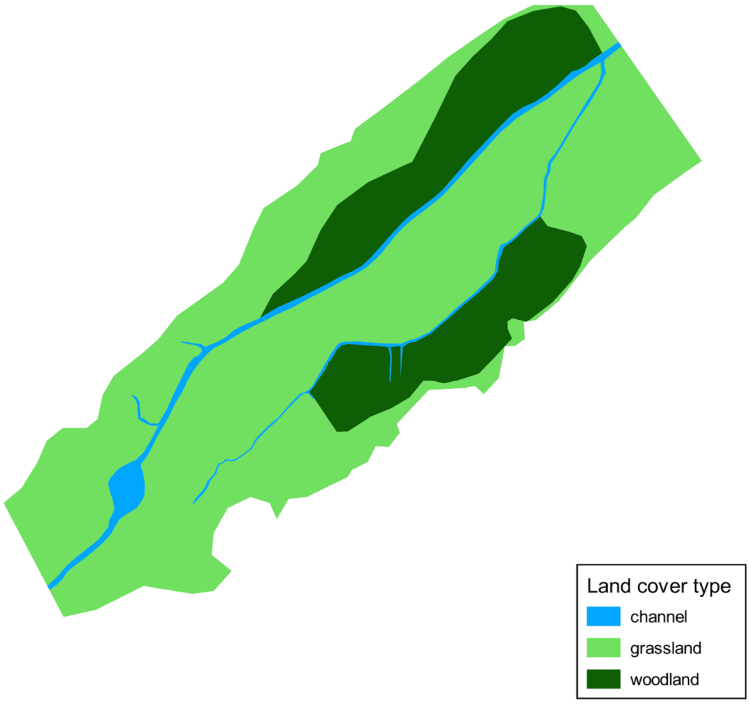


Figure 4.3. Baseline Manning's roughness grid.

[1] Chow, V.T. (1959) Open Channel Hydraulics, McGraw-Hill Book Company, NY.

Table 4.2. Manning's roughness values used within the hydraulic model.

Land Use	Manning's N	Photo
Channel	Channel: (n=0.05) has been used to represent the in-channel flow.	See Figure 4.2.
Grassland	Arable Field: (n=0.1) used to represent a smooth improved grass field.	See Figure 4.2.
Woodland	Tree coverage: (n=0.15) has been shown on site around the channel and within patches of woodland.	See Figure 4.2.

Post-change representation

The post-change scenario is represented through modifications to the underlying model surface through the direct use of high-resolution drone survey data post-restoration. No changes were made to the spatial distribution of the various land cover types within the model. This is due to the specific river restoration measures involved in this study, with the localised introduction of in-channel features and bank lowering captured within the updated model surface and a slight increase in channel roughness values (Table 4.3, Figure 4.4).

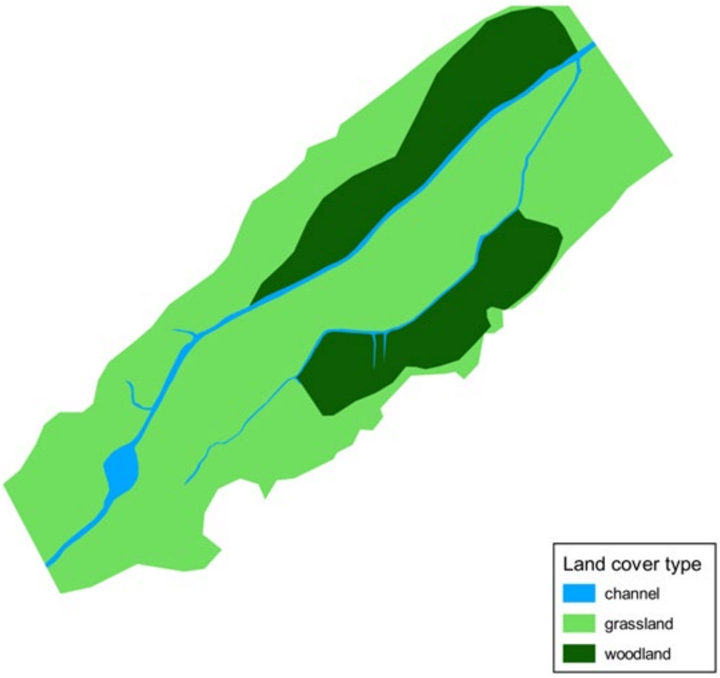


Figure 4.4. Post-change Manning's roughness grid.

4.3. Results

4.3.1. Hydraulic Conditions

Q95

The hydraulic modelling results show minimal change in the overall wetted area during Q95 flow conditions (Figure 4.5). There are however some small deviations observed in the channel course, with these differences likely linked to the creation of various in-channel features (point bars) associated with the post-restoration scenario.

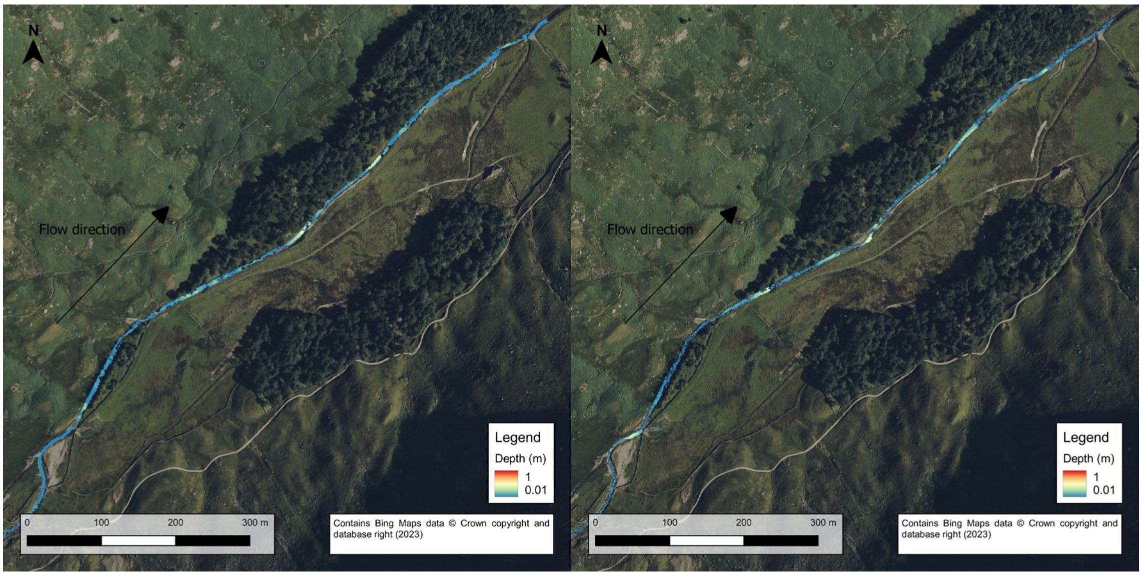


Figure 4.5. Pre (left) and post (right) change depths during Q95 flow.

Q10

In contrast to the lower Q95 flow, there is a notable increase in the overall wetted area observed during the Q10 flow (Figure 4.6). This increase is linked to improved floodplain connectivity observed during the post-restoration scenario, with no floodplain connectivity observed during the pre-restoration scenario. The hydraulic modelling suggests this water enters the floodplain via the field gate located just downstream of the anastomosed section. The model also shows that existing depressions within the floodplain act to hold some of the water which has escaped onto the floodplain during Q10 flows.

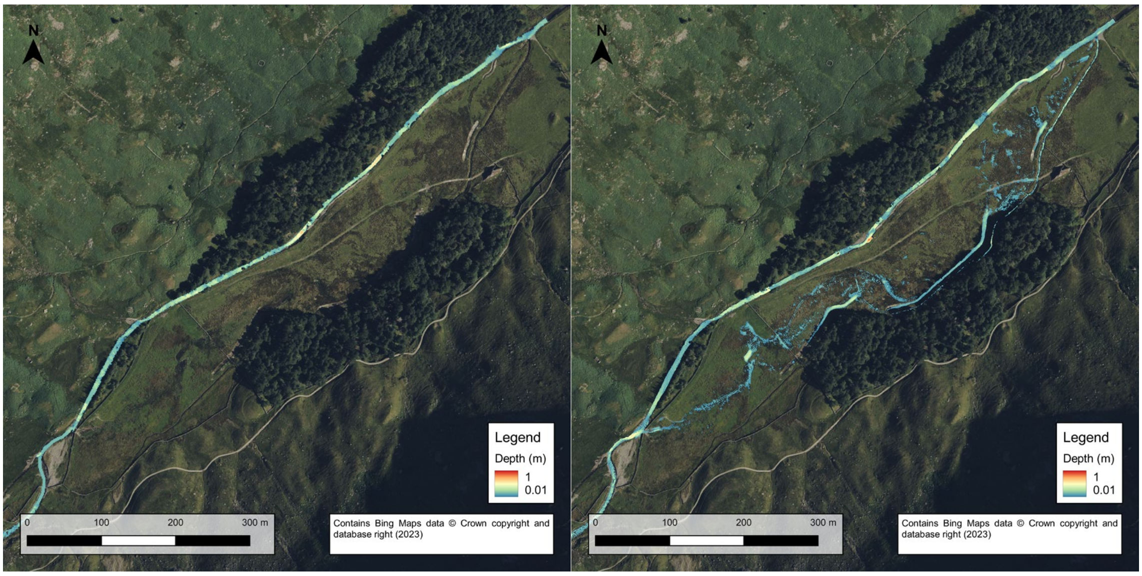


Figure 4.6. Post (left) and post (right) change depths during Q10 flow.

1 in 2-year flood

As with Q10 scenario, there is an increase in the overall wetted area observed post-restoration during a 2-year flood flow (Figure 4.7). Again, this increase is linked to improved floodplain connection post-restoration, however unlike during lower Q10 flows there is already some floodplain connectivity observed in the pre-change scenario.

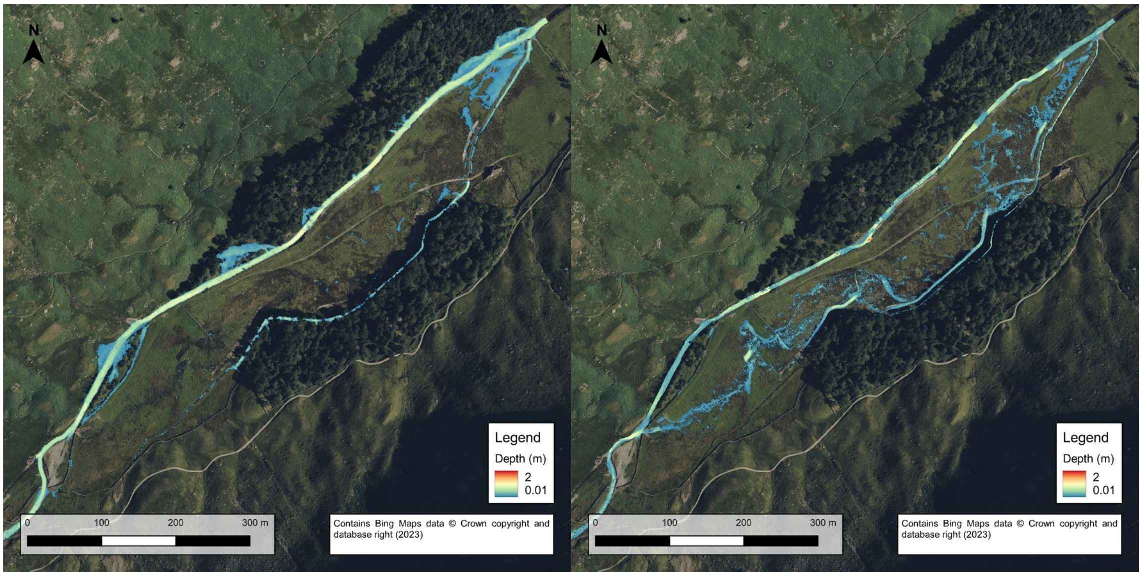


Figure 4.7. Post (left) and post (right) change depths during Q10 flow.

4.3.2. Flow Biotopes

Q95

The hydraulic modelling results suggest there is an increase in the quantity and proportion of lower energy pool biotopes and a reduction in the proportion of higher energy run and riffle biotopes post-restoration (Figure 4.8, 4.9). This increase is attributed to changes in the underlying DTM together with an increased in channel variation associated with the addition of in-channel features. These in-channel features are observed to interact with the flow to create lower energy pool and glide biotopes.

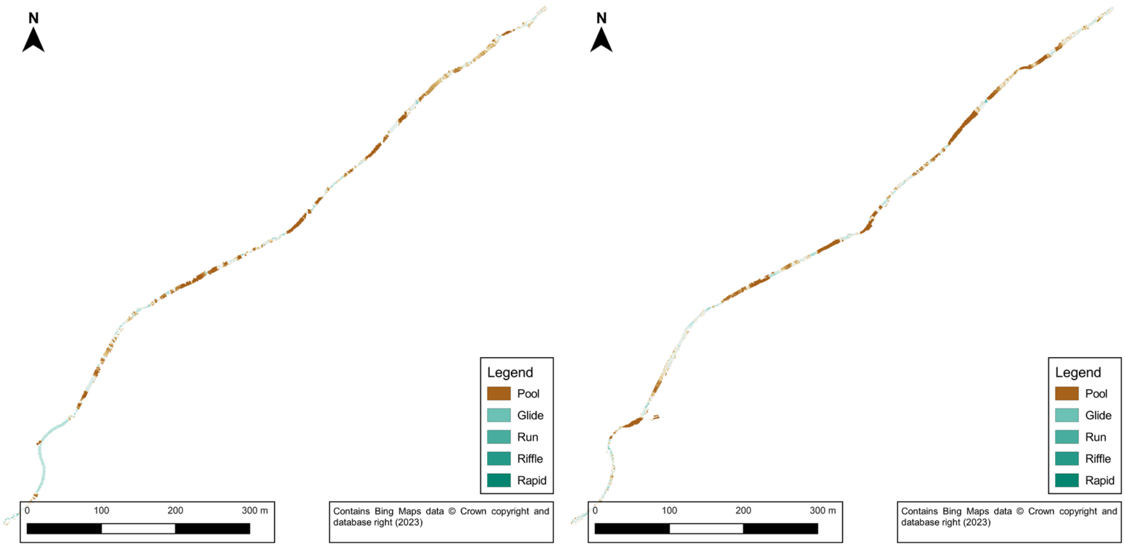


Figure 4.8. Flow biotopes observed pre (left) and post (right) restoration scenario during Q95 flows.

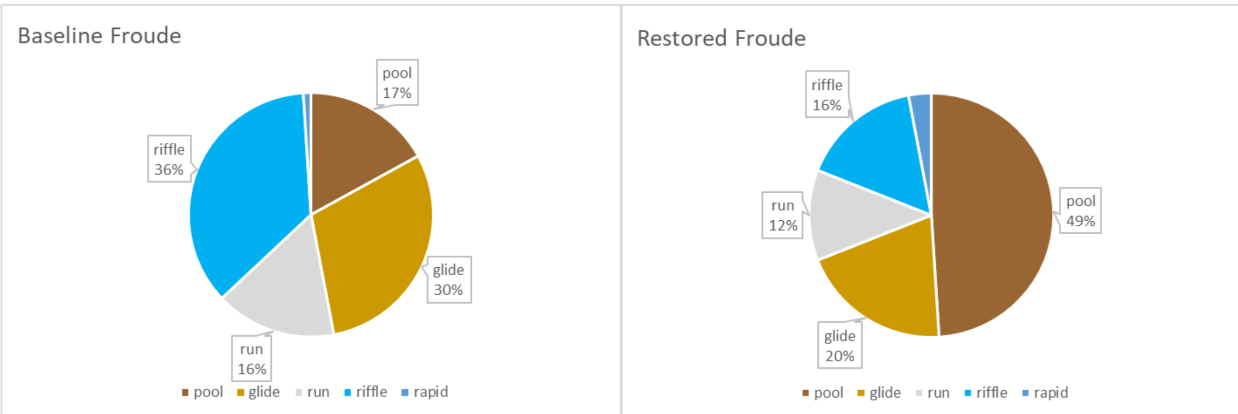


Figure 4.9. Proportion of flow biotopes observed pre (left) and post (right) restoration scenario during Q95 flows.

Table 4.3. Flow biotope changes during Q95 flows.

Flow Biotope	Count pre-change	Proportion of overall habitat pre-change (%)	Count post-change	Proportion of overall habitat post-change (%)
Pool	756	17	3071	49
Glide	1285	30	1239	20
Run	683	16	733	12
Riffle	1563	36	1020	16
Rapid	39	1	187	3

Q10

The hydraulic modelling results show that the restoration measures lead to an increase in both the quantity and proportion of lower energy pool and glide biotopes (Table 4.4). This increase is linked to increased floodplain connectivity, with much of the newly connected floodplain areas characterised by these slower biotopes. The results also show increases in the quantity of run and rapid biotopes, although the overall proportion of these biotope types is shown to reduce (Figure 4.10, 4.11). Riffle represents the only flow biotope where there is a reduction in the overall quantity.

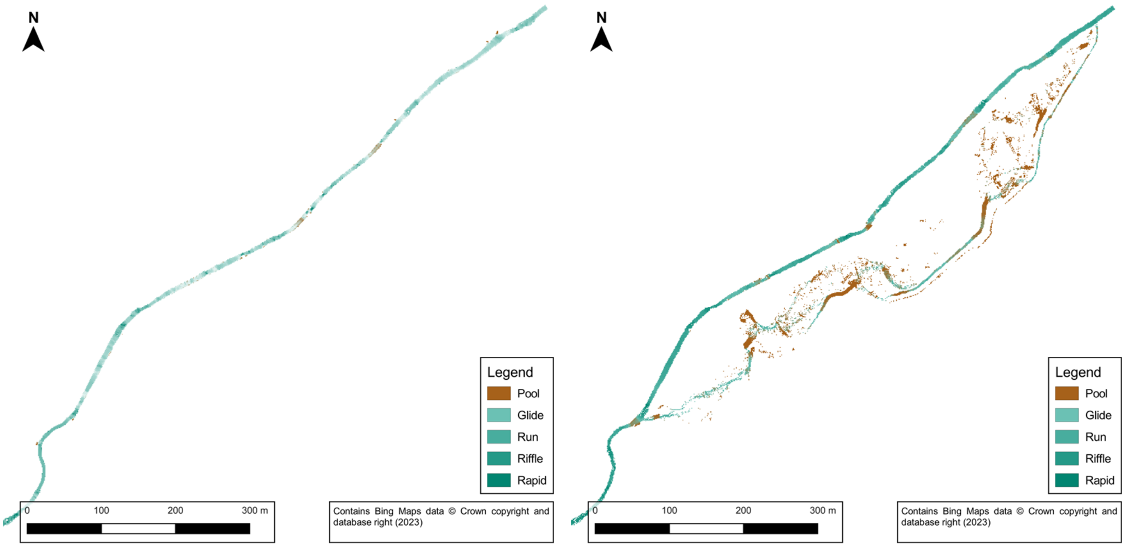


Figure 4.10. Flow biotopes observed pre (left) and post (right) restoration scenario during Q10 flows.

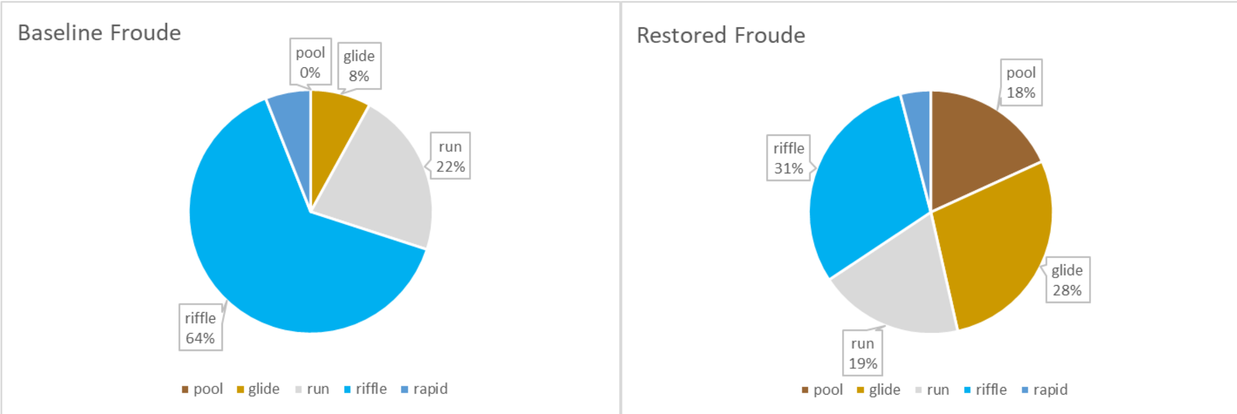


Figure 4.11. Proportion of flow biotopes observed pre (left) and post (right) restoration scenario during Q10 flows.

Table 4.4. Flow biotope changes during Q10 flows.

Flow Biotope	Count pre-change	Proportion of overall habitat pre-change (%)	Count post-change	Proportion of overall habitat post-change (%)
Pool	21	0	2084	18
Glide	500	8	3206	28
Run	1409	22	2090	19
Riffle	4217	64	3425	30
Rapid	403	6	465	4

2-year flood flow

With the exception of rapid biotopes, the model results show the post-restoration scenario results in an increase in the quantity of all flow biotopes during 2-year flood flows (Table 4.5). There is however a shift in the proportion of all biotopes, with a reduction in the proportion of higher energy and increase in the proportion of lower energy flow biotopes observed post-restoration (Figure 4.12, 4.13). This shift is linked to increased floodplain connectivity, with an increase in wetted floodplain habitat post restoration. The majority of these newly wetted cells are classified as lower energy pool and glide biotopes, resulting in an increase in the proportion of these biotopes.

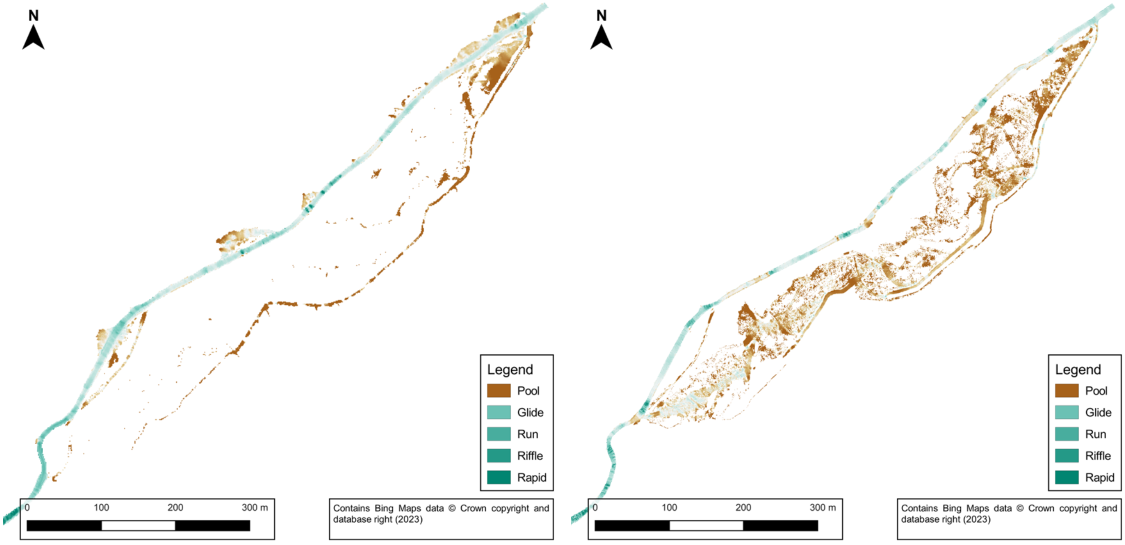


Figure 4.12. Flow biotopes observed pre (left) and post (right) restoration scenario during 2-year flood flows.

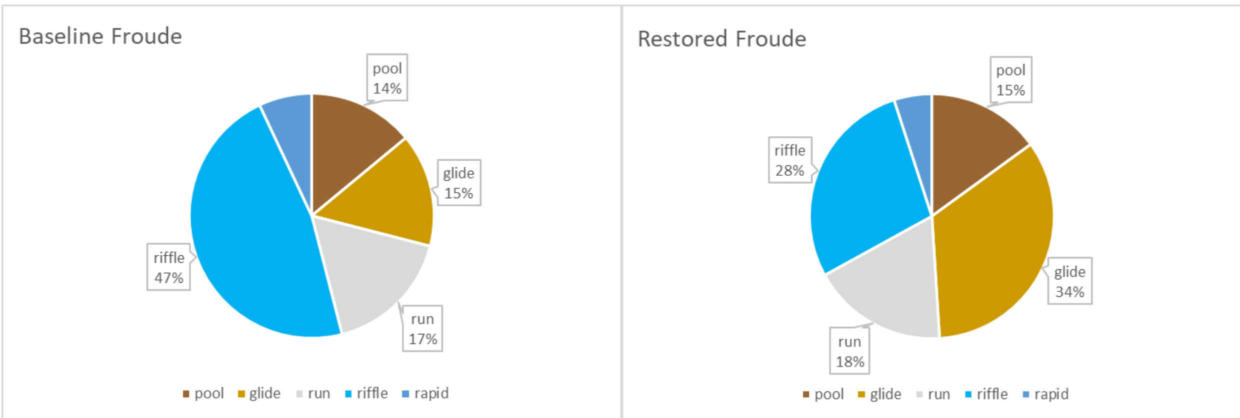


Figure 4.13. Proportion of flow biotopes observed pre (left) and post (right) restoration scenario during 2-year flood flows.

Table 4.5. Flow biotope changes during 2-year flood flows.

Flow Biotope	Count pre-change	Proportion of overall habitat pre-change (%)	Count post-change	Proportion of overall habitat post-change (%)
Pool	2640	14	2672	15
Glide	2811	15	6010	34
Run	3134	17	3170	18
Riffle	8682	47	4994	28
Rapid	1282	7	793	5

4.3.3. Shear Stress

Figure 4.14 shows the change in shear stresses observed pre and post restoration for a 2-year return period flood flow. This larger flow was used to investigate the impact of the restoration measures on shear stresses, as it is larger events that are most likely to be geomorphologically significant. The modelled shear stress results suggest there is a reduction of in-channel shear stresses associated with the post-restoration scenario. This reduction is attributed to a larger volume of water escaping onto the floodplain in the post-restoration scenario, as opposed to being contained within channel. The in-channel structures may also contribute towards the reduced in-channel shear stresses observed.

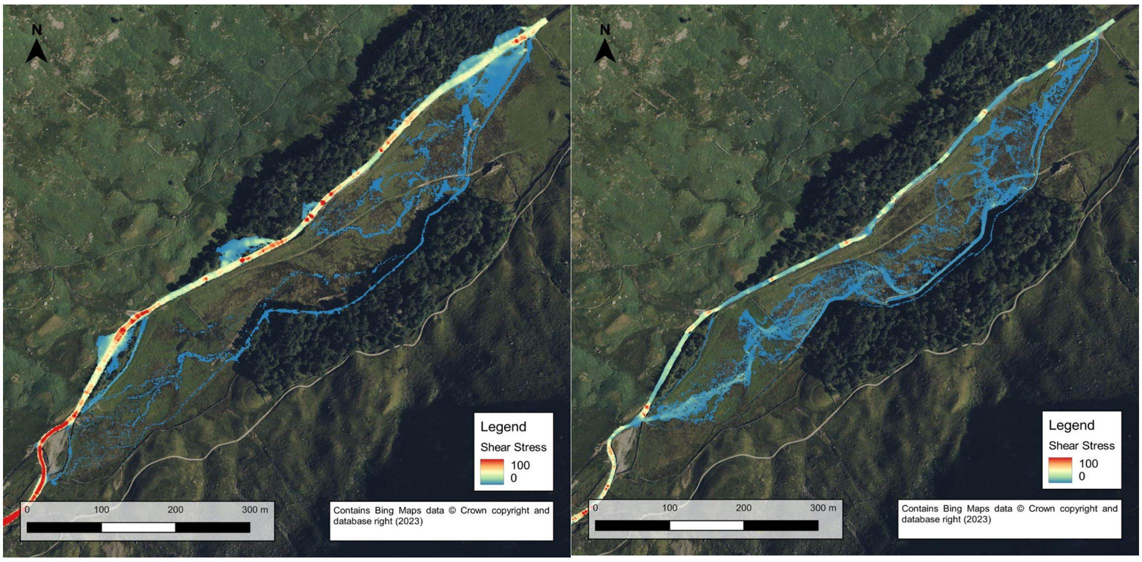


Figure 4.14. Shear stresses observed pre (left) and post (right) restoration scenario during 2-year flood flows.

4.3.4. Habitat

Fuzzy-logic habitat modelling was conducted to assess the impact of the restoration measures on habitat to support the various life stages of Brown trout through the study reach. The results of this modelling show that the restoration led to increases in total habitat supporting some life-stages and reductions in total habitat supporting other life-stages (Table 4.6, 4.7).

Adult habitat is shown to reduce very slightly during low Q95 flows, however increased slightly during Q10 flows.

Juvenile 0+ habitat is shown to increase by the greatest quantity post-restoration, with large increases observed during Q10 flows with smaller increases observed during Q95 flows. It should be recognised however that much of the additional 0+ habitat is located in newly wetted floodplain areas, which whilst offering suitable depths and velocities, does pose a risk of fish becoming stranded as water levels subside.

Juvenile 1+ habitat is also shown to increase across the larger Q10 flow scenarios, however reduced slightly during low Q95 flows. This reduction in 1+ fish habitat during Q95 flows is likely linked to their improved swimming abilities and preference for deeper areas, which offer improved cover from predation.

The increased floodplain connection associated with the post-restoration scenario is also shown to increase the quantity of refuge habitat available during larger Q10 and during 2-year flood flows.

Table 4.6. Total Habitat Suitability Index (HSI)

	Q95 pre	Q95 post	Q10 pre	Q10 post	2-year flood pre	2-year flood post
Adult	474	460	1,134	1,838	NA	NA
1+	992	860	1,475	2,422	NA	NA
0+	1,390	1,508	1,113	3,007	NA	NA
Spawning	398	378	2,310	2,795	NA	NA
Refuge	NA	NA	2,208	6,371	7,084	7,295

Table 4.7. Habitat Quality Index (HQI)

	Q95 pre	Q95 post	Q10 pre	Q10 post	2-year flood pre	2-year flood post
Adult	10.5	7.4	18.2	16.3	NA	NA
1+	22.1	13.8	23.7	21.5	NA	NA
0+	30.9	24.1	17.9	26.7	NA	NA
Spawning	8.8	6.1	37.1	24.9	NA	NA
Refuge	NA	NA	38.3	43.4	37.8	41.4

4.4. Conclusions

Hydraulic modelling was used to investigate the impact of various restoration measures on Grisdale Beck, a single-thread river channel located in a predominantly rural catchment. Restoration measures included the creation of in-channel riffle-rapids and point bars, together with bank lowering and floodplain reconnection.

The results of this modelling show that the restoration measures were successful in improving floodplain connectivity, with increased floodplain activation observed during Q10 and Qmed flows. The restoration was observed to lead to a shift towards lower energy biotopes across the range of flows modelled.

Further hydraulic habitat analysis shows the restoration led to increases in habitat to support many stages of the Brown trout lifecycle, particularly during Q10 and 2-year flood flows. The quantity of juvenile 0+ habitat was shown to increase the most, although it should be recognised that habitat located on floodplain areas poses the risk of fish becoming stranded as river levels recede. The quantity of refuge habitat is also observed to increase post-restoration, with newly activated floodplain areas providing suitable areas for fish to escape high velocities during larger flood flows.

5. Scarrow

5.1. Background

Scarrow Beck is artificially straight, with straightening pre-dating the earliest available maps in 1890. The straightening is likely to have been undertaken to better drain surrounding agricultural land. There has been very little change to the planform over the last 130-135 years based on analysis of the current and the first epoch Ordnance Survey Maps.

The watercourse is likely to have been deepened artificially that has consequently exacerbated its disconnection to the floodplain. The restoration site displays subtle topographic variation with land rising to the north west. No palaeo-channel features were discernible across the site; instead, the central and eastern zones form lower areas representing the best opportunity zones for floodplain lowering and wetland development. The channel is obscured by vegetation with strong growth of marginal plants dominated by wetland species, especially where low berms are present and areas of aquatic vegetation growing mostly across the bed of the channel where fines dominate but also seen in more gravelly reaches. Despite being grossly over-deep, the bed of the channel displays some morphologic variation. Gravels are partially covered in a veneer of silt, but it is likely that this is flushed during higher winter flows.

The presence of areas of gravels suggests that the watercourse is occasionally energetic despite flowing over low slopes. This is partially influenced by the shape of the inset channel which concentrates flood flows within the channel; this morphology will be subject to change with floodplain reconnection. Change would be due to deposition, and to a degree this will be offset by flow splitting across the floodplain, moving some suspended sediment away from the main channel.

The National Fish Population database indicates the following fish species are present within the Scarrow Beck –

- 10-spined stickleback *Pungitius pungitius*)
- 3-Spined Stickleback (*Gasterosteus aculeatus*)
- Brook Lamprey > ammocoete (*Lampetra planeri)*
- Brown / sea trout (*Salmo trutta)*
- Stone Loach (*Barbatula Barbatula*)

The high levels of floodplain disconnection offered a strong justification for developing a floodplain reconnection scheme within the study area.

The restoration design included the following measures:

- riffle introduction,
- wetland creation,
- anastomosing sections
- floodplain reconnection

5.2. Site Specific Methodology

5.2.1. Model Schematisation

A HEC-RAS 2D model of the study area was developed for pre and post scheme representation (Figure 5.1). Environment Agency LiDAR data flown in 2020 were used to create the pre-change DTM, whilst a client supplied drone survey was used to create the post-change DTM.

A mesh resolution of 4m by 4m was used. Additionally, the sub-grid scale feature in HEC-RAS 2D computes storage-level and conveyance=level relationships for each cell face from the underlying DTM (in this case 1m by 1m LiDAR). As the conveyance tables are across cell faces, in areas where there is significant topographic level change, a break-line along the face ensures flow is unable to progress until the topographic crest level is overtopped. Break-lines were included for significant topographic crests, along with break-lines along the river channel to ensure the flows are perpendicular to the cell faces in the direction of greatest flow.

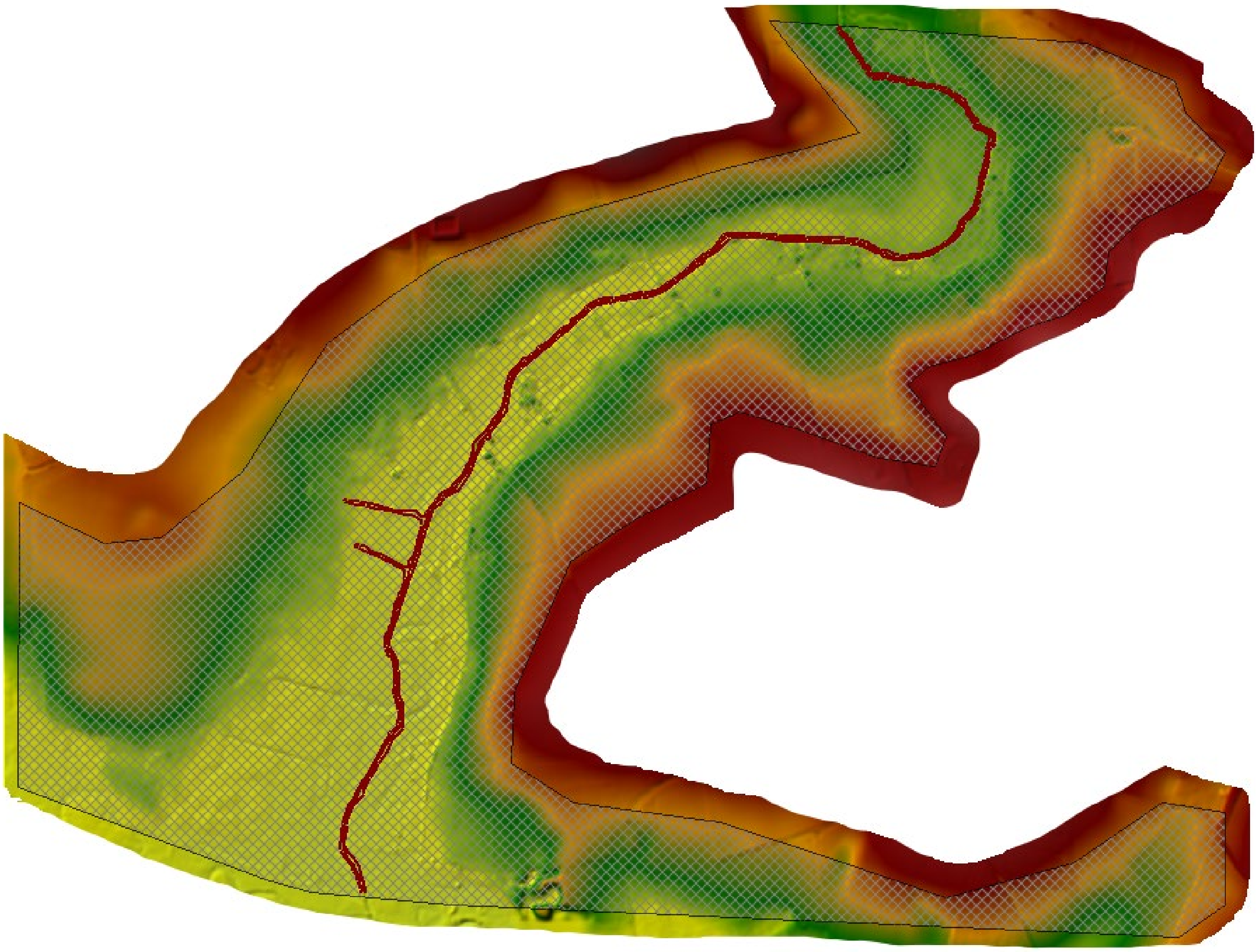


Figure 5.1 HEC-RAS 2D - grid set-up of the study site.

5.2.2. Inflows

The flows used in the modelling are shown in Table 5.1. The low flows for Q95 and Q10 were derived using Low Flows 2 software. The 2-year return period flows were estimated using Flood estimation Handbook techniques.

Table 5.1 Inflows to the model.

Flow Statistic	Flow (m^3/s)
Q95 (summer flow)	0.2
Q10 (winter flow)	0.7
1 in 2 year event	1.65

5.2.3. Manning's roughness

Satellite imagery was used to inform the choice of Manning's n values used within the hydraulic model. Values of 0.06 and 0.05 were used to represent the channel and floodplain roughness respectively for pre and post change scenarios. The Manning's n value of 0.05 was chosen for the landcover at the study site – estimated as 'cultivated crops' - as this value is suggested within HEC-RAS documentation.

5.2.4. Pre and post change representation

The post change DTM was generated from drone survey data, which captured the restoration measures implemented at the study site. Freely available 2020 LiDAR data supplied by the Environment Agency was used to represent pre-change conditions.

5.3. Results

5.3.1. Hydraulic Conditions

Q95

The hydraulic modelling results suggest a slightly improved connection to the floodplain at Q95, with more water escaping the channel in particular towards the south of the study reach (Figure 5.2).

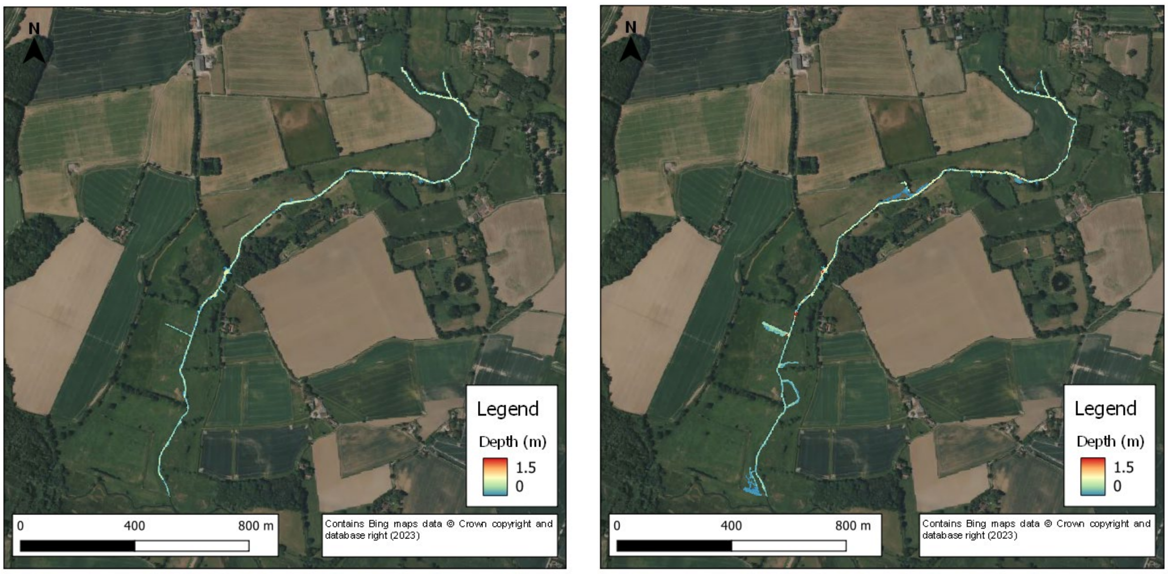


Figure 5.2 Depth pre and post restoration scenarios during Q95 flow.

Q10

Figure 5.3 shows an improved connection to the floodplain, with greater channel-floodplain connectivity observed in the Q10 scenario.

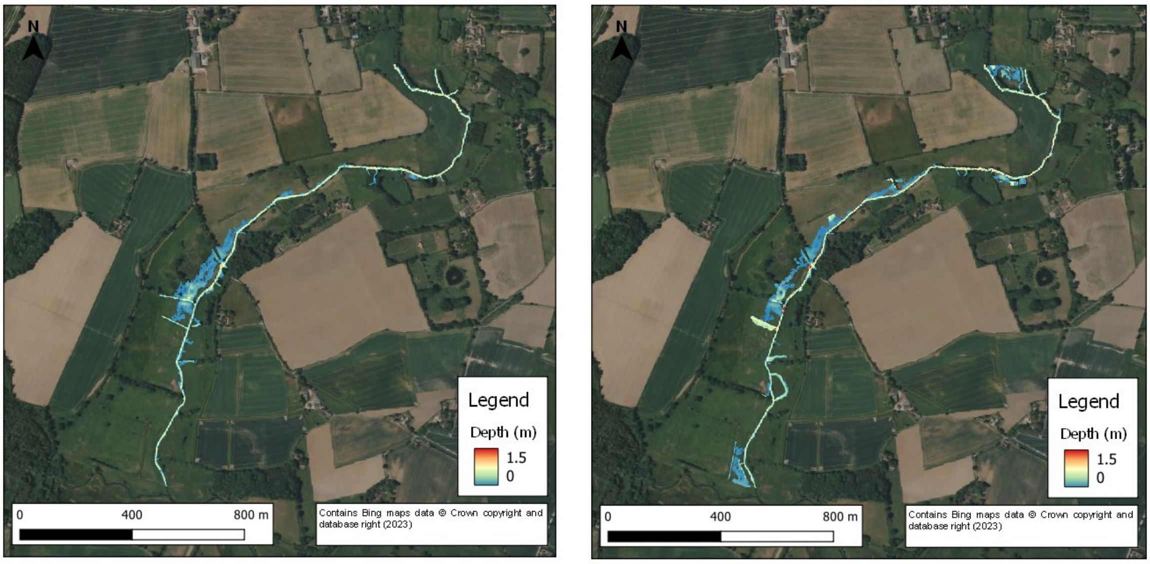


Figure 5.3 Depth pre and post restoration scenarios during Q10 flow.

1 in 2 year event

Figure 5.4 shows that in general a greater area of floodplain is wet in the post change scenario compared to the pre change scenario.

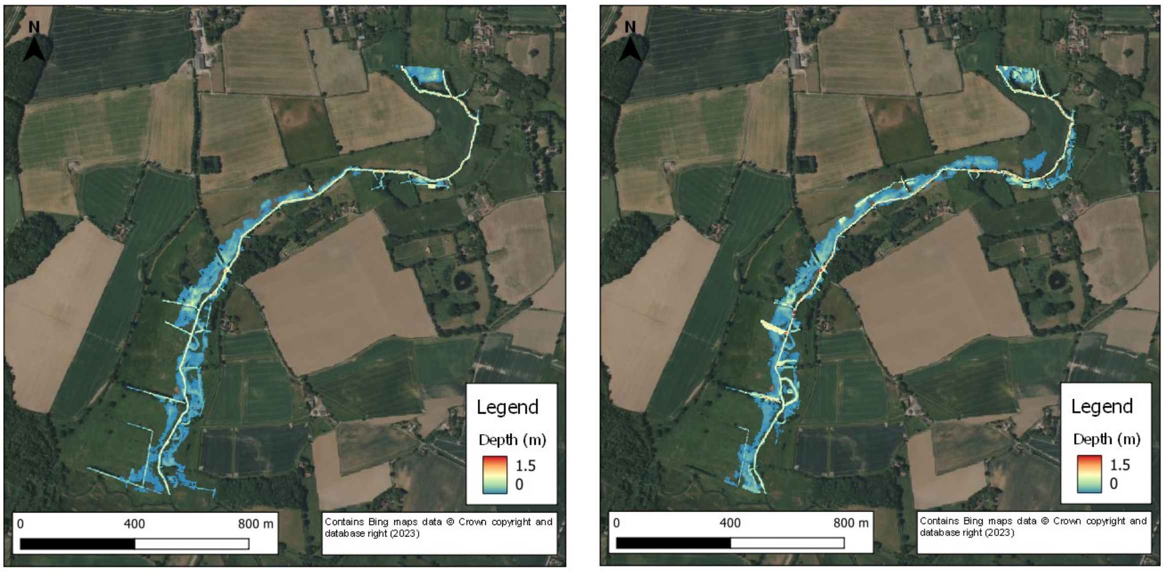


Figure 5.4 Depth pre and post restoration scenarios during 1 in 2 year event flow.

5.3.2. Flow Biotopes

Q95

The flow biotopes through the reach at Q95 are presented in Figure 5.5, Figure 5.6 and Table 5.2. The flow biotope maps show little change in biotype diversity pre and post restoration.

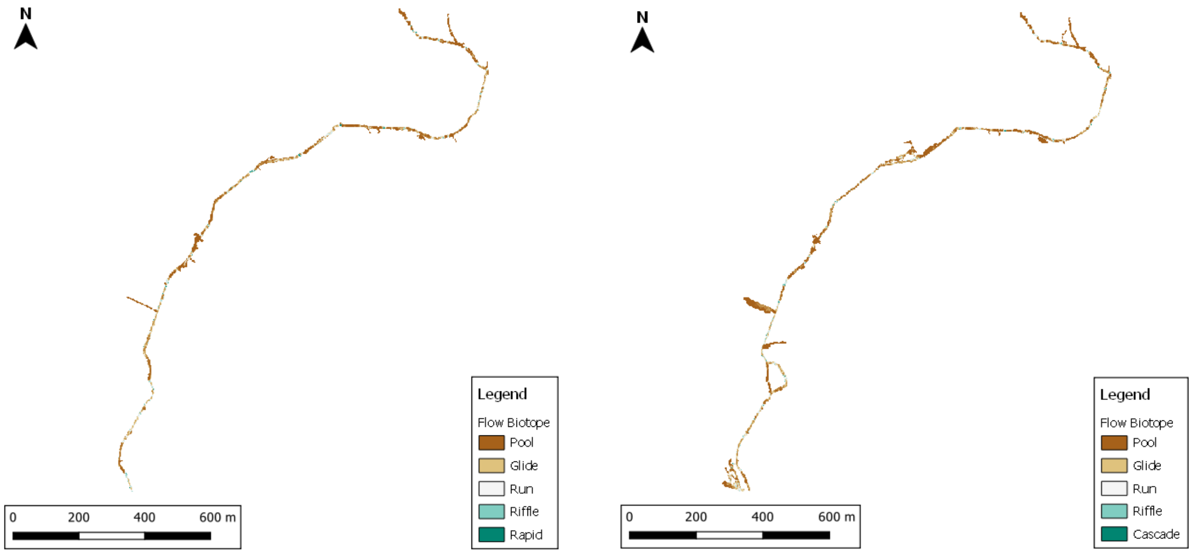


Figure 5.5 Flow biotype pre (left) and post (right) restoration scenarios during Q95 flow.

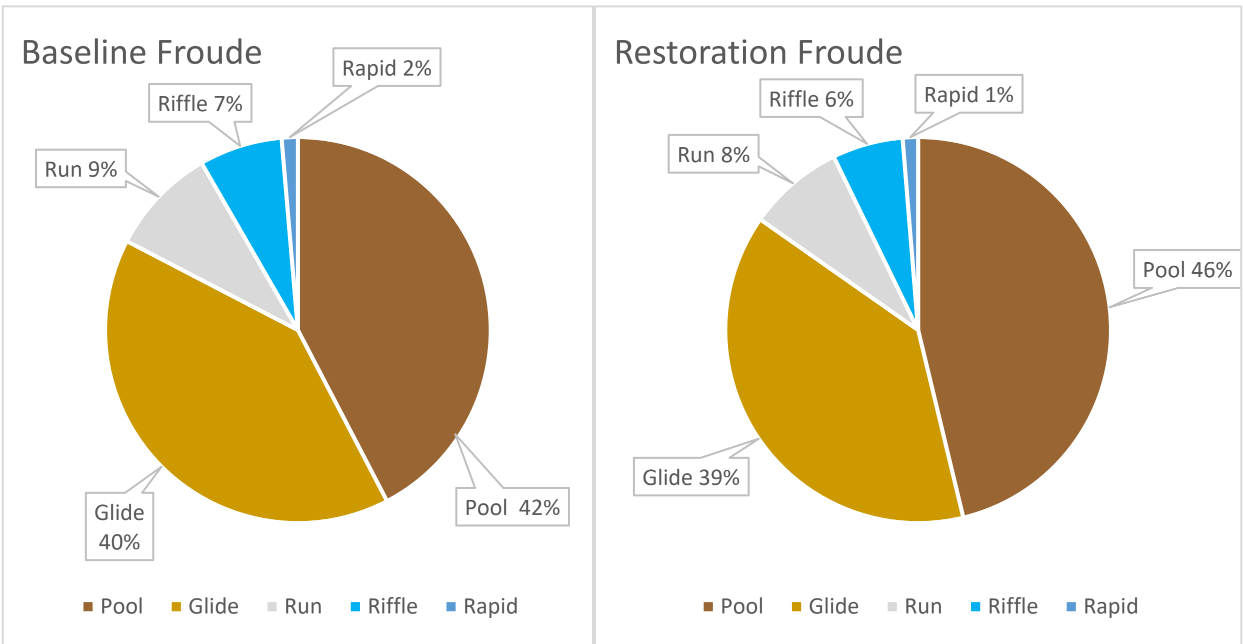


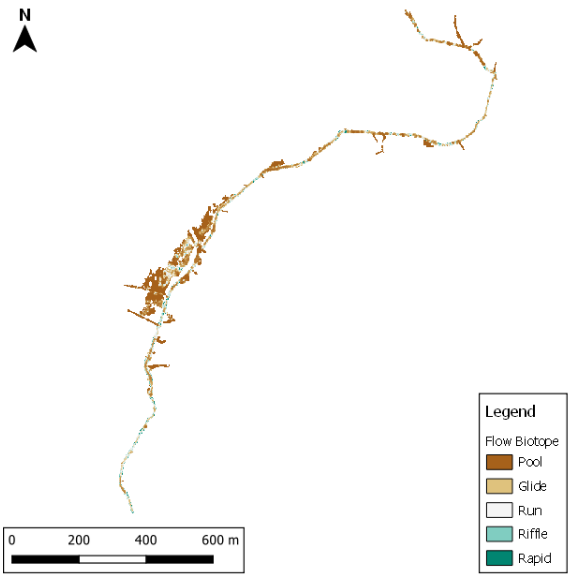
Figure 5.6 Proportion of each flow biotope pre (left) and post (right) restoration during a Q95 flow.

