A66 Northern Trans-Pennine Project
TR010062

3.4 Environmental Statement Appendix 14.9 Detailed Geomorphological Modelling

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A66 Northern Trans-Pennine Project Development Consent Order 202x

3.4 ENVIRONMENTAL STATEMENT APPENDIX 14.9 DETAILED GEOMORPHOLOGICAL MODELLING

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14.9 Detailed Geomorphological Modelling

14.9.1 Introduction

14.9.1.1 This assessment acts as supporting evidence to the Environment Statement (ES) Chapter 14: Road drainage and the water environment (Application Document 3.2) and its related appendices.

14.9.1.2 Analysis of hydromorphological conditions using hydraulic model data was included for the Trout Beck and the Moor Beck due to the complexity of the proposed works on both watercourses and the potential for detrimental impact to watercourses in the vicinity.

14.9.2 Temple Sowerby to Appleby

Introduction

Objectives

14.9.2.1 An understanding of geomorphological function on Trout Beck and Keld Sike (a tributary of the Trout Beck) within the study extent (study area is defined in ES Chapter 14: Road Drainage and the Water Environment (Application Document 3.2), and shown on ES Figure 14.1: Surface Water Features, sheets 3 to 6 (Application Document 3.4)) is required, in order to provide a comprehensive assessment of the constraints that local morphological function will have on the scheme and to assess the potential impacts that this scheme will have on morphological function.

14.9.2.2 The primary objectives are as follows:

- Undertake a geomorphological analysis of Trout Beck and Keld Sike using desk-based and field-based sources.
- Develop a hydraulic model within the study area, and analyse the results of this modelling study to provide further evidence to support the geomorphological analysis in the first objective
- Identify any constraints that local morphological function will have on the delivery of the scheme
- Identify any potential impacts of this scheme on local morphological function.

Study approach

Overview

14.9.2.3 A spatially integrated study has been conducted to gain the understanding necessary to describe system form and behaviour and predict future fluvial change. This assessment has been combined with an analysis of hydraulic model results ES Appendix 14.2: Flood Risk Assessment and Outline Drainage Strategy (Application Document 3.4), to provide a comprehensive assessment of the implications of developing the scheme. This study combines desk-based and field-based components, to deliver the geomorphological analysis of the Trout Beck and Keld Sike.

Desk-based assessment

14.9.2.4 The desk-based components included review of a wide range of information provided for this study, as well as other sources openly available through the internet (LiDAR, historical maps, literature). The desk-based component of the study is essential to gain understanding of the wider context of the catchment and its waterbodies, in order to appreciate the local and catchment-wide controls that are influencing geomorphology on Trout Beck and Keld Sike.

Site-based assessment

14.9.2.5 A complete walkover of Trout Beck and Keld Sike within the study area was undertaken by suitably qualified geomorphologists. Morphological features of the watercourses, the riparian strip and the associated floodplain were recorded, to provide a detailed understanding of the functioning of the river system and how this influences the geomorphology of the river, banks and floodplain.

14.9.2.6 Following completion of the field-based surveys, the desk-based component was re-visited, and the various sources of information were linked. Channel change, morphological evolution, river engineering, historic system functioning and wider catchment influences were assessed and placed within the context of the development of the scheme.

Hydraulic modelling

14.9.2.7 A linked 1D-2D hydraulic model of Trout Beck, Keld Sike and the River Eden was developed as part of this commission, to further supplement the analysis of morphological function undertaken in the desk-based and site-based assessment. The River Eden was included as the Trout Beck discharges into the River Eden downstream of Kirkby Thore. Hydraulic model results were analysed to determine the likely impact that he proposed scheme will have on morphological function in the channel and on the floodplain and on flood risk to third party land.

Hydraulic modelling approach

Model approach

14.9.2.8 A linked 1D-2D approach was adopted using Flood Modeller version 4.5 and TUFLOW build 2020-01-AB-iDP-w64. The baseline schematisation for the hydraulic model is shown in Plate 1: Overview of the model schematisation for the Temple Sowerby to Appleby scheme.