Table 5.2 Proportion of each flow biotope observed during Q95 flow.

Flow Biotope	Count pre-change	Proportion of overall habitat pre-change (%)	Count post-change	Proportion of overall habitat post-change (%)
Pool	1,348	42.3	1,474	46.2
Glide	1,282	40.3	1,227	38.5
Run	288	9.0	257	8.1
Riffle	222	7.0	189	5.9
Rapid	43	1.4	41	1.3

Q10

The flow biotopes through the reach in the Q10 scenario are presented in Figure 5.7, Figure 5.8 and Table 5.3. The flow biotope maps show that low energy biotope type dominate, however, there is a two-fold increase in pool biotope type pre and post restoration, and a similar reduction in glide. Figure 5.7 shows that much of the pool habitat is located on the floodplain.



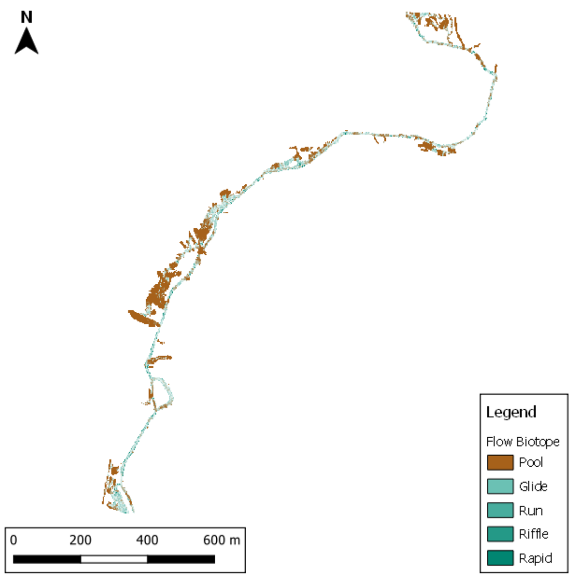


Figure 5.7 Flow biotype pre (left) and post (right) restoration scenarios during Q10 flow.

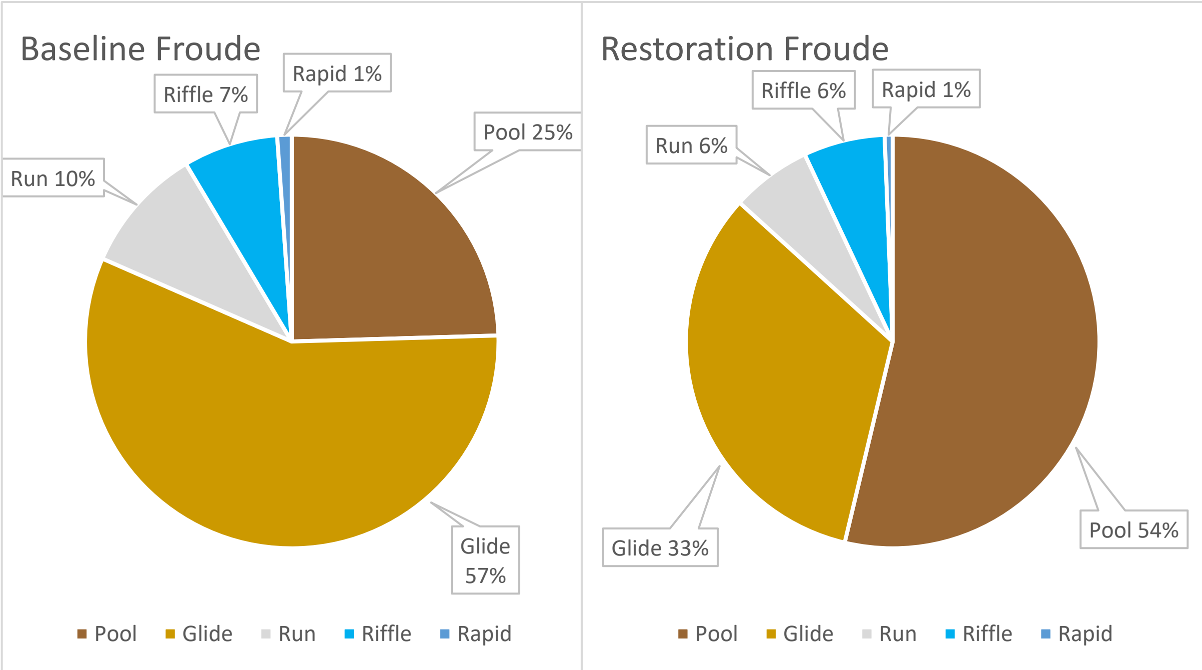


Figure 5.8 Proportion of each flow biotope pre (left) and post (right) restoration during a Q10 flow.

Table 5.3 Proportion of each flow biotope observed during Q10 flow.

Flow Biotope	Count pre-change	Proportion of overall habitat pre-change (%)	Count post-change	Proportion of overall habitat post-change (%)
Pool	780	24.5	1,720	53.7
Glide	1,813	57.0	1,056	33.0
Run	314	9.9	201	6.3
Riffle	236	7.4	204	6.4
Rapid	36	1.1	20	0.6

1 in 2 year event

The flow biotopes through the reach during the 1 in 2 year event are presented in Figure 5.9, Figure 5.10 and Table 5.4. The flow biotope maps indicate low energy biotope types still dominate even at higher flow. A slight increase in pool biotope is observed post restoration, with a corresponding reduction in glide biotope type. Again, much of the pool biotope is found on the floodplain. An increase in riffle habitat is also observed.

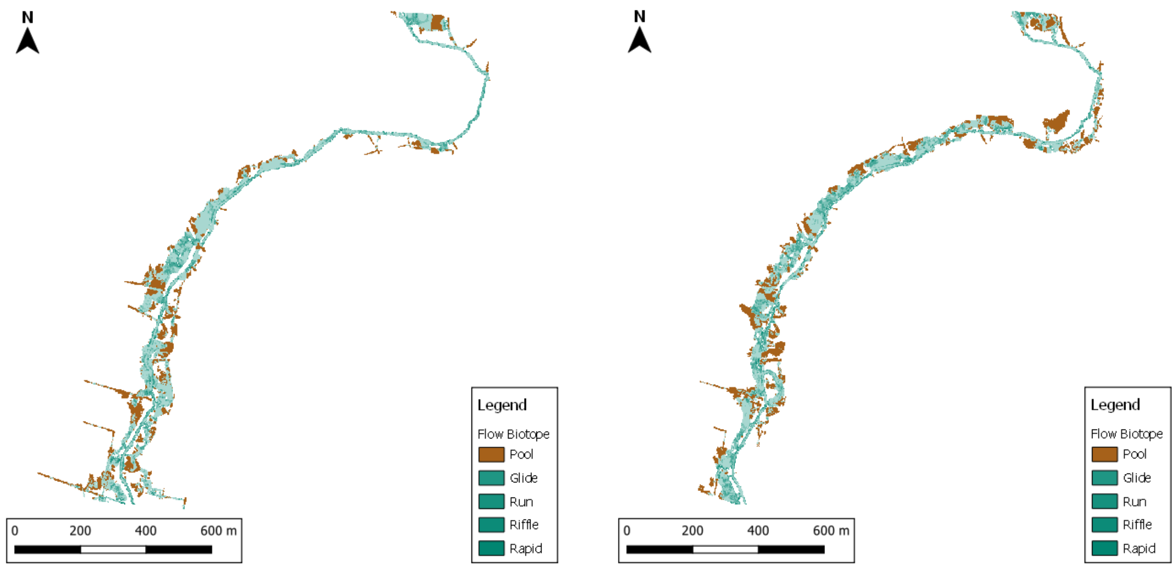
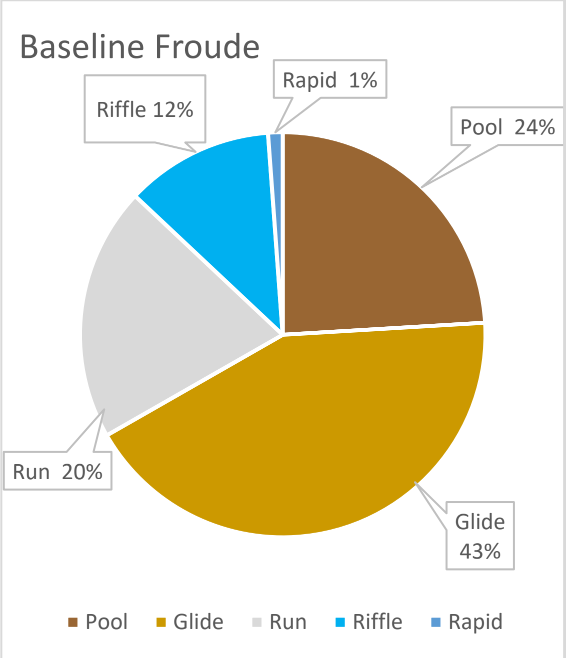


Figure 5.9 Flow biotype pre (left) and post (right) restoration scenarios during 1 in 2 year event flow.



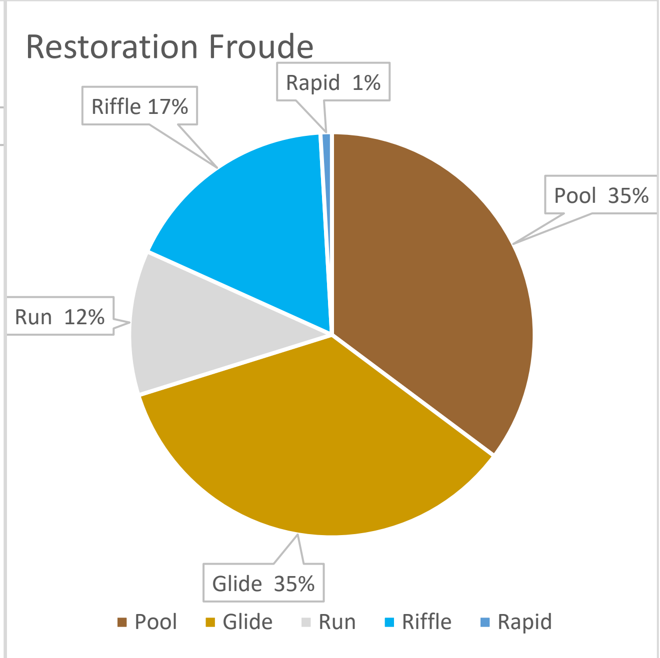


Figure 5.10 Proportion of each flow biotope pre (left) and post (right) restoration during a 1 in 2 year event flow.

Table 5.4 Proportion of each flow biotope observed during 1 in 2 year event flow.

Flow Biotope	Count pre-change	Proportion of overall habitat pre-change (%)	Count post-change	Proportion of overall habitat post-change (%)
Pool	767	24.1	1,123	35.2
Glide	1361	42.7	1,115	35.0
Run	647	20.3	369	11.6
Riffle	377	11.8	553	17.3
Rapid	37	1.2	29	0.9

5.3.3. Shear Stress

1 in 2 year event flow.

Figure 5.11 shows the change in shear stresses observed pre and post restoration for a 2-year return period flood flow. This larger flow was used to investigate the potential impact of the restoration measures on shear stresses as it is larger events that are most likely to be geomorphologically significant. The modelling suggests shear stress appears to change very little between pre and post restoration scenarios. This might be expected, given the relatively similar extent of flooding on the floodplain.

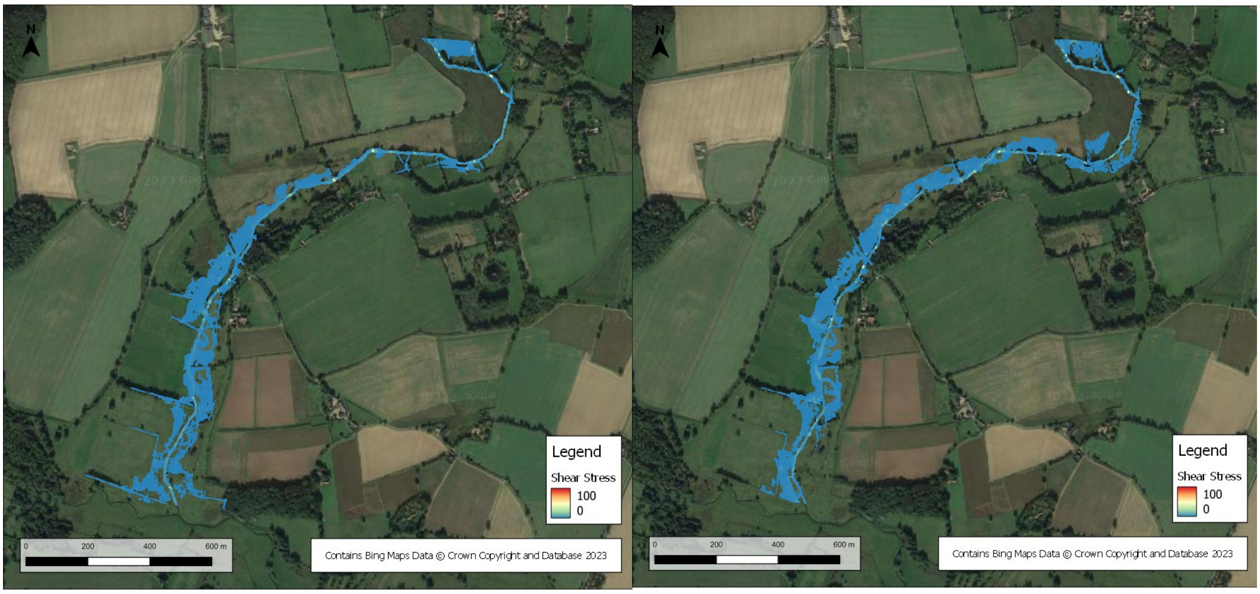


Figure 5.11 Shear stress pre (left) and post (right) restoration during 1 in 2 year event flow.

5.3.4. Fish Habitat

Fuzzy-logic habitat modelling was conducted to assess the impact of the restoration measures on habitat to support the various life stages of Brown trout through the study reach.

The results of this modelling show that the restoration measures generally had a positive impact on total habitat to support the various life stages of Brown trout throughout the study reach. During low Q95 flows, adult and 1+ habitat is shown to increase slightly, while 0+ habitat is shown to increase most significantly. Slight reductions in habitat quality were observed for adult and 1+ trout.

During larger Q10 flows, habitat modelling results suggest that restoration activities increased adult, 1+ and 0+ habitats. This increase in overall habitat to support various life stages may be due to the increased pool biotope, which increased two-fold post restoration. The quality of the habitat was broadly similar pre and post restoration (Table 5.5, 5.6).

In the 2-year flood event, a slight increase in refuge habitat was observed (no change to habitat quality).

Table 5.5 Habitat Suitability Index (HSI)

	Q95 pre	Q95 post	Q10 pre	Q10 post	2-year flood pre	2-year flood post
Adult	1,946	1,995	2,529	2,957	NA	NA
1+	1,409	1,415	2,490	2,722	NA	NA
0+	1,285	1,618	2,478	2,776	NA	NA
Spawning	968	1,062	1,753	1,851	NA	NA
Refuge	NA	NA	4,442	5,004	11,749	12,491

Table 5.6 Habitat Quality Index (HQI)

	Q95 base	Q95 post	Q10 base	Q10 post	2-year flood pre	2-year flood post
Adult	42.5	35.5	24.2	24.4	NA	NA
1+	30.8	25.1	23.8	22.4	NA	NA
0+	28.1	28.8	23.7	22.9	NA	NA
Spawning	21	18.9	16.8	15.3	NA	NA
Refuge	NA	NA	42.5	41.2	42.6	42.1

5.4. Conclusions

Scarrow Beck is an artificially straightened, over deepened watercourse with a shallow gradient. The restoration design included the following measures:

- riffle introduction,
- wetland creation,
- anastomosing sections
- floodplain reconnection

The results suggest that the restoration techniques implemented at the study site have had a generally positive effect on floodplain connection and fish habitat. The greatest improvement is observed at Q10 flows, with floodplain reconnection and fish habitat increasing across all life stages.

6. Long Preston

6.1. Background

The River Ribble at the Long Preston Deeps Site of Special Scientific Interest (SSSI) is an active single thread river. It is characterised by an active gravel bed with some gravel bars in the northern half of the SSSI area, losing energy and becoming increasingly silty downstream (to the south of The Crook). These river characteristics conform with changes in local controls on channel form, with steeper gradients characterising the active/incipient wandering channel. These decline to the low gradients characterising the single thread channel as it flows across old lake sediments.

Under naturalised/unconstrained conditions, the channel is likely to exhibit depositional features composed of gravels and some cobbles, with relatively little fine sediment infilling of these features as a result of the moderately energetic flow conditions associated with this river type. Bank erosion and planform change would be moderate and the hydromorphological diversity high with varied hydraulic habitat units created by the riffle–run–pool morphology common to this river type.

Pressures that are constraining the natural wandering characteristics of the river at the site include:

- increased channel capacity during floods – flood embankments
- a modified channel – through past straightening and river training (that is, bank protection)
- a heavily managed floodplain – there is significant livestock access to the channel

The National Fish Population database indicates a range of fish species are present within the River Ribble including:

- 3-Spined Stickleback (*Gasterosteus aculeatus*)
- Atlantic Salmon (*Salmo salar)*
- Brook Lamprey (*Lampetra planeri)*
- Brown / sea trout (*Salmo trutta)*
- Bullhead (*Cottus gobio)*
- European Eel (*Anguilla Anguilla)*
- Grayling (*Thymallus thymallus*)
- Gudgeon (*Gobio gobio*)
- Minnow (Phoxinus phoxinus)
- Stone loach (*Barbatula barbatula*)

Several different restoration techniques have been implemented at the site from 2009 through to 2021:

- Berm insertion.

- Bifurcation.
- Blocking of a tributary (for the purpose of wetland creation).
- Backwater reconnection.
- Setting back of embankments.

More detail of the interventions are provided in Figures 6.2 to 6.7.

6.2. Site Specific Methodology

6.2.1. Model schematisation

A HEC-RAS 2D model of the study area was developed for pre and post scheme representation (Figure 6.1).. Freely accessible LiDAR data from 2009 and 2022 were used to model baseline and post-intervention conditions respectively.

A mesh resolution of 5.5m by 5.5m was used. Additionally, the sub-grid scale feature in HEC-RAS 2D computes storage-level and conveyance=level relationships for each cell face from the underlying DTM (in this case 1m by 1m LiDAR). As the conveyance tables are across cell faces, in areas where there is significant topographic level change, a break-line along the face ensures flow is unable to progress until the topographic crest level is overtopped. Break-lines were included for significant topographic crests, along with break-lines along the river channel to ensure the flows are perpendicular to the cell faces in the direction of greatest flow.

The locations of interventions that have been implemented at the study area can be seen in Figure 6.2, while more detail is provided in Figures 6.3 – 6.7.

6.2.2. Inflows

There is no gauged flow data for the survey site, therefore mean daily flow data recorded at the gauge located at Arnford (71011) were used. The Arnford gauge is located approximately 4km downstream of the case study site, therefore the flow data were scaled by 0.81 the reflect the reduced flows expected at Long Preston. The scaled flows used in the modelling can be seen in Table 6.1.

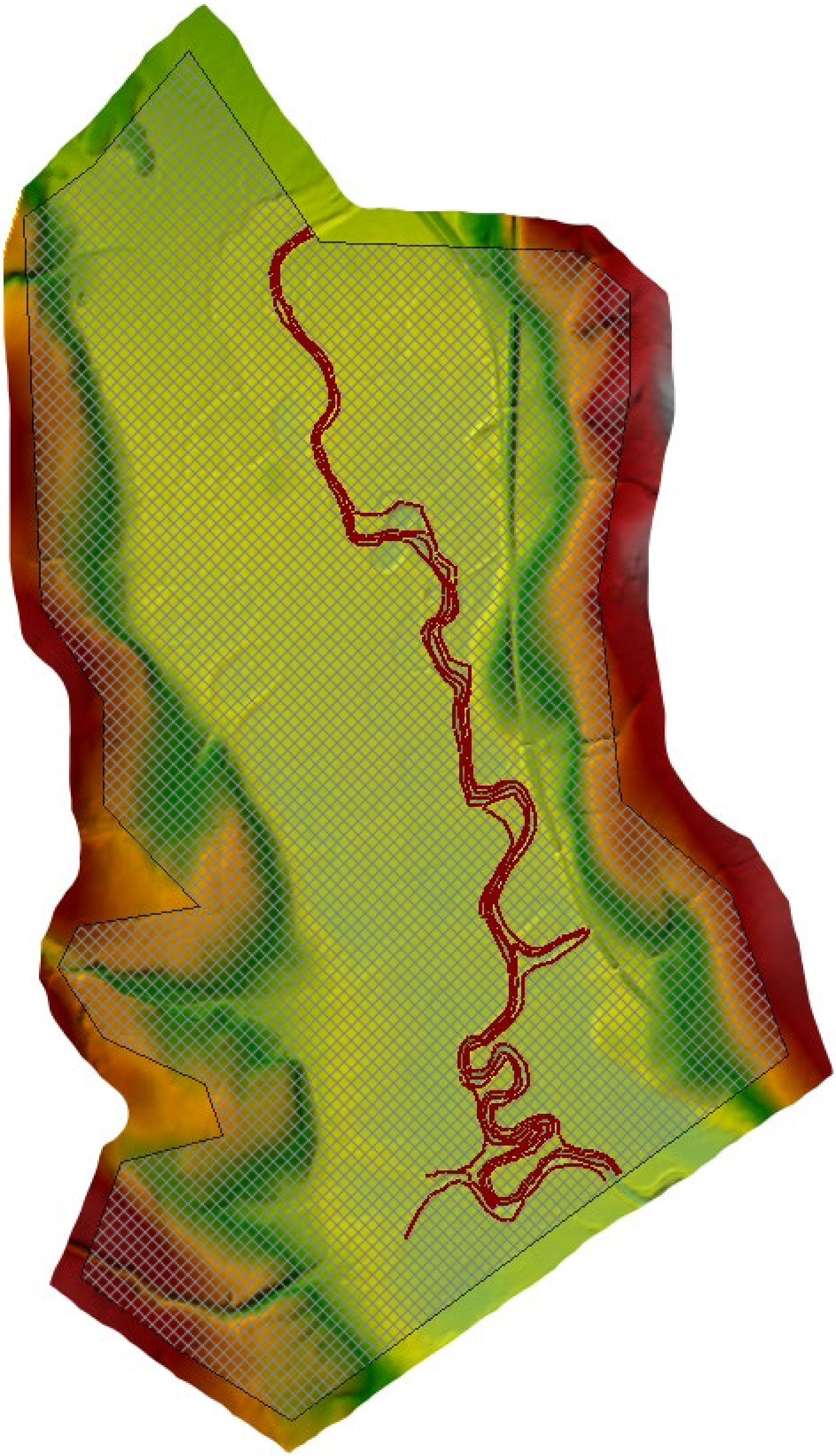


Figure 6.12 HEC-RAS 2D - grid set-up of the study site.

Table 6.7 Inflows to the model.

Scenario	Flow (m^3/s)
Q95 (summer flow)	0.39
Q10 (winter flow)	16.36
1 in 2 year event	99.27

6.2.3. Manning's roughness

Satellite imagery was used to inform the choice of Manning's n values used within the hydraulic model. Values of 0.06 and 0.05 were used to represent the channel and floodplain roughness respectively for pre and post change scenarios.

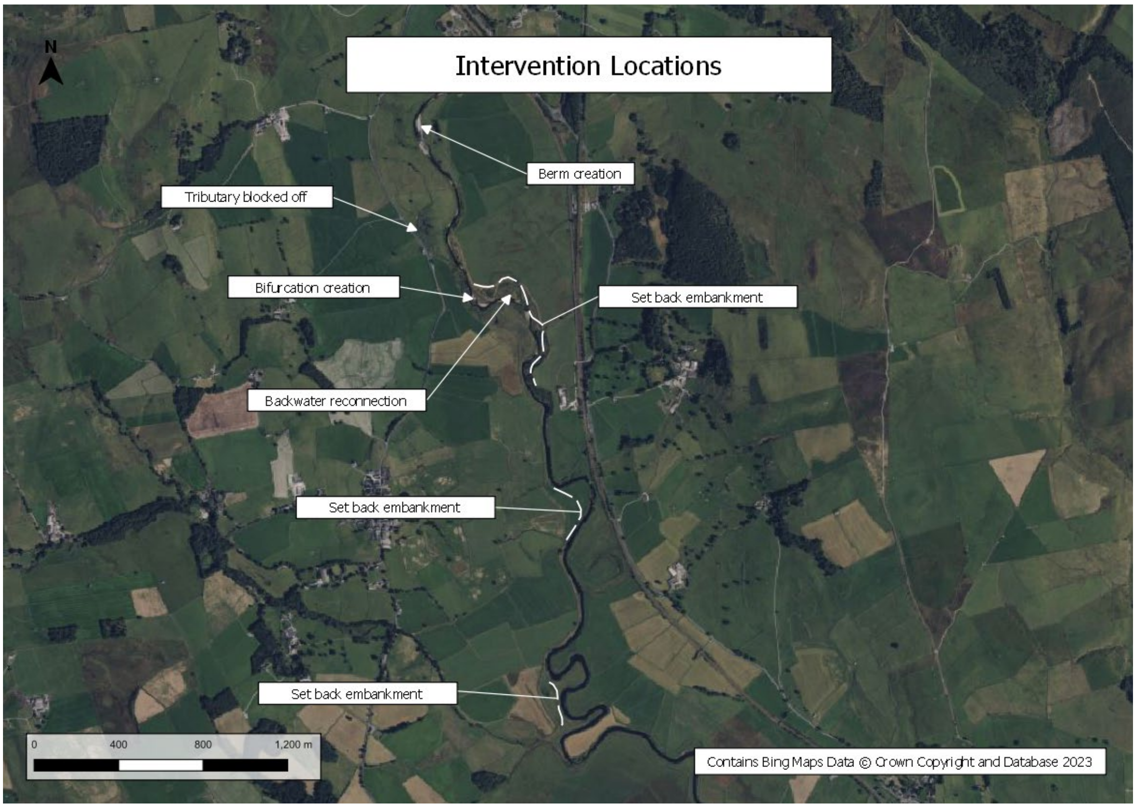


Figure 6.13 location of interventions at the study site. The white dashed lines denote the original positions of the embankments.

The LiDAR data show that restoration techniques implemented after 2011 are in place.

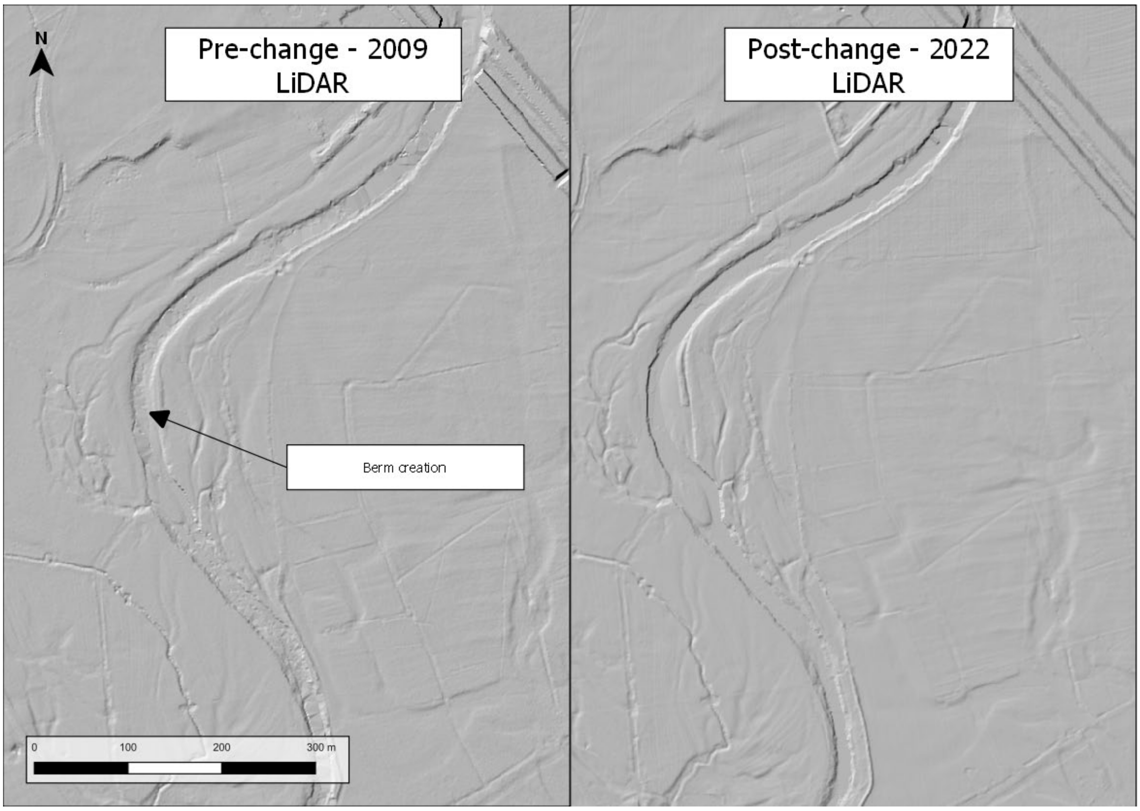


Figure 6.14 River channel pre (left) and post (right) berm creation.

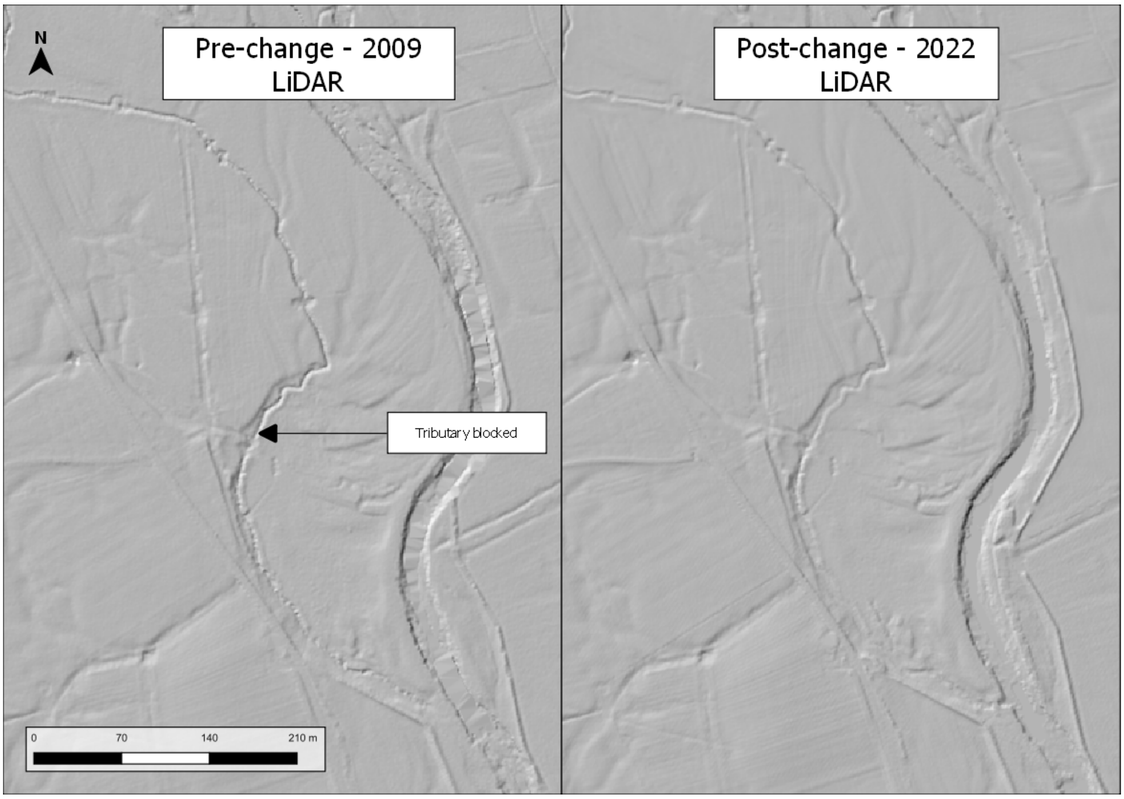


Figure 6.15 Tributary pre (left) and post (right) blocking.

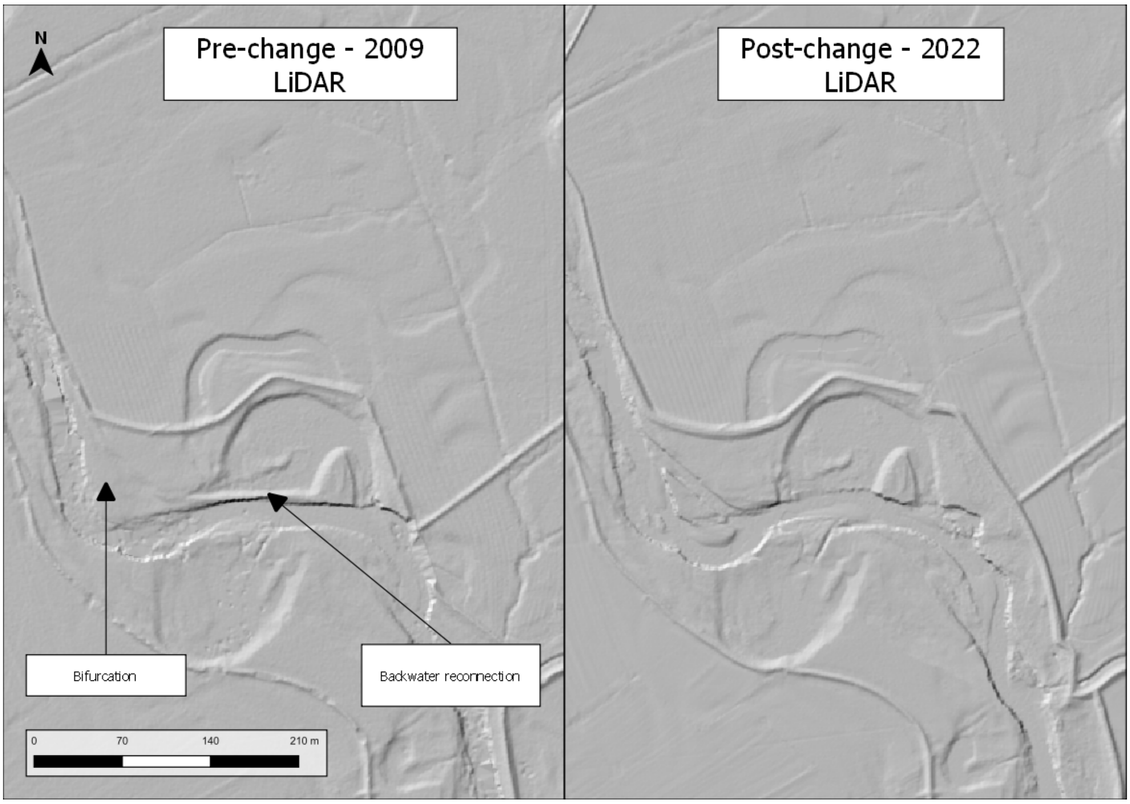


Figure 6.16 River channel pre (left) and post (right) bifurcation and backwater connection.

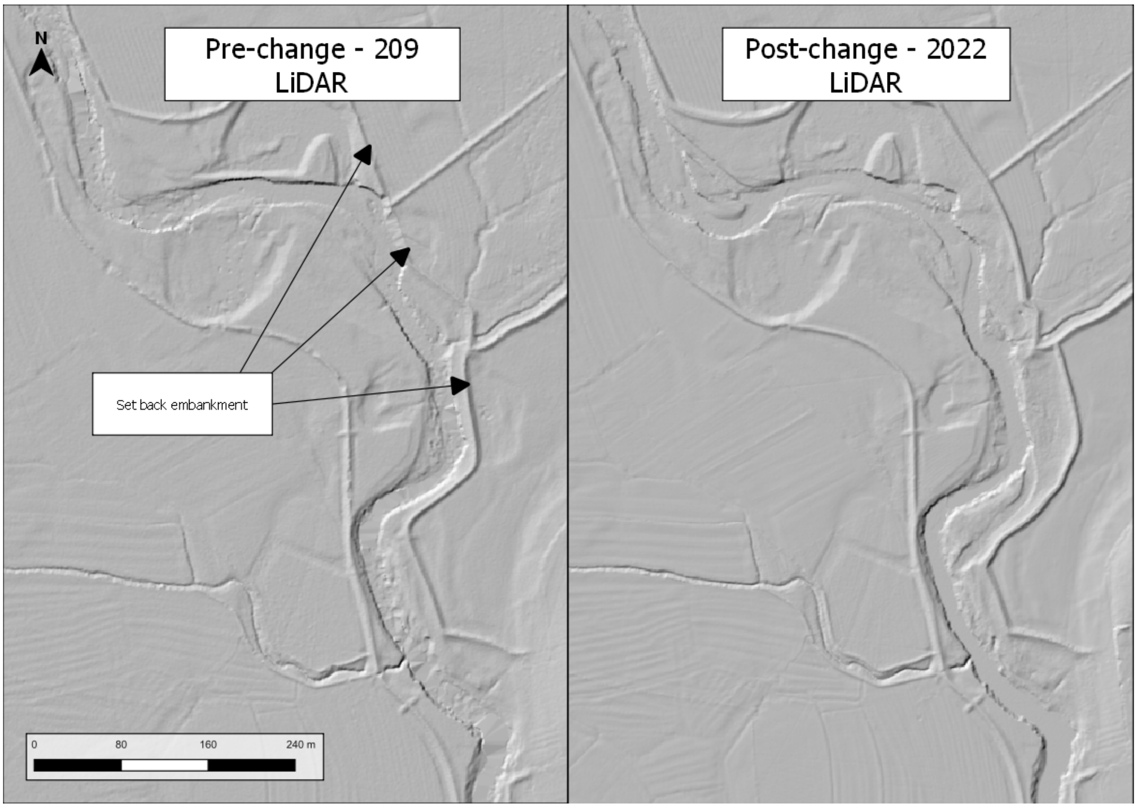


Figure 6.17 mid-reach embankments pre (left) and post (right) setting back.

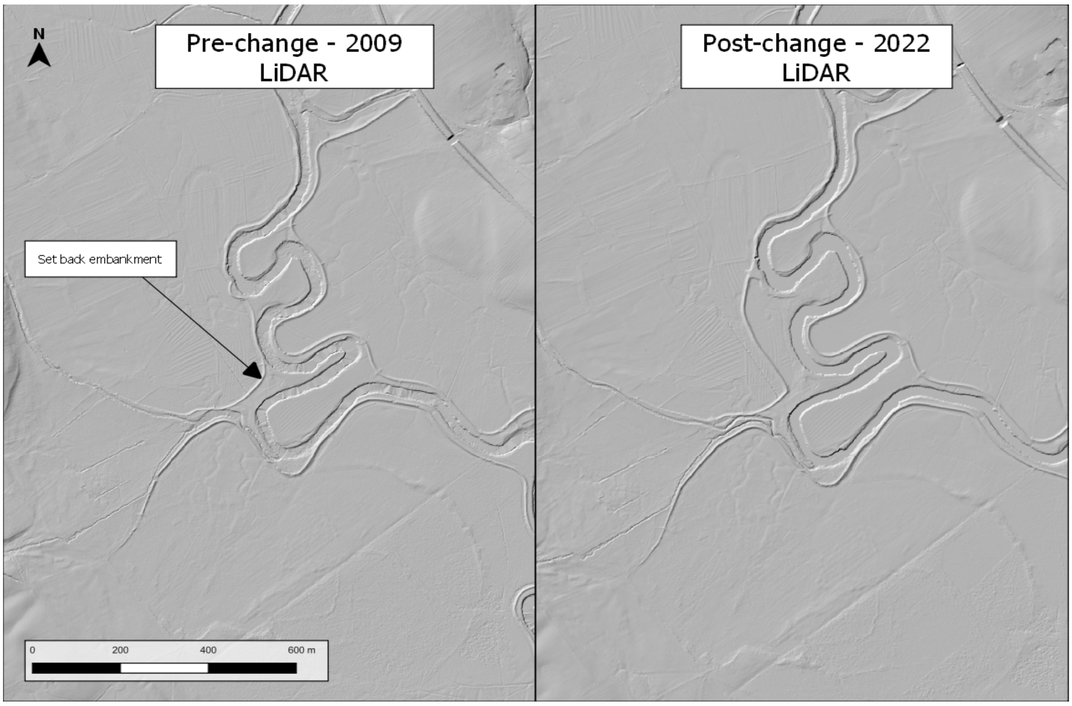


Figure 6.18 lower-reach embankments pre (left) and post (right) setting back.

6.3. Results

6.3.1. Hydraulic Conditions

Q95

The hydraulic modelling results show little change in the overall wetted area post restoration at Q95 (Figure 6.8). This is to be expected as the restoration measures were largely focussed on improving channel-floodplain connectivity at higher flows.

Figure 6.19 Modelled depth pre (left) and post (right) restoration at Q95 flow.

Q10

The hydraulic modelling results show a modest increase in the overall wetted area post restoration. This increase is due to the improved connection to the floodplain as a result of setting back embankments (Figure 6.9).

Figure 6.20 Modelled depth pre (left) and post (right) restoration at Q10 flow.

1 in 2 Year event

The hydraulic modelling results show little change in the overall wetted area post restoration in the 1 in 2 year event (Figure 6.10). The flow is so large in this event that all of the embankments and features are overwhelmed.

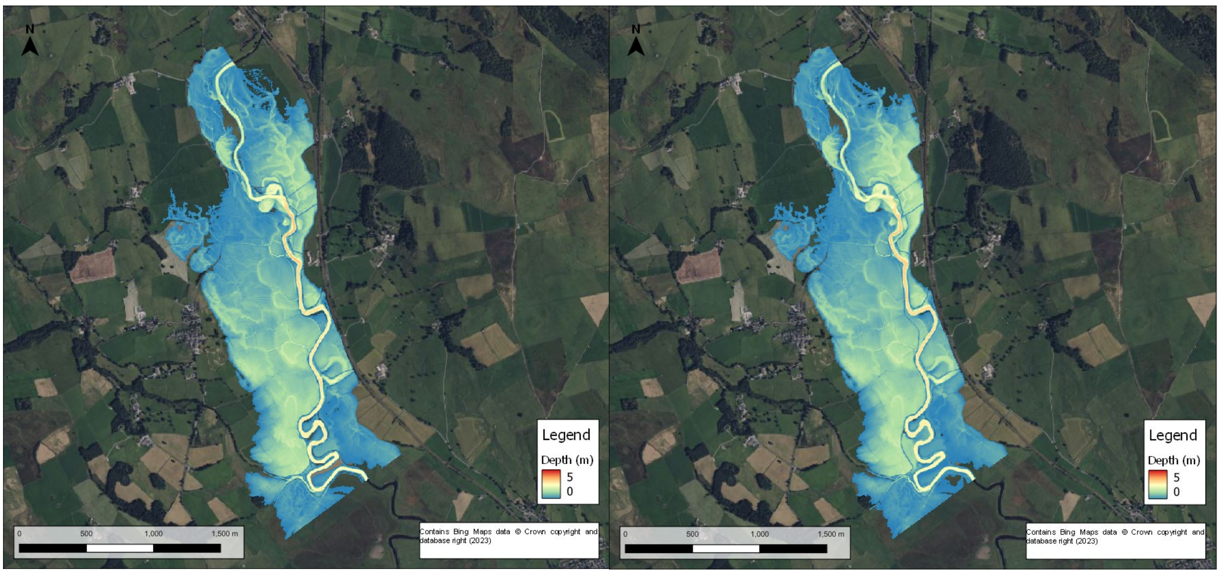


Figure 6.21 Modelled depth pre (left) and post (right) restoration at 1 in 2 year event flow.

6.3.2. Flow Biotopes

The flow biotopes through the reach during Q95 flow are presented in Figure 6.11, 6.12 and Table 6.2. The flow biotope maps show little change in biotype diversity pre and post restoration. This is to be expected as the restoration measures were largely focussed on improving channel-floodplain connectivity at higher flows.

Q95

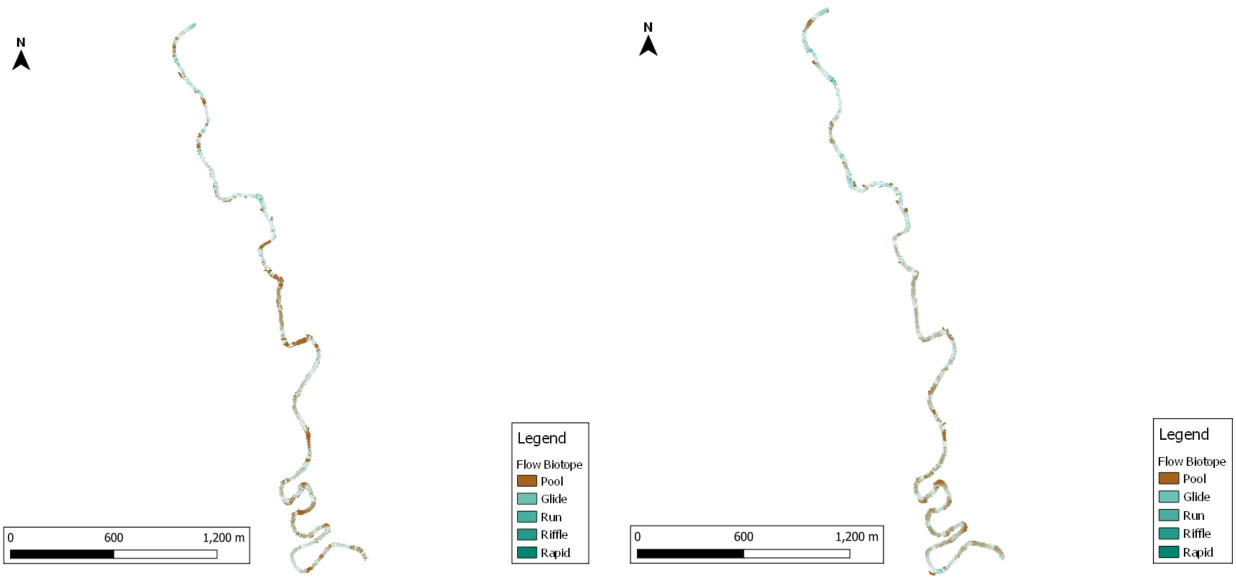


Figure 6.22 Flow biotope pre (left) and post (right) restoration at Q95 flow.

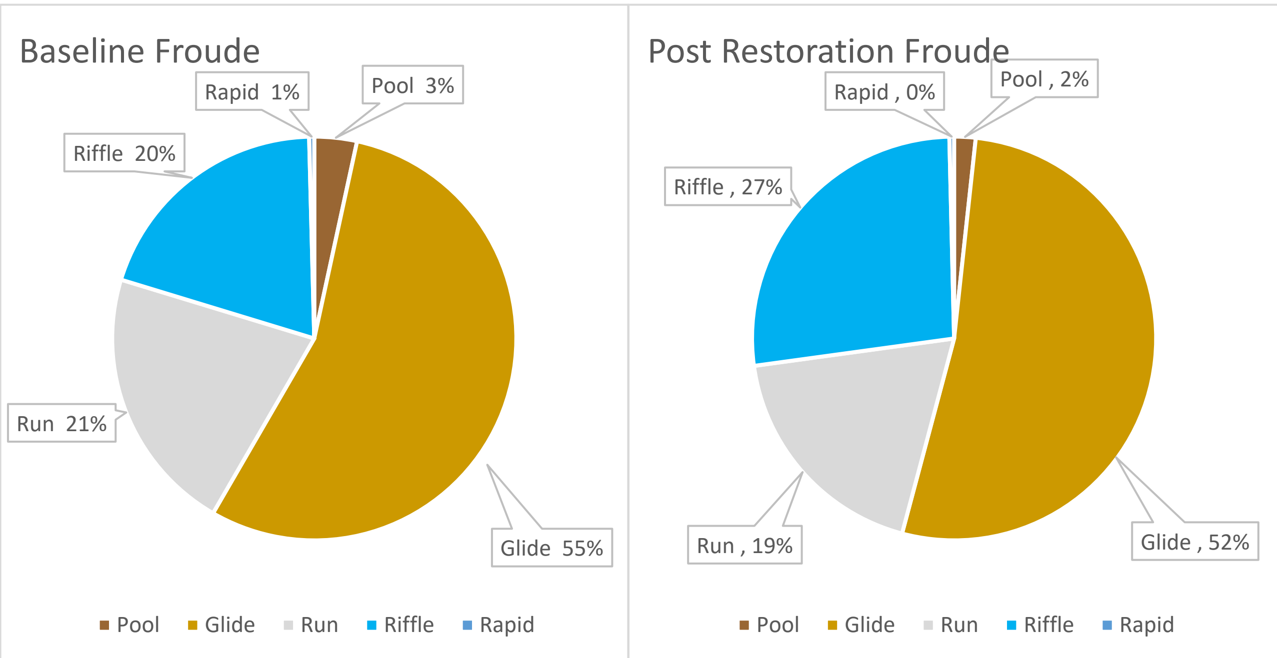


Figure 6.23 Proportion of each flow biotope pre (left) and post (right) restoration during Q95 flow.

Table 6.8 Proportion of each flow biotope observed during Q95 flow.

Flow Biotope	Count pre-change	Proportion of overall habitat pre-change (%)	Count post-change	Proportion of overall habitat post-change (%)
Pool	109	3.4	55	1.7
Glide	1,760	54.9	1,681	52.4
Run	684	21.4	599	18.7
Riffle	637	19.9	859	26.8
Rapid	13	0.4	12	0.4

Q10

The flow biotopes through the reach during Q10 flow are presented in Figure 6.13, 6.14 and Table 6.3. The flow biotope maps show a slight change in biotype diversity pre and post restoration. The most notable change is a nine percent decrease in pool and a six percent increase in riffle post restoration. Run remains a dominant flow type pre and post restoration.

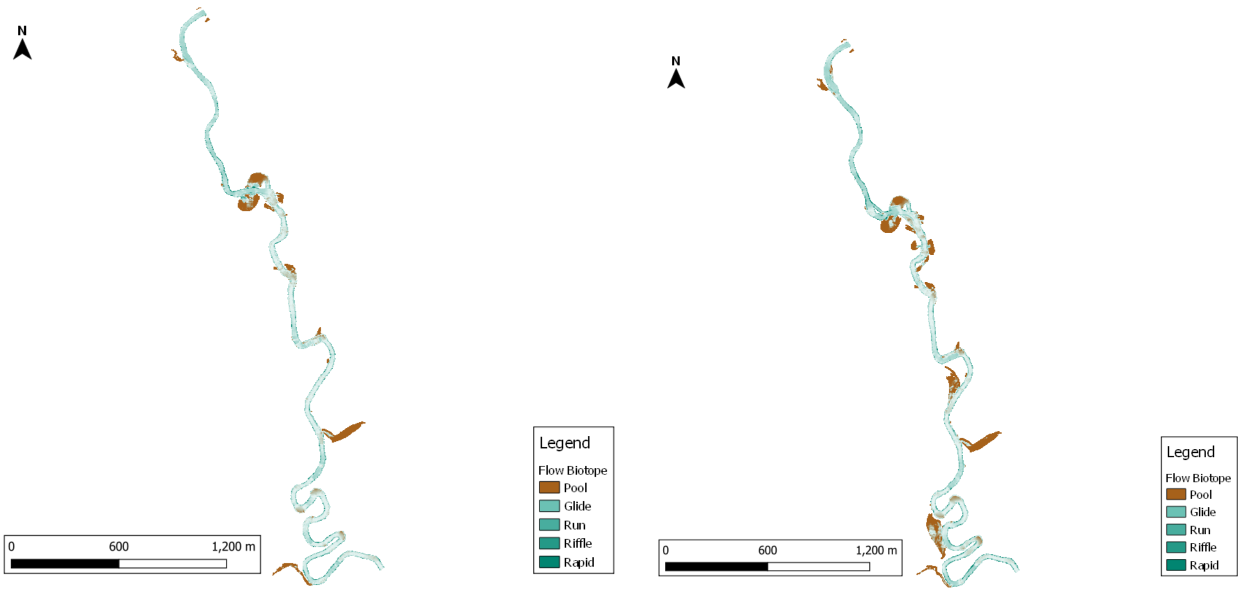
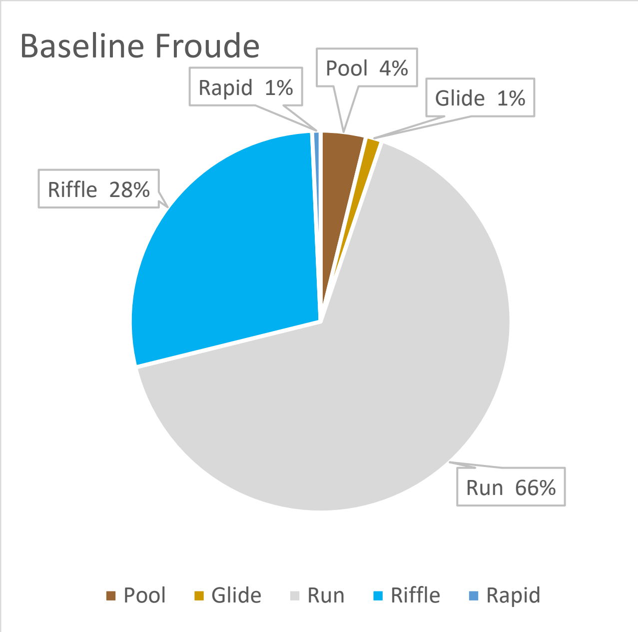


Figure 6.24 Flow biotope pre (left) and post (right) restoration at Q10 flow.



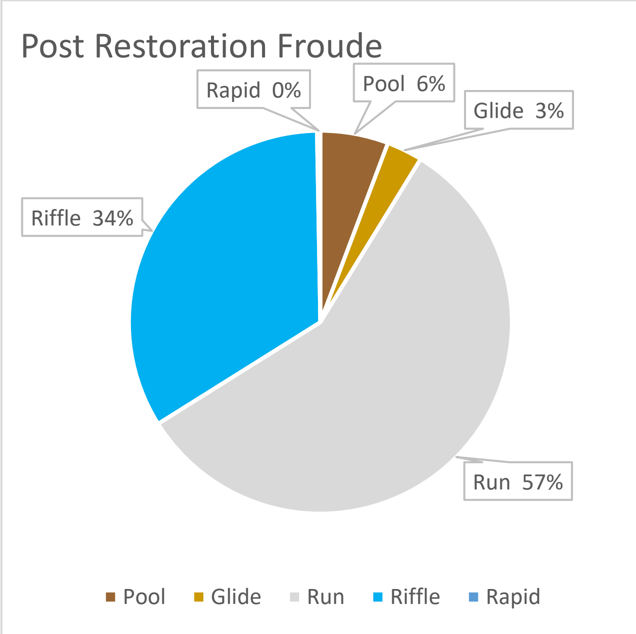


Figure 6.25 Proportion of each flow biotope pre (left) and post (right) restoration during Q10 flow.

Table 6.9 Proportion of each flow biotope observed during Q10 flow.

Flow Biotope	Count pre-change	Proportion of overall habitat pre-change (%)	Count post-change	Proportion of overall habitat post-change (%)
Pool	123	3.8	184	5.7
Glide	44	1.4	97	3.0
Run	2,111	65.9	1,836	57.3
Riffle	901	28.1	1,077	33.6
Rapid	23	0.7	9	0.3

1 in 2 Year

The flow biotopes through the reach during the 1 in 2-year event flow are presented in Figure 6.14, 6.15 and Table 6.4. The flow biotope maps show almost no change in biotype diversity pre and post restoration. This is due to all the restoration measures and embankments being overwhelmed at this very high flow.

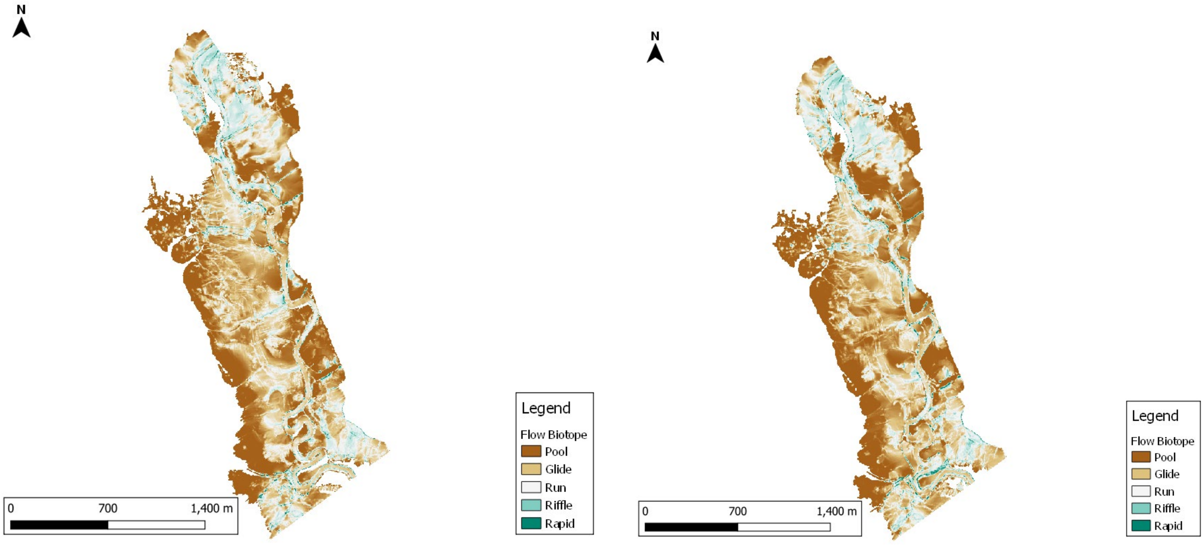


Figure 6.26 Flow biotope pre (left) and post (right) restoration at 1 in 2 year event flow.

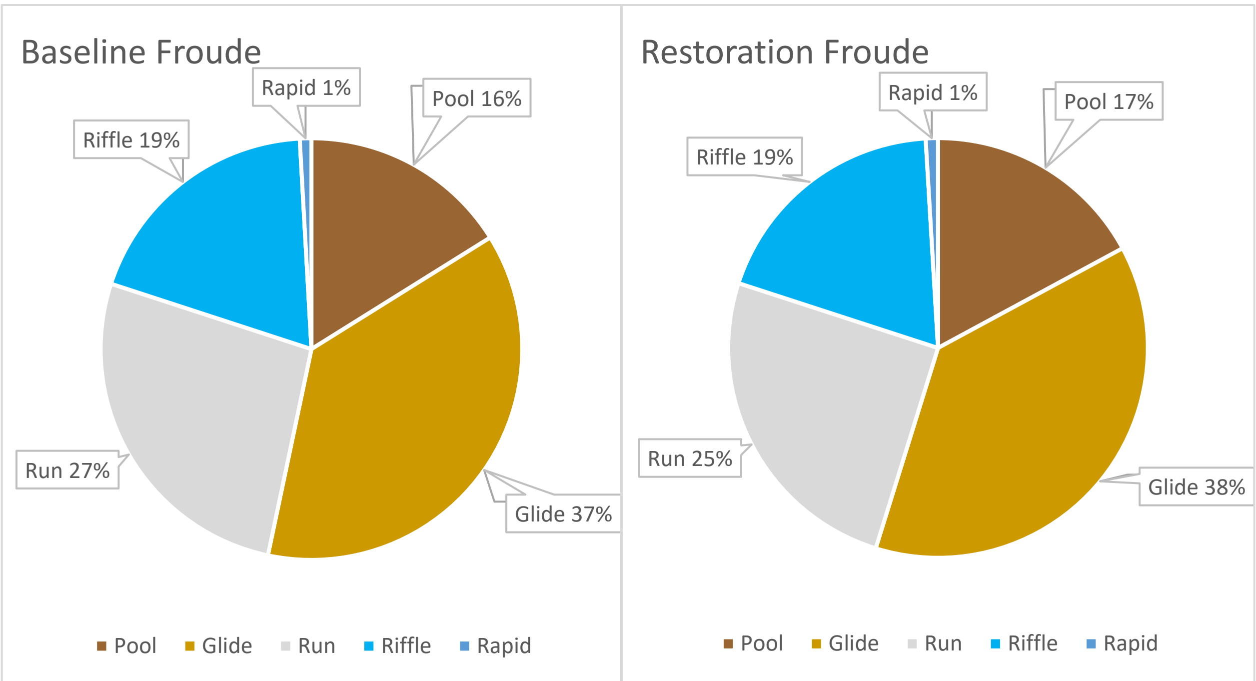


Figure 6.27 Proportion of each flow biotope pre (left) and post (right) restoration during 1 in 2 year event flow.

Table 6.10 Proportion of each flow biotope observed during 1 in 2 year event flow.

Flow Biotope	Count pre-change	Proportion of overall habitat pre-change (%)	Count post-change	Proportion of overall habitat post-change (%)
Pool	402,224	16.1	431,619	17.1
Glide	927,825	37.2	950,013	37.7
Run	666,161	26.7	635,261	25.2
Riffle	476,415	19.1	480,534	19.1
Rapid	22,149	0.9	23,742	0.9

6.3.3. Shear Stress

Figure 6.17 shows the change in shear stresses observed pre and post restoration for the 1 in 2 year event flow. The model results suggest post restoration shear stress levels remain broadly similar across the reach, with the exception of two locations - a small but noticeable increase in both the uppermost section of the reach (upstream of bifurcation intervention) and at the lowermost section (immediately upstream of the confluence with the Rathmell tributary).

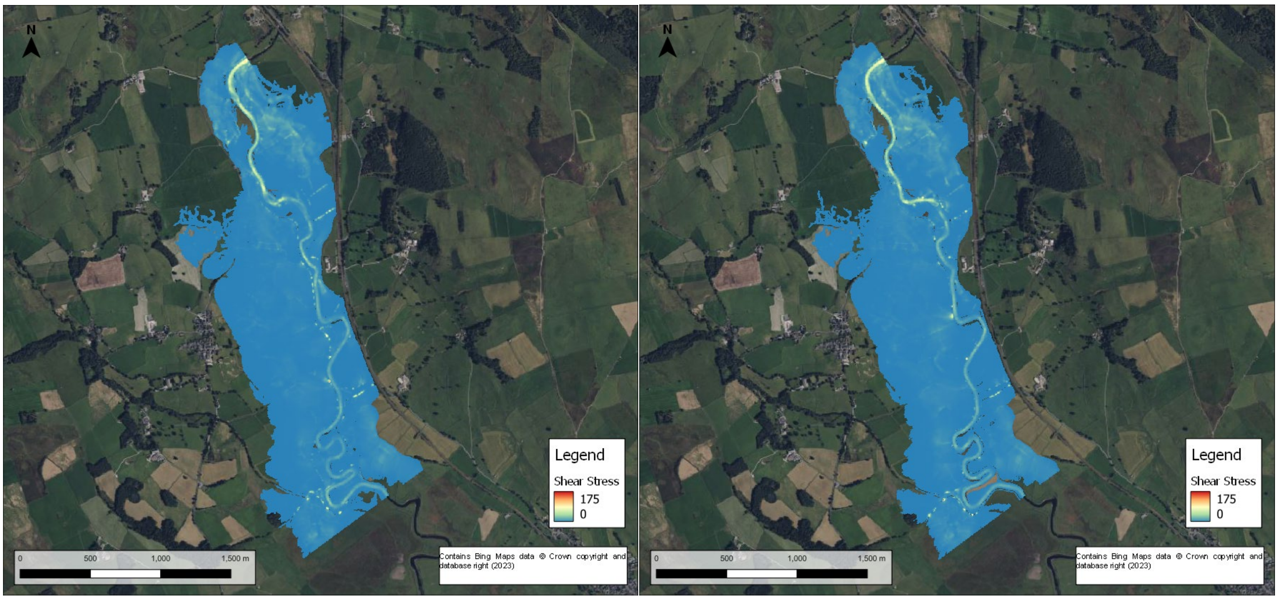


Figure 6.28 Shear stress pre (left) and post (right) restoration at 1 in 2 year flow.

6.3.4. Fish Habitat

Due to the limited hydraulic change, fish habitat modelling was not undertaken at this site.

6.4. Conclusions

The River Ribble at Long Preston Deeps SSSI is an active single thread river characterised by an active gravel bed. Pressures at the site that are constraining the river include embanking to the river to increase channel capacity, river straightening, bank protection and significant livestock access.

Several different restoration techniques have been implemented at the site from 2009 through to 2021:

- Berm insertion.
- Bifurcation.
- Blocking of a tributary (for the purpose of wetland creation).
- Backwater reconnection.
- Setting back of embankments.

The modelling shows that the restoration techniques implemented in the study area have brought about a modest improvement in floodplain connection – however, this improvement is largely confined to Q10 flows. Little change is observed during Q95 and 1 in 2 year event flows. Similarly, only subtle changes in biotope types are observed during the Q10 and Q95 flows where the riffle biotope increases (offset against a decrease in run biotope is observed in Q10). For the 1 in 2 year event, biotope type remained largely the same, post restoration. No change in shear stress was observed.

7. Selworthy

7.1. Background

The River Aller Stage 0 restoration scheme is located in former grassland fields on the floodplain adjacent to the River Aller and immediately upstream of Stratford Farm (Grid Ref: E291830, N145670). The site is part of Selworthy Farm, owned and currently managed by the National Trust. The fields have been set aside to develop innovative approaches to river restoration and habitat development (Figure 7.1). The aim was to restore natural processes at the site and monitor changes to hydrology and ecology. Monitoring is ongoing by the National Trust.

Figure 7. 1 Photographs of construction.

The River Aller has localised populations of brown trout (*S.trutta*). The connection to the sea is limited with presence of a shingle ridge, which narrows the chance of migratory salmonid ingress. The streams of North Somerset flow into the Severn estuary and are known for their European eel (*Anguilla anguilla*) populations. The Aller catchment is similar and offers good eel habitat, especially with the lowland section, where there are suitable ponds and wetlands. Other fish species present include stone loach (*Barbatula barbatula*), bullhead (*Cottus gobio*) and brook lamprey (*Lampetra planeri*).

7.2. Site Specific Methodology

7.2.1. Model schematisation

A HEC-RAS 2D model of the study area was developed for pre and post scheme representation. A mixture of LiDAR and in-channel survey was used to create the model DTM. The LiDAR was a combination of that flown in 2006 and a small section flown in 2017.

A mesh resolution of 10m by 10m was used but was refined in places using a variable higher resolution mesh. Additionally, the sub-grid scale feature in HEC-RAS 2D computes storage-level and conveyance=level relationships for each cell face from the underlying DTM (in this case 1m by 1m LiDAR). As the conveyance tables are across cell faces, in areas where there is significant topographic level change, a break-line along the face ensures flow is unable to progress until the topographic crest level is overtopped. Break-lines were included for significant topographic crests, along with break-lines along the river channel to ensure the flows are perpendicular to the cell faces in direction of greatest flow.

A cross section survey of the river channel was available from a 2019 1D-2D linked model. The LiDAR and the survey were compared, with the analysis showing that the LiDAR was around 0.2 to 0.6m higher than the channel cross section. The LiDAR was modified to better represent the channel survey levels (Figure 7. 2).

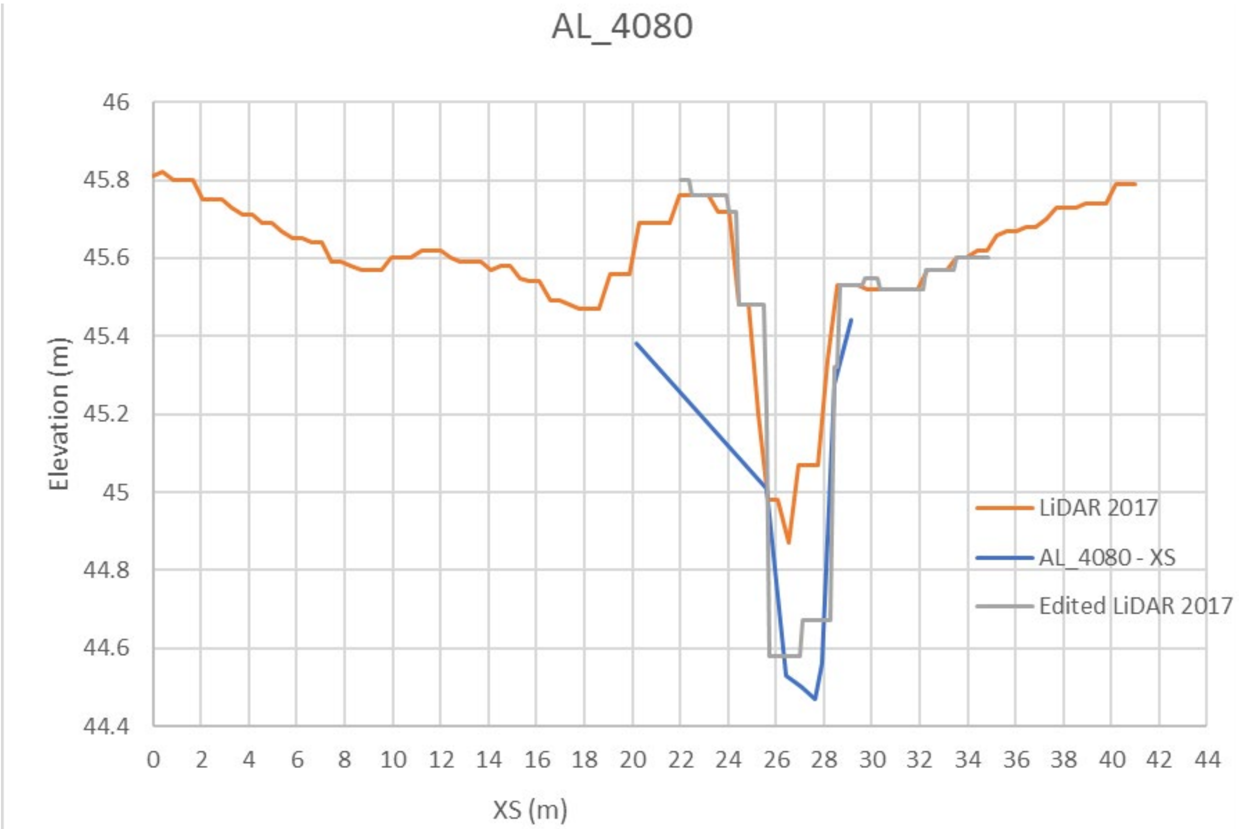


Figure 7. 2 Example of channel lowering.

The model extended 285m upstream of the works and 440m downstream of the works to avoid the upstream and downstream boundary of the model influencing results in the study area (Figure 7.3).

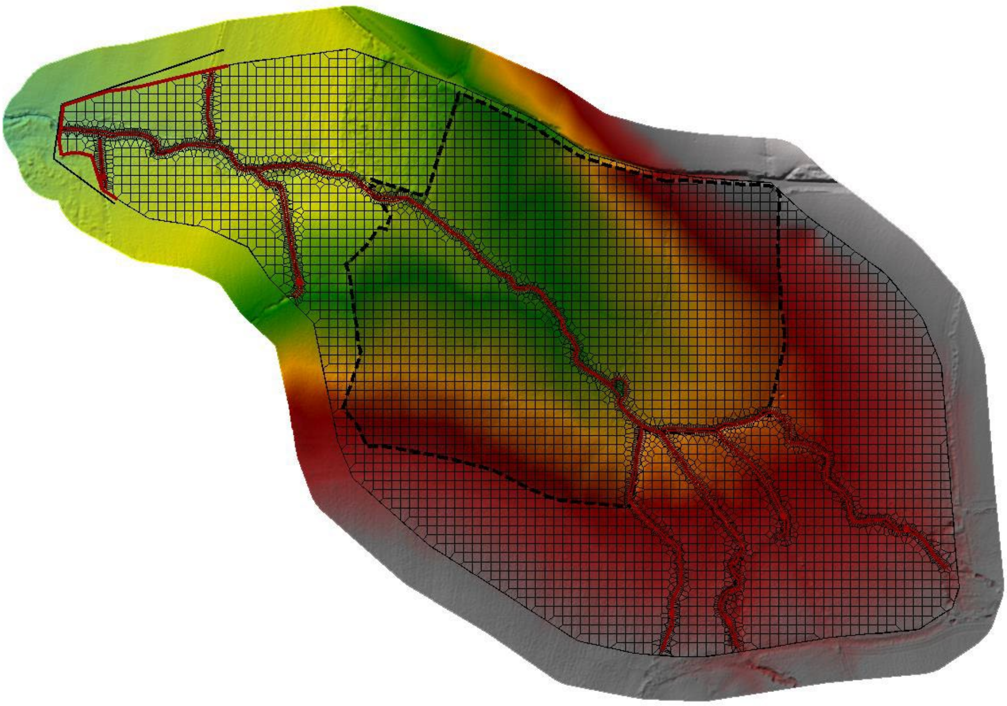


Figure 7. 3 HEC-RAS 2D – baseline grid set up of the study site.

7.2.2. Inflows

Three flows have been used in the model (Table 7.1). The Q95 and Q10 flows were derived from a low flows study using Low Flows 2 (LF2) Software. The 2-year flood flows were taken from the 2019 1D-2D linked hydraulic model.

Table 7.1 Inflows to the model

Scenario	Flow (m^3/s)
Q95 (summer flow)	0.05
Q10 (winter flow)	0.80
2-year return period flood	2.33

7.2.3. Manning's roughness

Photographs and observations of the channel and banks, from site visits and survey, informed the choice of Manning's n values. These have also been cross checked against values listed in Chow, 1959[2]. Table 7.2, 7.3 and Figure 7. 4 show these values and how they have been used.

[2] Chow, V.T. (1959) Open Channel Hydraulics, McGraw-Hill Book Company, NY.

Table 7.2 Manning's roughness values used (pre-restoration).

Land Use	Manning's N	Photo
Channel	0.06 has been used to represent the in-channel flow.	
Floodplain	Arable Field: (n=0.1) used to represent a smooth improved grass field.	
Tree Coverage	Tree coverage: (n=0.15) has been shown on site around the channel and within patches of woodland. This high Manning's value has been used to distinguish between the improved grassland and rougher vegetated areas, including established hedgerows.	

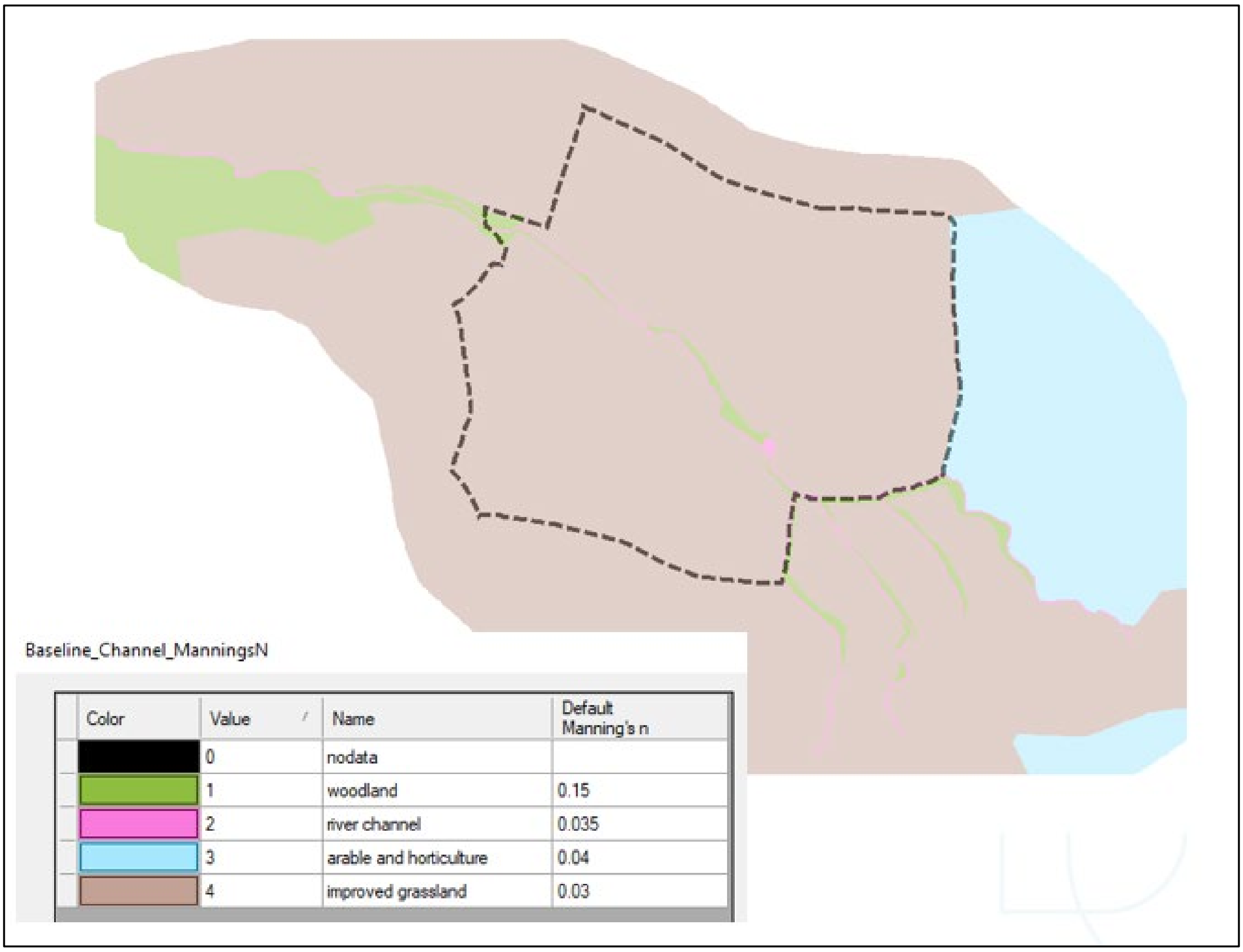


Figure 7. 4 Baseline Manning's roughness Grid.

7.2.4. Post change representation

A variety of roughness and topographical changes were used to represent the proposed design. To represent these changes within the HEC-RAS model, the DTM was directly modified to represent the new elevations across the floodplain. In addition to the direct DTM modifications, the baseline hydraulic roughness was modified to represent the much rougher vegetation across the restored floodplain.

Representing large woody debris as both changes to the topography (DTM) and as increases in roughness are common across modelling studies (Addy and Wilkinson, 2019[3]). Both approaches represent different processes of how large woody debris influences flow. A low-level DTM edit (~0.4m) to increase the elevation at a particular point

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[3] Addy, A., Wilkinson, M. (2019). Representing natural and artificial in-channel large wood in numerical hydraulic and hydrological models.

represents the blockage to flow which a pile of large woody debris on the floodplain would result in. The increase to roughness represents both the rougher texture of the wood itself, and the complexity of how water will flow through the structure at high flows. As the water is forced through many small gaps between individual pieces of wood, it is forced to slow down and take longer, less efficient pathways across the floodplain. Such a representation is not without its limitations, which includes a lack of representation of the gaps between the individual pieces. A possible effect of this is that water is attenuated slightly more than what may occur once constructed on site (Figure 7.5, 7.6).

Figure 7.5 Example stage zero restoration.

Table 7.3 Manning's roughness values used (post change)

Land Use	Manning's N	Photo
Channel	Channel: (n=0.035) This has been removed from the hydraulic roughness grid as the restored section would not include a "typical" channel flow path	
Floodplain	Across the study site the Arable Field: (n=0.04) and improved grassland: (n=0.03) have been replaced by a much rougher vegetation coverage. Several values have been used which aim to simulate these conditions. These include: 0.03 (smooth grassland), 0.05 (robust, stiff wet grassland type), 0.08 (lower woody debris value), 0.12 (higher woody debris value)	

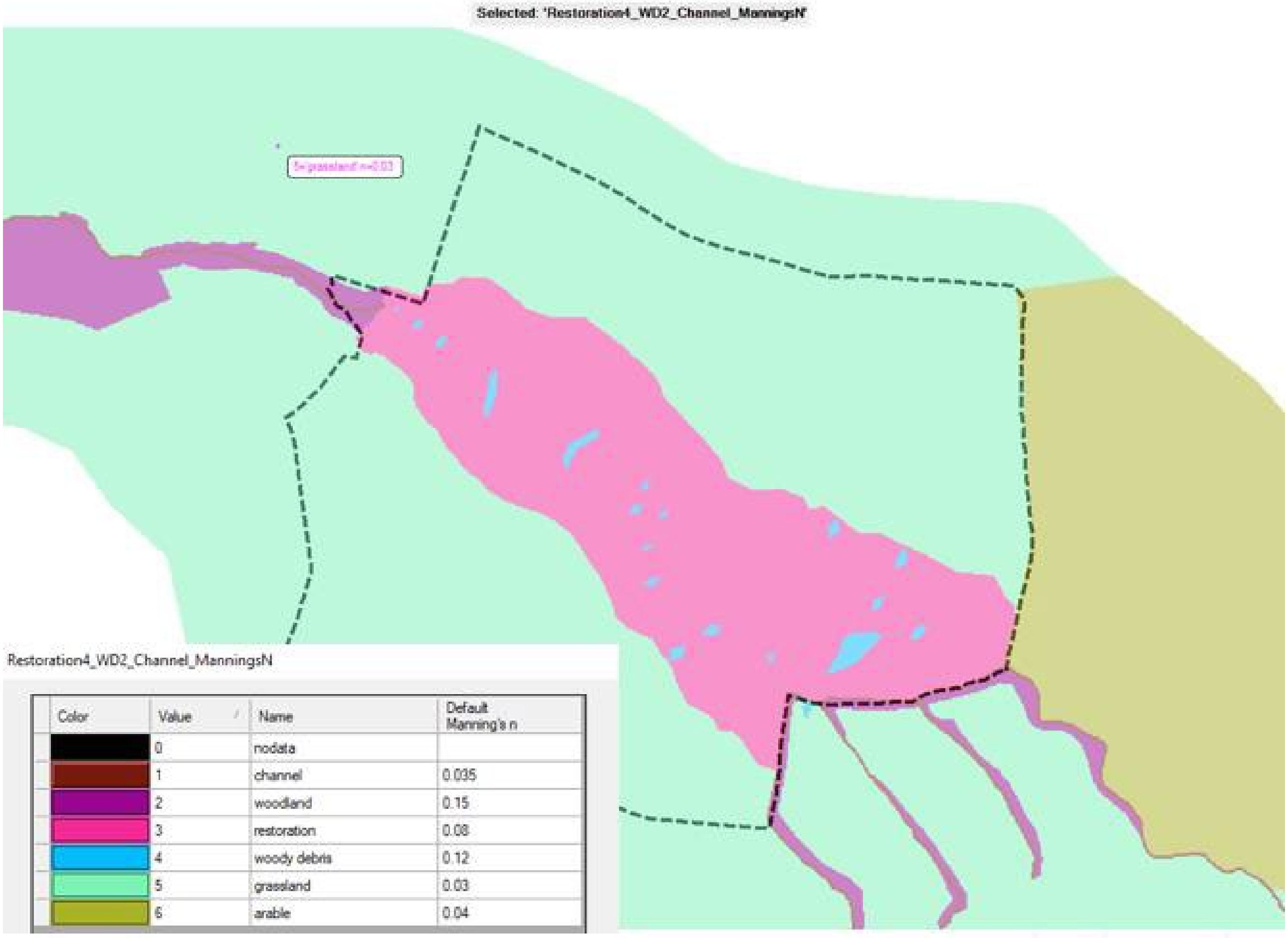


Figure 7.6 Post-change Manning's roughness grid.

7.3. Results

7.3.1. Hydraulic Conditions

Q95

The hydraulic modelling results show a large increase in the overall wetted area following stage-zero restoration, with the number of wetted cells increasing from 2,451 cells in the pre-change to 11,971 cells in the post-change scenario. This increase is due to the improved floodplain connection associated with the post-change scenario, with flow spread across a wider area rather than being contained within a single channel. It is however speculated that over time scour will lead to the formation of more defined channels within the restored floodplain. These channels will act to contain water, thereby reducing the overall wetted area during low flow events (Table 7.7).

Figure 7.7 Depths for pre (left) and post (right) restoration scenarios during a Q95 flow.

Q10

As with the Q95 scenario a similar large increase in the overall wetted area is observed during the Q10 scenario, with the total number of wetted cells increasing from 3,178 cells in the pre-change to 15,192 cells in the post-change scenario. This increase is again due to improved floodplain connection associated with the post-change scenario, with no floodplain activation observed in the pre-change scenario. Again, it is thought that over time scour will lead to the formation of more defined channels, slightly reducing the overall wetted area observed during Q10 flows (Figure 7.8).

Figure 7.8 Depth pre (left) and post (right) restoration during a Q10 flow.

2-year flood

As with both previously discussed scenarios, there is a large increase in the overall wetted area observed for the 2-year flood flow, with an increase from 3,432 wetted cells in the pre-change scenario to 15,192 wetted cells in the post-change scenario. The pre-change scenario shows some, albeit limited, floodplain connection during larger flood flow, however this is shown to greatly increase following the restoration (Figure 7.9).

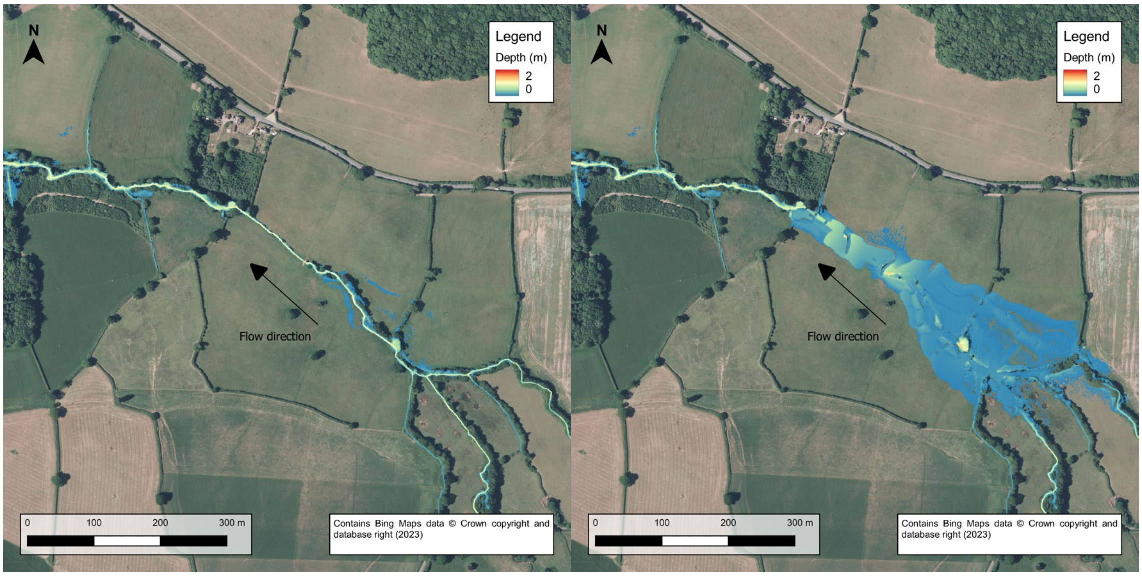


Figure 7.9 Depth pre (left) and post (right) restoration during a 2-year flood flow.

7.3.2. Flow Biotopes

Q95

The flow biotope maps associated with the pre and post restoration scenarios during Q95 flows are presented in Figure 7.10 and 7.11 together with breakdown of the change in each biotope provided in Table 7.4. The results show an increase in total pool, glide and run flow biotopes with particularly large increases in lower energy pool and glide biotopes observed. This is due to increased floodplain connection, with the majority of newly wetted cells classified as pool or glide biotopes. There is also a slight reduction in the overall quantity of riffle and rapid biotopes observed, with cells previously characterised by higher energy riffle and rapid biotopes located towards the downstream end reach replaced by lower energy biotope types.

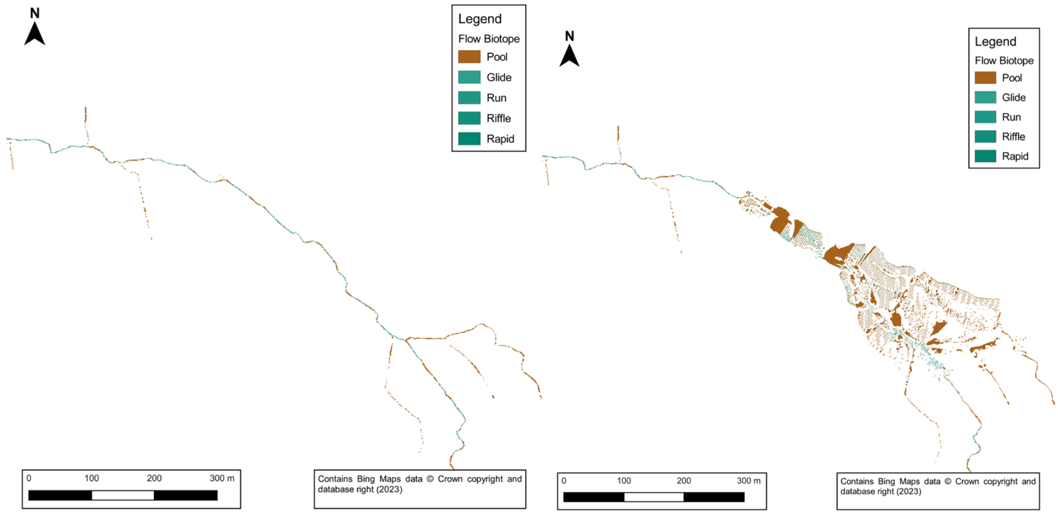


Figure 7.10 Flow biotope pre (left) and post (right) restoration during a Q95 flow.

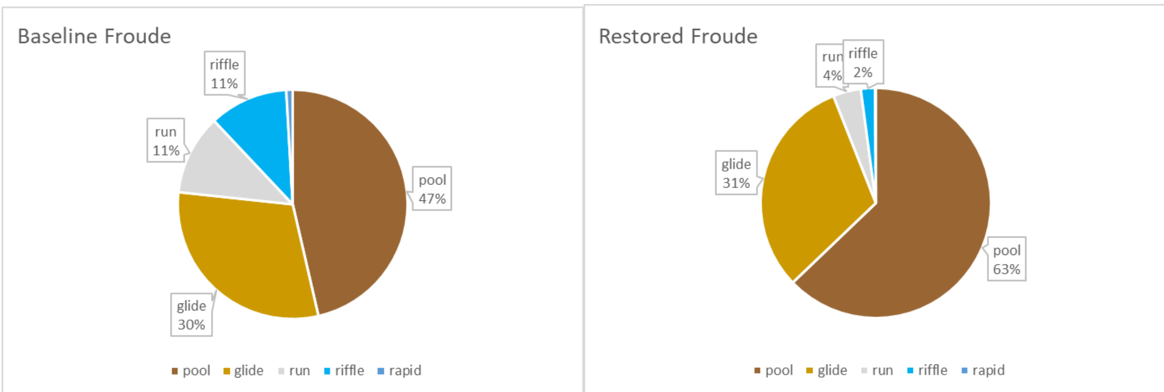


Figure 7.11 Proportion of each flow biotope pre (left) and post (right) restoration during a Q95 flow.

Table 7.4 Proportion of each flow biotope observed during a Q95 flow.

Flow Biotope	Count pre-change	Proportion of overall habitat pre-change (%)	Count post-change	Proportion of overall habitat post-change (%)
Pool	1,137	46.4	7,529	62.9
Glide	743	30.3	3,729	31.2
Run	278	11.3	468	3.9
Riffle	272	11.1	234	2.0
Rapid	21	0.9	11	0.1

Q10

As with smaller Q95 flow there is a large increase in the quantity of lower energy pool and glide biotopes observed during the Q10 flow scenario following restoration (Figure 7.12, 7.13, and Table 7.5). This shift is again linked to increased floodplain activation with additional cells on the floodplain predominantly classified as pool or glide biotopes. However, unlike Q95 flow there is also an increase in higher energy riffle and rapid biotopes observed during larger Q10 flows.

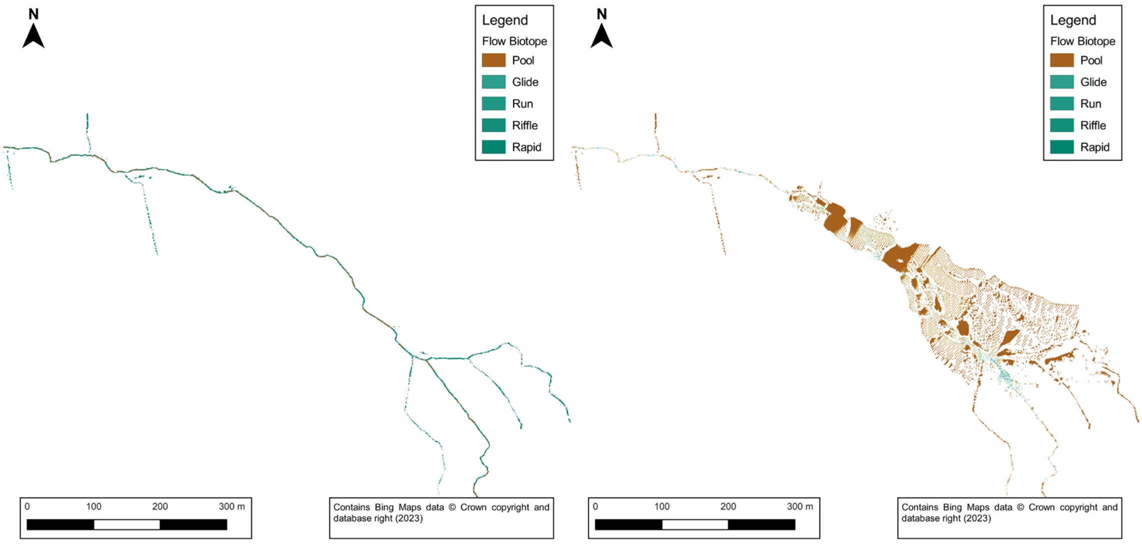


Figure 7.12 Flow biotope pre (left) and post (right) restoration during a Q10 flow.

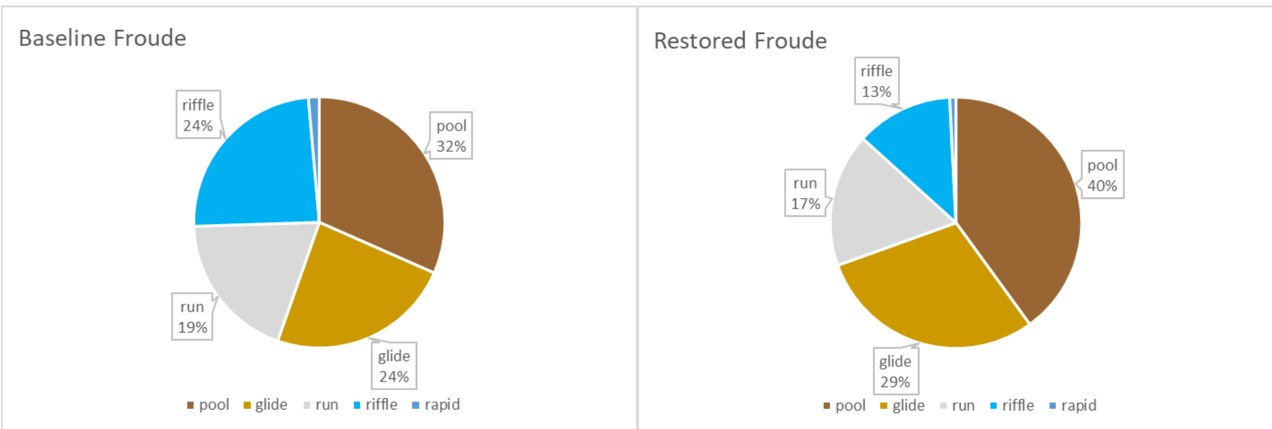


Figure 7.13 Proportion of each flow biotope pre (left) and post (right) restoration during a Q10 flow.

Table 7.5 Proportion of each flow biotope observed during a Q10 flow.

Flow Biotope	Count pre-change	Proportion of overall habitat pre-change (%)	Count post-change	Proportion of overall habitat post-change (%)
Pool	1,005	31.6	7,586	40
Glide	755	23.8	5,610	29.5
Run	607	19.1	3,272	17.2
Riffle	766	24.1	2,373	12.5
Rapid	45	1.4	147	0.8

2-year flood

As with the two previously discussed scenarios, there is an increase in quantity of all flow biotopes observed during the larger 2-year flood flow post restoration (Figure 7.14, 7.15, and Table 7.6). Again, the largest increases are observed in lower energy pool and glide biotopes, with smaller increases observed for higher energy riffle and rapid biotopes.

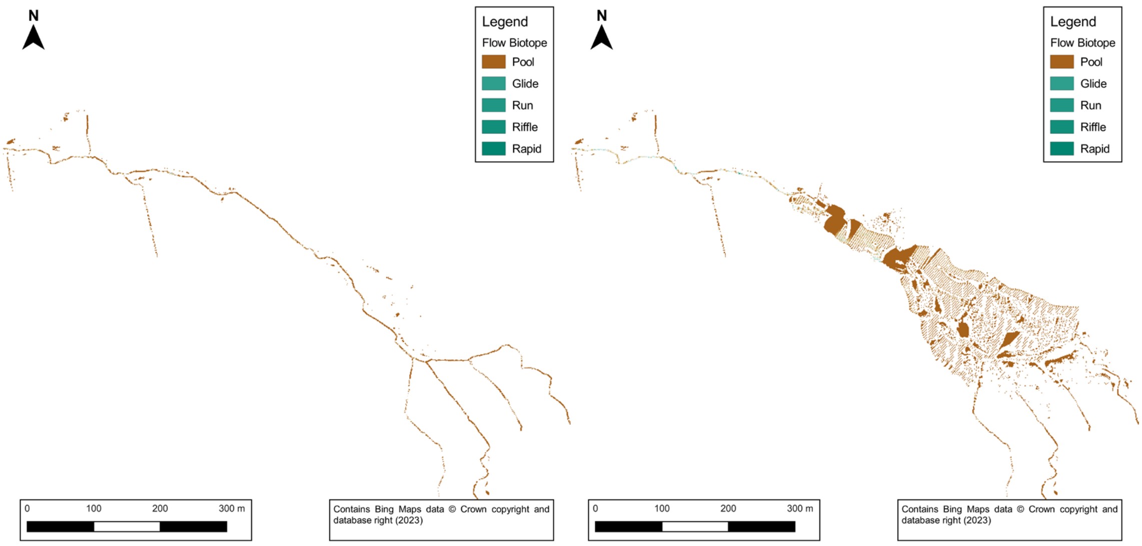


Figure 7.14 Flow biotope pre (left) and post (right) restoration during a 2-year flood flow.

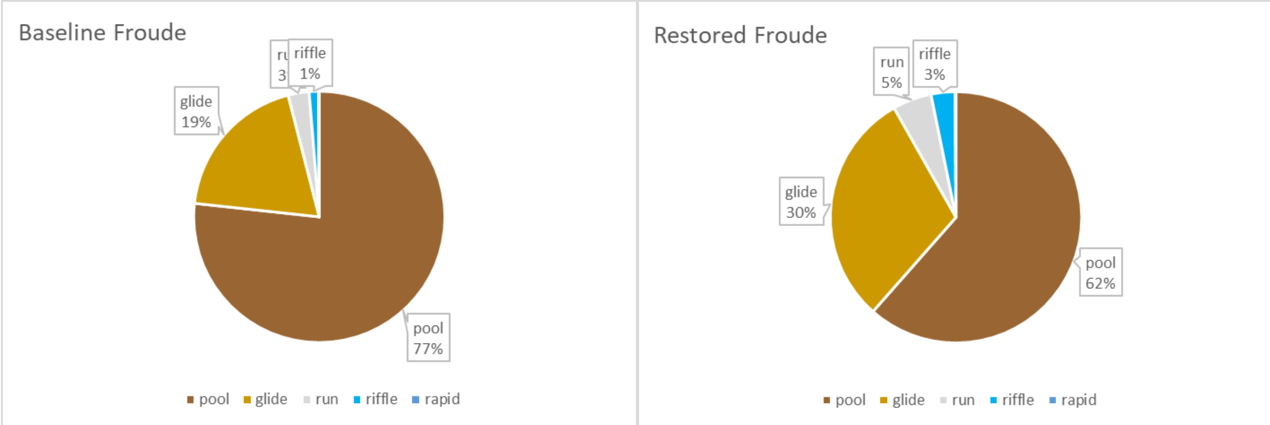


Figure 7.15 Proportion of each flow biotope pre (left) and post (right) restoration during a 2-year flood flow.

Table 7.6 Proportion of each flow biotope observed during a 2-year flood flow.

Flow Biotope	Count pre-change	Proportion of overall habitat pre-change (%)	Count post-change	Proportion of overall habitat post-change (%)
Pool	2,636	76.8	9,346	61.5
Glide	663	19.3	4,600	30.3
Run	91	2.7	760	5.0
Riffle	40	1.2	471	3.1
Rapid	2	0.1	15	0.1

7.3.3. Shear Stress

2-year flood

Figure 7.16 shows the change in shear stresses observed pre and post restoration for a 2-year return period flood flow. This larger flow was used to investigate the impact of the restoration measures on shear stresses as it is larger events that are most likely to be geomorphologically significant. The model results suggest there is a similar reduction in shear stresses observed in the post-change scenario, where the flow is allowed to spread across the wider floodplain, as opposed to being contained within the channel. In contrast, the highest shear stresses are observed towards the downstream end of the reach where the flow reconverges and is contained within a single channel. The results show that there is minimal change in shear stresses observed within this single thread channel towards the downstream end of the reach.

Figure 7.16 Shear stress pre (left) and post (right) restoration during a 2-year flood flow.

7.3.4. Habitat

Fuzzy-logic habitat modelling was conducted to assess the impact of the restoration measures on habitat to support the various life stages of Brown trout through the study reach. The results of this modelling show that the restoration resulted in a large increase in total habitat to support the various life stages of Brown trout across each of the flow scenarios tested (Table 7.7, 7.8).

The results show that during lower Q95 flows the largest increases are in 0+ habitat, although large increases in 1+ and adult habitat are also observed. Spawning habitat also increases during lower Q95 flows, however much larger increases in this habitat type are observed during larger Q10 flows.

There are substantial increases in the amount of refuge habitat at both Q10 and 2-year flood flows. It should be noted that while the fuzzy-logic habitat modelling suggests there is an increase in the quantity of suitable habitat, it does not consider the accessibility of this habitat, with some of the additional habitat potentially inaccessible.

Interestingly, although large increases in total habitat were observed, the modelling results suggest there is a reduction in the quality of each habitat type at Q95. The reduced quality of spawning habitat is linked to the increase in pool habitat, which is potentially suitable depth perspective but with slower velocities. The reduction in the quality of 0+ and 1+ habitat is likely linked to reduced velocities, with pool and glide biotopes less suitable for 1+ fish in particular. At this life stage Brown trout have slightly higher velocity preferences due to shallow broken water providing improved predation cover. Compared to juvenile habitat there is a reduction in the quality of adult habitat observed during the post-change scenario, particularly during higher flows. Unlike the 0+ and 1+ habitat, this is likely a function of reduced depths being observed post-change, with larger adult fish preferring increased depths and reduced velocities compared to juvenile fish. At higher flows, the quality of the predicted habitat is largely similar in the pre and post scenarios.

It should also be recognised that the post-change modelling results show the hydraulic conditions immediately post restoration, prior to natural processes leading to the formation of more defined channels flow pathways through the newly restored section. Over time the development of these channels is expected to increase the quality and reduce the quantity of fish habitat, particularly during lower flow conditions.

Table 7.7 Total Habitat Suitability Index (HSI)

	Q95 pre	Q95 post	Q10 pre	Q10 post	2-year flood pre	2-year flood post
Adult	502	1,478	1,136	5,110	NA	NA
1+	929	2,338	1,517	9,257	NA	NA
0+	1,048	3,997	759	11,361	NA	NA
Spawning	695	895	1,641	4,924	NA	NA
Refuge	NA	NA	2,208	16,371	4,477	25,295

Table 7.8 Habitat Quality Index (HQI)

	Q95 base	Q95 post	Q10 base	Q10 post	2-year flood pre	2-year flood post
Adult	14.1	7.5	19.7	13.2	NA	NA
1+	26.2	11.9	26.3	23.8	NA	NA
0+	29.5	20.3	13.2	29.2	NA	NA
Spawning	19.6	4.5	28.4	12.7	NA	NA
Refuge	NA	NA	38.2	42.1	36	48.7

7.4. Conclusions

Hydraulic modelling has been conducted to investigate the impact of stage 0 restoration on the River Aller at Selworthy Farm. The results of this modelling show that the restoration delivered a large increase in the overall wetted area across each of the various flow scenarios, from low Q95 flows to larger 2-year flood flows. This increase was predominantly associated with large increases of pool and glide flow biotopes along the restored section, although smaller increases in other biotopes were also observed. As would be expected with the dominance of pool and glide habitat, the shear stresses on the floodplain are much lower than in the pre-restoration scenario.

Fuzzy-logic habitat modelling revealed an increase in the quantity of habitat to support each life stage post-restoration across each flow scenario. Despite quantities of habitat increasing, the results also suggest a reduction in the average quality of habitat at very low flows. This is due to much of the additional habitat characterised by lower velocities and shallow depths, making the newly created habitat suboptimal for various life stages. At higher flows there were large increases in the refuge habitat available for aquatic organisms.

8. Fowlea

8.1. Background

The Fowlea Brook is a lowland river that flows through single thread alluvial channels. At the study reach, the Fowlea Brook flows through a uniform, over-wide channel which is prone to siltation. As with many channels in the catchment, the channel has been subject to historic modification and has been straightened with managed morphology.

The Fowlea Brook at Etruria Valley generally has a low-gradient slope, which has led to a reach characterised by depositional processes. Evidence of erosional processes was limited, with little bank scour evident, and vegetation growth on the bank sides suggesting erosion was likely only during high flow events. Whilst there are some gravels present on the river bed (typically 10-20mm), these tend to be stored in short bedform features such as riffles. Given the lack of depositional features and infrequent bank erosion, it is assumed the supply of coarse material to the Etruria Valley reach is low.

Restoration measures involved the creation of a new meandering channel, which included strategically placed hydromorphic features such as depositional bars, riffles and pools (Figure 8.1). The aim of these features was to create a more varied morphology, which in turn can provide variable flow conditions and habitats. The comparatively narrow channel created, and its increased sinuosity will encourage bedform development through erosional, transportational and depositional processes.

Figure 8.1 Photographs taken during the construction phase.

The Fowlea Brook is a small urban river which feeds into the River Trent close to the centre of Stoke. The Environment Agency National Fish Population Database was interrogated and found to contain no records of fish surveys conducted in the Fowlea Brook, however it is assumed that the Fowlea Brook should support similar fish species to those identified in the adjacent reaches of the River Trent. These species include salmonids such as Brown trout (*Salmo trutta*) together with coarse fish species including Dace (*Leuciscus leuciscus*), Gudgeon (*Gobio gobio*), Minnow (*Phoxinus phoxinus*), Roach (*Rutilis rutilis*) and 3-spined stickleback (*Gasterosteus aculeatus*).

8.2. Site Specific Methodology

8.2.1. Model schematisation

A TUFLOW 2D model of the study area was developed for pre and post scheme representation. The pre-restoration DTM used within the model was created using LiDAR data clipped to the area of interest (Figure 8.2).

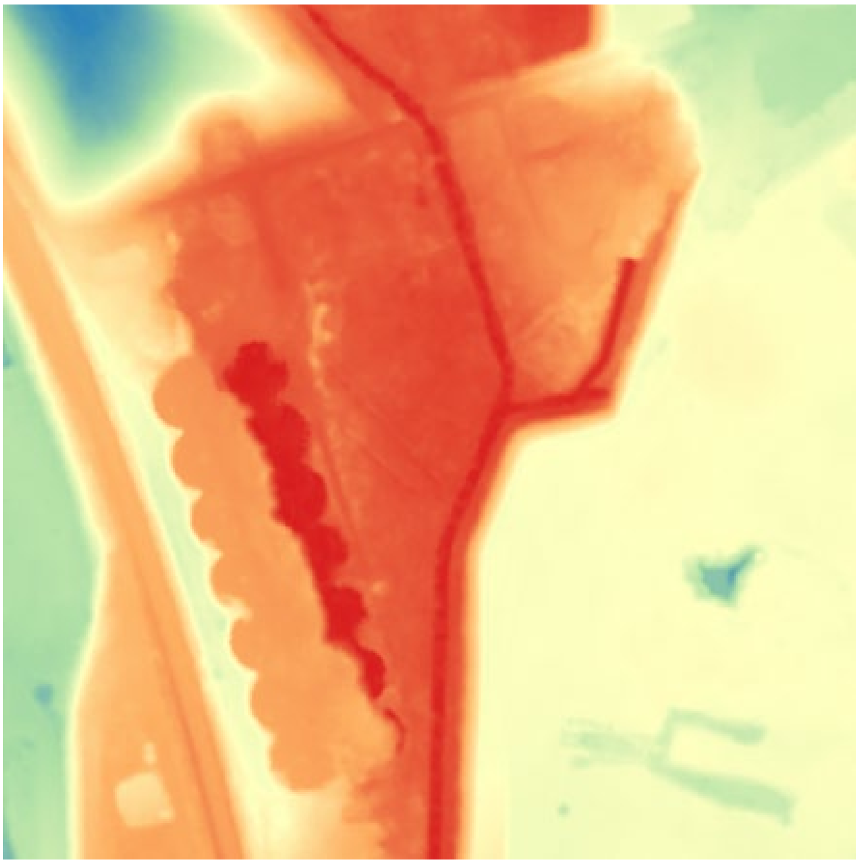


Figure 8.2 Pre-change surface used within the TUFLOW model.

The model used a grid cell size of 0.5m and each flow event was simulated for a period of 12 hours to enable model stabilisation. Various Manning's n values were assigned to the different land cover types in the study area. These values are presented in Table 8.1.

Table 8.1 Manning's n values used in the pre-restoration scenario.

Land Cover	Manning's n value
General Floodplain	0.06
Buildings	0.3
Roads, Tracks and Paths	0.025
Existing Channel	0.03
Railway Track	0.05
Woodland / Scrub	0.1

8.2.2. Inflows

Three flows have been used in the model (Table 8.2). The Q95 and Q10 flows used were derived from a low flows study using Low Flows 2 (LF2) Software, while the larger 2-year flood flow was calculated using Flood Estimation Handbook techniques.

Table 8.2 Inflows to the model

Scenario	Flow (m^3/s)
Q95 (summer flow)	0.037
Q10 (winter flow)	0.574
2-year return period flood	4.9

8.2.3. Post change representation

The post-restoration scenario was represented within the model by updating the underlying DTM to capture the new, more sinuous channel. The post-restoration DTM used within the model is shown within (Figure 8.3). The post-restoration surface was created using Civils 3D software, from which a DTM was produced for use within the hydraulic model. This captured the alignment of the naturalised channel, with the bed levels adjusted to represent natural bedforms.

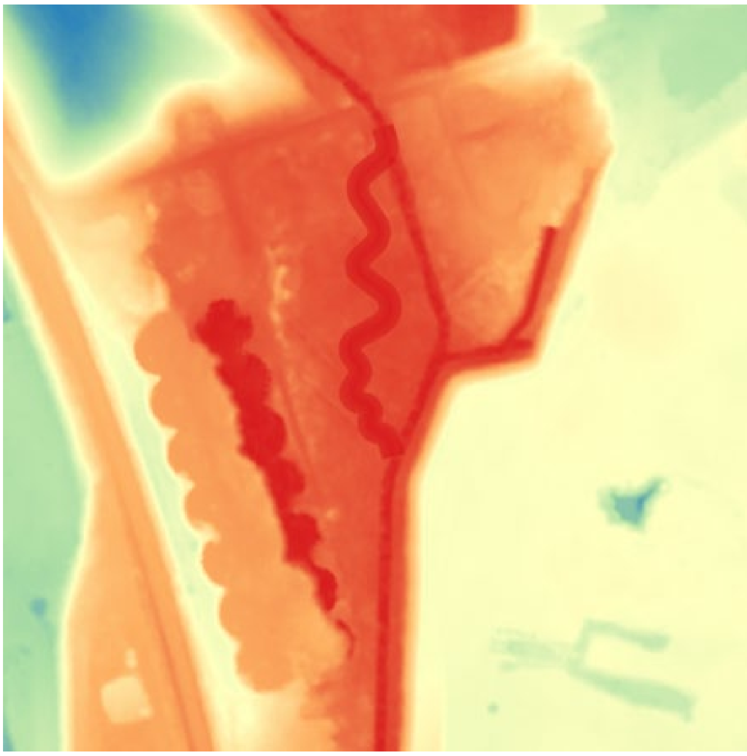


Figure 8.3 Post-change surface used within the TUFLOW model.

The Manning's n values used in the post-restoration scenario are presented in Table 8.3. These values are the same as those associated with the pre-restoration scenario, however an increased Manning's n value was assigned to the newly-created, more sinuous channel.

Table 8.3 Manning's n values used in the post-restoration scenario.

Land Cover	Mannings n value
General Floodplain	0.06
Buildings	0.3
Roads, Tracks and Paths	0.025
Existing Channel	0.03
New Channel	0.04
Railway Track	0.05
Woodland / Scrub	0.1

8.3. Results

8.3.1. Hydraulic Conditions

Q95

The hydraulic modelling results show that while water is contained within the channel under both pre and post restoration scenarios, there is more variation in depths observed within the newly created channel in the post-restoration scenario (Figure 8.4). In comparison, the unrestored channel appears relatively homogenous in terms of depths, with consistent depths observed through the reach.

Figure 8.4 Pre (left) and post (right) change depths during Q95 flows.

Q10

During higher Q10 flow conditions, the hydraulic modelling results show that flow is still contained within the channel, with no floodplain activation observed under the pre and post restoration scenarios (Figure 8.5).

Figure 8.5 Pre (left) and post (right) change depths during Q10 flows.

2-year flood

Figure 8.6 shows that floodplain activation is observed under pre and post restoration scenarios. The level of floodplain activation is observed to be broadly similar under both scenarios, with the creation of the new more sinuous channel seemingly only leading to a small reduction in the wetted area associated with a 2-year flood flow.

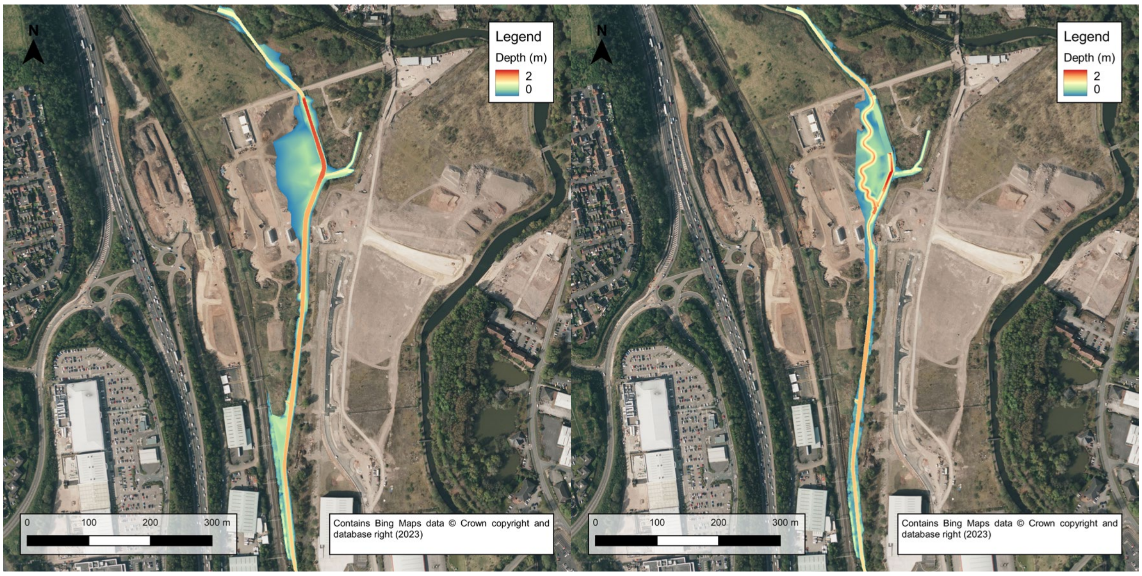


Figure 8.6 Pre (left) and post (right) change depths during a 2-year flood flow.

8.3.2. Flow Biotopes

Q95

Figure 8.7, 8.8 and Table 8.4 show increased biotope diversity through the restored section, with a range of flow biotopes observed within the newly created channel. In contrast, the unrestored section, featuring a much straighter channel, is dominated by lower energy pool and glide biotopes, and seems to lack higher energy riffle and rapid biotopes during low flow conditions.

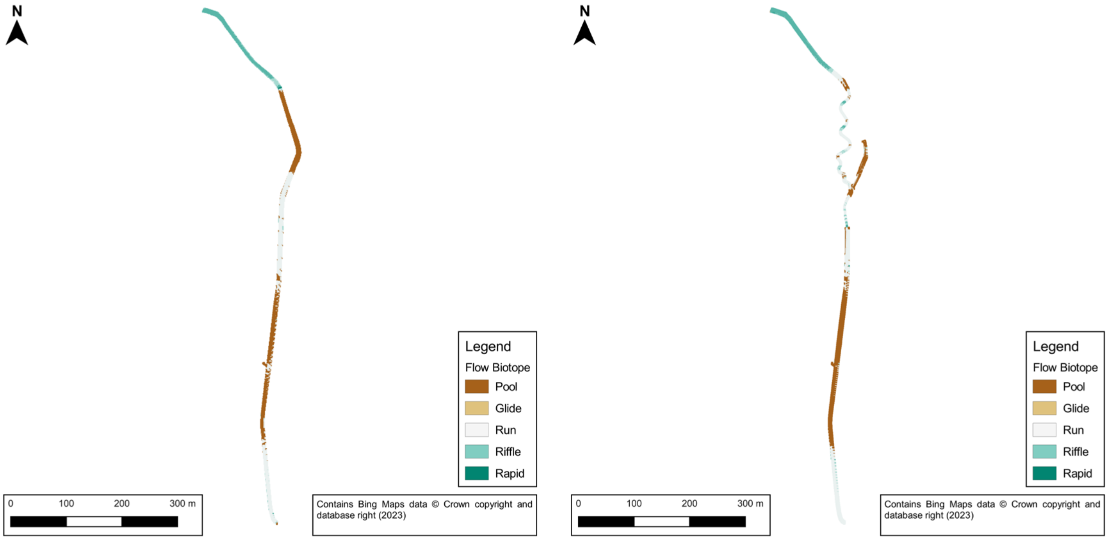


Figure 8.7 Flow biotopes pre (left) and post (right) restoration during Q95 flows.

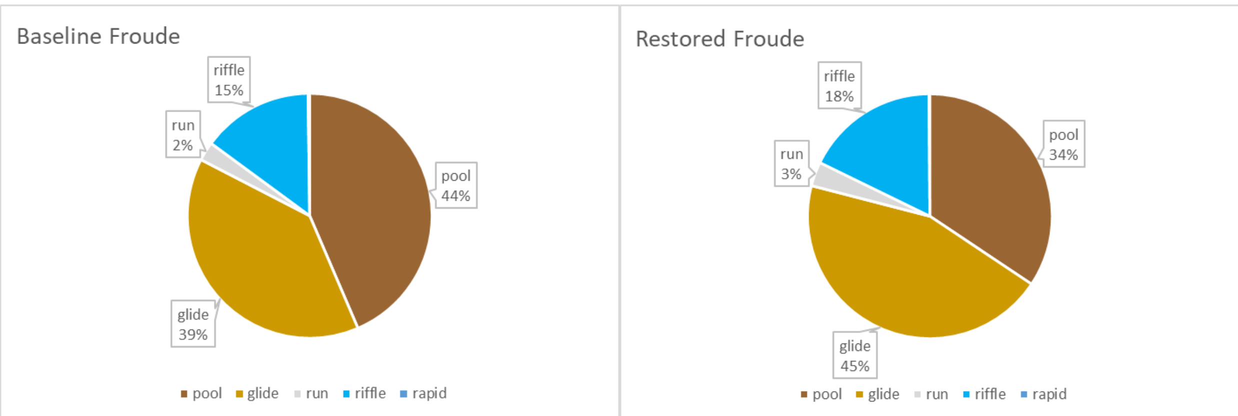


Figure 8.8 Proportion of each flow biotope observed during a Q95 flow.

Table 8.4 Proportion and quantity of each flow biotope observed during a Q95 flow.

Flow Biotope	Count pre-change	Proportion of overall habitat pre-change (%)	Count post-change	Proportion of overall habitat post-change (%)
Pool	10,817	43.5	6,356	34.4
Glide	9,706	39.0	8,254	44.7
Run	629	2.5	594	3.2
Riffle	3,657	14.7	3,266	17.7
Rapid	53	0.2	10	0.1

Q10

Figure 8.9, 8.10 shows that as with the lower Q95 flow scenario there is increased biotope diversity through the restored section at Q10, with a range of lower and higher energy biotopes observed. In contrast, the unrestored section features a much straighter channel, which again lacks diversity and is dominated by lower energy glide biotopes. Table 8.5 shows a large increase in riffle habitat in the post restoration scenario.

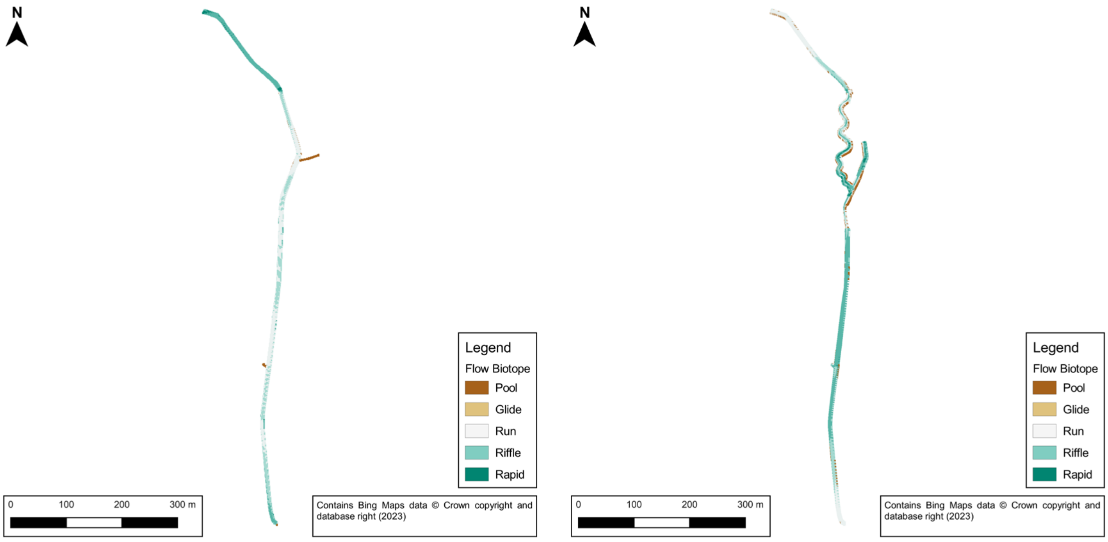


Figure 8.9 Flow biotopes pre (left) and post (right) restoration during Q95 flows.

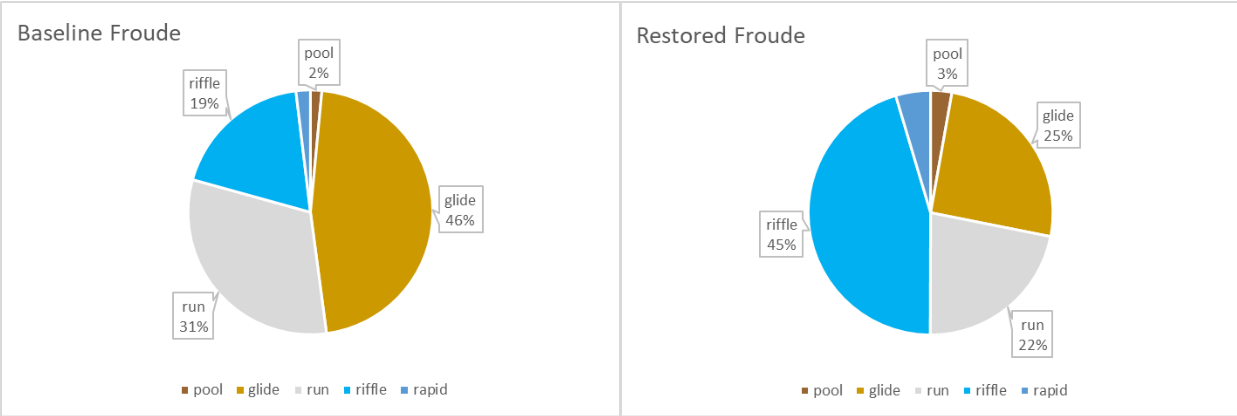


Figure 8.10 Proportion of each flow biotope observed during a Q10 flow.

Table 8.5 Proportion and quantity of each flow biotope observed during a Q10 flow.

Flow Biotope	Count pre-change	Proportion of overall habitat pre-change (%)	Count post-change	Proportion of overall habitat post-change (%)
Pool	367	1.5	805	2.8
Glide	11,654	46.4	7,185	25.3
Run	7,899	31.4	6,202	21.9
Riffle	4,728	18.8	12,861	45.3
Rapid	486	1.9	1,316	4.6

2-year flood

Figure 8.11, Figure 8.12 and Table 8.6 show that the post-restoration scenario is also associated with a shift towards higher energy biotopes, with slight increases in the proportion of riffles and rapids observed. There is also a reduction in pool habitat associated with the post-restoration scenario, with areas formerly pool biotope now classified as glide. A greater diversity in flow biotopes can also be observed upstream of the scheme.

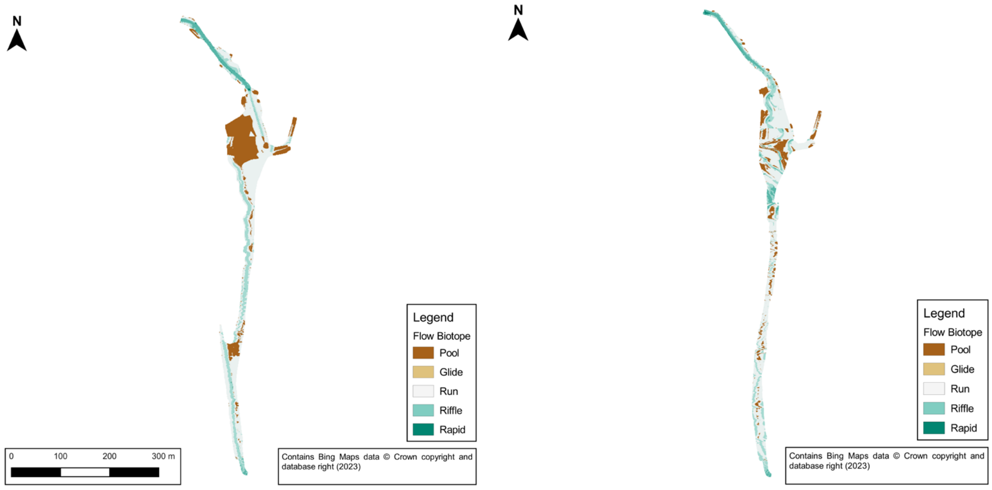


Figure 8.11 Flow biotopes pre (left) and post (right) restoration during a 2-year flood flow.

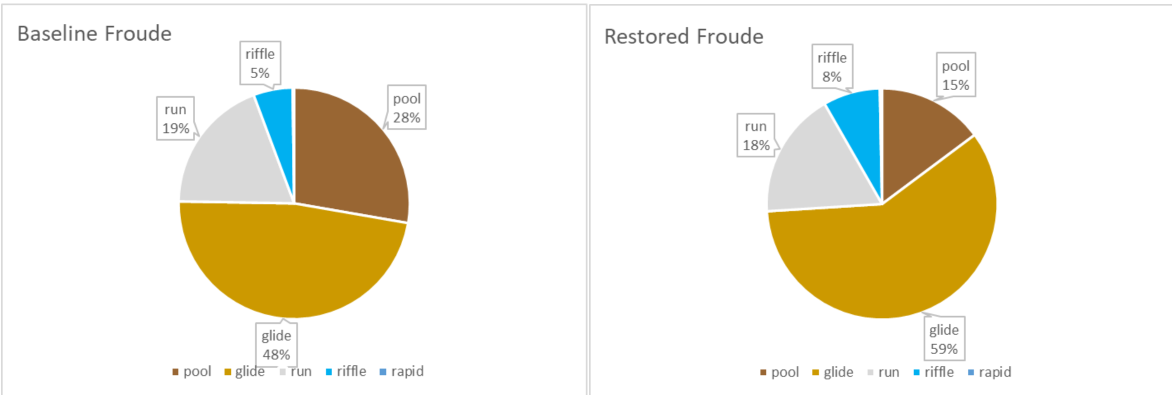


Figure 8.12 Proportion of each flow biotope observed during a 2-year flood flow.

Table 8.6 Proportion of each flow biotope observed during a 2-year flood flow.

Flow Biotope	Count pre-change	Proportion of overall habitat pre-change (%)	Count post-change	Proportion of overall habitat post-change (%)
Pool	28,310	27.7	12,138	14.8
Glide	48,539	47.5	48,556	59.2
Run	19,418	19.0	14,550	17.7
Riffle	5,593	5.5	6,554	8.0
Rapid	222	0.2	228	0.3

8.3.3. Shear Stress

Figure 8.13 shows that shear-stresses remain relatively low through much of the reach, particularly in those areas where floodplain activation is shown to occur. The highest shear stresses are observed towards downstream extent of the site where no changes were made. The sinuous channel in the restored scenario is shown to feature areas of higher shear stress on the outside bend of meanders. This suggests an increase in morphological and sediment dynamics in the new channel when compared to the reaches upstream and downstream. There are areas within the channel where sediment will be entrained, transported, or eroded. This is due to a more diverse morphology that should be better equipped to sustain itself and flush through fine sediment when it is delivered to this reach.

Figure 8.13 Shear stresses reach under pre (left) and port (right and bottom) during a 2-year flood flow.

8.3.4. Habitat

Fuzzy-logic habitat modelling was conducted to assess the impact of the restoration measures on habitat to support the various life stages of Brown trout through the study reach. The results of this modelling show that the restoration measures had a mixed impact (Table 8.7, 8.8).

During low Q95 flows, adult and 1+ habitat is shown to reduce slightly, while 0+ habitat is shown to increase. This reduction in adult and 1+ habitat is likely linked to the loss of deeper pool and glide biotopes.

During larger Q10 flows, the results suggest that restoration activities had a more positive impact, with increases in adult, 1+ and 0+ habitat observed. This increase in overall habitat to support various life stages is due to the increased hydraulic diversity post restoration, with a more even split of each flow biotope observed.

In the 2-year flood flow scenario the results suggest that restoration leads to a very slight reduction in refuge habitat, however this change is marginal and improved refuge was not a priority for the restoration scheme.

Table 8.7 Habitat Suitability Index (HSI).

	Q95 pre	Q95 post	Q10 pre	Q10 post	2-year flood pre	2-year flood post
Adult	1,027	846	2,433	2,492	NA	NA
1+	1,278	1,155	1,847	1,976	NA	NA
0+	1,920	2,003	804	1,259	NA	NA
Spawning	683	650	2,963	2,767	NA	NA
Refuge	NA	NA	2,208	2,952	9,697	8,136

Table 8.8 Habitat Quality Index (HQI).

	Q95 base	Q95 post	Q10 base	Q10 post	2-year flood pre	2-year flood post
Adult	16.5	15.4	38.9	35.3	NA	NA
1+	20.5	21	29.4	28	NA	NA
0+	30.9	36.4	12.8	17.8	NA	NA
Spawning	10.9	11.8	47.2	39.2	NA	NA
Refuge	NA	NA	38.2	42.1	38	39.7

8.4. Conclusions

The Fowlea Brook is a single-thread lowland river that has been subject to extensive modification which has restricted natural hydromorphological processes. The scheme comprised the creation of a new more sinuous channel with additional geomorphic features to encourage natural processes.

Hydraulic modelling shows that the new channel provides a more varied morphology, which in turn can provide variable flow conditions and habitats. Shear stress results show that the new channel has the potential to diversify sediment transport in the Fowlea Brook due to the combination of channel narrowing and increased sinuosity. The largest changes in flow biotopes and fish habitat were observed at Q10. At Q95 the fish habitat modelling suggests the restoration has mixed results depending on the life stage of interest.

9. Goldrill

9.1. Background

Goldrill Beck river restoration scheme is located on the floodplain adjacent to the Goldrill Beck immediately downstream of Brothers Water, Cumbria. The site is owned by the National Trust. The land was set aside for river restoration and habitat development. Figure 9.1 and Figure 9.2 show the site pre and post restoration.

Goldrill Beck is notified as a Site of Special Scientific Interest (SSSI) and Special Area of Conservation (SAC) as a part of the Eden and Tributaries SSSI/SAC. The SSSI Units have been subject to physical modifications affecting their optimal functioning as a habitat for characteristic wildlife communities. As a result it is classed as being in 'unfavourable condition'.

The watercourse drains the catchment above Patterdale via a series of steep bedrock influenced headwater tributaries including Caiston Beck, Cauldale Beck and Dovedale Beck which pass through Brothers Water and the principal tributary, Pasture Beck, which confluences below this waterbody. Angletarn Beck drains from Angle Tarn, discharging onto the Goldrill Beck floodplain from the right bank where it had formed a significant fan deposit. Goldrill Beck has been significantly modified and, pre-restoration, it flowed along the left-hand edge of the valley bottom through the study reach where it is presently impacting the A592 highway. The restoration design was in line with Natural England and Environment Agency initiatives to deliver against all of the following priorities:

- Remove the erosion risk to the A592 posed by the existing river channel;
- Deliver against the river restoration remedy for the SAC;
- No increase in, and where possible decrease in, flood risk to infrastructure and communities downstream of the project;
- No risk to upstream infrastructure through changes in river bed level. Where potential risk is identified mitigation must be built in;
- Deliver a river and floodplain which are governed by natural process and require no ongoing management;
- Ensure Atlantic salmon habitat is enhanced in both quality and quantity.

The restoration design included the following measures:

- Channel realignment and bifurcation;
- Anastomosed channels;
- Floodplain reconnection;
- Riffle-rapid introduction.


Figure 9.1 Aerial Photographs of pre-construction (left) and post-construction (right)

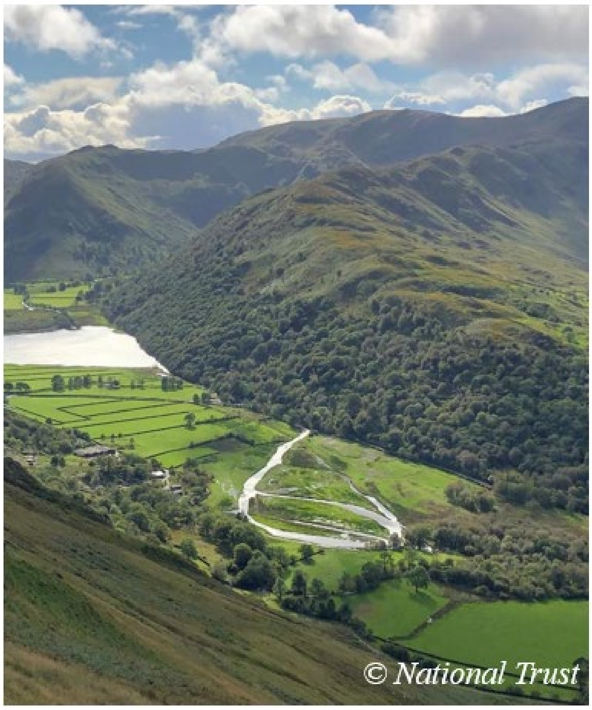


Figure 9.2 Photographs of pre-construction (left) and post-construction (right) (National Trust imagery)

9.2. Site Specific Methodology

9.2.1. Model schematisation

To help review the post restoration work of the Goldrill Beck site described above, a 2D HEC-RAS (v6.3) model of the study reach has been developed, using available Environment Agency 1 m cell size LiDAR and check survey for the baseline. It should be noted that there remains some uncertainty in levels where vegetation growth and sedimentation have occurred along the reach, therefore there may be some discrepancy in baseline levels. For the post-restoration model, a 25 cm photogrammetric drone-based DEM of the restored site has been utilised to enable the pre and post comparison to be made.

The purpose of the modelling was to appraise the restoration with regards to the specific outputs required to assess the impacts on hydraulics as a result of the scheme compared to the pre restored conditions. This enabled assessment of the impacts to in-channel processes and the hydrological regime.

The model has been built using a Digital Elevation Model (DEM) across the model domain that provides a ground elevation value for each 1 m grid cell for both the pre and post restoration conditions. The model extent (also showing grid orientation) and resulting model surface is shown below in Figure 9.3.

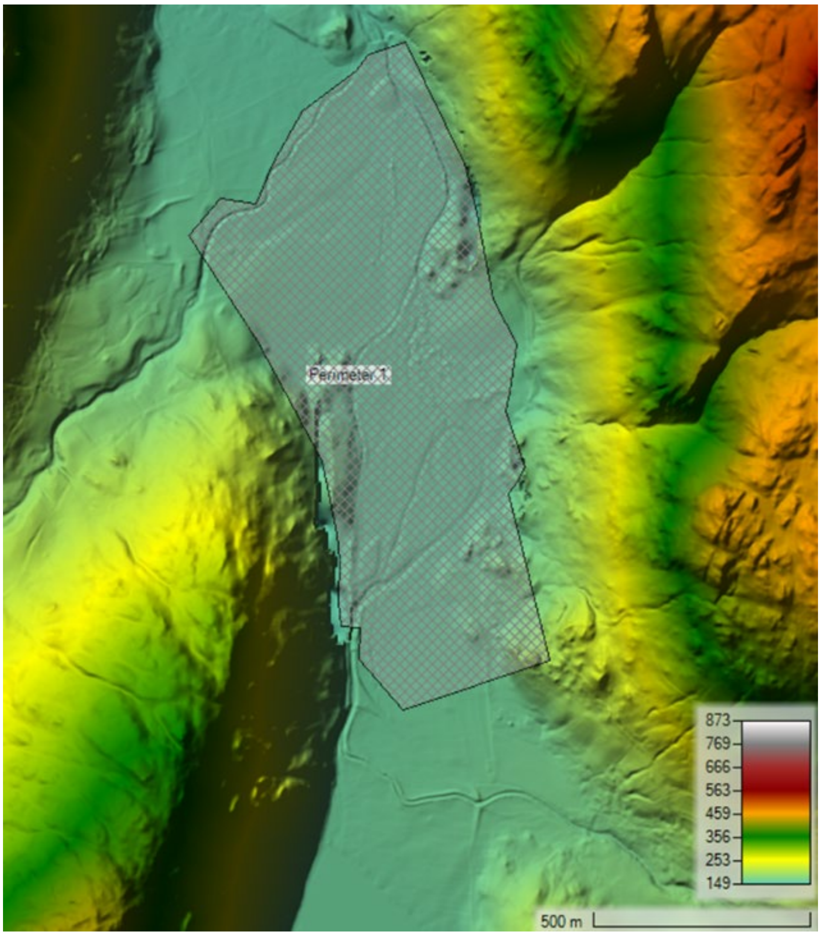


Figure 9.3 HEC-RAS 2D – baseline grid set up of the study site at Goldrill Beck

9.2.2. Inflows

The flows used in the modelling are shown in Table 9.1 below. The low flows for Q95, Q50, Q30 and Q10 were derived using Low Flows 2 software. The 2-year return period flows were used from the previous design study.

Table 9.1 Inflows to the model

Scenario	Flow (m^3/s)
Q95 (summer flow)	0.16
Q50	1.0
Q30	2.0
Q10 (winter flow)	4.5
2-year return period flood	31.3

9.2.3. Manning's roughness

Observations of the channel and banks, from site visits and a survey, informed the choice of Manning's n values. These have also been cross checked against values listed in Chow, 1959[4]. Table 9.2 and Table 9.3, and Figure 9.4 and Figure 9.5 show these values and how they have been used.

Table 9.2 Manning's roughness values used (pre change)

Land Use	Manning's N	Photo
Channel	0.045 has been used to represent the in channel flow.	See Figures 9.1 and 9.2
Floodplain	Arable Field: (n=0.05) used to represent a vegetated field	See Figures 9.1 and 9.2

[4] Chow, V.T. (1959) Open Channel Hydraulics, McGraw-Hill Book Company, NY.

Figure 9.4 Baseline Manning's roughness Grid.

9.2.4. Post change representation

Post restoration modifications were made to the underlying model surface through direct use of the post restoration drone DEM and changes in roughness across the model domain linked to new features introduced. As an example, roughness was increased across the post restoration floodplain to represent vegetation change over time post completion of the scheme (previous arable fields).

Table 9.3 Manning's roughness values used (post change)

Land Use	Manning's N	Photo
Channel	Channel: (n=0.045). This has been used to represent the new channels.	See Figures 9.1 and 9.2
Floodplain	Arable Field: (n=0.05) used to represent a vegetated field. Roughened Floodplain post change (n=0.1) to represent the change in land use post river restoration and floodplain reconnection.	See Figures 9.1 and 9.2

Figure 9.5 Post-change Manning's roughness grid

9.3. Results

9.3.1. Hydraulic Conditions

Q95

Figure 9.6 shows a large increase in overall wetted area for the Q95 flow, with the overall wetted area increasing from 14195 m^2 in the pre-restoration scenario to 21938 m^2 in the post-restoration scenario. This increase is due to the improved floodplain connection with the channel now better connected to the floodplain through new features in the new channel associated with the post-restoration scenario. This situation will be dynamic over time, however significant wetted area under low flows is likely to be retained as the channel and floodplain develop.

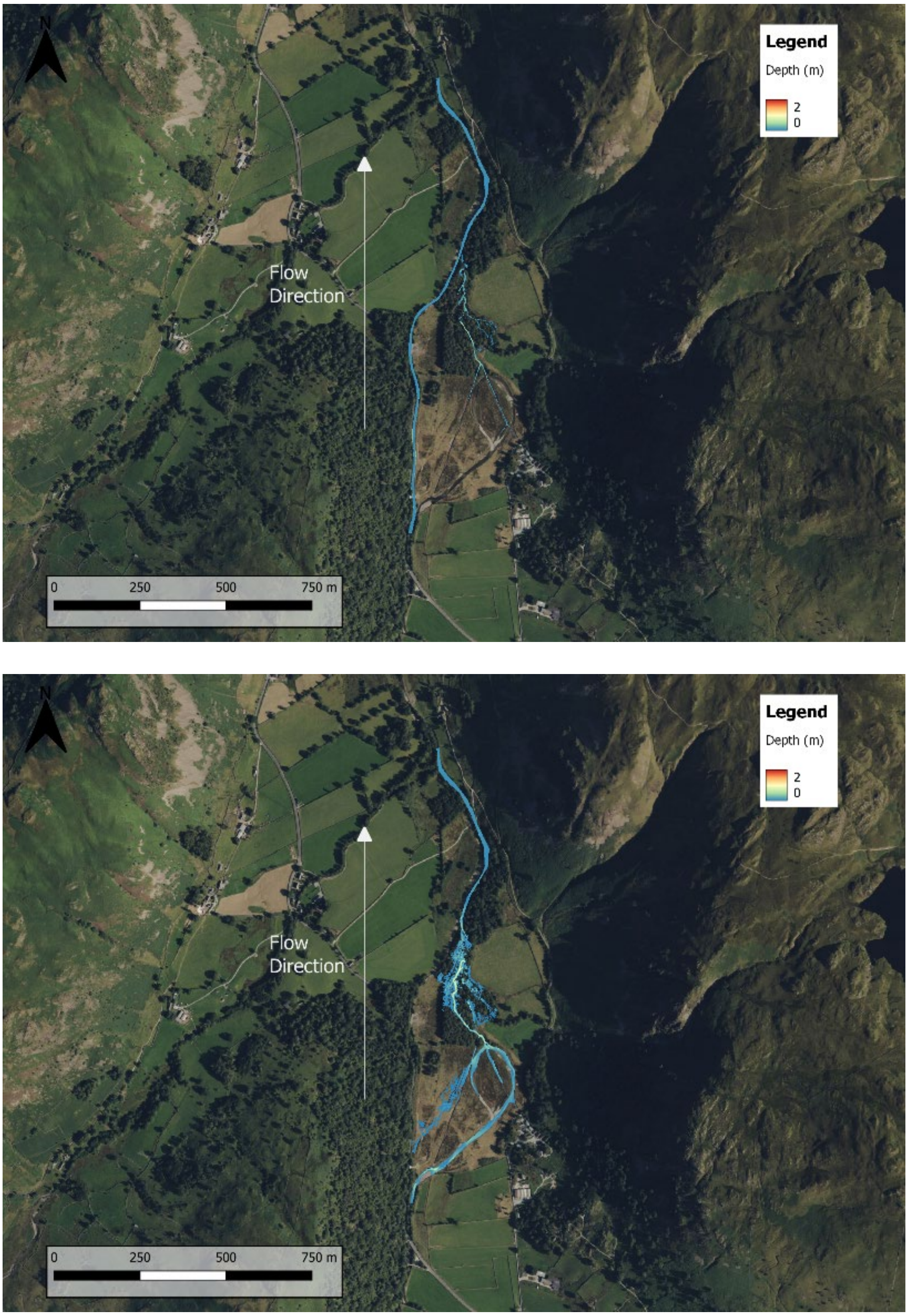


Figure 9.6 Water depth pre (top) and post (bottom) restoration scenarios during the Q95 flow.

Q10

Figure 9.7 shows a large increase in overall wetted area for the Q10 flow, with the overall wetted area increasing from 17153 m^2 in the pre-restoration scenario to 81644 m^2 in the post-restoration scenario. This increase is again due to the improved floodplain connection with the channel now better connected to the floodplain through new features in the new channel associated with the post-restoration scenario. This situation will be dynamic over time, however significant wetted area under winter flows is likely to be retained as the channel and floodplain develop.

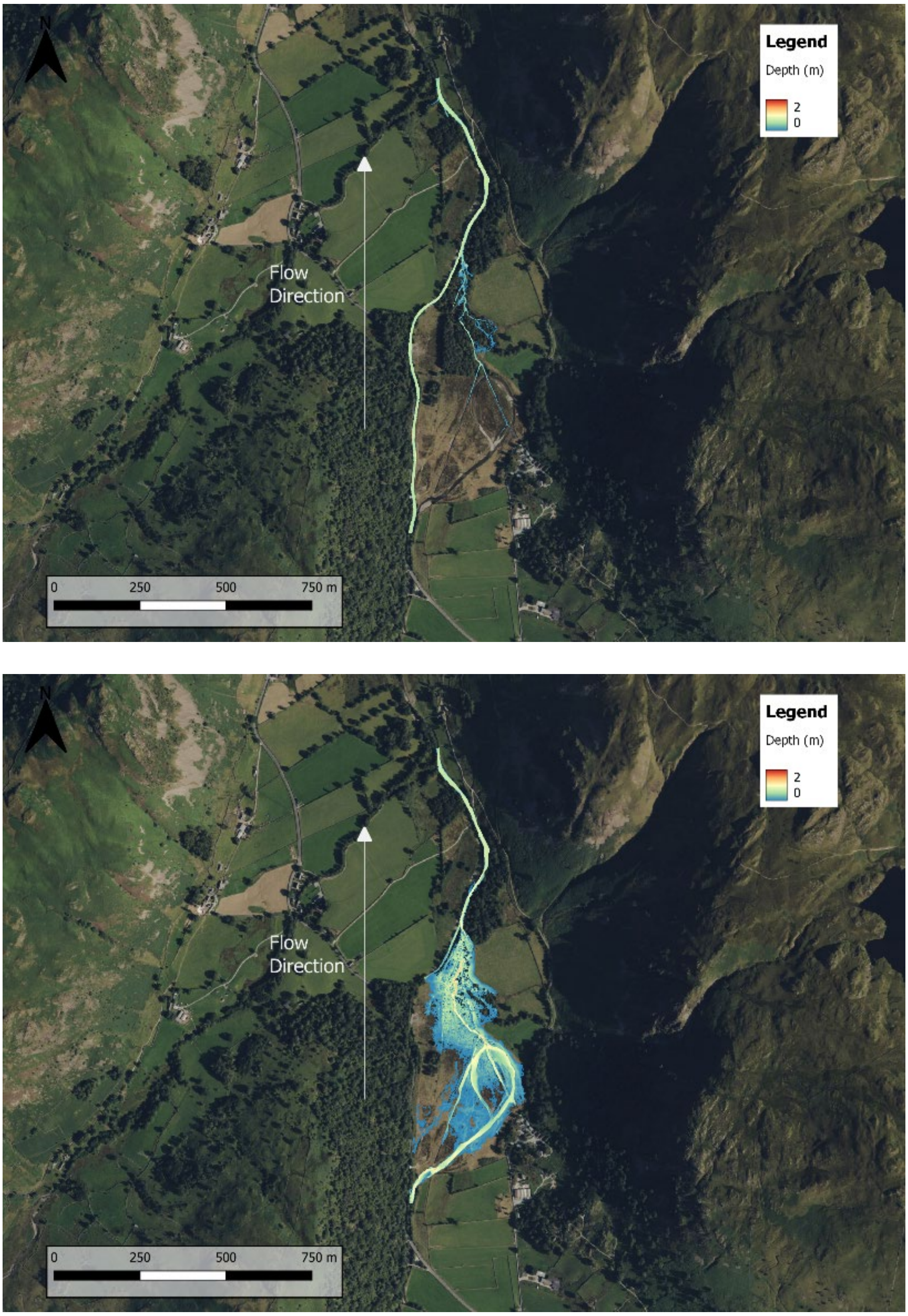


Figure 9.7 Water depth pre (top) and post (bottom) restoration scenarios during the Q10 flow.

2-year flood

Figure 9.8 shows a large increase in overall wetted area for the 2-year flow, with the overall wetted area increasing from 115769 m^2 in the pre-restoration scenario to 179454 m^2 in the post-restoration scenario. This increase is due to the improved floodplain connection with the channel now better connected to the floodplain through new features in the new channel associated with the post-restoration scenario. This situation will be dynamic over time, however significant wetted area under winter flows is likely to be retained as the channel and floodplain develop. Shallower flow is evident overall as the channel is now not as deep following the restoration.

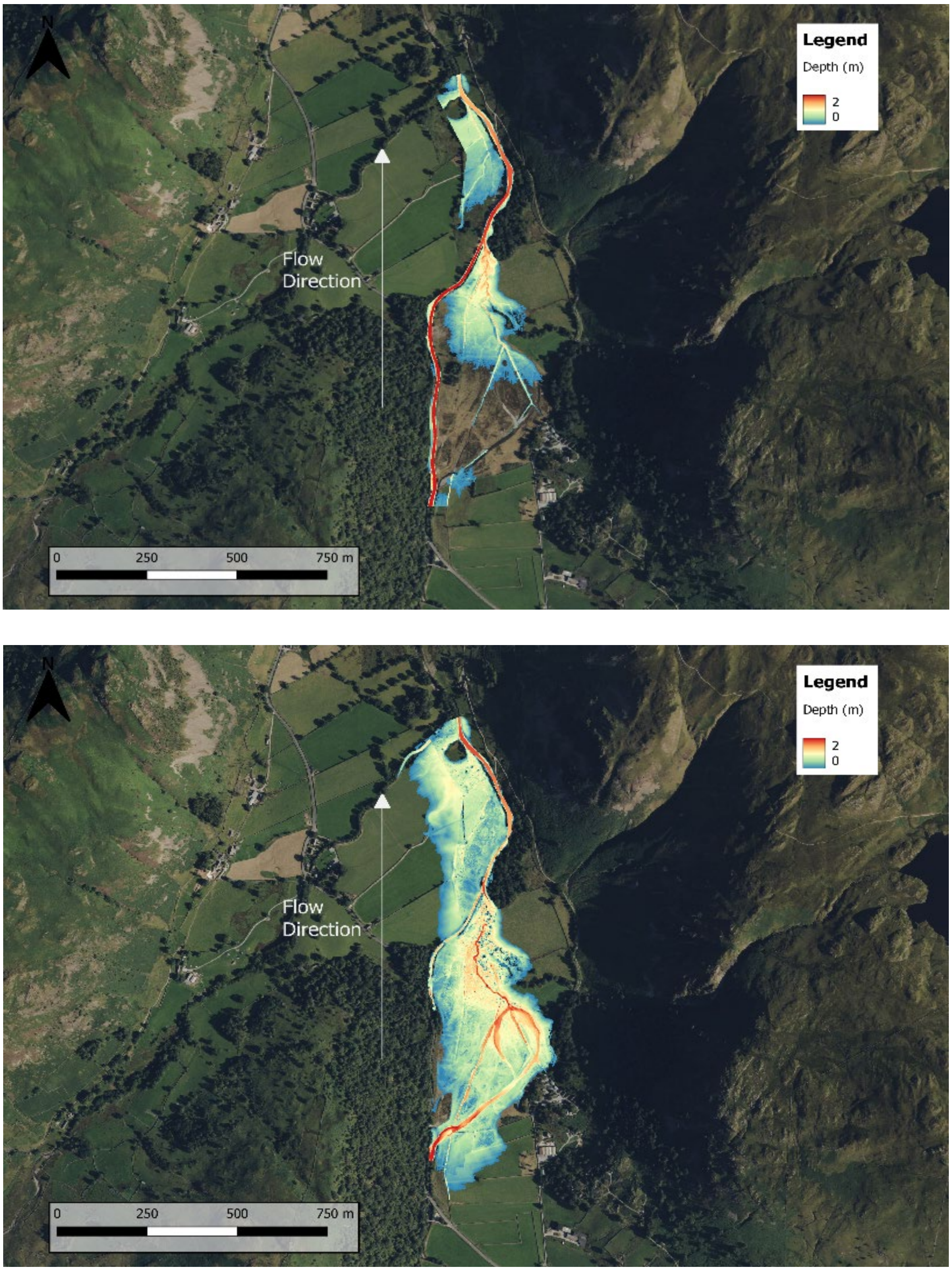


Figure 9.8 Water depth pre (top) and post (bottom) restoration scenarios during the 2-year flood flow.

9.3.2. Flow Biotopes

Q95

Figures 9.9 and 9.10, and Table 9.4, show that there has been both a significant change in hydraulic habitat diversity and overall hydraulic habitat area as a result of the restoration scheme for a summer flow (as overall flow area does significantly increase compared to baseline). There is a decrease in the percentage cover of higher energy biotopes overall (riffles) as a result of the impact of the restoration undertaken through the Goldrill Beck site, namely the improved floodplain connectivity and newly meandered channel providing lower in-channel energy conditions compared to baseline. The higher percentage of lower energy biotopes (pools and glides) is mainly as a result of the increased wetted area across the floodplain, where flow is slowed.

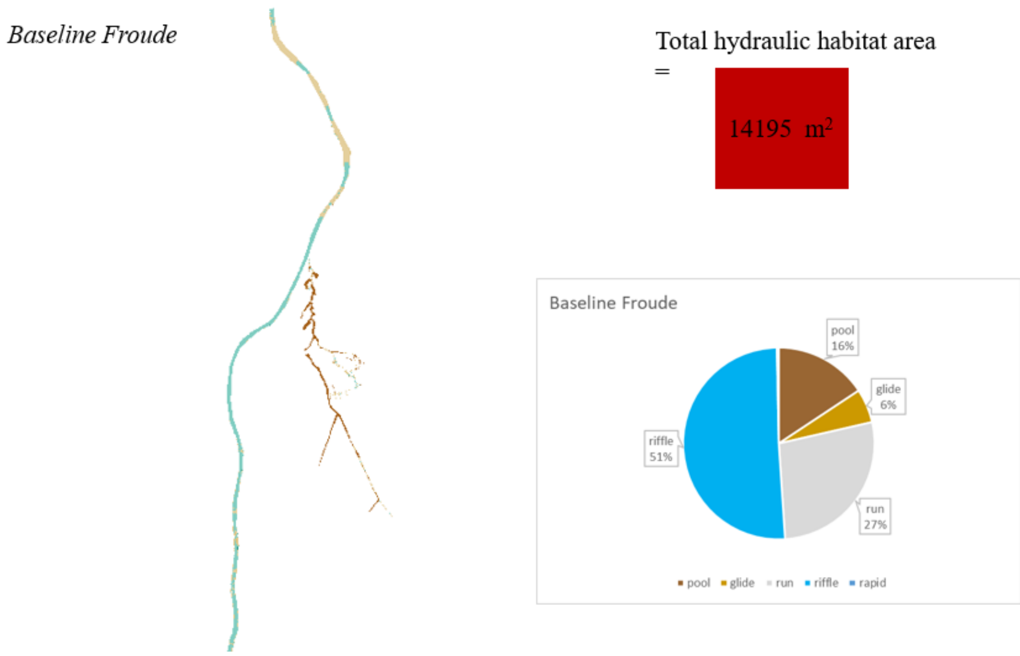


Figure 9.9 Flow biotope pre-restoration during the Q95 flow.

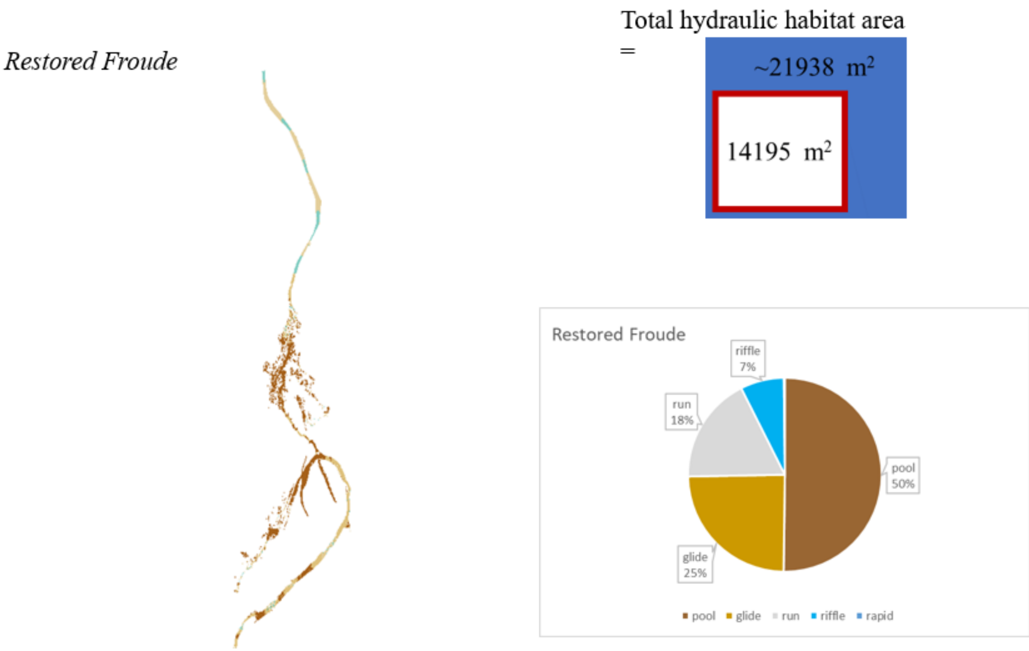


Figure 9.10 Flow biotope post-restoration during the Q95 flow.

Table 9.4 Flow biotope change between pre and post restoration.

Flow Biotope	Area pre-restoration (m^2)	Proportion of overall habitat pre-restoration (%)	Area post-restoration (m^2)	Proportion of overall habitat post-restoration (%)	Overall Area Change (%)
Pool	2229	15.70	11016	50.21	394%
Glide	812	5.72	5373	24.49	562%
Run	3908	27.53	3917	27.85	0%
Riffle	7201	50.73	1596	7.27	-78%
Rapid	45	0.32	36	0.17	-19%

Q10

Figure 9.11, and Table 9.5 (unmanaged scenario), show that there has been both a significant change in hydraulic habitat diversity and overall hydraulic habitat area as a result of the restoration scheme for a winter flow (as overall flow area does significantly increase compared to baseline). There is a decrease in the percentage cover of higher energy biotopes overall (riffles) as a result of the impact of the restoration undertaken through the Goldrill Beck site, namely the improved floodplain connectivity and newly meandered channel providing lower in-channel energy conditions compared to baseline. The higher percentage of lower energy biotopes (pools, runs and glides) is mainly as a result of the increased wetted area across the floodplain where flow is slowed.

The unmanaged scenario shows the development of a chute that is now further developing as a result of the restoration scheme. This has been used in Table 9.5 for comparative purposes.

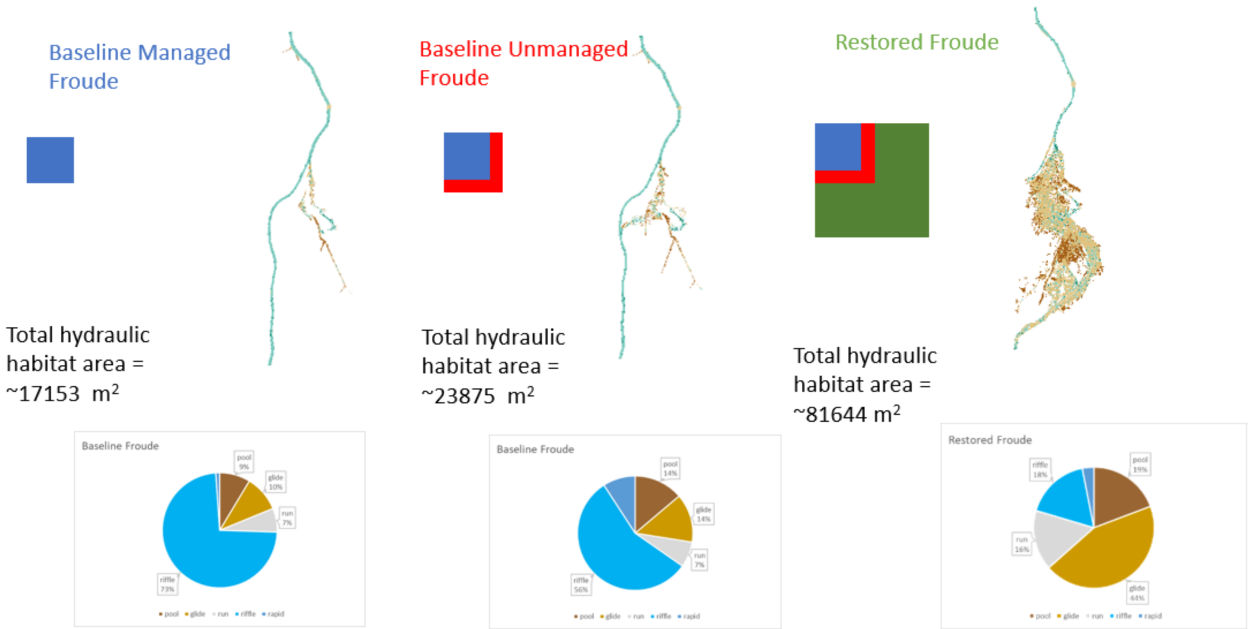


Figure 9.11 Flow biotope pre restoration managed (left), pre restoration unmanaged (centre) and post restoration (right) during the Q10 flow.

Table 9.5 Flow biotope change between pre restoration (unmanaged) and post restoration (unmanaged).

Flow Biotope	Area pre-restoration (unmanaged) (m^2)	Proportion of overall habitat pre-restoration (%)	Area post-restoration (unmanaged) (m^2)	Proportion of overall habitat post-change (%)	Overall Area Change (%)
Pool	3286	13.76	15733	19.27	379%
Glide	3282	13.75	36076	44.19	999%
Run	1727	7.23	13164	16.12	662%
Riffle	13405	56.15	14117	17.29	5%
Rapid	2175	9.11	2554	3.13	17%

9.3.3. Shear Stress

Baseline bed shear stress model outputs show that generally under lower order flood flows (2-year return period shown in Figure 9.12 and Figure 9.13) values range between 10-150 N/m^2 (Figure 9.12) with the majority of these falling within the lower estimate of this range, particularly across the wetted floodplain area. Higher values are located at particular points in the channel where change was known to have occurred pre restoration and where the channel gradient is locally higher. This range does not change significantly for the restored model scenario (Figure 9.13), however, there is an increase in shear stress across the wetted floodplain area in places as a result of the improved connectivity. This may result in some concentrated erosion over time, but is a natural process associated to rivers of this type. There are some higher shear stresses across the introduced gravel/cobble features. There is an overall significant reduction in bed shear stress within the channel as a result of the restoration scheme, from the flow splits created and the much improved floodplain connectivity.

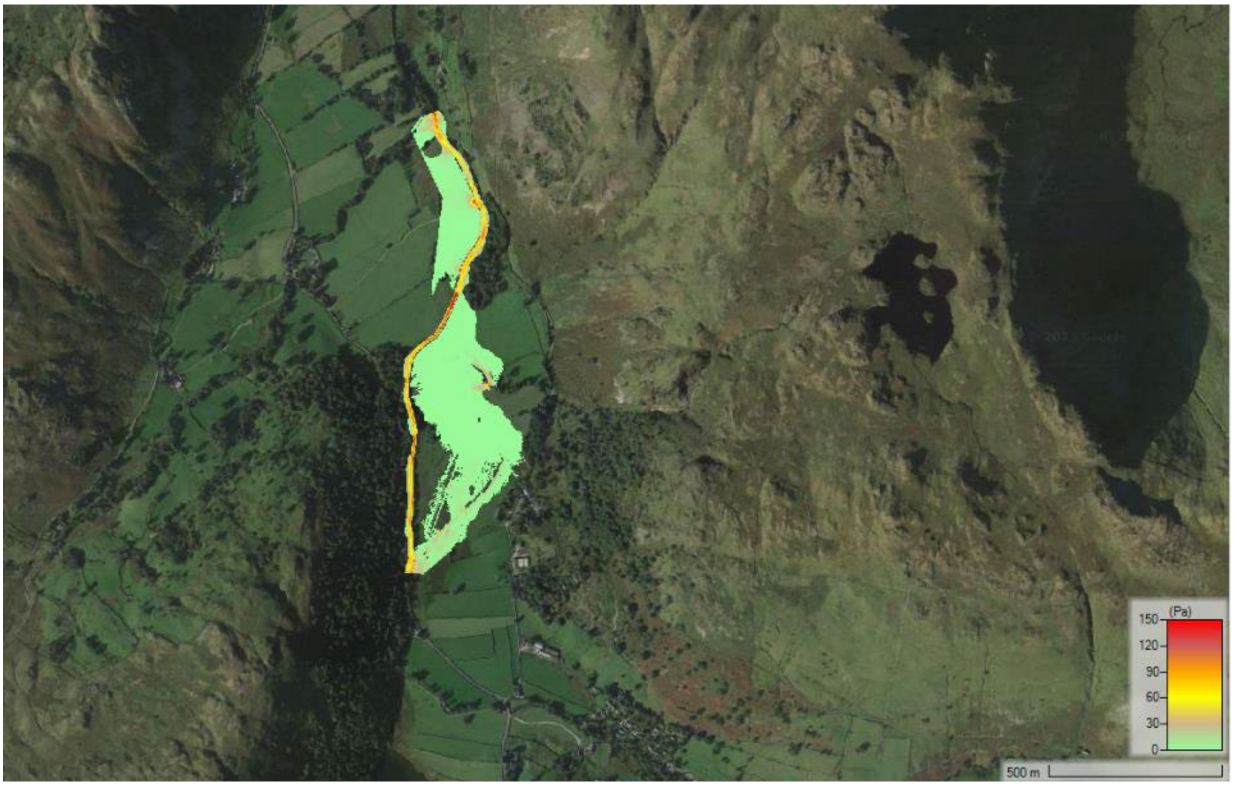


Figure 9.12 2-year flood flow bed shear stress pre-restoration.

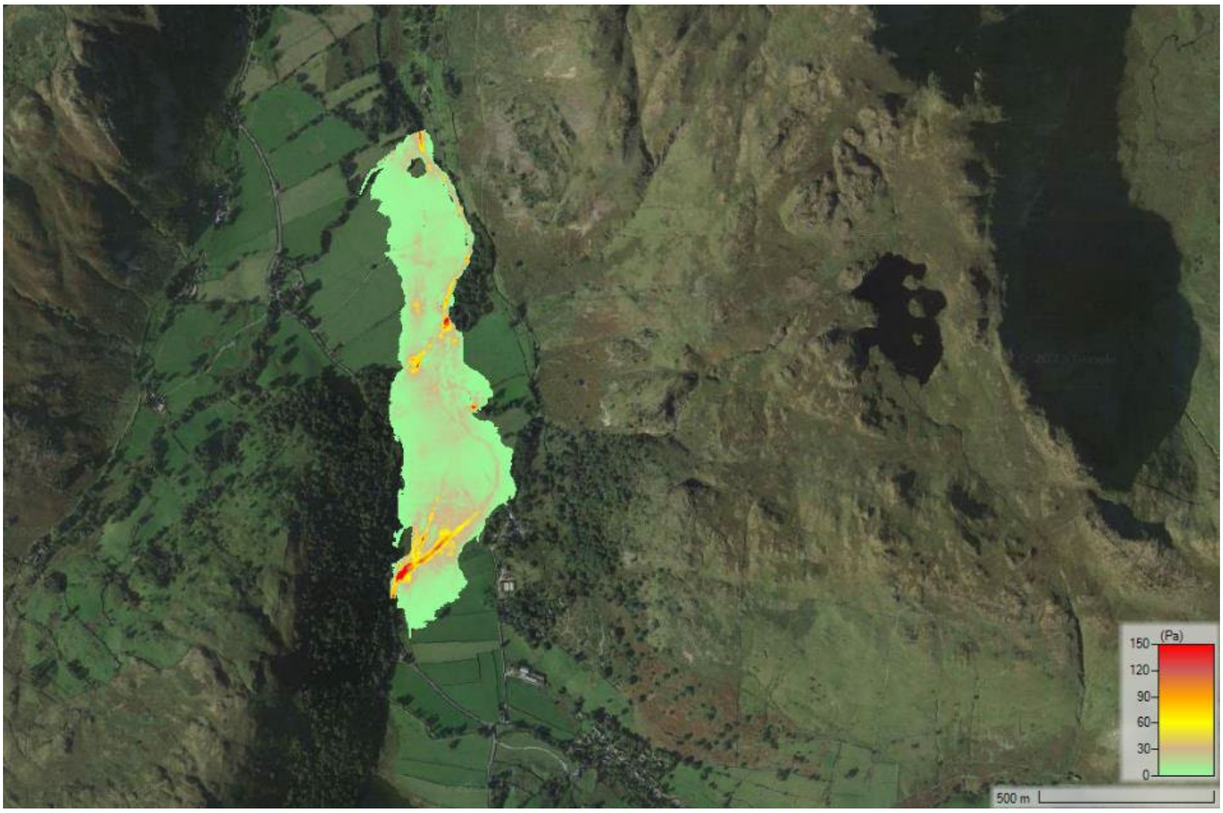


Figure 9.13 2-year flood flow bed shear stress post-restoration.

9.3.4. Floodplain habitat creation

This section demonstrates the overall floodplain habitat gains/creation as a result of the restoration scheme. Table 9.6 summarises the wetting thresholds used to map the floodplain habitat and shows the optimal vegetation development over time based on the new hydrological regime at the site, this may differ in reality due to species competition and other factors, but this provides a template for anticipated development. The summer (Q95), autumn (Q30), winter (Q10) and spring (Q50) inundation area has been extrapolated to predict water table levels across the wider floodplain for the study site based on the restored scenario. Figure 9.14 summarises the probable mosaic of swamp, mire and wet grassland habitat that will develop under a sensitive grazing regime and the coverage is summarised in Table 9.7. It is clear that the predicted habitat gains will be diverse and considerable across the valley bottom and that these areas will act immediately to sequester carbon, turning much of the valley bottom from a carbon emitter to a sequestering area.

Table 9.6 Summer, winter, spring, autumn wetting threshold for each habitat.

Habitat Type	Habitat Code	Water table depth below FP surface (negative numbers indicated flooded ground)			
		Winter	Spring	Summer	Autumn
Wet Grassland	MG13	0.1-0.25	0.03-0.45	0.2-0.8	0.1-1
	MG4	0.1-0.6	0.25-0.7	0.4-1.0	0.25-1
	MG8	0.03-0.3	0.03-0.35	0.15-0.5	0.1-0.4
Fen Mire	M24	--	--	0.249-0.533	--
	M13	--	--	0.096-0.386	--
	S24	--	--	0.167-0.784	--
	S2	0-(0.4)	--	<0.15	--
Ditch Swamp	S4	0-(1.5)	0.25-(1.25)	0.8-(0.5)	1-(0.75)
	S5	0.3-(0.9)	0.6-(0.7)	0.8-(0.8)	0.6-(0.8)

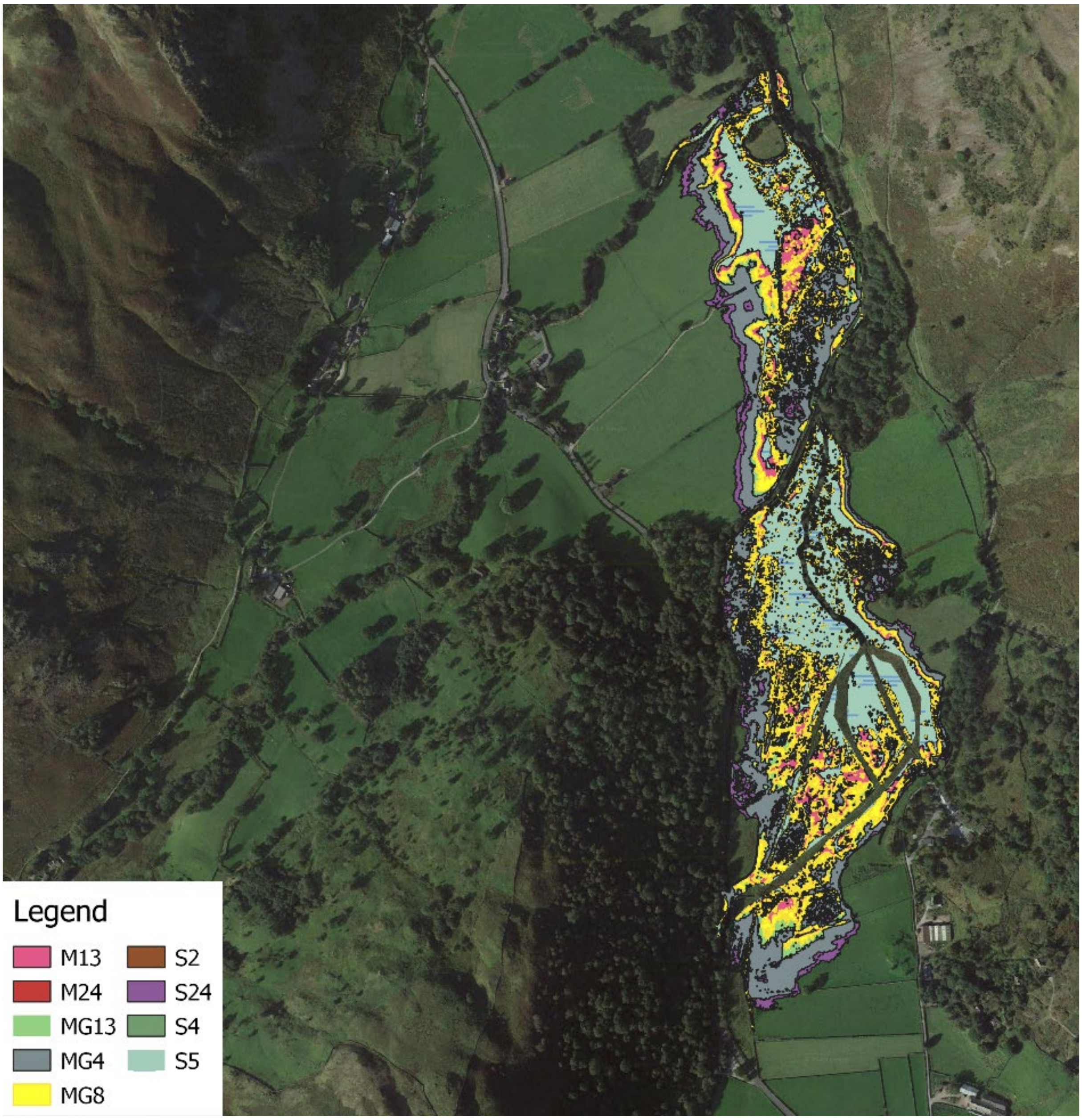


Figure 9.14 Floodplain habitat biotope post-restoration.

Table 9.7 Total Habitat area created (m^2).

Habitat Type	Habitat Code	Area (m^2)
Wet Grassland	MG13	35394
	MG4	68190
	MG8	26126
Fen Mire	M24	83219
	M13	82816
	S24	157609
	S2	11827
Ditch Swamp	S4	NA
	S5	183057

9.4. Conclusions

The restoration design included the following measures at Goldrill Beck:

- Channel realignment and bifurcation;
- Anastomosed channels;
- Floodplain reconnection;
- Riffle-rapid introduction.

The significant increase in overall wetted area under low flows shown by the modelling demonstrates the increased resilience to low flows created as a result of the restoration scheme. There is also an overall improvement in biotope diversity under summer and winter flows when compared to baseline conditions. Floodplain habitat creation and likely development is also predicted to be diverse as a result of the new hydrological regime created.

10. Hartsop

10.1. Background

Kirkstone Beck just upstream of Brothers Water at Hartsop, Cumbria is an active single thread river system that has been subject to significant historic modification, particularly across the delta at Brothers Water. The site is owned by the National Trust and is intensively farmed. This land use was a constraint to the restoration scheme.

The mandatory requirements of the two EU legislative frameworks are not being met (‘unfavourable improving condition’ for the Habitats Directive and ‘good ecological condition’ for the WFD). The historic modifications to the Kirkstone Beck at Brothers Water include straightening, disconnection of the floodplain, and creation of a single thread channel from a previous deltaic fan system. Restricted movement has led to extensive perching and has increased the risk of uncontrolled breaching of embankments during extreme events.

Kirkstone Beck drains the fells above Brothers Water. It occupies a steep valley flowing as a bedrock dominated, step-pool system before the valley widens and the watercourse is joined by Dovedale Beck and Caudale Beck above the glacial lake. The gradient of the valley bottom here reduces dramatically as the watercourses flow over previously deposited fluvio-glacial fans and lacustrine deposits and there is evidence of former multi-channel networks preserved in the sediment leading through to Brothers Water.

The channel network above Brothers Water is well connected to upper catchment coarse sediment supplies and there are a number of active source zones and temporary storage areas on the watercourses, suggesting a strong bedload transport regime through to the valley bottom.

The restoration scheme had to work within the constraints of still providing embankments that offer some protection to surrounding land, therefore full floodplain reconnection was not possible, except at the downstream end towards Brothers Water.

The restoration design included the following measures (Figures 10.1, 10.2):

- embankment setting back,
- wandering / multi-channel creation,
- floodplain reconnection,
- riffle-rapids,
- channel widening.

Figure 10.1 Aerial Photographs of pre-restoration (top) and post-restoration (bottom).

Figure 10.2 Photographs taken pre-restoration (top) and post-restoration (bottom).

10.2. Site Specific Methodology

10.2.1. Model schematisation

To help review the post-restoration work at the Hartsop Hall site described above, a 2D HEC-RAS (v6.3) model of the study reach has been developed, using available Environment Agency 1 m cell size LiDAR and a check survey for the baseline. It should be noted that there remains some uncertainty in levels where vegetation growth and sedimentation have occurred along the reach, therefore there may be some discrepancy in baseline levels. For the post-restoration model, a 25 cm photogrammetric drone-based DEM of the restored site has been utilised to enable the pre and post comparison to be made.

The purpose of the modelling was to appraise the restoration with regards to the specific outputs required to assess the impacts on hydraulics as a result of the scheme compared to the pre restored conditions. This enabled assessment of the impacts on in-channel processes and the hydrological regime.

The model has been built using a Digital Elevation Model (DEM) across the model domain that provides a ground elevation value for each 1 m grid cell for both the pre and post restoration conditions. The model extent (also showing grid orientation) and resulting model surface is shown below in Figure 10.3.

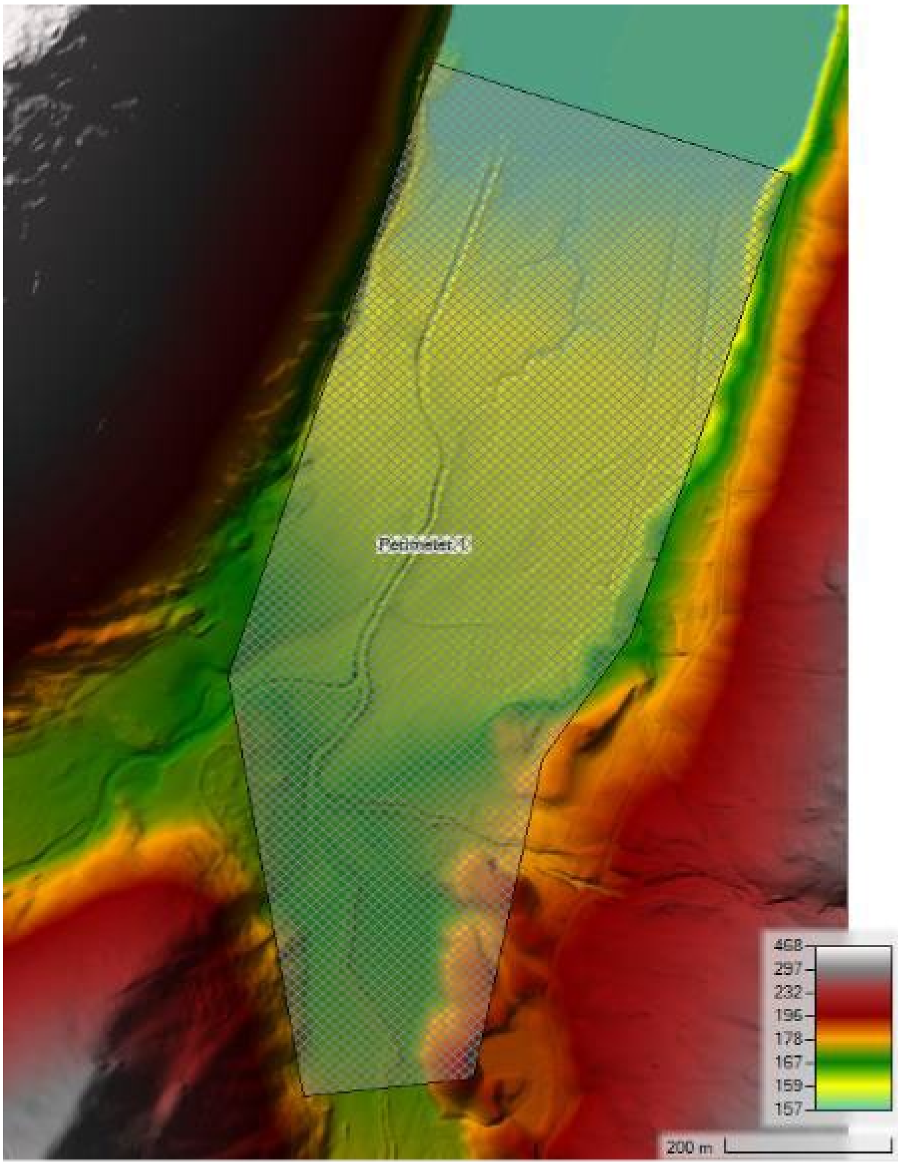


Figure 10.3 HEC-RAS 2D – baseline grid set up of the study site at Hartsop Hall.

10.2.2. Inflows

The flows used in the modelling are shown in Table 10.1 below. The flows for Q95, Q50, Q30 and Q10 were derived using Low Flows 2 software. The 2-year return period flows were used from the previous design study.

Table 10.1 Inflows to the model

Scenario	Flow (m^3/s)
Q95 (summer flow)	0.07
Q50	0.41
Q30	0.88
Q10 (winter flow)	1.95
2-year return period flood	30.65

10.2.3. Manning's roughness

Observations of the channel and banks, from site visits and surveying, informed the choice of Manning's n values. These have also been cross checked against values listed in Chow, 1959[5]. Table 10.2 and Table 10.3, and Figure 10.4 and Figure 10.5 show these values and how they have been used.

Table 10.2 Manning's roughness values used (pre change)

Land Use	Manning's N	Photo
Channel	0.045 has been used to represent the in channel flow.	See Figures 10. 1 and 10. 2
Floodplain	Arable Field: (n=0.05) used to represent a vegetated field	See Figures 10. 1 and 10. 2

[5] Chow, V.T. (1959) Open Channel Hydraulics, McGraw-Hill Book Company, NY.

Figure 10.4 Baseline Manning's roughness Grid.

10.2.4. Post change representation

Post restoration modifications were made to the underlying model surface through direct use of the post restoration drone DEM and changes in roughness across the model domain linked to new features introduced. As an example, roughness was modified across the post restoration upstream wandering channel to reflect the new widened channel roughness conditions.

Table 10.3 Manning's roughness values used (post change)

Land Use	Manning's N	Photo
Channel	Channel: (n=0.045). This has been used to represent the new channels.	See Figures 10. 1 and 10. 2
Floodplain	Arable Field: (n=0.05) used to represent a vegetated field.	See Figures 10. 1 and 10. 2

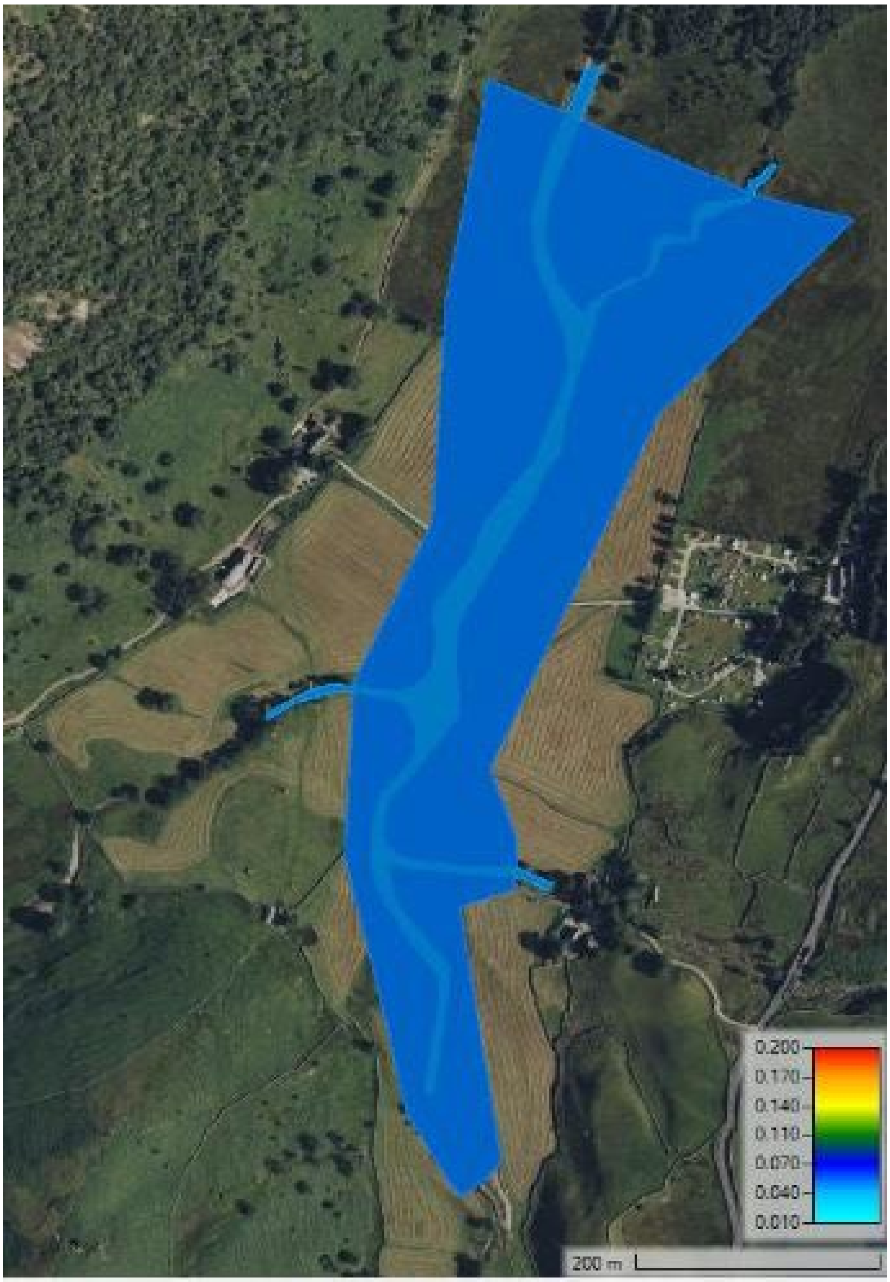


Figure 10.5 Post-change Manning's roughness grid.

10.3. Results

10.3.1. Hydraulic Conditions

Q95

Figure 10.6 shows a significant increase in overall wetted area for the Q95 flow, with the overall wetted area increasing from 4,800 m^2 in the pre-restoration scenario to 8,400 m^2 in the post-restoration scenario. This increase is due to the widened wandering channel created through the upstream reaches and at the confluences of the three watercourses, as well as the improved floodplain connectivity created at the downstream end of the reach through riffle-rapid creation and embankment breaching. This situation will be dynamic over time, particularly through the upstream wandering channel, however significant wetted area under low flows is likely to be retained as the channel and floodplain develop.

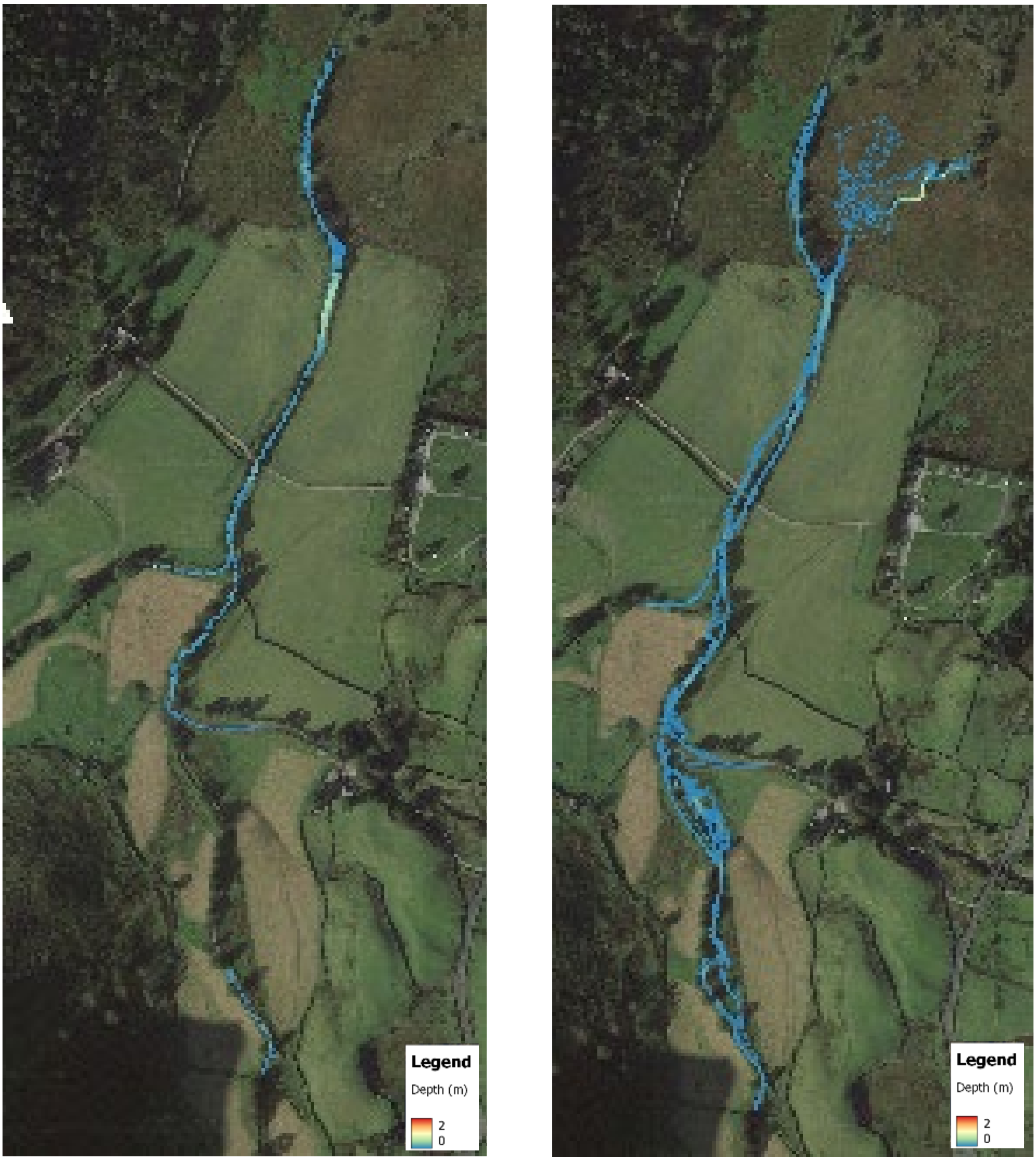


Figure 10.6 Water depth pre (left) and post (right) restoration scenarios for the Q95 flow. Flow direction from south to north.

Q10

Figure 10.7 shows a large increase in overall wetted area for the Q10 flow, with the overall wetted area increasing from 8,200 m^2 in the pre-restoration scenario to 22,600 m^2 in the post-restoration scenario. This increase is again due to the widened wandering channel created through the upstream reaches and at the confluences of the three watercourses, as well as the improved floodplain connectivity created at the downstream end of the reach through riffle-rapid creation and embankment breaching. This situation will be dynamic over time, particularly through the upstream wandering channel, however significant wetted area under winter flows is likely to be retained as the channel and floodplain develop.

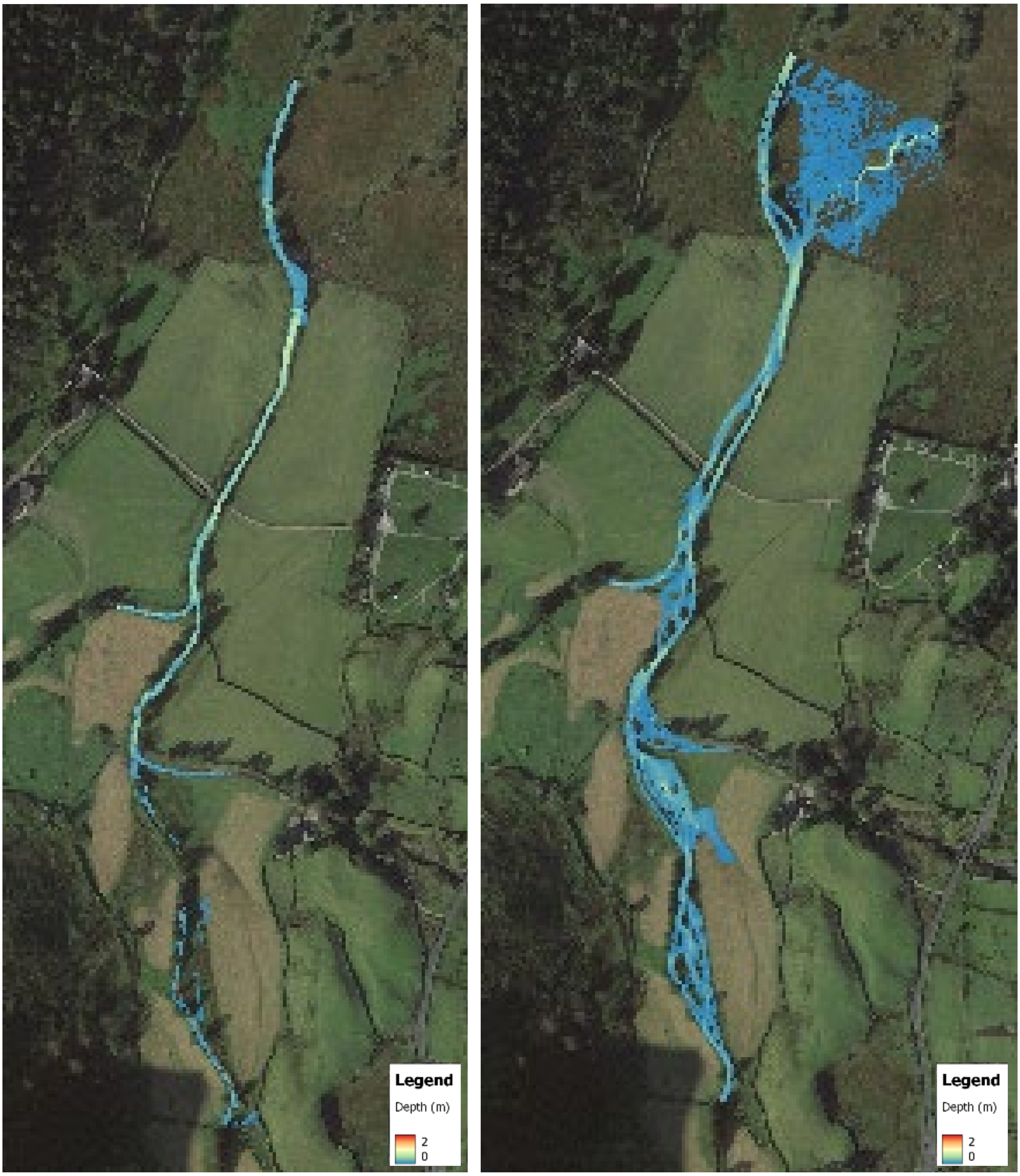


Figure 10.7 Water depth pre (left) and post (right) restoration scenarios for the Q10 flow. Flow direction from south to north.

1 in 2-year

Figure 10.8 shows a reduction in overall wetted area for the 2-year flow, with the overall wetted area reducing from 120,200 m^2 in the pre-restoration scenario to 70,800 m^2 in the post-restoration scenario. This reduction is due to the embankments, that have been realigned, being repaired along the study reach, meaning areas that overtopped during the 2-year baseline event, no longer overtop in the restored conditions.

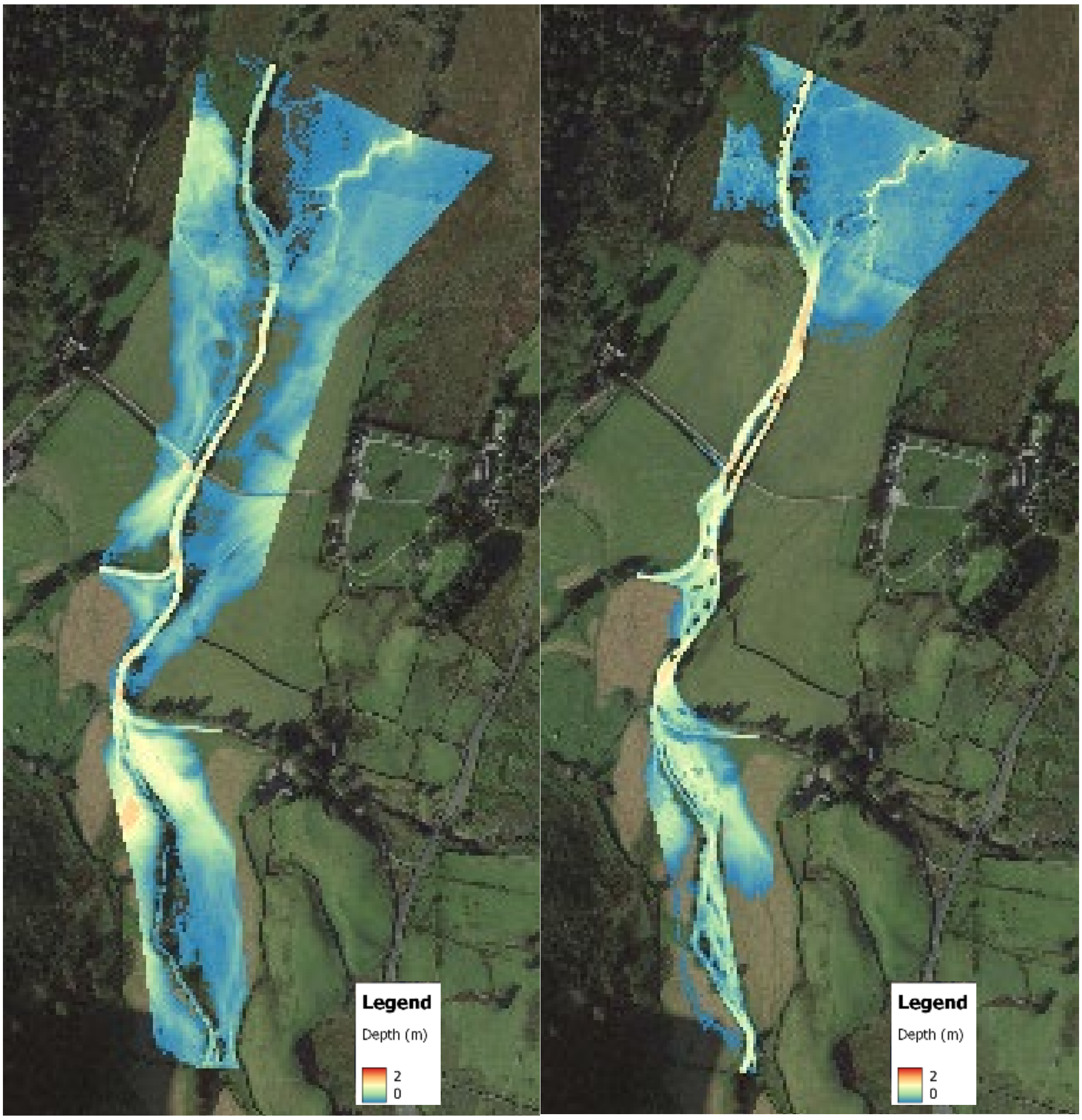


Figure 10.8 Water depth pre (left) and post (right) restoration scenarios for the 2-year flow. Flow direction from south to north.

10.3.2. Flow Biotopes

Q95

Figures 10.9 and 10.10, and Table 10.4, show that there has been both a significant change in hydraulic habitat diversity and overall hydraulic habitat area as a result of the restoration scheme for a summer flow; overall flow area significantly increased compared to the baseline. There are considerable increases in areas of all biotope types through the study reach, with a slight reduction in the proportion of rapids as a result of the channel now occupying a wider flow area. Riffle, run and pool type flows have increased the most, as a result of the diversity created through the widened and wandering channel sections.

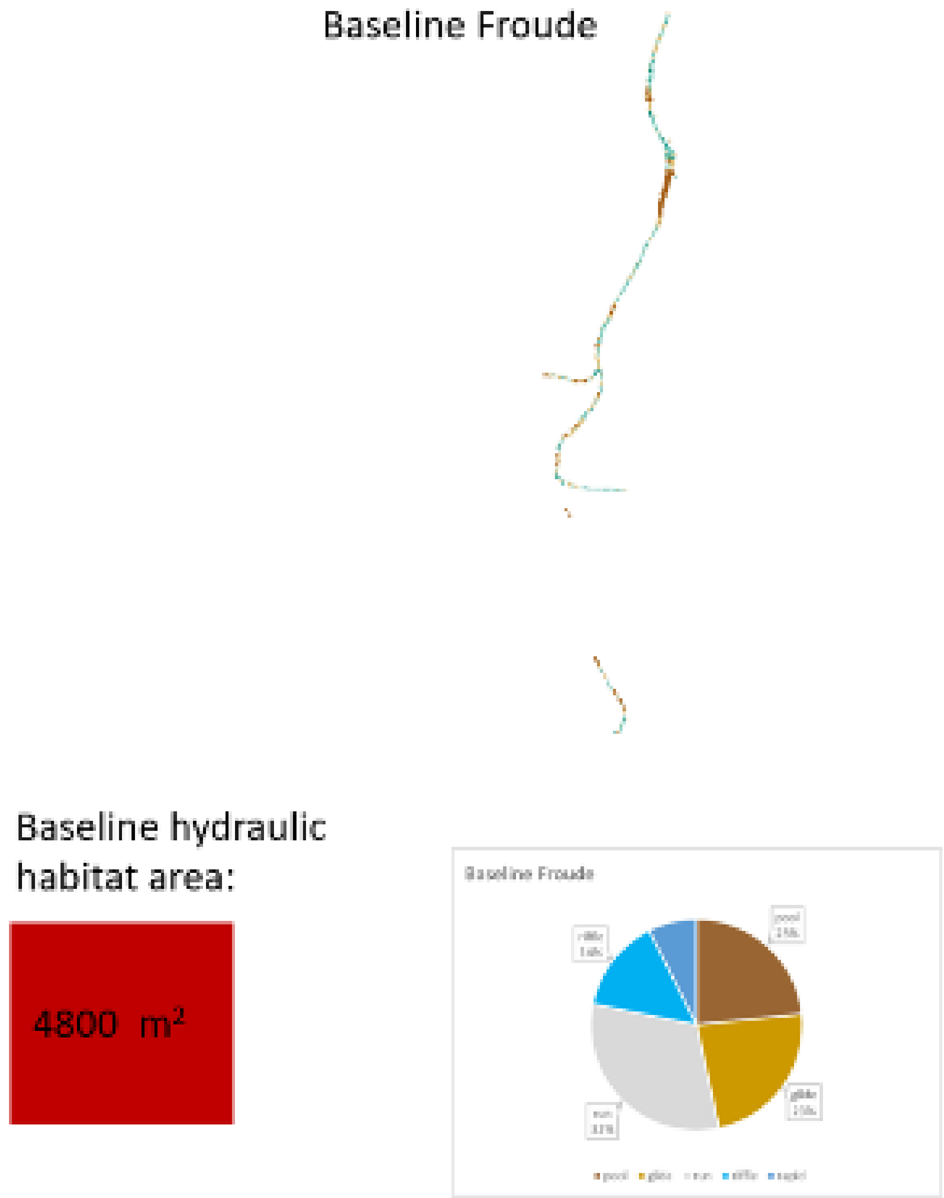


Figure 10.9 Flow biotope pre-restoration during Q95 flow.

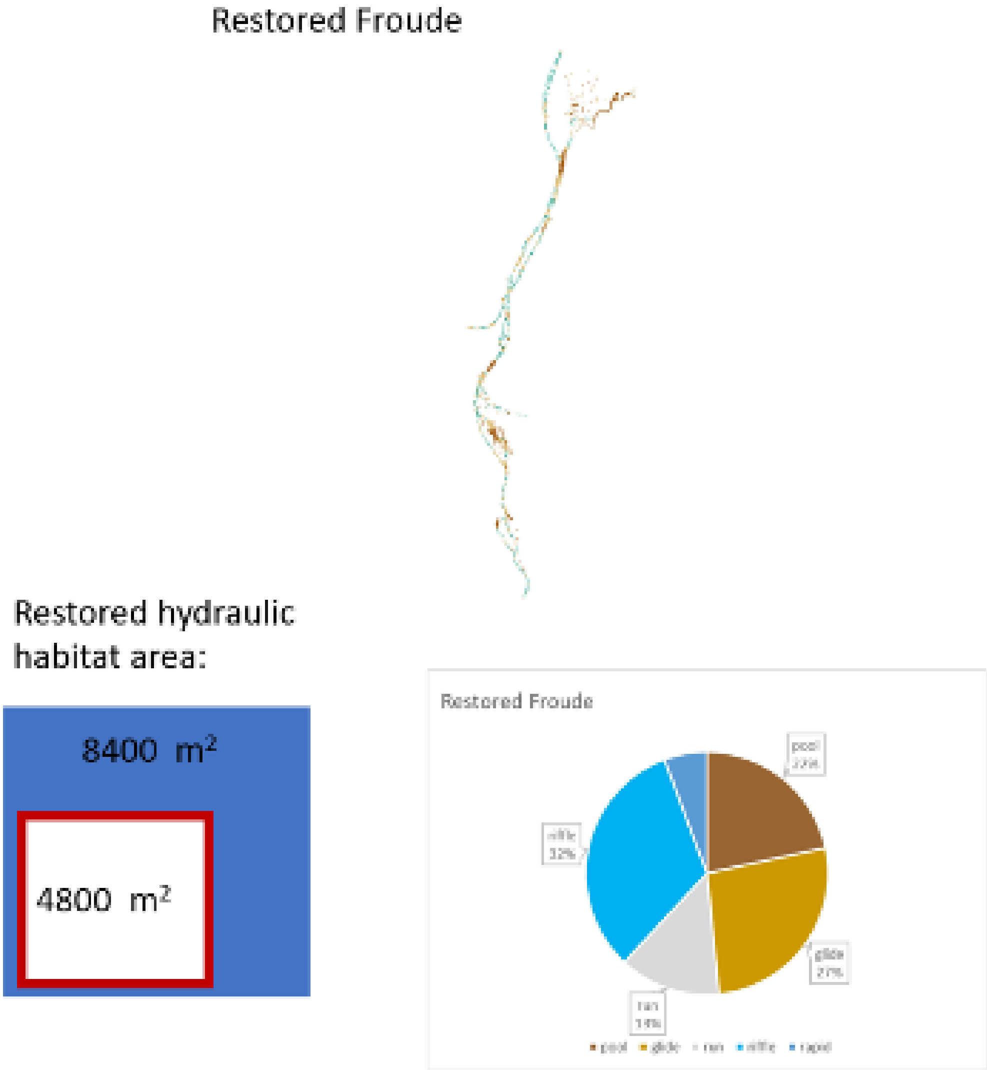


Figure 10.10 Flow biotope post-restoration during Q95 flow.

Table 10.4 Flow biotope change between pre and post restoration.

Flow Biotope	Area pre-restoration (m^2)	Proportion of overall habitat pre-restoration (%)	Area post-restoration (m^2)	Proportion of overall habitat post-restoration (%)	Overall Area Change (%)
Pool	1135	23.33	1933	23.80	70%
Glide	1133	23.28	1742	21.44	54%
Run	534	10.97	972	11.97	82%
Riffle	1706	35.06	3063	37.70	80%
Rapid	358	7.36	414	5.10	16%

Q10

Figure 10.11 and Table 10.5 show that there has been a significant change in overall hydraulic habitat area as a result of the restoration scheme for a winter flow. Overall flow area significantly increased compared to the baseline, but there were no significant changes in overall biotope diversity. There are considerable increases in areas of all biotope types through the study reach, with less of an increase in riffle type flow as this is the dominant flow type under baseline conditions. Pool, glide, run and rapid type flows have increased the most, as a result of the diversity created through the widened and wandering channel sections and higher energy flows compared to summer.

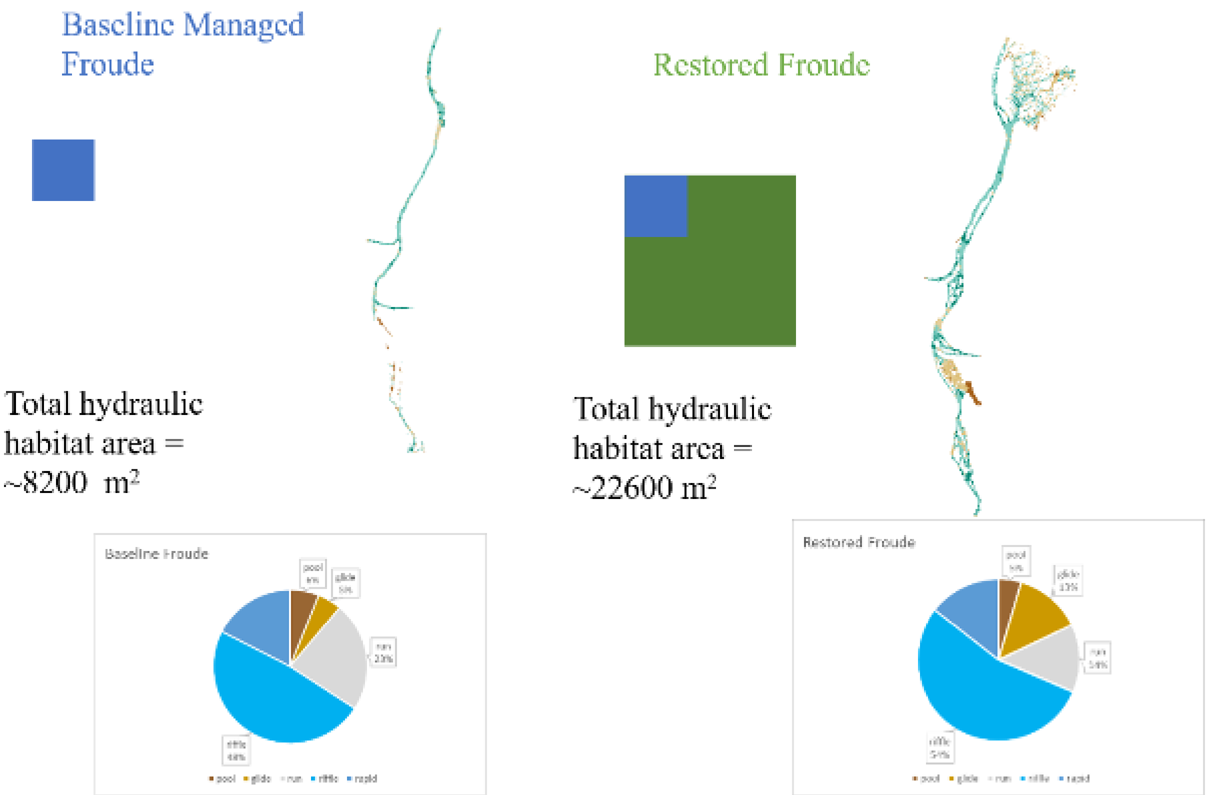


Figure 10.11 Flow biotope pre (left) and post restoration (right) during Q10 flow.

Table 10.5 Flow biotope change between pre and post restoration.

Flow Biotope	Area pre-restoration (managed) (m^2)	Proportion of overall habitat pre-restoration (%)	Area post-restoration (m^2)	Proportion of overall habitat post-change (%)	Overall Area Change (%)
Pool	1480	8.63	15733	19.27	963%
Glide	1748	10.19	36076	44.19	1964%
Run	1146	6.68	13164	16.12	1049%
Riffle	12588	73.39	14117	17.29	12%
Rapid	191	1.11	2554	3.13	1237%

10.3.3. Shear Stress

Baseline bed shear stress model outputs show that generally under lower order flood flows (2-year return period shown in Figure 10.12 and Figure 10.13) values range between 10-150 N/m^2 (Figure 10.12), with the majority of the lower values falling within the wetted floodplain areas. Higher values are located at particular points in the channel where local channel gradients are high and the channel particularly narrowed and confined by the flood embankments. This range does not change significantly for the restored model scenario (Figure 10.13), however, there are larger areas of reasonably high shear stresses (although slightly reduced on the peaks experienced under baseline conditions), as a result of the wandering character of the channel that has been created. This will result in channel change over time, but this is a natural process associated to rivers of this type. There are some higher shear stress areas across the introduced gravel/cobble features. There are also some areas of higher shear stress in the channel compared to baseline as a result of the embankment repairs, particularly through the mid-reach areas, where flows are now contained within the channel.

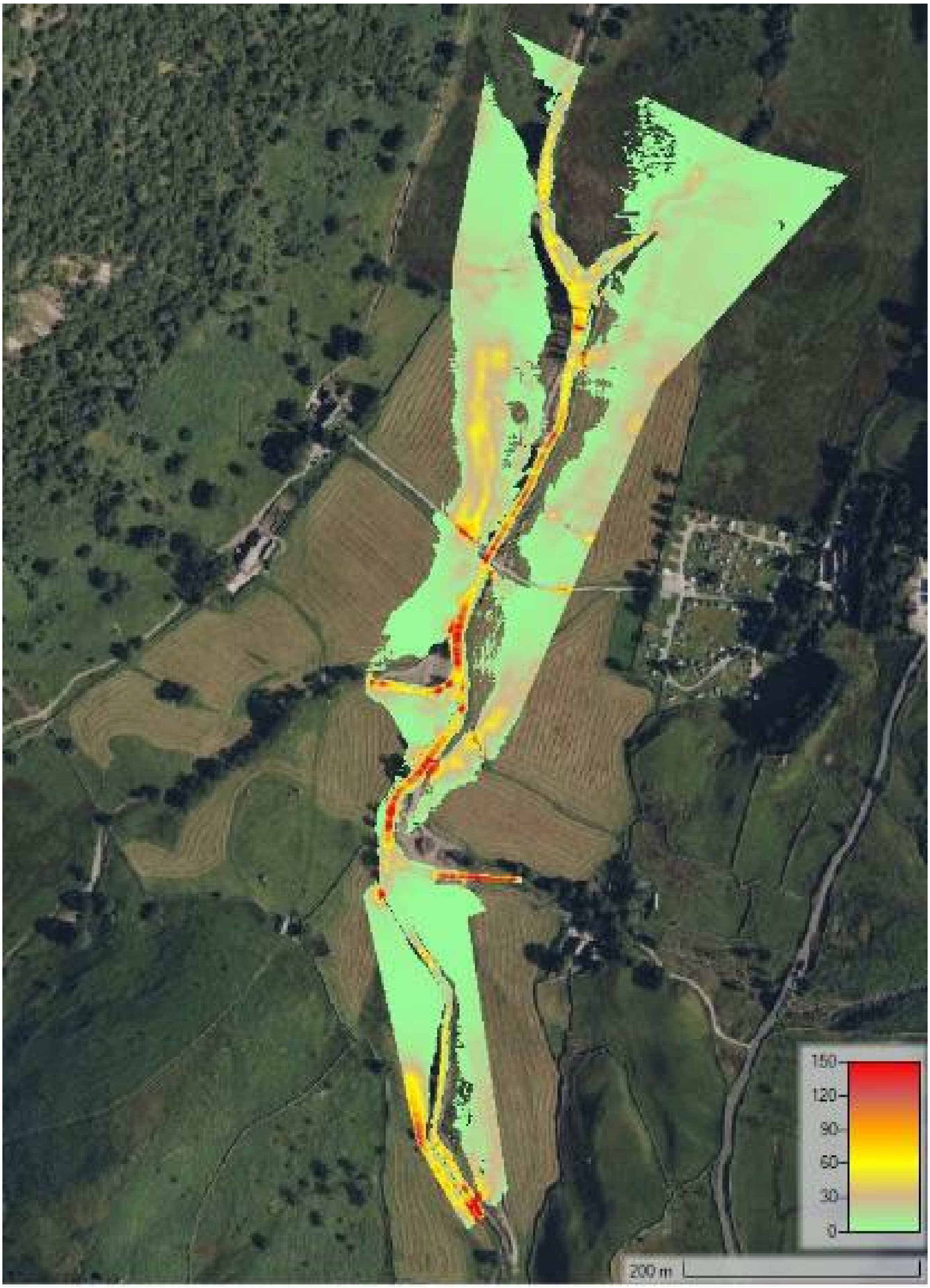


Figure 10.12 1 in 2yr bed shear stress pre-restoration.

Figure 10.13 1 in 2yr bed shear stress post-restoration.

10.3.4. Floodplain habitat creation

This section demonstrates the overall floodplain habitat gains/creation as a result of the restoration scheme. Table 10.6 summarises the wetting thresholds used to map the floodplain habitat and shows the optimal vegetation development over time based on the new hydrological regime at the site. This may differ in reality due to species competition and other factors, but provides a template for anticipated development. The summer (Q95), autumn (Q30), winter (Q10) and spring (Q50) inundation area has been extrapolated to predict water table levels across the wider floodplain for the study site based on the restored scenario. Figure 10.14 summarises the probable mosaic of swamp, mire and wet grassland habitat that will develop under a sensitive grazing regime; the coverage is summarised in Table 10.7. It is clear that the predicted habitat gains will be diverse and considerable across the valley bottom and that these areas will act immediately to sequester carbon, turning much of the valley bottom from a carbon emitter to a sequestering area. Wet grassland is likely to be the dominant habitat type due to the influence of the embankments. However, the farming regime at the site would need to change to allow this habitat to develop over time.

Table 10.6 Summer, winter, spring, autumn wetting threshold for each habitat.

Habitat Type	Habitat Code	Water table depth below FP surface (negative numbers indicated flooded ground)			
		Winter	Spring	Summer	Autumn
Wet Grassland	MG13	0.1-0.25	0.03-0.45	0.2-0.8	0.1-1
	MG4	0.1-0.6	0.25-0.7	0.4-1.0	0.25-1
	MG8	0.03-0.3	0.03-0.35	0.15-0.5	0.1-0.4
Fen Mire	M24	--	--	0.249-0.533	--
	M13	--	--	0.096-0.386	--
	S24	--	--	0.167-0.784	--
	S2	0-(0.4)	--	<0.15	--
Ditch Swamp	S4	0-(1.5)	0.25-(1.25)	0.8-(0.5)	1-(0.75)
	S5	0.3-(0.9)	0.6-(0.7)	0.8-(0.8)	0.6-(0.8)

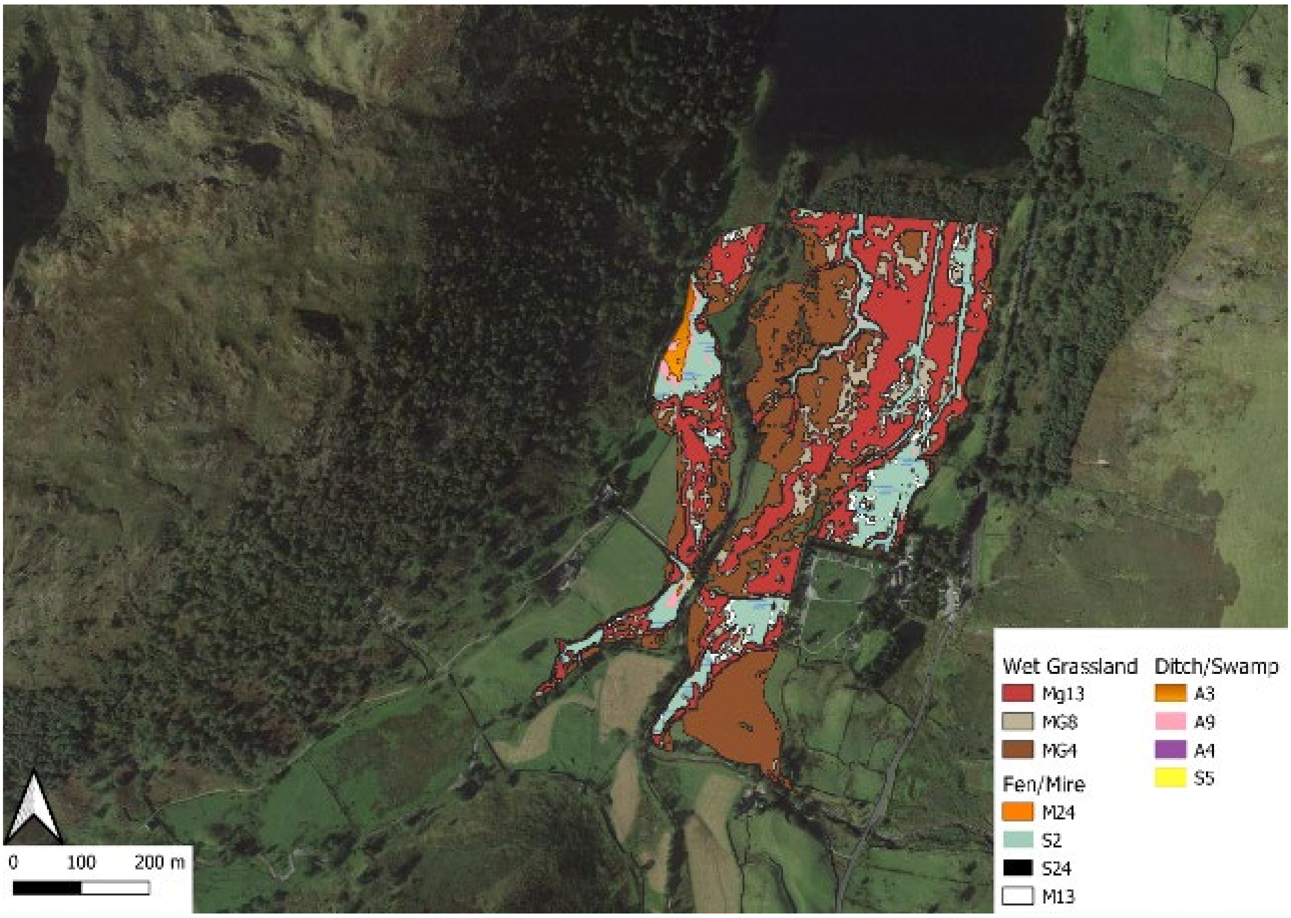


Figure 10.14 Potential floodplain habitat biotope post-restoration.

Table 10.7 Total habitat area created (m^2).

Habitat Type	Habitat Code	Area (m^2)
Wet Grassland	MG13	73,298
	MG4	72,482
	MG8	114,102
Fen Mire	M24	148,514
	M13	119,629
	S24	181,542
	S2	29,245
Ditch Swamp	S4	NA
	S5	158,888
	A3	2,166
	A4	8,067
	A9	5,240

10.4. Conclusions

The restoration design included the following measures at Hartsop Hall:

- embankment setting back,
- wandering / multi-channel creation,
- floodplain reconnection,
- riffle-rapids,
- channel widening.

The significant increase in overall wetted area under low and winter flows shown by the modelling demonstrates the increased resilience to low flows created as a result of the restoration scheme that created a morphology more suitable to an active single thread and wandering river system. Floodplain habitat creation and likely development is also predicted to be moderately diverse, with wet grassland likely to be prominent, as a result of the new hydrological regime created, if the farming regime were to change to allow this to develop over time. The 2-year overall wetted area decreases as a result of repaired embankments that were a compromise as part of delivering the overall restoration scheme.

11. Geltsdale

11.1. Background

The RSPB Geltsdale site has a variety of landscape features, including bog, heath, grassland, meadows and woodland, rising from 200m above sea level to 620m at Cold Fell.

The blanket bogs, heath, upland farmland and woodland support a great diversity of wildlife. Many breeding birds are found there, including black grouse, golden plovers, curlew, ring ouzel, merlin and short-eared owl, and the reserve is one of only a handful of nesting sites of hen harriers in England.

The Geltsdale site was identified as a river and floodplain restoration site by the RSPB to restore the single thread channel back to a more natural state. Historically, the watercourse was artificially straightened and deepened to better drain the surrounding valley bottom. The watercourse had no significant characteristic morphology.

The objectives of the restoration scheme were to diversify the current straight channel and to reconnect the floodplain.

The restoration design included the following measures (Figure 11.1):

- floodplain reconnection,
- chute channel creation,
- channel blocking,
- channel realignment / remeandering,
- bifurcation.

Figure 11.1 Aerial Photographs of pre-construction (top) and post-construction (bottom).

11.2. Site Specific Methodology

11.2.1. Model schematisation

To help review the post restoration work of the Geltsdale site described above, a 2D HEC-RAS (v6.3) model of the study reach has been developed, using available Environment Agency 1 m cell size LiDAR. It should be noted that there remains some uncertainty in levels where vegetation growth and sedimentation have occurred along the reach, therefore there may be some discrepancy in baseline levels. For the post-restoration model, a 25 cm photogrammetric drone-based DEM of the restored site has been utilised to enable the pre and post comparison to be made.

The purpose of the modelling was to appraise the restoration with regards to the specific outputs required to assess the impacts on hydraulics as a result of the scheme compared to the pre restored conditions. This enabled assessment of the impacts on in-channel processes and the hydrological regime.

The model has been built using a Digital Elevation Model (DEM) across the model domain that provides a ground elevation value for each 1 m grid cell for both the pre and post restoration conditions. The model extent (also showing grid orientation) and resulting model surface is shown below in Figure 11.2.

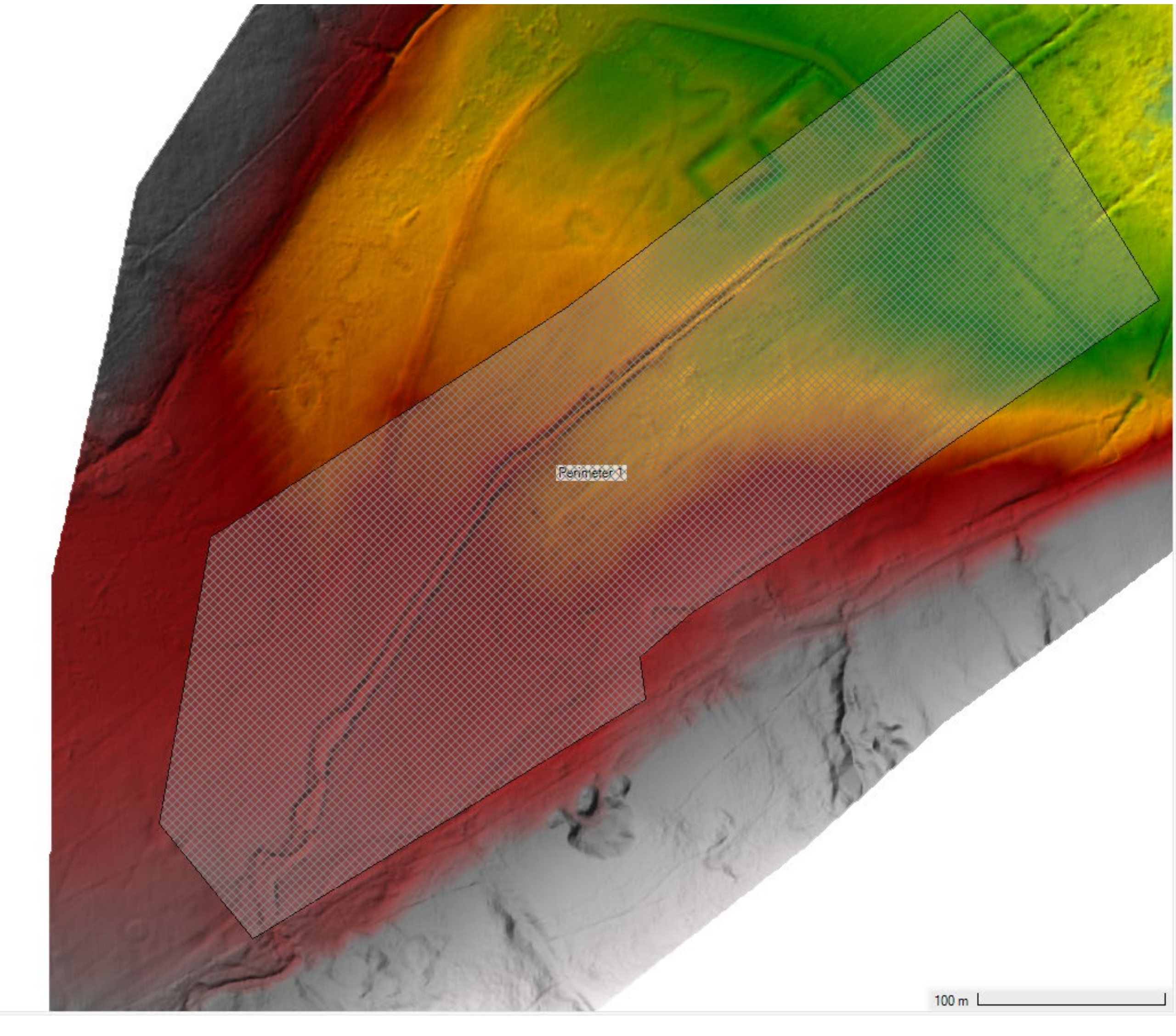


Figure 11.2 HEC-RAS 2D – baseline grid set up of the study site at Geltsdale.

11.2.2. Inflows

The flows used in the modelling are shown in Table 11.1 below. The low flows for Q95, Q50, Q30 and Q10 were derived using Low Flows 2 software. The 2-year return period flows were derived using Flood Estimation Handbook Techniques.

Table 11.1 Inflows to the model.

Scenario	Flow (m^3/s)
Q95 (summer flow)	0.015
Q50	0.05
Q30	0.1
Q10 (winter flow)	0.3
2-year return period flood	5.3

11.2.3. Manning's roughness

Observations of the channel and banks, from site visits and surveying, informed the choice of Manning's n values. These have also been cross checked against values listed in Chow, 1959[6]. Table 11.2 and Table 11.3, and Figure 11.3 and Figure 11.4 show these values and how they have been used.

Table 11.2 Manning's roughness values used (pre change).

Land Use	Manning's N	Photo
Channel	0.045 has been used to represent the in channel flow.	See Figure 11.3
Floodplain	Arable Field: (n=0.05) used to represent a vegetated field	See Figure 11.3

[6] Chow, V.T. (1959) Open Channel Hydraulics, McGraw-Hill Book Company, NY.

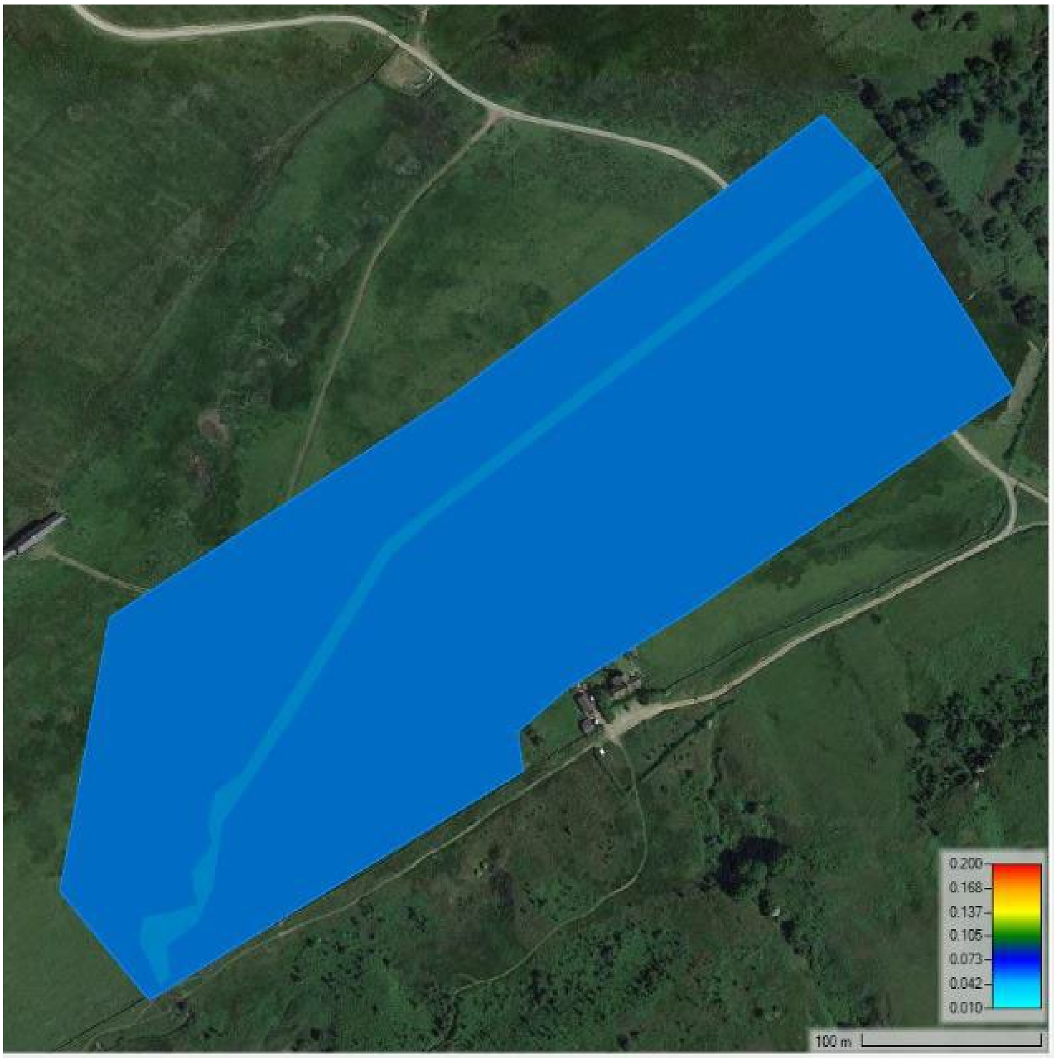


Figure 11.3 Baseline Manning's roughness grid.

11.2.4. Post change representation

Post restoration modifications were represented in the model through direct use of the post restoration drone DEM and changes in roughness across the model domain linked to new features introduced. As an example, roughness was modified across the post restoration, realigned and meandered channel to reflect the new channel roughness conditions.

Table 11.3 Manning's roughness values used (post change).

Land Use	Manning's N	Photo
Channel	Channel: (n=0.045). This has been used to represent the new channels.	See Figure 11.4
Floodplain	Arable Field: (n=0.05) used to represent a vegetated field.	See Figure 11.4

Figure 11.4 Post-change Manning's roughness grid.

11.3. Results

11.3.1. Hydraulic Conditions

Q95

Figure 11.5 shows a large increase in overall wetted area for the Q95 flow, with the overall wetted area increasing from 1,260 m^2 in the pre-restoration scenario to 3,276 m^2 in the post-restoration scenario. This increase is due to the improved floodplain connection with the new channels now better connected to the floodplain through new features created, as well as the channel blocking that has created diffuse flow towards the upstream end of the study reach, even under low flow conditions. An overall increase in channel length is also influencing the increased wetted areas modelled as a result of the restored channel network. Water depth variation is much more apparent under restored conditions. This situation will be dynamic over time, however significant wetted area under low flows is likely to be retained as the channels and floodplain develop.

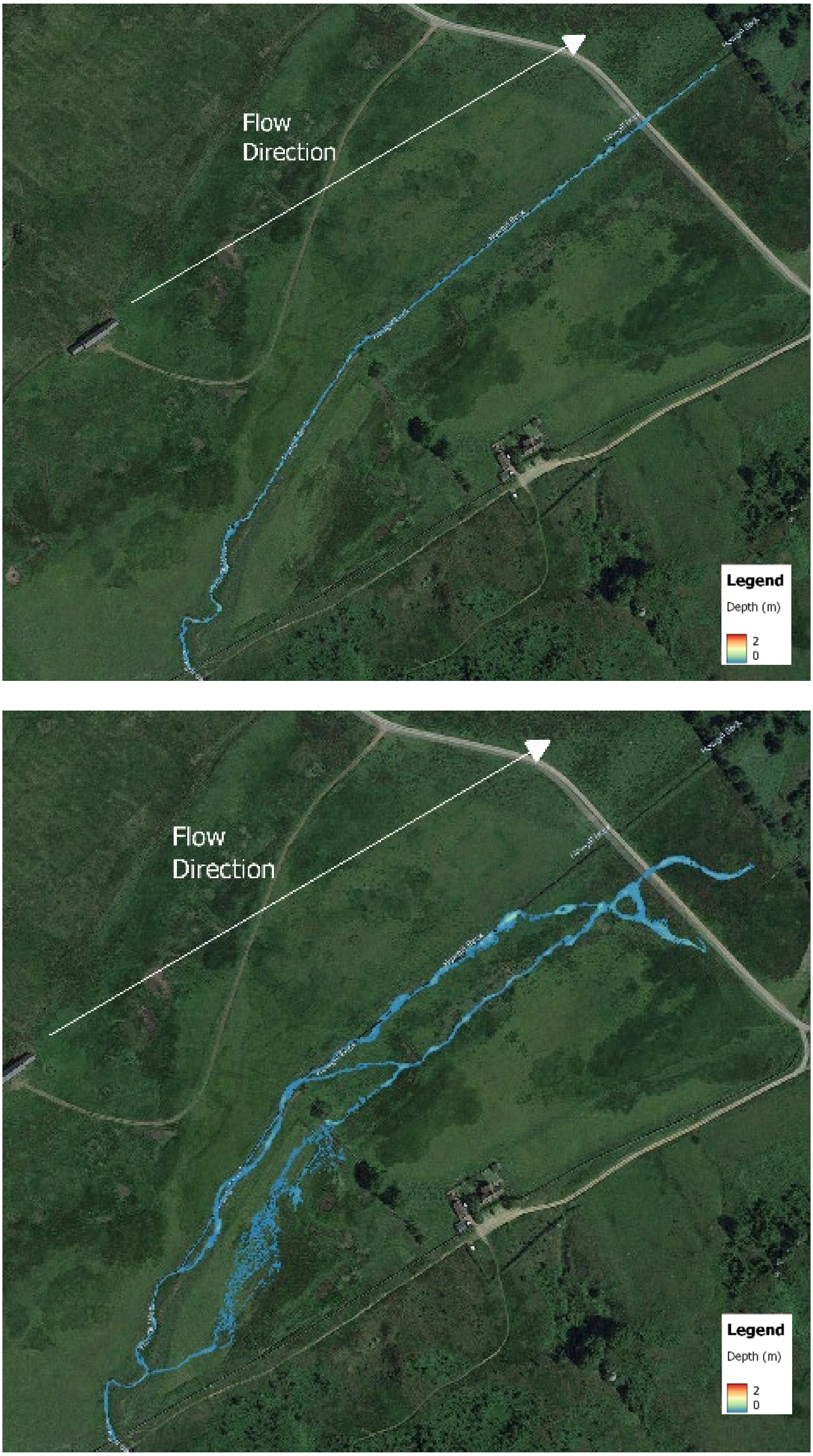
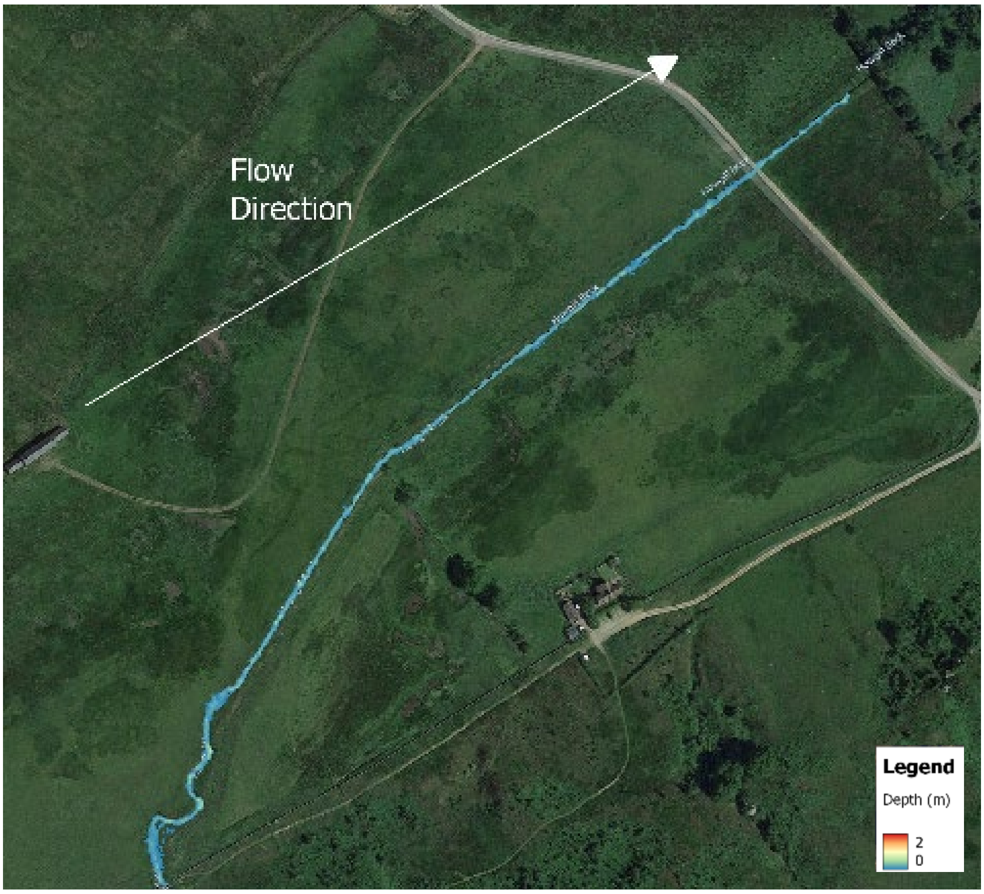


Figure 11.5 Water depth pre (top) and post (bottom) restoration scenarios for the Q95 flow.

Q10

Figure 11.6 shows a large increase in overall wetted area for the Q10 flow, with the overall wetted area increasing from 2,130 m^2 in the pre-restoration scenario to 7,631 m^2 in the post-restoration scenario. This increase is again due to the improved floodplain connection with the new channels now better connected to the floodplain through new features created (no floodplain wetting occurs under winter flows for the baseline conditions), as well as the channel blocking that has created diffuse flow under winter flow conditions towards the upstream end of the study reach. An overall increase in channel length is also influencing the increased wetted areas modelled as a result of the restored channel network. Water depth variation is much more apparent under restored conditions. This situation will be dynamic over time, however significant wetted area under winter flows is likely to be retained as the channels and floodplain develop.



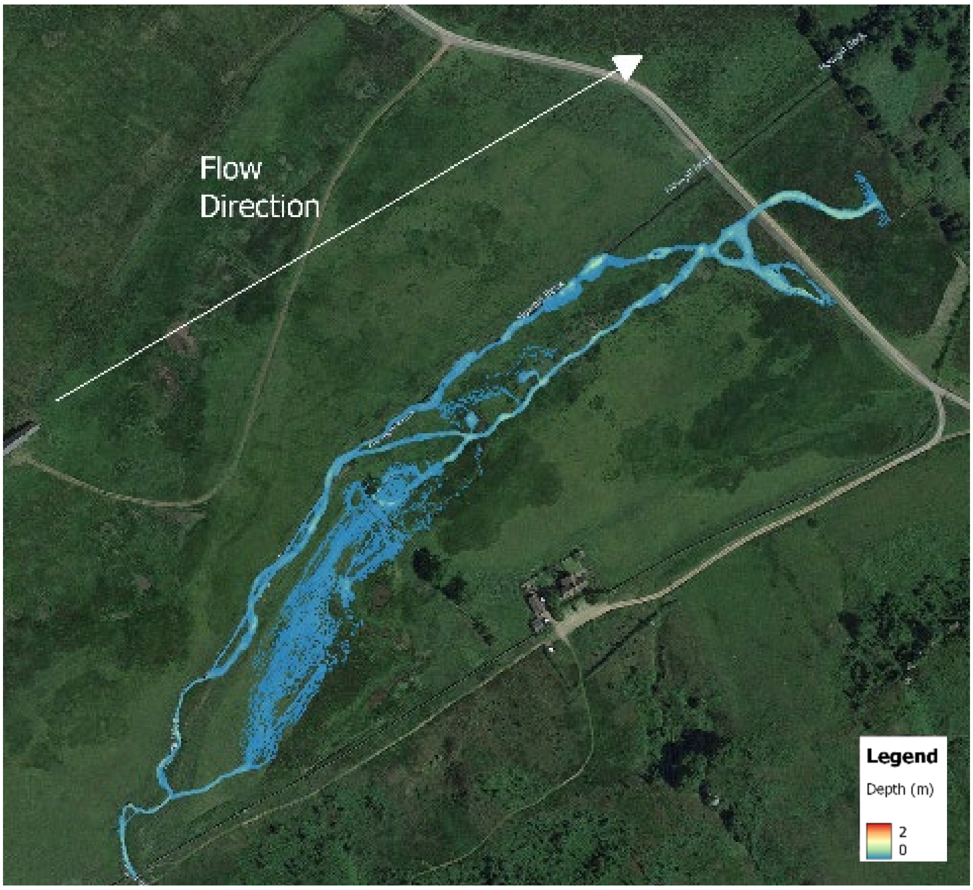


Figure 11.6 Water depth pre (top) and post (bottom) restoration scenarios for the Q10 flow.

2-year

Figure 11.7 shows a reduction in overall wetted area for the 2-year flow, with the overall wetted area reducing from 80,725 m^2 in the pre-restoration scenario to 50,373 m^2 in the post-restoration scenario. This reduction is due to the overall increase in channel length created, meaning less water is directed over the left hand floodplain compared to baseline. The overall wetted area over the right hand floodplain target area has increased compared to baseline, as a result of the improved floodplain connectivity created. Water depth variation is much more apparent under restored conditions.

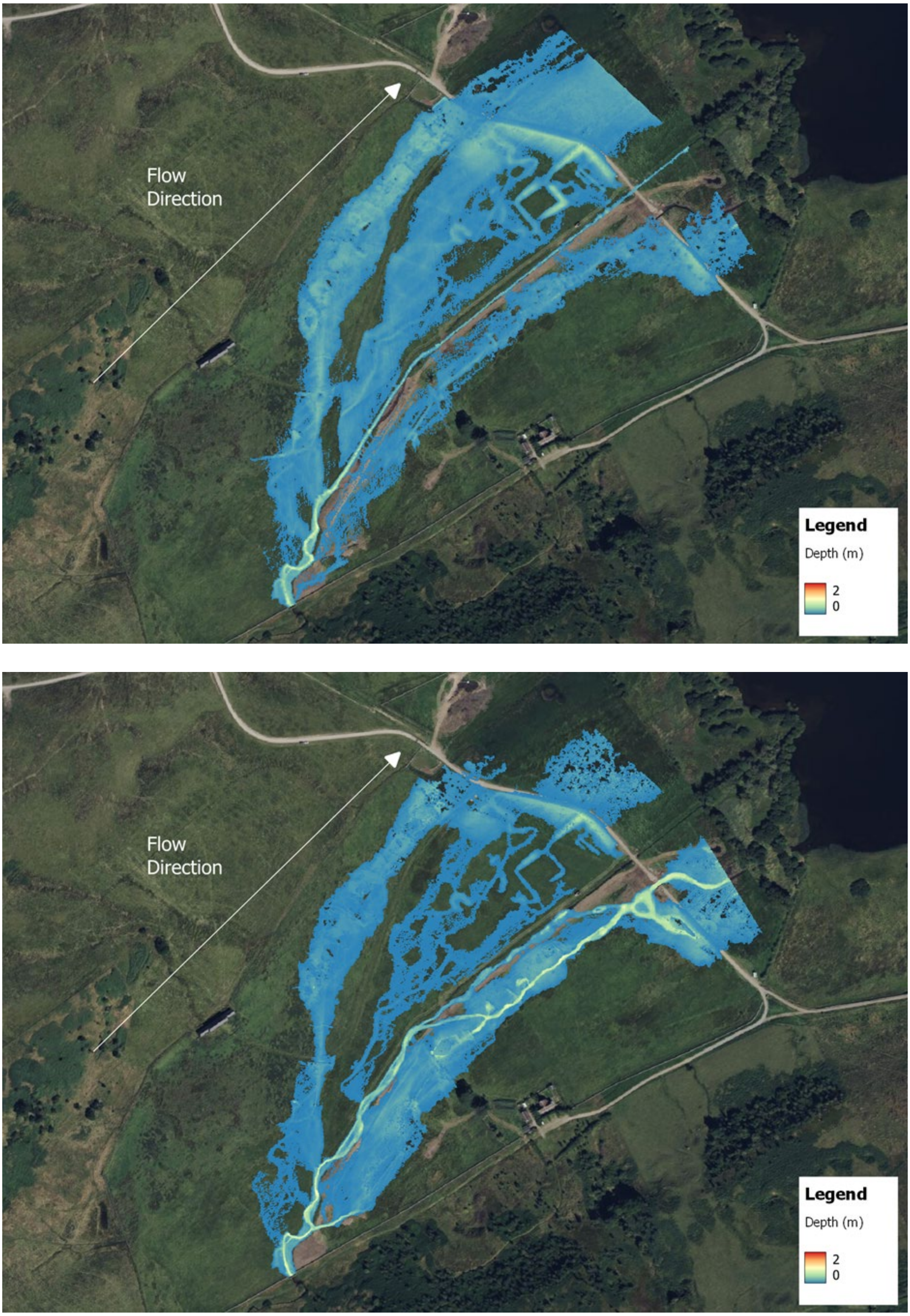


Figure 11.7 Water depth pre (top) and post (bottom) restoration scenarios for the 2-year flow.

11.3.2. Flow Biotopes

Q95

Figures 11.8 and 11.9, and Table 11.4, show that there has been both a significant change in hydraulic habitat diversity and overall hydraulic habitat area for a summer flow as a result of the restoration scheme, with overall flow area significantly higher compared to the baseline. The overall area for all biotopes mapped significantly increases as a result of the scheme, changing from having no wetted area under low flows across the floodplain under baseline conditions. This is particularly the case for pool hydraulic habitat, and is a result of the lower energy areas created through the new channels and improved connectivity to the floodplain, generally providing lower energy conditions. The previous straight channel was over energetic and this is reflected in a proportional reduction in riffles as a result of the restoration scheme when compared to pre-restoration.

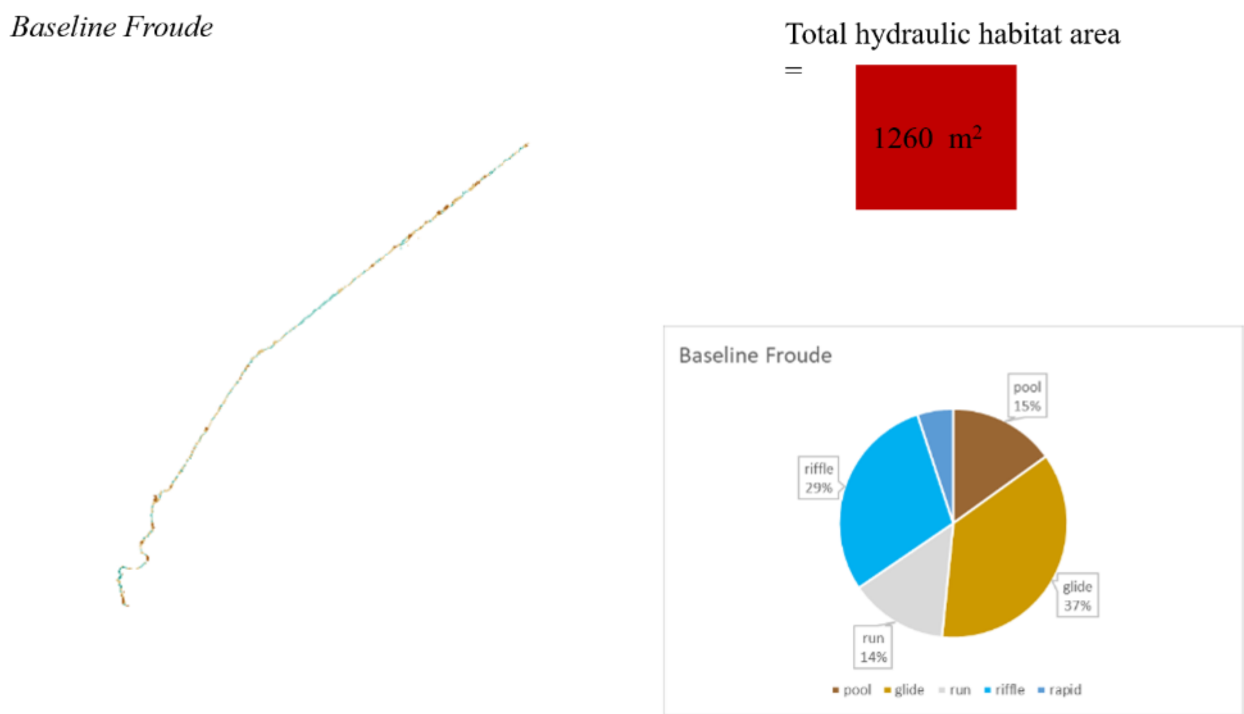


Figure 11.8 Flow biotope pre-restoration during Q95 flow.

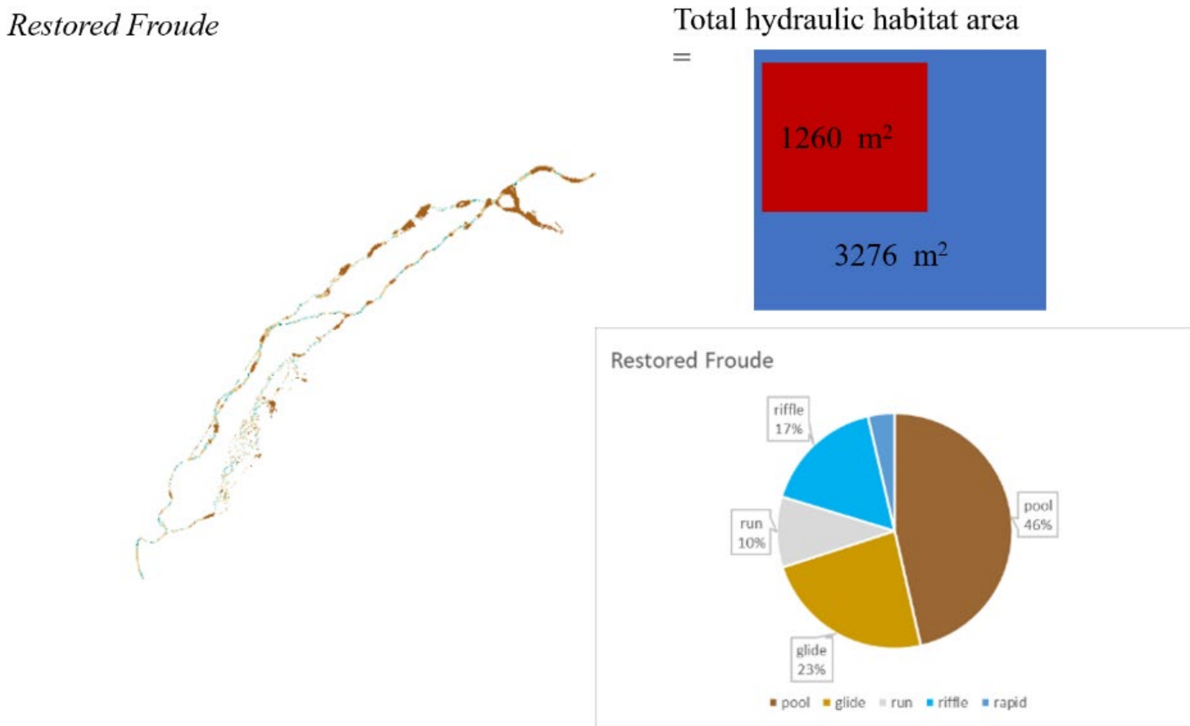


Figure 11.9 Flow biotope post-restoration during Q95 flow.

Table 11.4 Flow biotope change between pre and post restoration.

Flow Biotope	Area pre-restoration (m^2)	Proportion of overall habitat pre-restoration (%)	Area post-restoration (m^2)	Proportion of overall habitat post-restoration (%)	Overall Area Change (%)
Pool	190	15.12	1521	46.44	701%
Glide	460	36.60	772	23.55	68%
Run	173	13.76	318	9.71	84%
Riffle	370	29.44	546	16.66	47%
Rapid	64	5.09	119	3.64	86%

Q10

Figure 11.10 and Table 11.5, again show that there has been both a significant change in hydraulic habitat diversity and overall hydraulic habitat area as a result of the restoration scheme for a winter flow, as overall flow area significantly increased compared to the baseline. The overall area for all biotopes mapped significantly increases as a result of the scheme, changing from having no wetted area under low flows across the floodplain under pre-restoration conditions. This is particularly the case for lower energy pool, glide and run hydraulic habitat, and is a result of the lower energy areas created through the new channels and improved connectivity to the floodplain, generally providing lower energy conditions. The previous straight channel was over energetic in this respect, with a dominance of riffle type flow under winter flows. This is also reflected in a proportional reduction in riffles as a result of the restoration scheme when compared to pre-restoration.

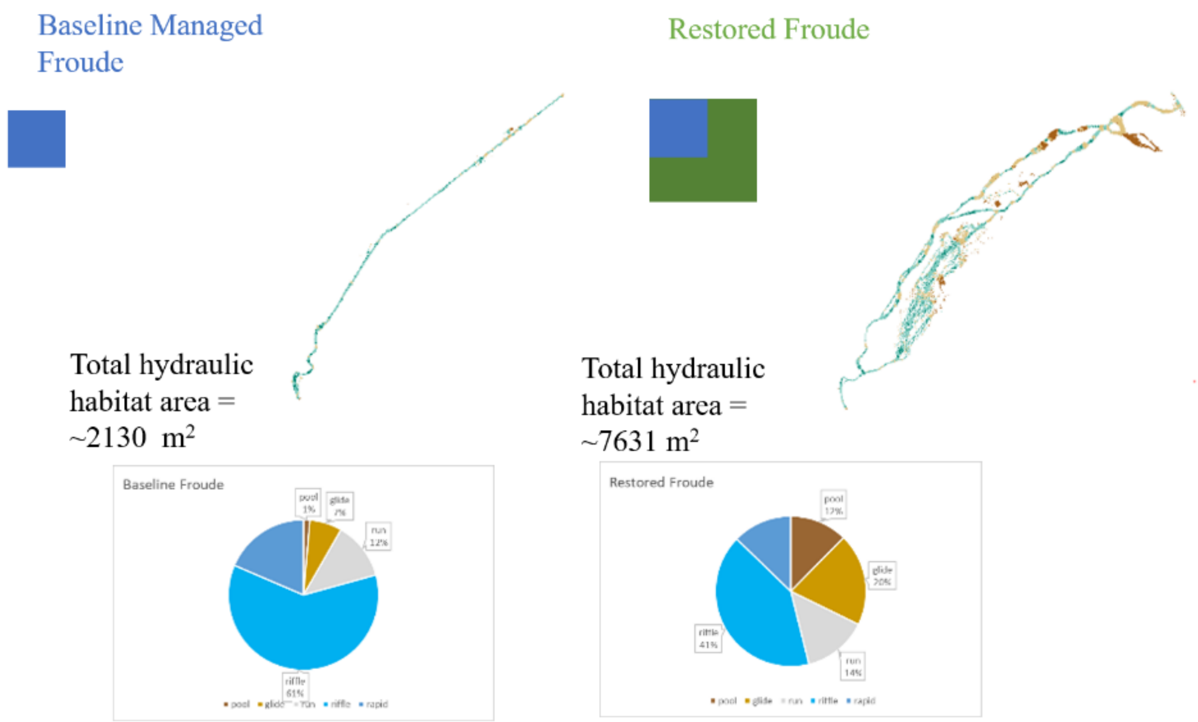


Figure 11.10 Flow biotope pre restoration managed (left) and post restoration (right) during Q10 flow.

Table 11.5 Flow biotope change between pre restoration (managed) and post restoration.

Flow Biotope	Area pre-restoration (managed) (m^2)	Proportion of overall habitat pre-restoration (%)	Area post-restoration (m^2)	Proportion of overall habitat post-change (%)	Overall Area Change (%)
Pool	11	0.53	942	12.35	8467%
Glide	141	6.78	1520	19.92	978%
Run	256	12.31	1056	13.83	312%
Riffle	1273	61.23	3140	41.14	147%
Rapid	398	19.14	973	12.76	145%

11.3.3. Shear Stress

Baseline bed shear stress model outputs show that generally under lower order flood flows (2-year return period shown in Figure 11.11 and Figure 11.12) values range between 10-100 N/m^2 (Figure 11.11). The majority of shear stress values fall within the lower estimate of this range, particularly across the wetted floodplain area. Higher values are located at particular points in the channel where local channel gradients are high and the channel is particularly narrowed and confined. This range does not change significantly for the restored model scenario (Figure 11.12), however, there is an increase in shear stress across the wetted floodplain area over the right hand bank where diffuse flow has been encouraged as a result of the improved connectivity. this increase may result in some concentrated erosion over time, but it is a natural process associated to rivers of this type. There are some areas of higher shear stress across the introduced gravel/cobble features. There is an overall reduction in bed shear stress within the channel as a result of the restoration scheme when compared to baseline, as a result of the flow splits created and the much improved floodplain connectivity.

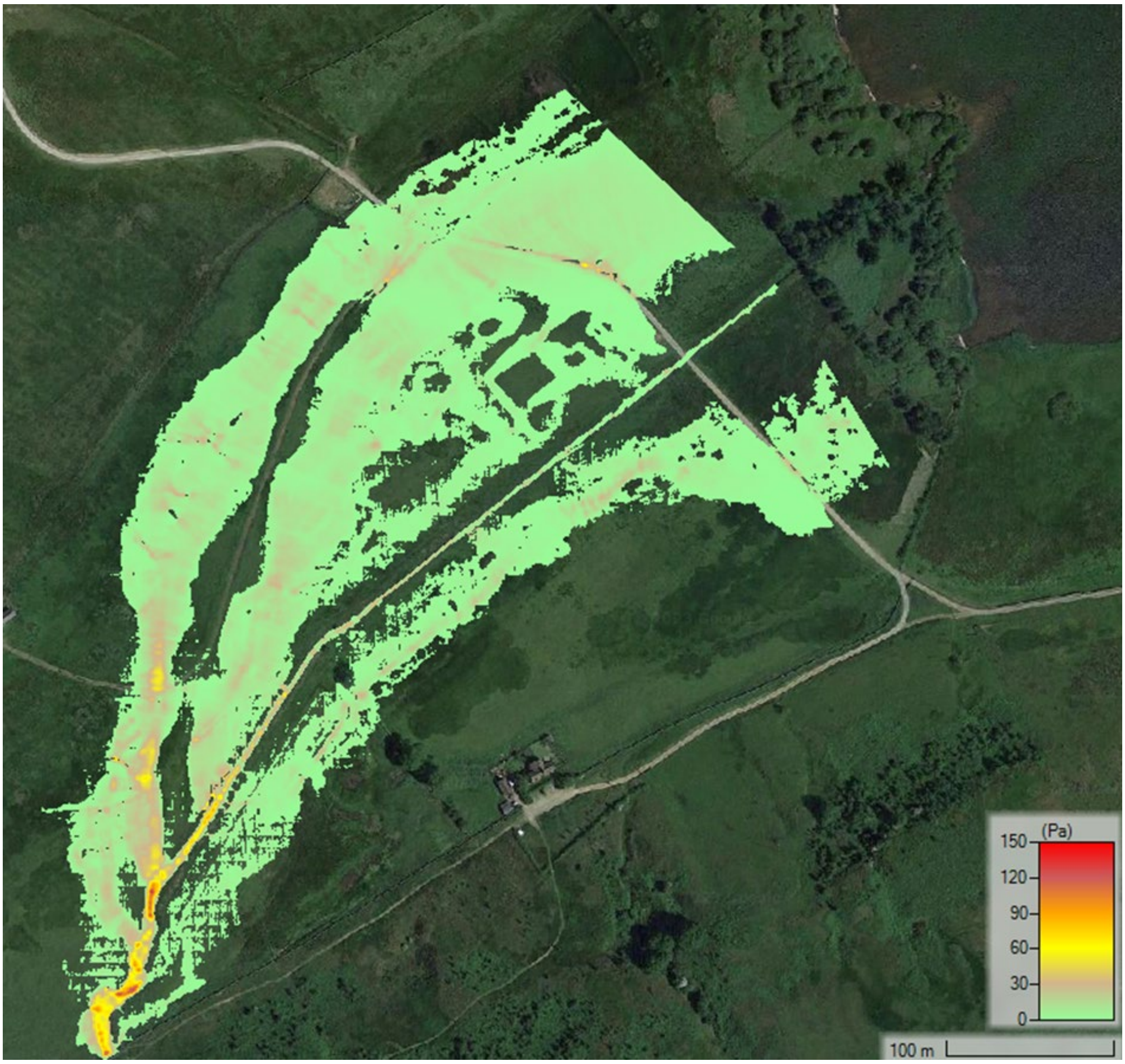


Figure 11.11 1 in 2yr bed shear stress pre-restoration.

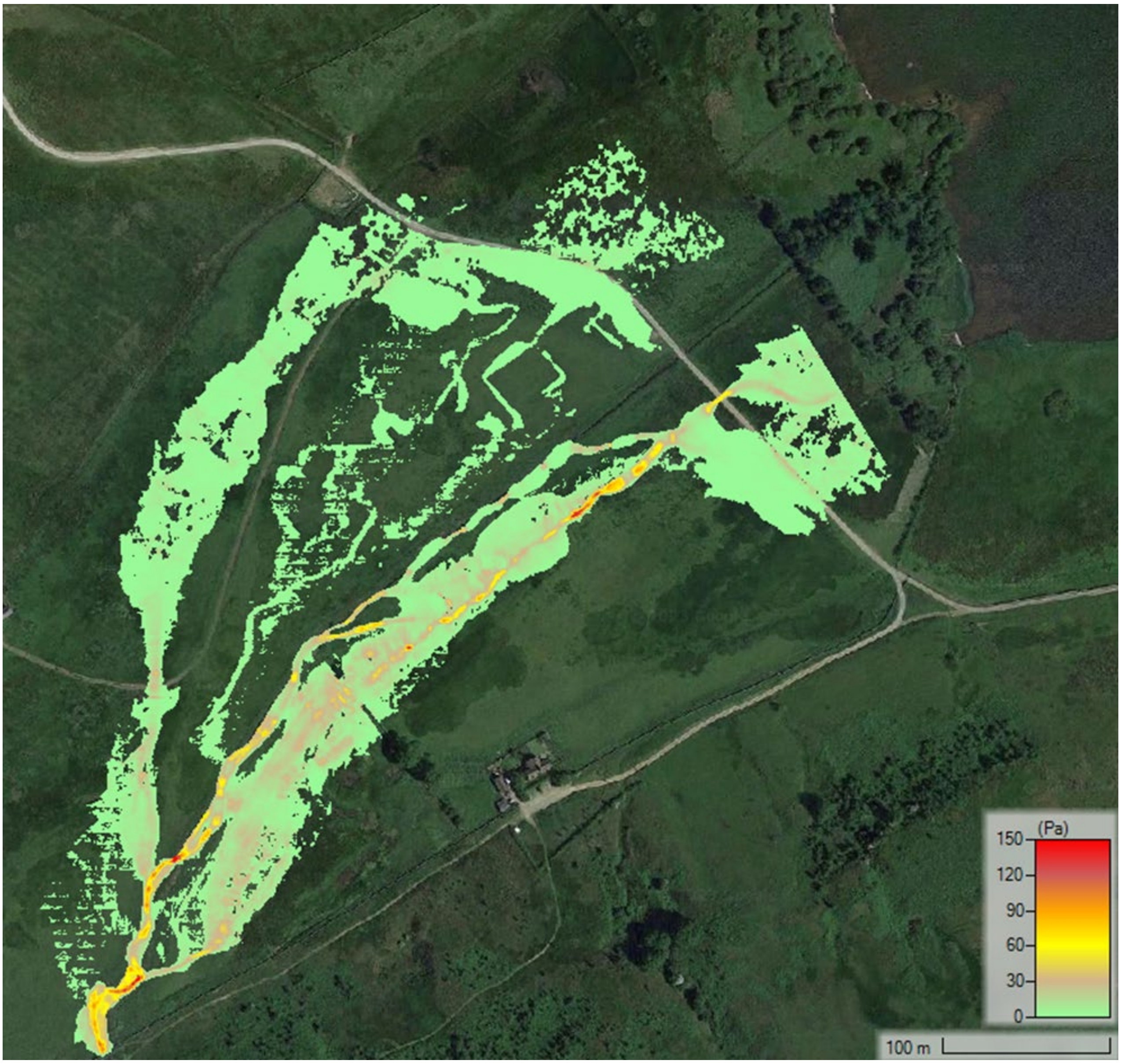


Figure 11.12 1 in 2yr bed shear stress post-restoration.

11.3.4. Floodplain habitat creation

This section demonstrates the overall floodplain habitat gains/creation as a result of the restoration scheme. Table 11.6 summarises the wetting thresholds used to map the floodplain habitat. Figure 11.13 shows the optimal vegetation development over time based on the new hydrological regime at the site. This may differ in reality due to species competition and other factors, but it provides a template for anticipated development. The summer (Q95), autumn (Q30), winter (Q10) and spring (Q50) inundation area has been extrapolated to predict water table levels across the wider floodplain for the study site based on the restored scenario. Figure 11.13 summarises the probable mosaic of swamp, mire and wet grassland habitat that will develop under a sensitive grazing regime (area coverage is summarised in Table 11.7). It is clear that the predicted habitat gains will be diverse and considerable across the valley bottom and that these areas will act immediately to sequester carbon, turning much of the valley bottom from a carbon emitter to a sequestering area. In particular, fen mire, ditch swamp and wet grassland are likely to develop as a result of the significant wetting created as part of the scheme through floodplain reconnection.

Table 11.6 Summer, winter, spring, autumn wetting threshold for each habitat.

Habitat Type	Habitat Code	Water table depth below FP surface (negative numbers indicated flooded ground)			
		Winter	Spring	Summer	Autumn
Wet Grassland	MG13	0.1-0.25	0.03-0.45	0.2-0.8	0.1-1
	MG4	0.1-0.6	0.25-0.7	0.4-1.0	0.25-1
	MG8	0.03-0.3	0.03-0.35	0.15-0.5	0.1-0.4
Fen Mire	M24	--	--	0.249-0.533	--
	M13	--	--	0.096-0.386	--
	S24	--	--	0.167-0.784	--
	S2	0-(0.4)	--	<0.15	--
Ditch Swamp	S4	0-(1.5)	0.25-(1.25)	0.8-(0.5)	1-(0.75)
	S5	0.3-(0.9)	0.6-(0.7)	0.8-(0.8)	0.6-(0.8)

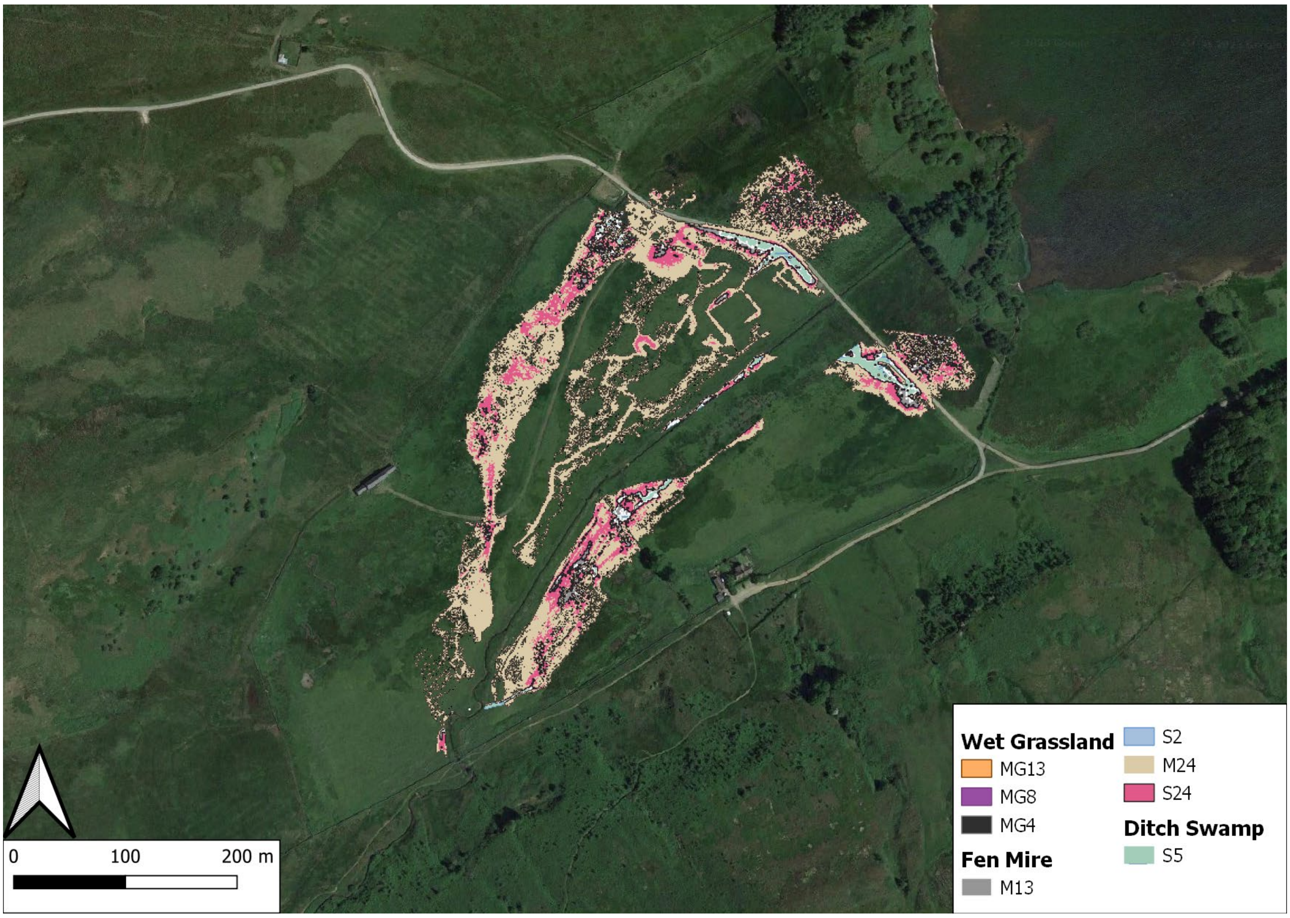


Figure 11.13 Floodplain habitat biotope post-restoration.

Table 11.7 Total Habitat area created (m^2).

Habitat Type	Habitat Code	Area (m^2)
Wet Grassland	MG13	27719
	MG4	NA
	MG8	35349
Fen Mire	M24	26286
	M13	38511
	S24	35572
	S2	3342
Ditch Swamp	S4	NA
	S5	40630

11.4. Conclusions

The restoration design included the following measures at Geltsdale:

- Floodplain reconnection,
- chute channel creation,
- channel blocking,
- channel realignment / remeandering,
- bifurcation.

The significant increase in overall wetted area under low and winter flows shown by the modelling demonstrates the increased resilience to low flows created as a result of the restoration scheme. There is also an overall improvement in biotope diversity under summer and winter flows when compared to baseline conditions, with more characteristic lower energy biotopes created, as well as a significant increase in overall wetted area. The development of diverse floodplain habitat is also predicted as a result of the new hydrological regime. In particular, fen mire, ditch swamp and wet grassland are likely to develop as a result of the significant wetting created as part of the scheme through floodplain reconnection.

12. Dunston

12.1. Background

The Dunston Beck near Dunston is a passive, low energy, single thread channel with a shallow gradient. Two areas of the river channel and floodplain were targeted for river and floodplain restoration works to create improved connectivity to the floodplain for wetland habitat creation purposes, and to create a more characteristic in-channel morphology for a watercourse of this type. Under natural conditions, it is likely a watercourse of this type would flow as a set of diffuse channels across a well-connected floodplain area, however this was not possible as a restoration target given the surrounding agricultural land use.

The watercourse flows over a subdued topography at both sites with no clear evidence of former palaeo-channels within the site boundary. At both site locations, the channel is strongly inset, artificially straightened (likely for agricultural and drainage purposes) and connectivity to the floodplain is consequentially poor. Such low gradients would normally suggest an aggradational environment, but it would appear that the strongly inset nature of the channel concentrates flow energy, preventing severe in-channel fine sediment build up.

Surrounding land use is agricultural, with very little variation in habitat across the floodplain area where semi-improved grassland is generally dominant.

The restoration design included the following measures (Figure 12.1, 12.2):

- riffle creation and point bars,
- floodplain lowering,
- wetland creation,
- channel bifurcation,
- channel realignment and remeandering,
- pond creation.

Figure 12.1 Aerial Photographs of pre-construction (top), post Phase 1 construction (middle), post Phase 2 construction (bottom).

Figure 12.2 Photographs of pre-construction (top) and during-construction (bottom).

12.2. Site Specific Methodology

12.2.1. Model schematisation

To help review the post restoration work of the Dunston Beck sites described above, a 2D HEC-RAS (v6.3) model of the study reach has been developed, using available Environment Agency 1 m cell size LiDAR. It should be noted that there remains some uncertainty in levels where vegetation growth and sedimentation have occurred along the reach, therefore there may be some discrepancy in baseline levels. For the post-restoration model, a 25 cm photogrammetric drone-based DEM of the restored site has been utilised to enable the pre and post comparison to be made.

The purpose of the modelling was to appraise the restoration with regards to the specific outputs required to assess the impacts on hydraulics as a result of the scheme compared to the pre restored conditions. This enabled assessment of the impacts on in-channel processes and the hydrological regime.

The model has been built using a Digital Elevation Model (DEM) across the model domain that provides a ground elevation value for each 1 m grid cell for both the pre and post restoration conditions. The model extent (also showing grid orientation) and resulting model surface is shown below in Figure 12.3.

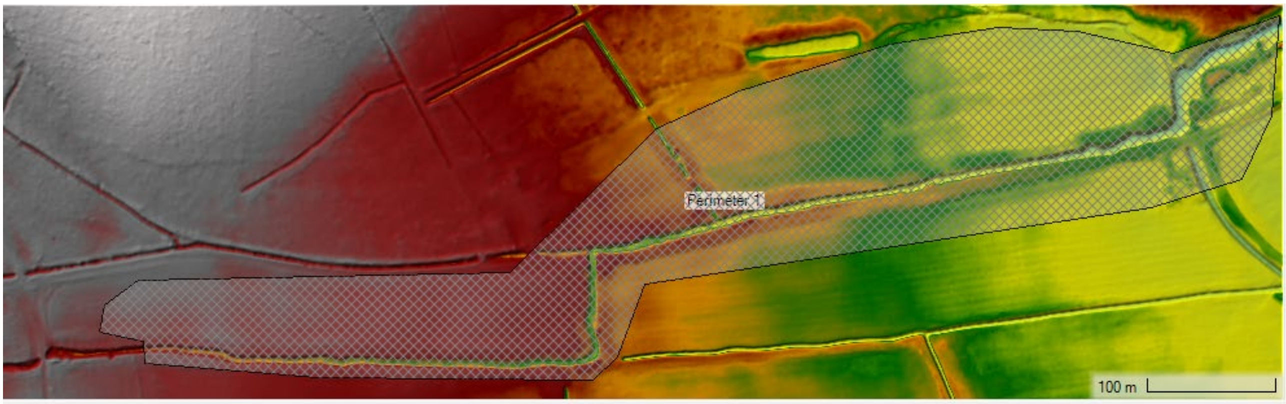


Figure 12.3 HEC-RAS 2D – baseline grid set up of the study sites at Dunston Beck.

12.2.2. Inflows

The flows used in the modelling are shown in Table 12.1 below. The low flows for Q95, Q50, Q30 and Q10 were derived using Low Flows 2 software. The 2-year return period flows were generated using Flood Estimation Handbook techniques.

Table 12.1 Inflows to the model.

Scenario	Flow (m^3/s)
Q95 (summer flow)	0.07
Q50	0.18
Q30	0.25
Q10 (winter flow)	0.4
2-year return period flood	1.12

12.2.3. Manning's roughness

Observations of the channel and banks, from site visits and surveying, informed the choice of Manning's n values. These have also been cross checked against values listed in Chow, 1959[7]. Table 12.2 and Table 12.3, and Figure 12.4 and Figure 12.5 show these values and how they have been used.

Table 12.2 Manning's roughness values used (pre change).

Land Use	Manning's N	Photo
Channel	0.045 has been used to represent the in channel flow.	See Figures 12.1 and 12.2
Floodplain	Arable Field: (n=0.05) used to represent a vegetated field	See Figures 12.1 and 12.2

[7] Chow, V.T. (1959) Open Channel Hydraulics, McGraw-Hill Book Company, NY.

Figure 12.4 Baseline Manning's roughness grid.

12.2.4. Post change representation

Post restoration modifications were made to the underlying model surface through direct use of the post restoration drone DEM and changes in roughness across the model domain linked to new features introduced. For example, roughness was modified across the post restoration, realigned and meandered channel to reflect the new channel roughness conditions.

Table 12.3 Manning's roughness values used (post change).

Land Use	Manning's N	Photo
Channel	Channel: (n=0.045). This has been used to represent the new channels.	See Figures 12.1 and 12.2
Floodplain	Arable Field: (n=0.05) used to represent a vegetated field. Roughened Floodplain post change (n=0.1) to represent the change in land use post river restoration and floodplain reconnection.	See Figures 12.1 and 12.2

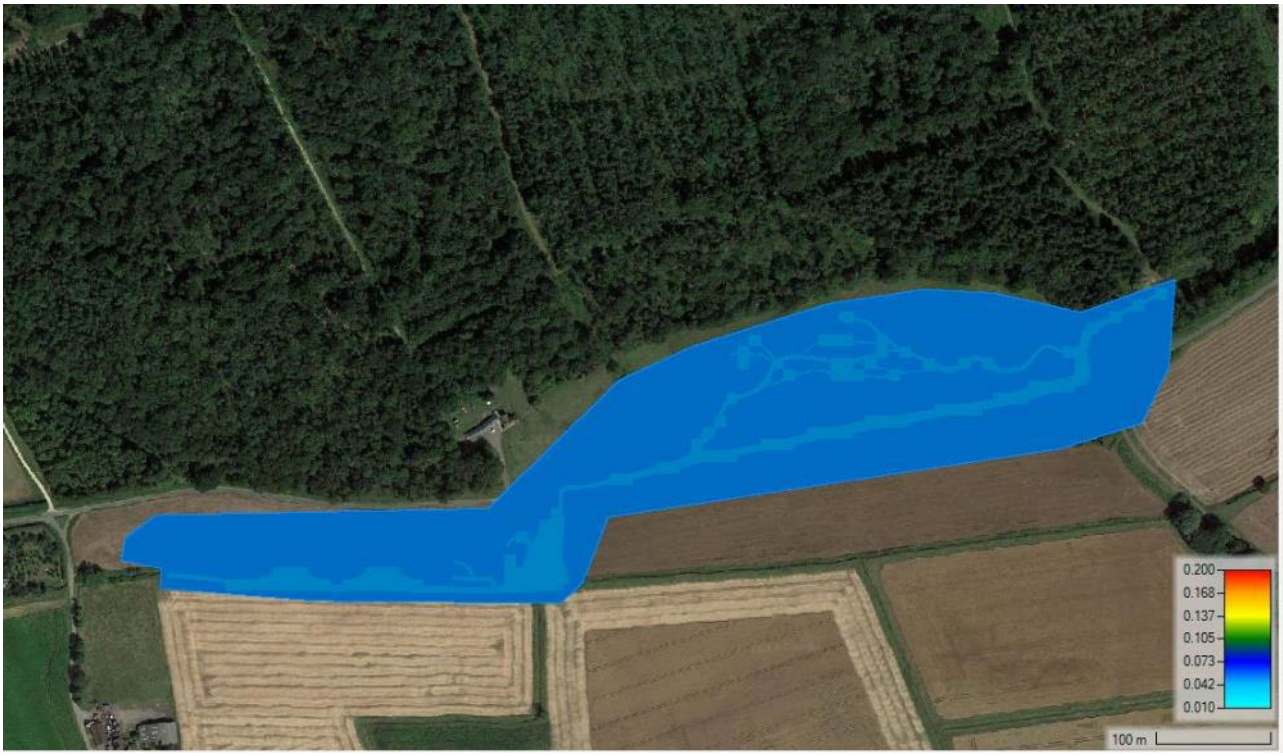


Figure 12.5 Post-change Manning's roughness grid.

12.3. Results

12.3.1. Hydraulic Conditions

Q95

Figure 12.6 shows an increase in overall wetted area for the Q95 flow, with the overall wetted area increasing from 3,573 m^2 in the pre-restoration scenario to 4,800 m^2 in the post-restoration scenario. This increase is due to the local reconnected floodplain areas that have been created through a combination of floodplain lowering and in-channel feature creation. This creates local diverse wetland areas within the confines of the wider agricultural land use. Overall wetted area has also increased due to the increased channel length created as a result of the restoration scheme. Water depth variation is much more apparent under restored conditions. This situation will be dynamic over time as the wetland develops, however wetted area under low flows is likely to be retained as the channels and floodplain develop.

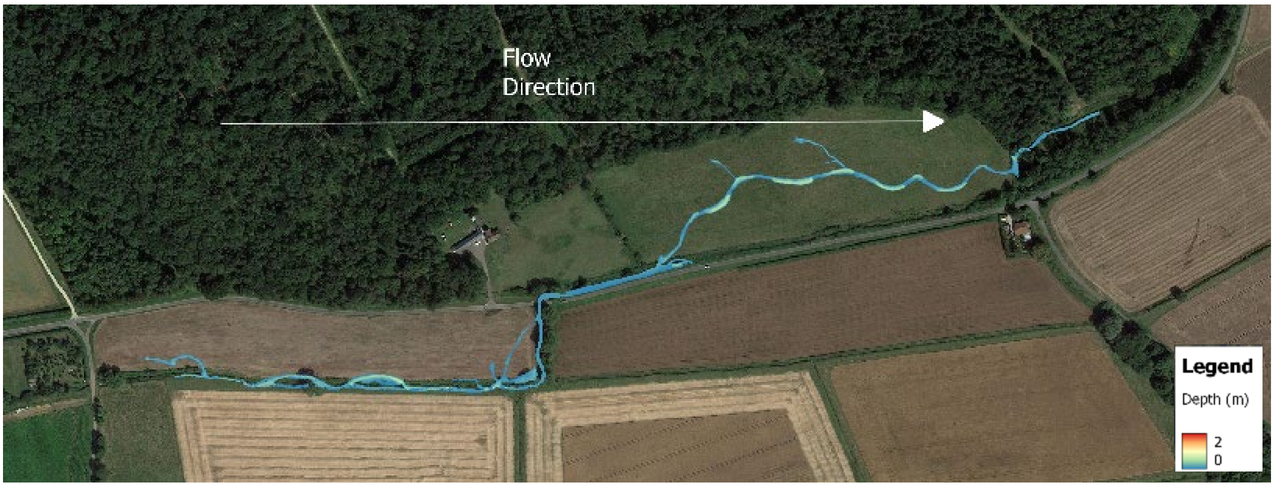


Figure 12.6 Water depth pre (top) and post (bottom) restoration scenarios for the Q95 flow.

Q10

Figure 12.7 shows an increase in overall wetted area for the Q10 flow, with the overall wetted area increasing from 4,500 m^2 in the pre-restoration scenario to 7,300 m^2 in the post-restoration scenario. This increase is again due to the local reconnected floodplain areas that have been created through a combination of floodplain lowering and in-channel feature creation. This creates local diverse wetland areas within the confines of the wider agricultural land use, connected by a network of small sub-channels. Overall wetted area has also increased due to the increased channel length created as a result of the restoration scheme. Water depth variation is much more apparent under restored conditions. This situation will be dynamic over time as the wetland develops, however wetted area under winter flows is likely to be retained as the channels and floodplain develop.

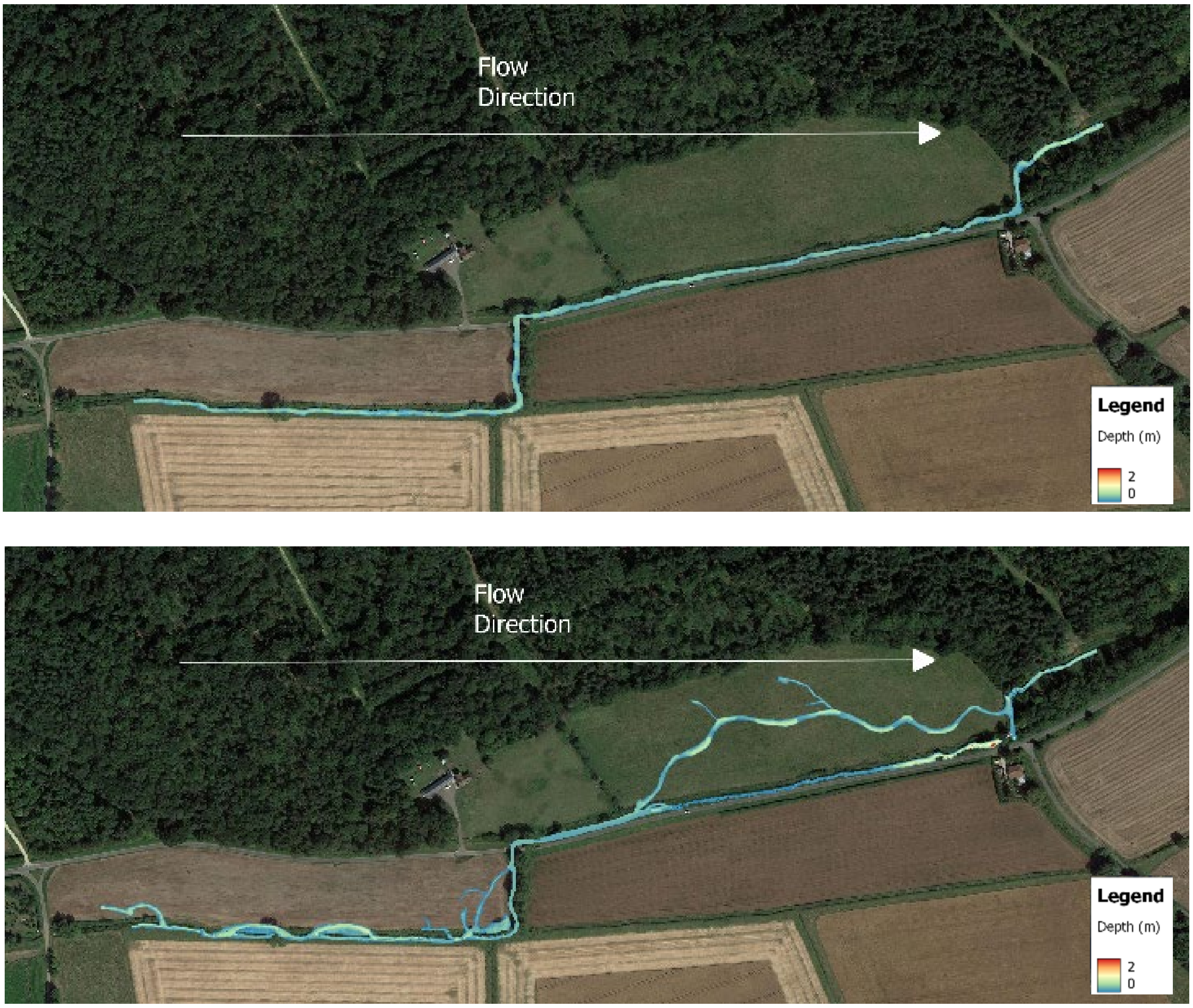


Figure 12.7 Water depth pre (top) and post (bottom) restoration scenarios for the Q10 flow.

2-year

Figure 12.8 shows a large increase in overall wetted area for the 2-year flow, with the overall wetted area increasing from 5,560 m^2 in the pre-restoration scenario to 9,440 m^2 in the post-restoration scenario. There is limited wider floodplain connectivity under this 2 year flow as it was not possible to fully reconnect the wider floodplain area due to its agricultural use. Therefore, the increases in wetted area are still limited to the lowered local floodplain areas and associated sub-network of small channels connecting wetland features. Water depth variation is much more apparent under restored conditions.

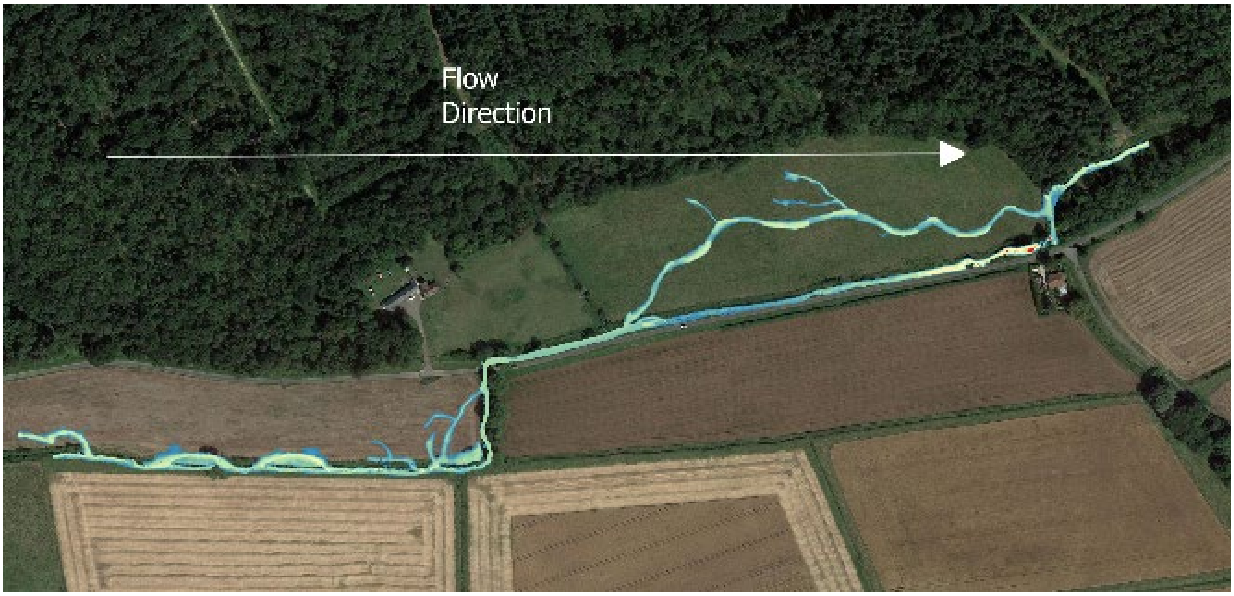


Figure 12.8 Water depth pre (top) and post (bottom) restoration scenarios for the 2-year flow.

12.3.2. Flow Biotopes

Q95

Figures 12.9 and 12.10, and Table 12.4, show that there has been both a significant change in hydraulic habitat diversity and overall hydraulic habitat area as a result of the restoration scheme for a summer flow, with the overall flow area increased compared to the baseline. The overall area for pool and riffle biotopes mapped significantly increases as a result of the proposed scheme, reflecting the riffle-pool sequences created and lower energy wetland zones, replacing long lengths of glide type flow. This is most notable for pool hydraulic habitat and is a result of the lower energy areas created through the new channel and wetland zones.

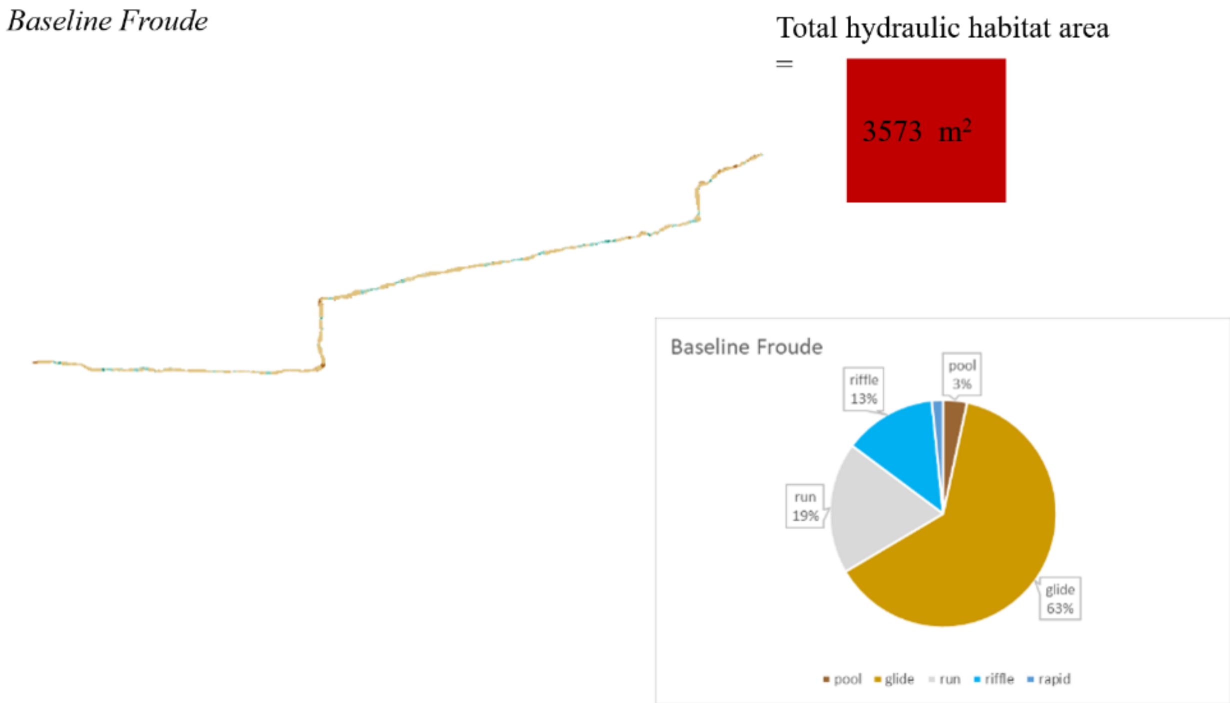


Figure 12.9 Flow biotope pre-restoration during Q95 flow.

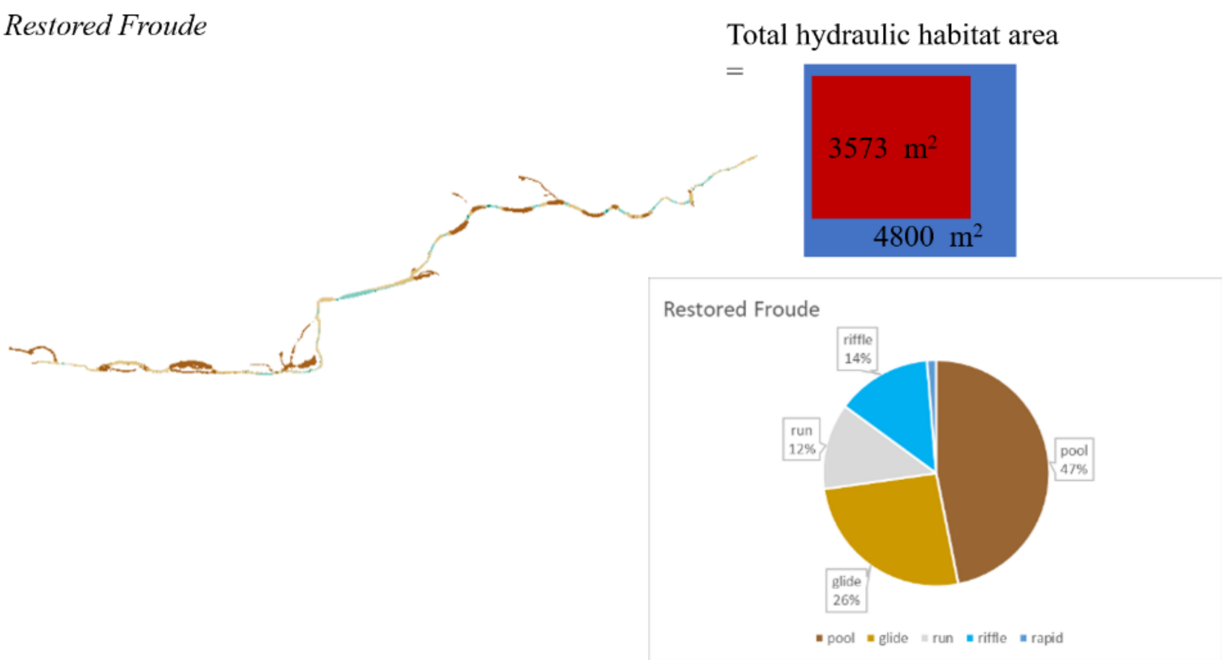


Figure 12.10 Flow biotope post-restoration during Q95 flow.

Table 12.4 Flow biotope change between pre and post restoration.

Flow Biotope	Area pre-restoration (m^2)	Proportion of overall habitat pre-restoration (%)	Area post-restoration (m^2)	Proportion of overall habitat post-restoration (%)	Overall Area Change (%)
Pool	122	3.41	2,252	46.86	1746%
Glide	2,254	63.08	1,245	25.90	-45%
Run	668	18.70	592	12.31	-11%
Riffle	472	13.21	655	13.63	39%
Rapid	57	1.60	62	1.29	9%

Q10

Figure 12.11 and Table 12.5, show that there has been both a significant change in hydraulic habitat diversity and overall hydraulic habitat area as a result of the restoration scheme for a winter flow, with overall flow area increased compared to the baseline. The overall area for pool biotopes mapped significantly increases as a result of the proposed scheme, reflecting the riffle-pool sequences created and lower energy wetland zones, replacing long lengths of run type flow. The previous straightened channel is considered to be over-energetic in this respect for a winter flow. A significant proportion of riffles and runs under baseline conditions were replaced with increased pool and glide type flow as a result of a more appropriate morphology and the lower energy wetland zones created.

Figure 12.11 Flow biotope pre restoration managed (left), and post restoration (right) during Q10 flow.

Table 12.5 Flow biotope change between pre restoration (managed) and post restoration.

Flow Biotope	Area pre-restoration (managed) (m^2)	Proportion of overall habitat pre-restoration (%)	Area post-restoration (m^2)	Proportion of overall habitat post-change (%)	Overall Area Change (%)
Pool	16	35.00	1,904	46.86	11800%
Glide	1,123	24.76	2,611	25.90	133%
Run	1,994	43.96	1,356	12.31	-32%
Riffle	1,330	29.32	1,289	13.63	-3%
Rapid	73	1.61	107	1.29	47%

12.3.3. Shear Stress

Baseline bed shear stress model outputs show that generally under lower order flood flows (2-year return period shown in Figure 12.12 and Figure 12.13) values range between 5-40 N/m^2 (Figure 12.12). The majority of shear stress values fall within the lower estimate of this range, due to the subdued topography and shallow channel gradient. There are slightly higher values at certain points under baseline conditions, reflecting local topographical changes and constrictions in the channel. This range does not change significantly for the restored model scenario (Figure 12.13), however, there is an overall reduction in bed shear stress within the channel as a result of the restoration scheme, due to the flow splits created and increased channel length. The restored bed shear stresses are considered to be more appropriate for a passive river system than those shown under baseline conditions.

Figure 12.12 1 in 2yr bed shear stress pre-restoration.

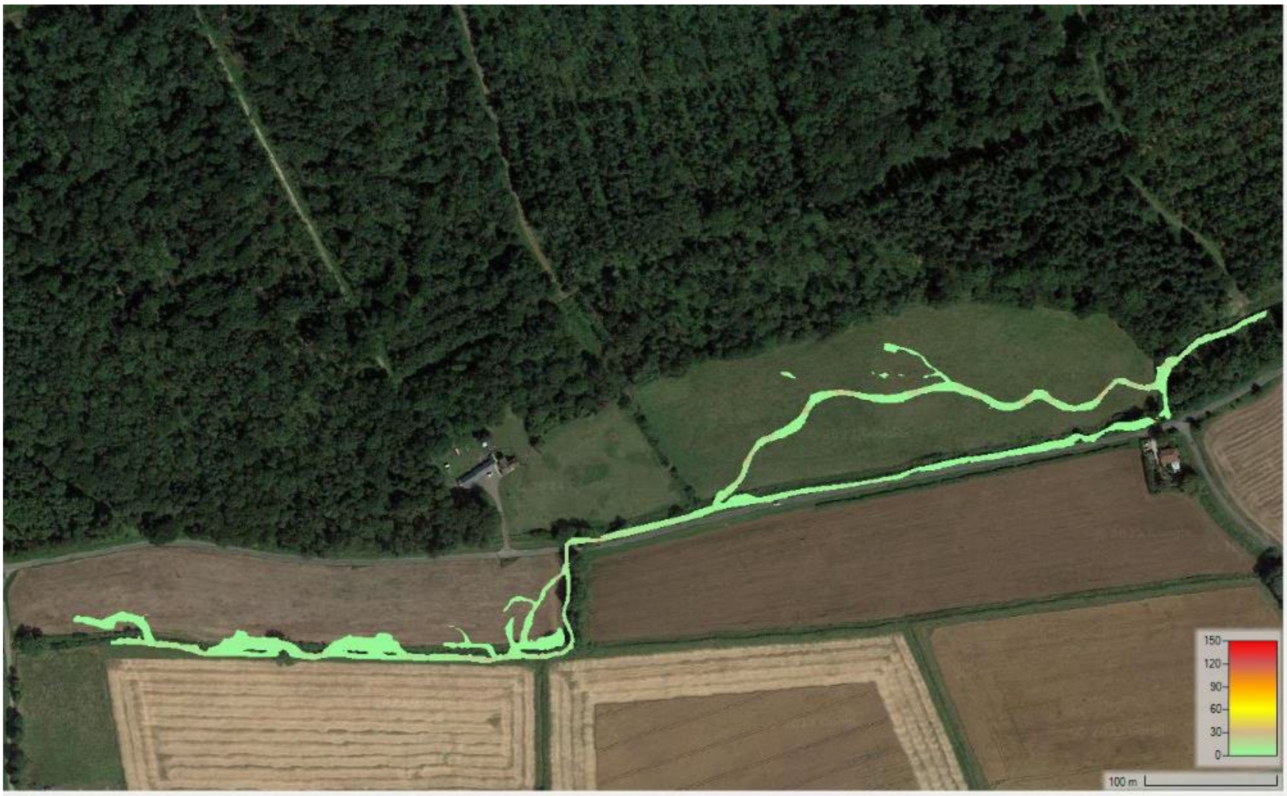


Figure 12.13 1 in 2yr bed shear stress post-restoration.

12.3.4. Floodplain habitat creation

This section demonstrates the potential overall floodplain habitat gains/creation as a result of the restoration scheme. Table 12.6 summarises the wetting thresholds used to map the floodplain habitat. Figure 12.14 shows the optimal vegetation development over time based on the new hydrological regime at the site. This may differ in reality due to species competition and other factors, but it provides a template for anticipated development. The summer (Q95), autumn (Q30), winter (Q10) and spring (Q50) inundation area has been extrapolated to predict water table levels across the wider floodplain for the study site based on the restored scenario. Figure 12.14 summarises the potential mosaic of swamp, mire and wet grassland habitat that could develop under a sensitive grazing regime (the coverage is summarised in Table 12.7). It is clear that the predicted habitat gains will be diverse and considerable across the valley bottom and that these areas will act immediately to sequester carbon, turning much of the valley bottom from a carbon emitter to a sequestering area. Wet grassland and fen mire could develop across the reconnected floodplain areas, however this development is reliant on a suitable grazing regime at the site.

Table 12.6 Summer, winter, spring, autumn wetting threshold for each habitat.

Habitat Type	Habitat Code	Water table depth below FP surface (negative numbers indicated flooded ground)			
		Winter	Spring	Summer	Autumn
Wet Grassland	MG13	0.1-0.25	0.03-0.45	0.2-0.8	0.1-1
	MG4	0.1-0.6	0.25-0.7	0.4-1.0	0.25-1
	MG8	0.03-0.3	0.03-0.35	0.15-0.5	0.1-0.4
Fen Mire	M24	--	--	0.249-0.533	--
	M13	--	--	0.096-0.386	--
	S24	--	--	0.167-0.784	--
	S2	0-(0.4)	--	<0.15	--
Ditch Swamp	S4	0-(1.5)	0.25-(1.25)	0.8-(0.5)	1-(0.75)
	S5	0.3-(0.9)	0.6-(0.7)	0.8-(0.8)	0.6-(0.8)

Figure 12.14 Potential floodplain habitat biotope post-restoration.

Table 12.7 Total Habitat area created (m^2).

Habitat Type	Habitat Code	Area (m^2)
Wet Grassland	MG13	10898
	MG4	46801
	MG8	12572
Fen Mire	M24	31538
	M13	26005
	S24	46289
	S2	1819
Ditch Swamp	S4	NA
	S5	20684

12.4. Conclusions

The restoration design included the following measures at Dunston Beck:

- riffle creation and point bars,
- floodplain lowering,
- wetland creation,
- channel bifurcation,
- channel realignment and remeandering,
- pond creation.

The modelling of the scheme indicated an increase in overall wetted area under low and winter flows, demonstrating the increased resilience to low flows created as a result of the restoration scheme. There is also an overall improvement in biotope diversity under summer and winter flows when compared to pre-restoration conditions, with more characteristic riffles and pools being created as a result of the scheme under summer flows, as well as an increase in overall wetted area. The development of diverse floodplain habitat is also predicted as a result of the new hydrological regime created. Wet grassland

and fen mire could develop across the reconnected floodplain areas, however this development is reliant on a suitable grazing regime at the site.

Since the scheme was completed, ground observations suggest that floodplain habitat connectivity is currently minimal. Evidence of lateral migration suggests the river channel is attempting to bypass some of the newly constructed riffles, indicating that they may have been oversized for the type of channel at Dunston (both in terms of feature size and the particle size of gravel used). Whilst a degree of natural / unplanned adjustment following completion is to be expected and planned for with river restoration, Dunston provides a valuable example of the disparity that may occur between modelled and observed outcomes, and the importance therefore of adopting adaptive management practices informed by robust monitoring strategies in order to maximise benefits delivered and mitigate risks as they arise.

13. Manthorpe

13.1. Background

The River Witham at Manthorpe is a chalk river system that drains the catchment south of South Witham, flowing through Grantham and through to Boston on the east coast. Whilst being underlain by chalk, the Witham shows very little in the way of typical chalk river characteristics, having been significantly modified in the past through channel deepening, straightening and embanking. The watercourse also suffers from significant fine sediment pressures from both agricultural practices and urban runoff.

The restoration reach of the River Witham at Manthorpe had been significantly straightened, deepened and embanked resulting in a very disconnected floodplain and a poor diversity of flow types within the channel, with very few characteristic gravel features evident in the channel (often smothered by fine sediments).

The watercourse flows over a subdued topography with no clear evidence of former palaeo-channels. Such low gradients suggest an aggradational environment and the River Witham at Manthorpe does suffer from excess fine sediment deposition. Surrounding land use is a mixture of agricultural and urban, with very little variation in habitat across the floodplain area and semi-improved grassland generally dominating.

The restoration design included the following measures (Figure 13.1, 13.2):

- riffle and gravel bar feature creation,
- channel widening,
- embankment removal,
- floodplain lowering to improve floodplain connectivity.

Figure 13.1 Aerial Photographs of pre-construction (left) and post-construction (right).

Figure 13.2 Photographs of pre-construction (top) and post / during-construction (bottom).

13.2. Site Specific Methodology

13.2.1. Model schematisation

To help review the post restoration work of the River Witham at Manthorpe described above, a 2D HEC-RAS (v6.3) model of the study reach has been developed, using Environment Agency 1 m cell size LiDAR. It should be noted that there remains some uncertainty in levels where vegetation growth and sedimentation have occurred along the reach, therefore there may be some discrepancy in baseline levels. For the post-restoration model, a 25 cm photogrammetric drone-based DEM of the restored site has been utilised to enable the pre and post comparison to be made.

The purpose of the modelling was to appraise the restoration with regards to the specific outputs required to assess the impacts on hydraulics as a result of the scheme compared to the pre restored conditions. This enabled assessment of the impacts on in-channel processes and the hydrological regime.

The model has been built using a Digital Elevation Model (DEM) across the model domain that provides a ground elevation value for each 1 m grid cell for both the pre and post restoration conditions. The model extent (also showing grid orientation) and resulting model surface is shown below (Figure 13.3).

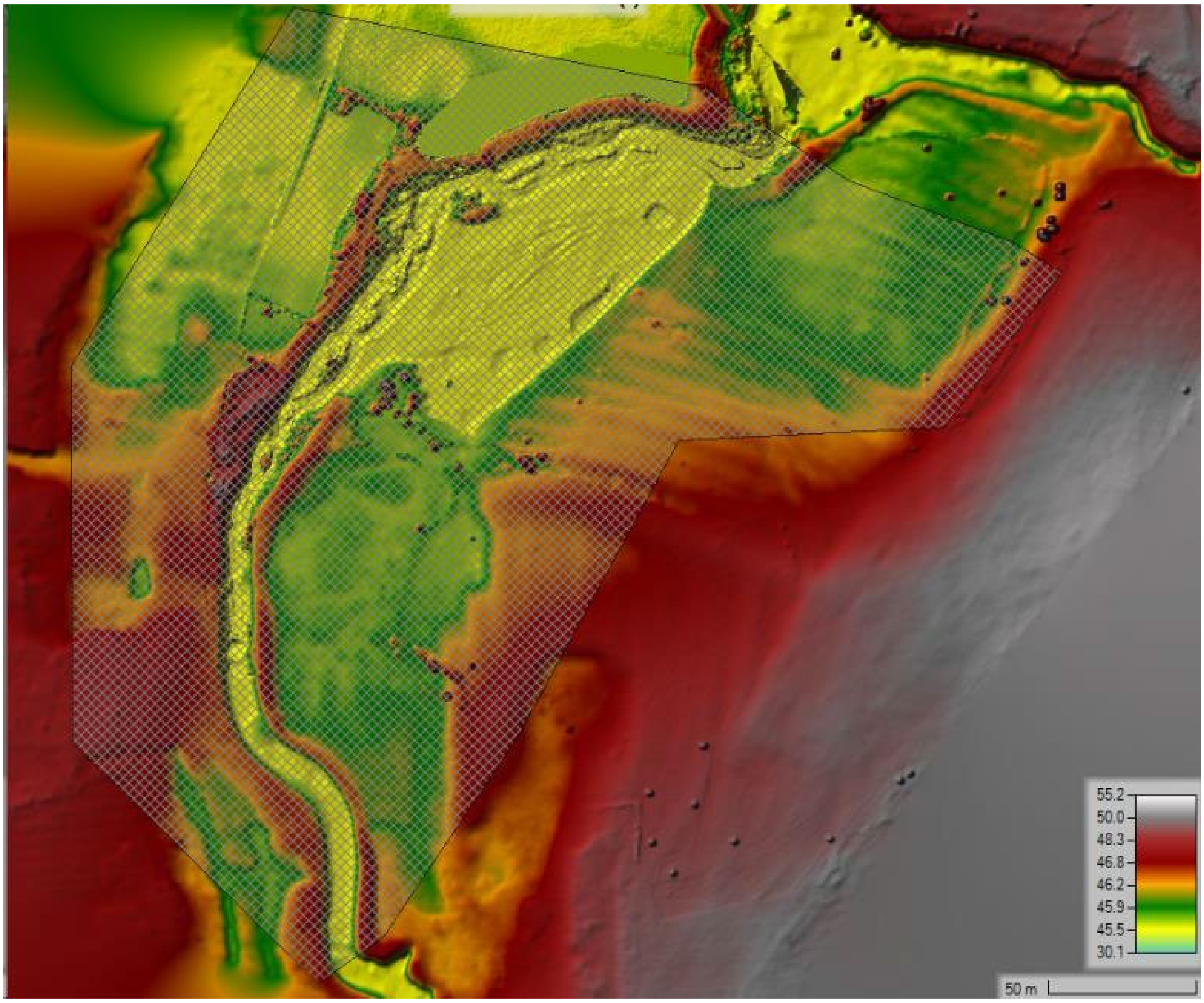


Figure 13.3 HEC-RAS 2D – baseline grid set up of the study site at Manthorpe.

13.2.2. Inflows

The flows used in the modelling are shown in Table 13.1 below. The low flows for Q95, Q50, Q30 and Q10 were derived using Low Flows 2 software. The 2-year return period flows were estimated using Flood Estimation Handbook techniques.

Table 13.1 Inflows to the model

Scenario	Flow (m^3/s)
Q95 (summer flow)	0.15
Q50	0.45
Q30	1.0
Q10 (winter flow)	1.8
2-year return period flood	5.2

13.2.3. Manning's roughness

Observations of the channel and banks, from site visits and surveying, informed the choice of Manning's n values. These have also been cross checked against values listed in Chow, 1959[8]. Table 13.2 and Table 13.3, and Figure 13.4 and Figure 13.5 show these values and how they have been used.

Table 13.2 Manning's roughness values used (pre change).

Land Use	Manning's N	Photo
Channel	0.045 has been used to represent the in channel flow.	See Figures 13.1 and 13.2
Floodplain	Arable Field: (n=0.05) used to represent a vegetated field	See Figures 13.1 and 13.2

[8] Chow, V.T. (1959) Open Channel Hydraulics, McGraw-Hill Book Company, NY.

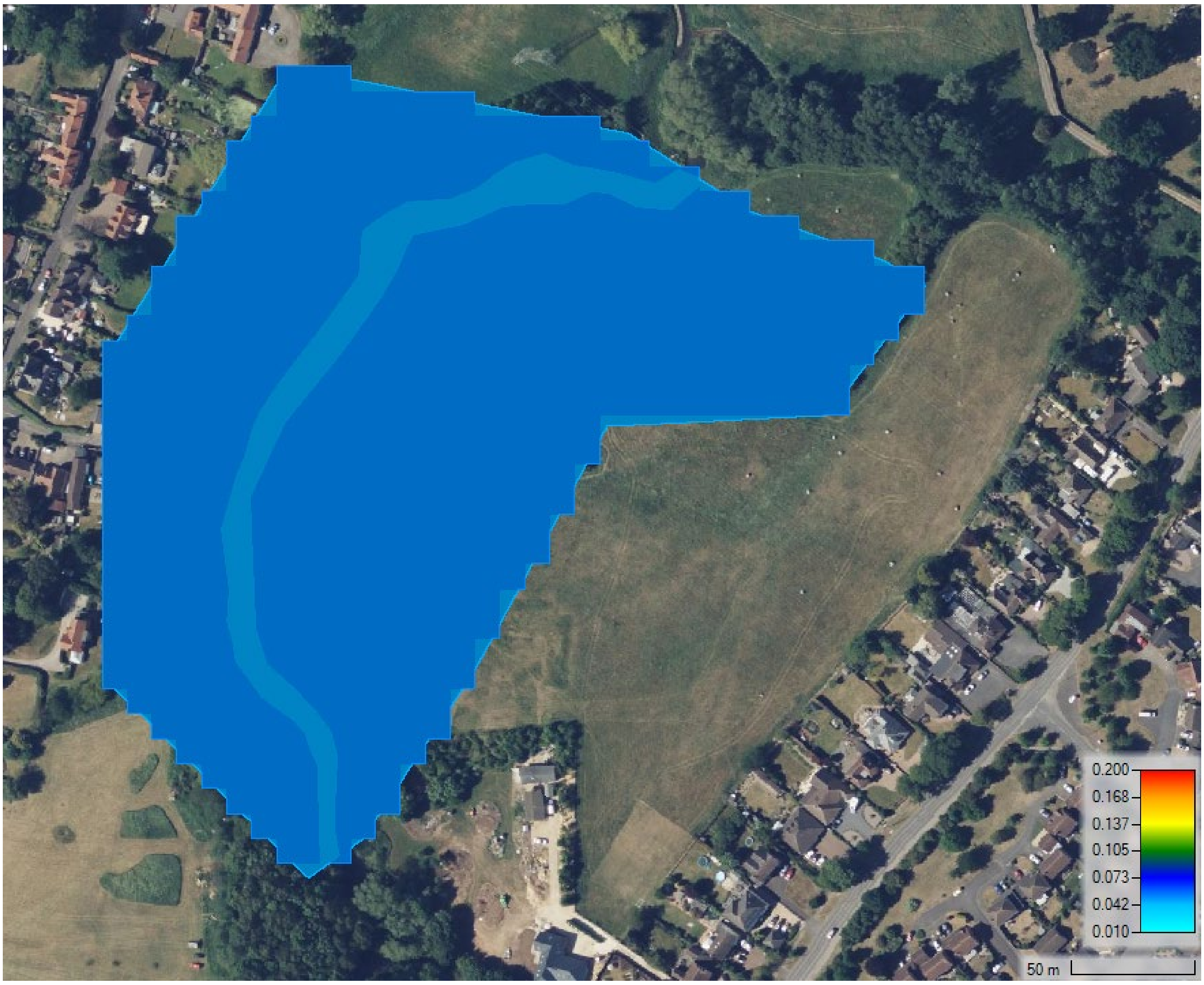


Figure 13.4 Baseline Manning's roughness grid.

13.2.4. Post change representation

Post restoration modifications were made to the underlying model surface through direct use of the post restoration drone DEM and changes in roughness across the model domain linked to new features introduced. For example, roughness was increased across the post restoration floodplain to represent vegetation change over time post completion of the scheme (previously arable fields).

Table 13.3 Manning's roughness values used (post change).

Land Use	Manning's N	Photo
Channel	Channel: (n=0.045). This has been used to represent the new channels.	See Figures 13.1 and 13.2
Floodplain	Arable Field: (n=0.05) used to represent a vegetated field. Roughened Floodplain post change (n=0.1) to represent the change in land use post river restoration and floodplain reconnection.	See Figures 13.1 and 13.2

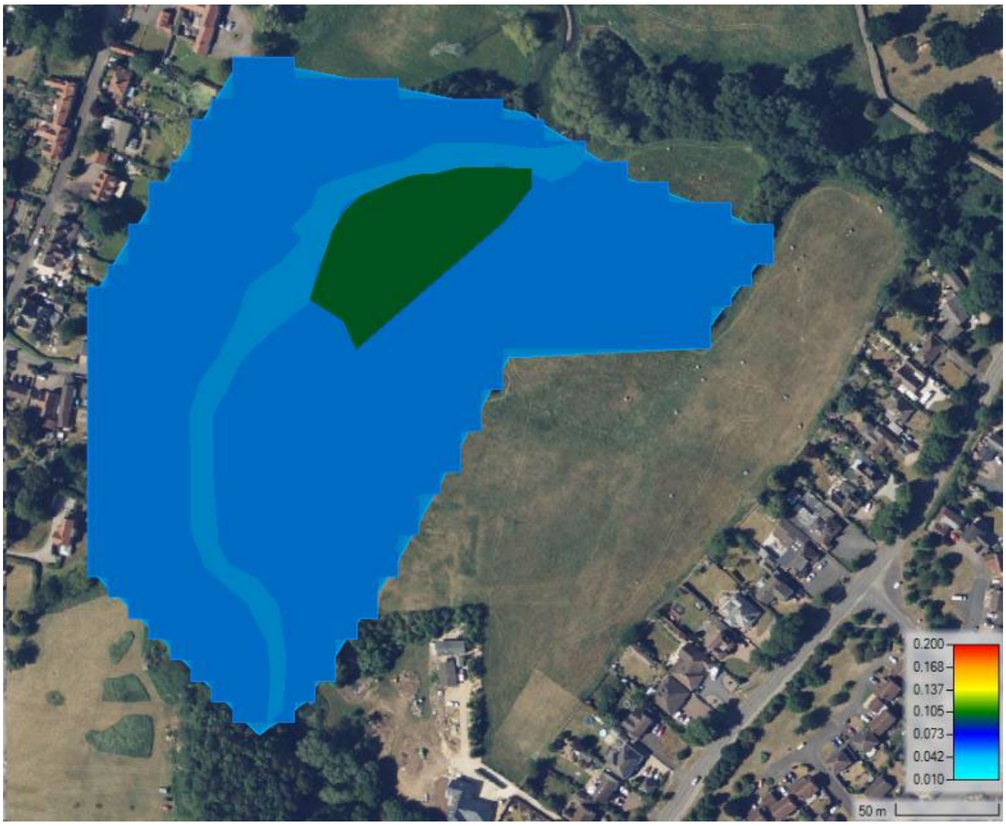


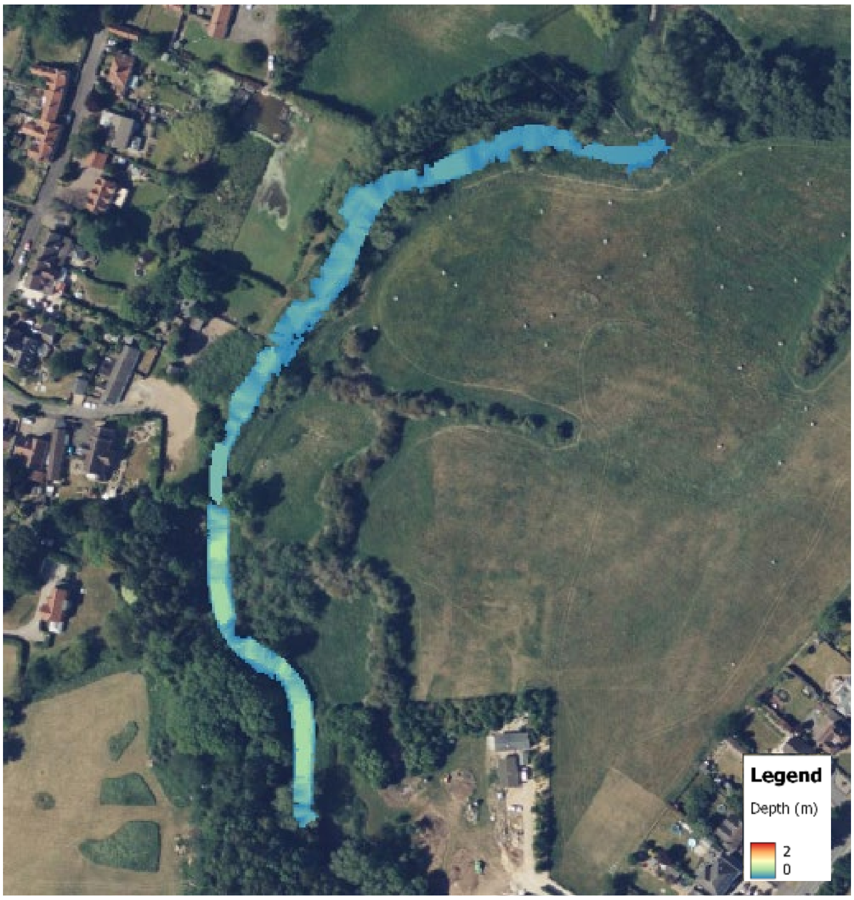
Figure 13.5 Post-change Manning's roughness grid.

13.3. Results

13.3.1. Hydraulic Conditions

Q95

Figure 13.6 shows an increase in overall wetted area for the Q95 flow, with the overall wetted area increasing from 2,947 m^2 in the pre-restoration scenario to 3,666 m^2 in the post-restoration scenario. This increase is due to the channel widening and morphological feature creation as a result of the restoration scheme. Water depth variation is much more apparent under restored conditions. This situation will be dynamic over time, however wetted area under low flows is likely to be retained as the channel and floodplain develop.



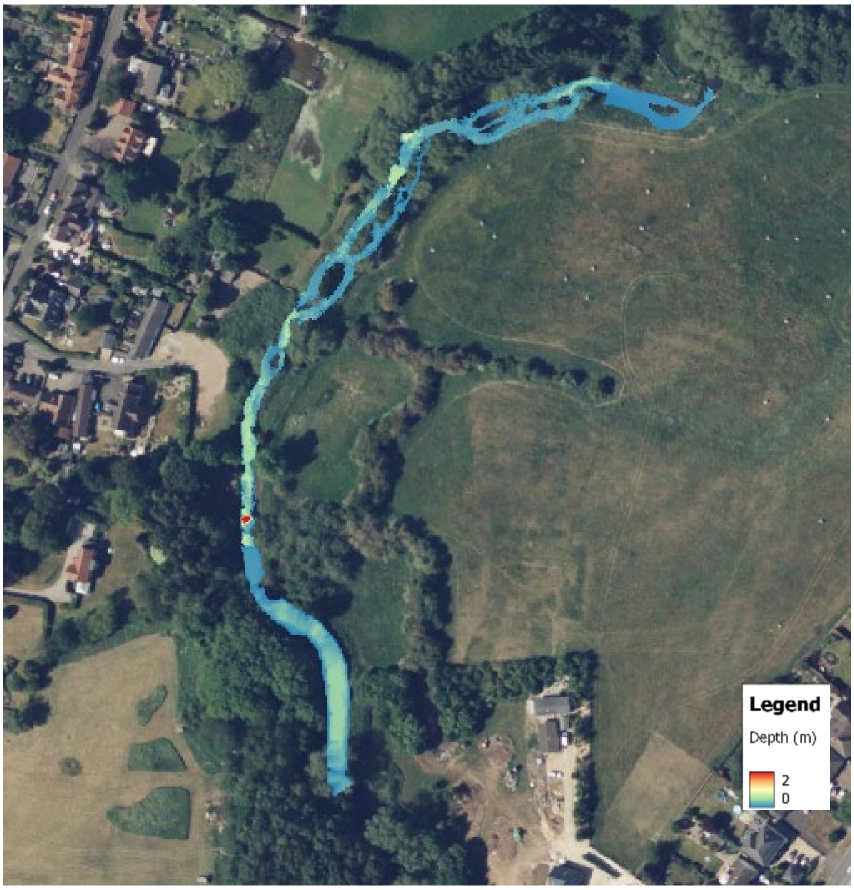
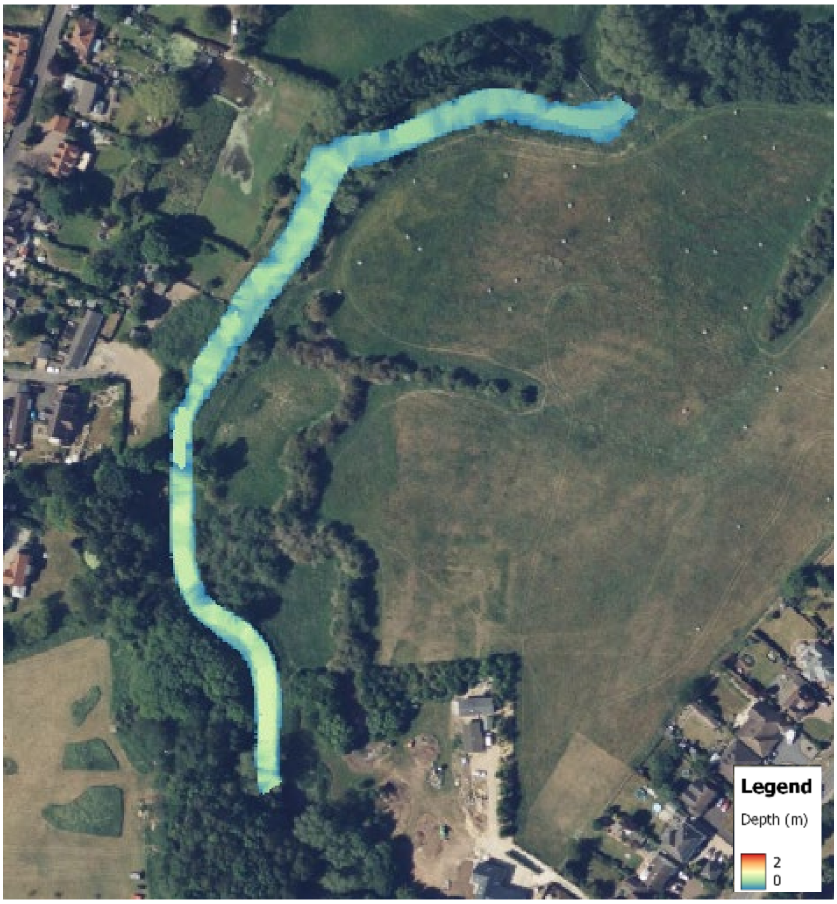


Figure 13.6 Water depth pre (top) and post (bottom) restoration scenarios for the Q95 flow.

Q10

Figure 13.7 shows an increase in overall wetted area for the Q10 flow, with the overall wetted area increasing from 3,966 m^2 in the pre-restoration scenario to 4,821 m^2 in the post-restoration scenario. This increase is due to the channel widening and morphological feature creation as a result of the restoration scheme. The lowered floodplain and associated wetland just starts to activate under this flow (water will be retained in this feature after high flows). Water depth variation is much more apparent under restored conditions. This situation will be dynamic over time, however wetted area under winter flows is likely to be retained as the channel and floodplain develop.



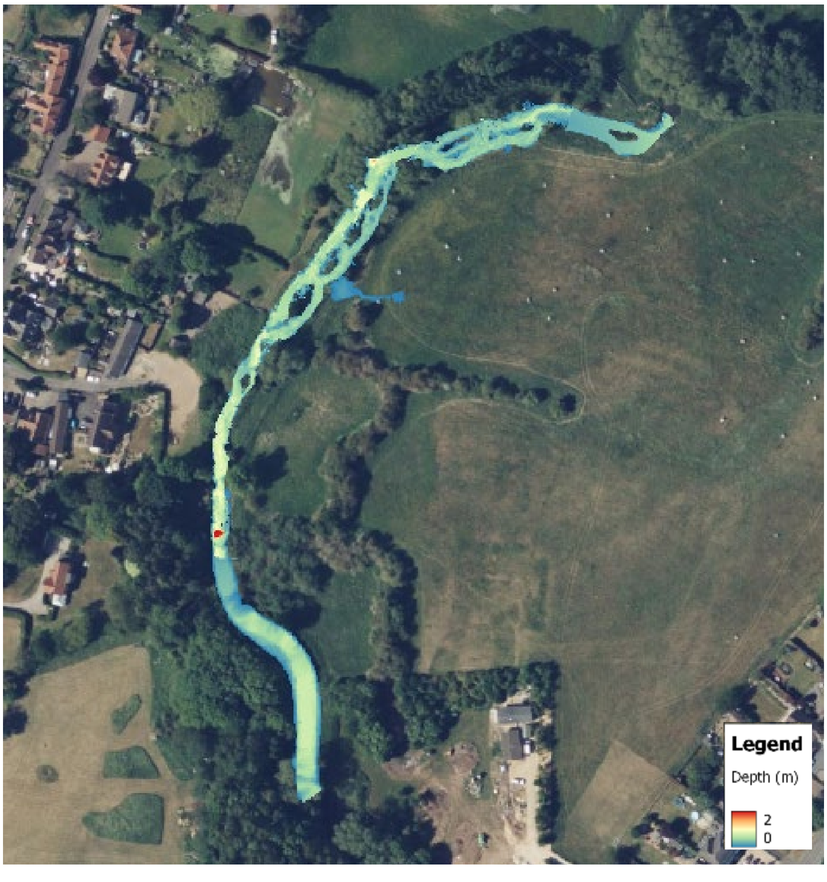


Figure 13.7 Water depth pre (top) and post (bottom) restoration scenarios for the Q10 flow.

2-year

Figure 13.8 shows an increase in overall wetted area for the 2-year flow, with the overall wetted area increasing from 5,510 m^2 in the pre-restoration scenario to 9,480 m^2 in the post-restoration scenario. This increase is due to the channel widening, morphological feature creation and embankment removal as a result of the restoration scheme. The lowered floodplain and associated wetland activates under this flow as a result of the removed embankment (water will be retained in the floodplain wetland after high flows). Water depth variation is much more apparent under restored conditions. This situation will be dynamic over time, but water will be retained in the lowered floodplain and wetland area.

Figure 13.8 Water depth pre (top) and post (bottom) restoration scenarios for the 2-year flow.

13.3.2. Flow Biotopes

Q95

Figures 13.9 and 13.10, and Table 13.4, show that there has been both a significant change in hydraulic habitat diversity and overall hydraulic habitat area as a result of the restoration scheme for a summer flow, with overall flow area increased compared to the baseline. There is an increase in the percentage cover of higher energy biotopes overall (riffles) as a result of the impact of the restoration undertaken through the Manthorpe site, namely the introduced gravel features. This results in an overall reduction in the proportion of lower energy biotopes including pools, glides and runs when compared to the baseline. It is considered that the pre restoration channel was overwide and deep, creating low energy flow conditions.

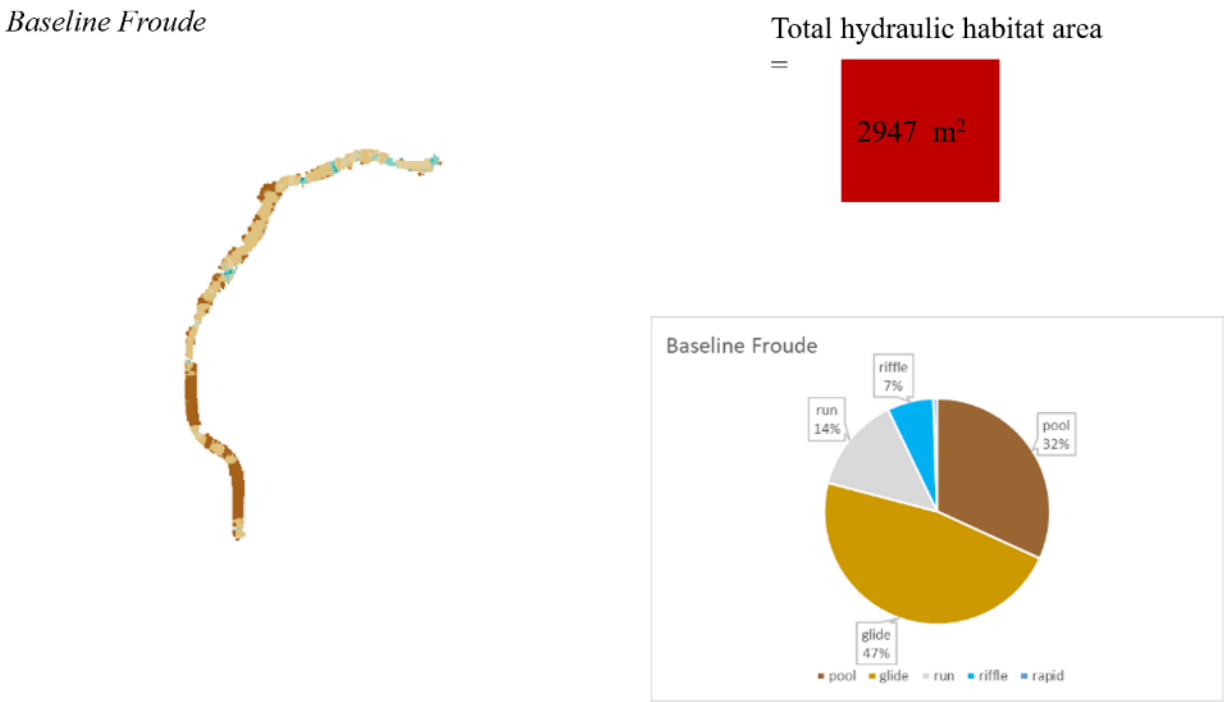
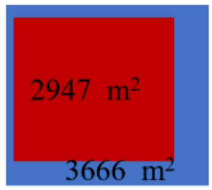


Figure 13.9 Flow biotope pre-restoration during Q95 flow.

Restored Froude

Total hydraulic habitat area =



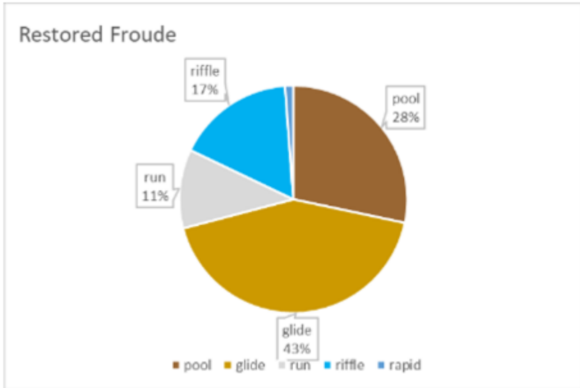


Figure 13.10 Flow biotope post-restoration during Q95 flow.

Table 13.4 Flow biotope change between pre and post restoration.

Flow Biotope	Area pre-restoration (m^2)	Proportion of overall habitat pre-restoration (%)	Area post-restoration (m^2)	Proportion of overall habitat post-restoration (%)	Overall Area Change (%)
Pool	1,167	32%	835	28%	-28%
Glide	1,732	47%	1,255	43%	-28%
Run	504	14%	330	11%	-34%
Riffle	244	7%	493	17%	102%
Rapid	19	1%	35	1%	82%

Q10

Figure 13.11 and Table 13.5 show that there has been an increase in overall hydraulic habitat area as a result of the restoration scheme for a winter flow, with overall flow area increased compared to the baseline. However, there is no significant change in hydraulic habitat diversity under a winter flow, likely because the riffle features are drowned out under this higher flow.

Figure 13.11 Flow biotope pre restoration managed (left), and post restoration (right) during Q10 flow.

Table 13.5 Flow biotope change between pre restoration (managed) and post restoration.

Flow Biotope	Area pre-restoration (managed) (m^2)	Proportion of overall habitat pre-restoration (%)	Area post-restoration (m^2)	Proportion of overall habitat post-change (%)	Overall Area Change (%)
Pool	124	1%	2	3%	-98%
Glide	790	25%	1,207	20%	53%
Run	1,548	42%	2,019	39%	30%
Riffle	1,355	32%	1,565	34%	15%
Rapid	151	1%	28	4%	-81%

13.3.3. Shear Stress

Baseline bed shear stress model outputs show that generally under lower order flood flows (2-year return period shown in Figure 13.12 and Figure 13.13) values range between 5-50 N/m^2 (Figure 13.12). The majority of shear stress values fall within the lower estimate of this range, due to the subdued topography and shallow channel gradient. There are slightly higher values at certain points under baseline conditions, reflecting local topographical changes and constrictions in the channel. This range does not change significantly for the restored model scenario (Figure 13.13), however, there is some concentration in bed shear stress across introduced gravel riffle features. Bed shear stress across the reconnected floodplain area is generally low and is unlikely to experience significant erosion in response to wetting, with fine sediments expected to deposit across this reconnected area.

Figure 13.12 1 in 2yr bed shear stress pre-restoration.

Figure 13.13 1 in 2yr bed shear stress post-restoration.

13.3.4. Floodplain habitat creation

This section demonstrates the overall floodplain habitat gains/creation as a result of the restoration scheme. Table 13.6 summarises the wetting thresholds used to map the floodplain habitat. Figure 13.14 shows the optimal vegetation development over time based on the new hydrological regime at the site. This may differ in reality due to species competition and other factors, but it provides a template for anticipated development. The summer (Q95), autumn (Q30), winter (Q10) and spring (Q50) inundation area has been extrapolated to predict water table levels across the wider floodplain for the study site based on the restored scenario. Figure 13.14 summarises the probable mosaic of swamp, mire and wet grassland habitat that will develop under a sensitive grazing regime (coverage is summarised in Table 13.7). It is clear that the predicted habitat gains will be diverse and considerable across the valley bottom and that these areas will act immediately to sequester carbon, turning much of the valley bottom from a carbon emitter to a sequestering area. A variety of fen mire, wet grassland and swamp type habitat are likely to develop over time in response to the improved connectivity to the floodplain and raising of groundwater level.

Table 13.6 Summer, winter, spring, autumn wetting threshold for each habitat

Habitat Type	Habitat Code	Water table depth below FP surface (negative numbers indicated flooded ground)			
		Winter	Spring	Summer	Autumn
Wet Grassland	MG13	0.1-0.25	0.03-0.45	0.2-0.8	0.1-1
	MG4	0.1-0.6	0.25-0.7	0.4-1.0	0.25-1
	MG8	0.03-0.3	0.03-0.35	0.15-0.5	0.1-0.4
Fen Mire	M24	--	--	0.249-0.533	--
	M13	--	--	0.096-0.386	--
	S24	--	--	0.167-0.784	--
	S2	0-(0.4)	--	<0.15	--
Ditch Swamp	S4	0-(1.5)	0.25-(1.25)	0.8-(0.5)	1-(0.75)
	S5	0.3-(0.9)	0.6-(0.7)	0.8-(0.8)	0.6-(0.8)

Figure 13.14 Floodplain habitat biotope post-restoration.

Table 13.7 Total Habitat area created (m^2).

Habitat Type	Habitat Code	Area (m^2)
Wet Grassland	MG13	2775
	MG4	3303
	MG8	2741
Fen Mire	M24	4143
	M13	1553
	S24	4511
	S2	199
Ditch Swamp	S4	NA
	S5	4731

13.4. Conclusions

The restoration design included the following measures at Manthorpe:

- riffle and gravel bar feature creation
- channel widening
- embankment removal
- floodplain lowering to improve floodplain connectivity.

The increase in overall wetted area under low and winter flows shown by the modelling demonstrates the increased resilience to low flows created as a result of the restoration scheme. There is also an overall improvement in biotope diversity under summer flows when compared to baseline conditions. More characteristic riffle biotopes were created as a result of the introduced features, as well as an increased overall wetted area. The development of diverse floodplain habitat is also predicted as a result of the new hydrological regime created. A variety of fen mire, wet grassland and swamp type habitat are likely to develop over time in response to the improved connectivity to the floodplain and raising of groundwater level.

References

ARMSTRONG, J.D., KEMP, P.S., KENNEDY, G.J.A., LADLE, M. AND MILNER, A.J. 2003. Habitat requirements of Atlantic salmon and brown trout in rivers and streams. Fisheries Research, 62 (2), 143-170.

BOULTON, A.J. AND LAKE, P.S., 2008. Effects of drought on stream insects and its ecological consequences. In Aquatic Insects: Challenges to Populations (ed. J. Lancaster and R.A. Briers), pp. 81-102. Wallingford: CAB International.

CLOUGH, S.C, AND TURNPENNY, A.W.H., 2001. *Swimming speeds in fish: Phase 1.* R&D Technical Report W2-0.26/TR1. Bristol: Environment Agency.

DE CRISPIN DE BILLY, V. AND USSEGLIO-POLATERA, P., 2002. Traits of brown trout prey in relation to habitat characteristics and benthic invertebrate communities. Journal of Fish Biology, 60 (3), 687-714.

ENVIRONMENT AGENCY, 2013c. Migration and seasonal habitat requirements of UK freshwater fish species. Unpublished internal report.

ENVIRONMENT AGENCY, 2014. Restoration measures to improve river habitats during low flows. Report SC120050/R. Bristol: Environment Agency.

GILVEAR, D.J., SPRAY, C.J. AND CASAS-MULET, R., 2013. River rehabilitation for the delivery of multiple services at the river network scale. Journal of Environmental Management, 126, 30-43.

GORDON, N.D., MCMAHON, T.A. AND FINLAYSON, B.L., 1994. Stream Hydrology: An Introduction for Ecologists. Chichester: Wiley.

HARVEY, G.L. AND CLIFFORD, N.J., 2008. Distribution of biologically functional habitats within a lowland river. Aquatic Ecosystem Health and Management, 11 (4), 465-473.

HARVEY, G.L., CLIFFORD, N.J. AND GURNELL, A.M., 2008. Towards an ecologically meaningful classification of the flow biotope for river inventory, rehabilitation, design and appraisal purposes. Journal of Environmental Management, 88 (4), 638-650.

HEGGENES, J, 1989. Physical habitat selection by brown trout (Salmo trutta) in riverine systems. Nordic Journal of Freshwater Research, 64, 64-90.

HERITAGE, G.L., MILAN, D.J., AND ENTWISTLE, N., 2009. An investigation of the role of geomorphology in influencing biotope distribution. In Ecohydrology of Surface and Groundwater Dependent Systems: Concepts, Methods and Recent Developments (ed. M. Thoms, K. Heal, E. Bogh, A. Chambel and V. Smakthin), Proceedings of JS.1 at the Joint IAHS and IAH Convention, Hyderabad, India, September 2009, IAHS Publication 328, pp. 68-76. Wallingford: IAHS Press.

KEMP, J.L., HARPER, D.M. AND CROSA, G.A., 2000. The habitat-scale of ecohydraulics of rivers. Ecological Engineering, 16 (1), 17-29.

LAKE, P.S., 2000., Disturbance, patchiness and diversity in streams. Journal of the North American Benthodological Society, 19(4), 573-592.

LAKE, P.S. 2007. Flow-generated disturbances and ecological response: floods and droughts. In Hydroecology and Ecohydrology: Past, Present and Future (ed. P.J. Wood, D.M. Hannah and J.P. Sadler), pp. 75-88. Chichester: John Wiley.

MANN, R.H.K., 1995. Natural factors influencing recruitment success in coarse fish populations. In The Ecological Basis for River Management (ed. D.M. Harper and A.J.D. Ferguson), pp. 339-348. Chichester: John Wiley.

NEWSON, M.D., 2002. Geomorphological concepts and tools for sustainable river ecosystem management. Aquatic Conservation: Marine and Freshwater Ecosystems, 12 (4), 365-379.

WADESON, R.A., 1994. A geomorphological approach to the identification and classification of instream flow environments. Southern African Journal of Aquatic Science, 20 (1), 38-61.

List of abbreviations

DEM	Digital Elevation Model
DTM	Digital Terrain Model
EA	Environment Agency
FEH	Flood Estimation Handbook
GEP	Good Ecological Potential
GES	Good Ecological Status
JBA	Jeremy Benn and Associates Limited
LiDAR	Light Detection and Ranging
LWD	Large Woody Debris
m	Metres
m^2	Square metre
m^3/s	Cubic metres per second
masl	Metres above sea level
Nm^{-2}	Newton per square metre
SSSI	Site of Special Scientific Interest
WFD	Water Framework Directive

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