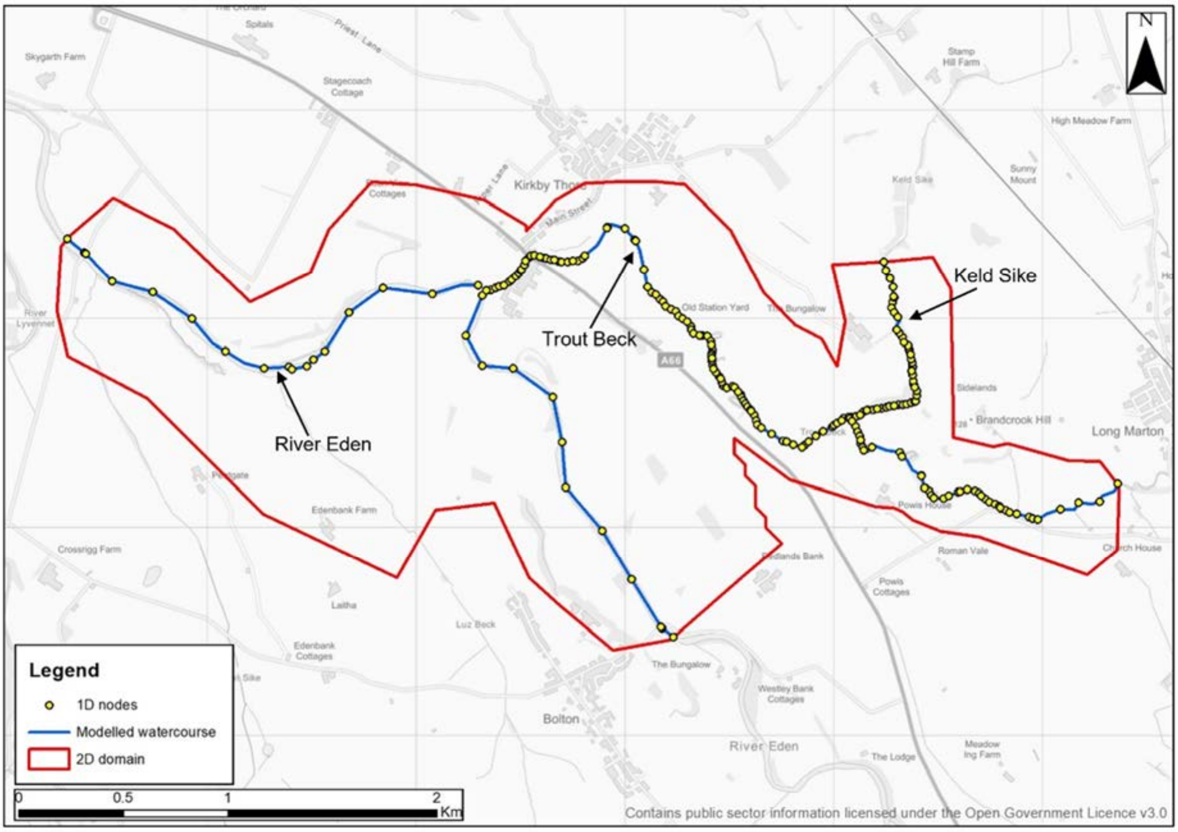


Plate 1: Overview of the model schematisation for the Temple Sowerby to Appleby scheme

1D model development

14.9.2.9 The modelled length of the River Eden, Trout Beck and Keld Sike in the study area is approximately 4.5km, 4.3km and 1.1km respectively and these were modelled in the 1D Flood Modeller domain. The channel system was constructed using cross-section survey (ref: X-2020s1208-01 collected by Maltby's, 2021) for the River Eden, and cross-section surveys for Trout Beck and Keld Sike (see ES Appendix 14.2: Flood Risk Assessment and Outline Drainage Strategy (Application Document 3.2)). Where both hard bed and soft bed (silt) levels were surveyed, hard bed levels have been used to inform channel dimensions. The surveyed cross-sections were trimmed to bank top to allow the floodplain to be represented in the 2D model domain.

14.9.2.10 Within the 1D domain there are 13 structures comprising of bridges, culverts and weirs. The majority of the structures are modelled as surveyed. At some culverts, only the upstream face was surveyed and therefore the downstream invert level was assumed to give a proportionate reduction in elevation from the upstream level, in line with the gradient of the reach.

14.9.2.11 The downstream boundary of the 1D model takes the form of a Normal-Depth (ND) boundary, where a gradient of 0.0016 has been applied, representing the gradient of the lower reach of the model.

14.9.2.12 The values for channel roughness were based on photographs gathered by Maltby's and JBA during the survey collection. Manning's 'n' values in the floodplain were set to represent the different land uses within the modelling extent. Land uses were defined using OS mapping and satellite imagery. The values used in the 1D and 2D domains are shown in Table 1: Manning's n values.

Table 1: Manning's n values

Features	Manning's n value
Buildings	0.300
Water	0.045
Woodland	0.090
Rail	0.045
Roads and Tracks	0.035
General surface	0.060
Greenspace	0.060
Default roughness	0.050

2D model development

14.9.2.13 To represent the topography within the 2D model domain, 1m LiDAR data (digital terrain model (DTM)) (dated 2020) was obtained from the Environment Agency's survey open data website. This was used to inform bank levels for the study area apart from where 1D cross sections are present, in which case bank levels were informed using channel survey data. The 2D model domain uses a 2m grid size which covers an area of approximately 6.3km^2.

14.9.2.14 Several topographic modifications were made to the DTM using the z-shape/line functions in TUFLOW. These aim to improve representation of channel banks and flow/spillways within the 2D domain.

14.9.2.15 In the 2D domain, a stage-flow (HQ) boundary line based on the floodplain slope was used across the downstream boundary line of the model to allow water to leave the model domain without glass-walling.

Hydrological inflows

14.9.2.16 The locations of the Flow Estimation Points (FEP) are shown in Plate 2: FEP locations. Flow-Time boundary units were applied to the model to represent the inflows to the River Eden, Trout Beck and Keld Sike. Lateral inflows were also applied to various nodes within the model to represent intervening catchments. In addition, several sweetener flows have been added in various locations to aid model stability. Effort has been made to keep these sweetener flows as low as possible.

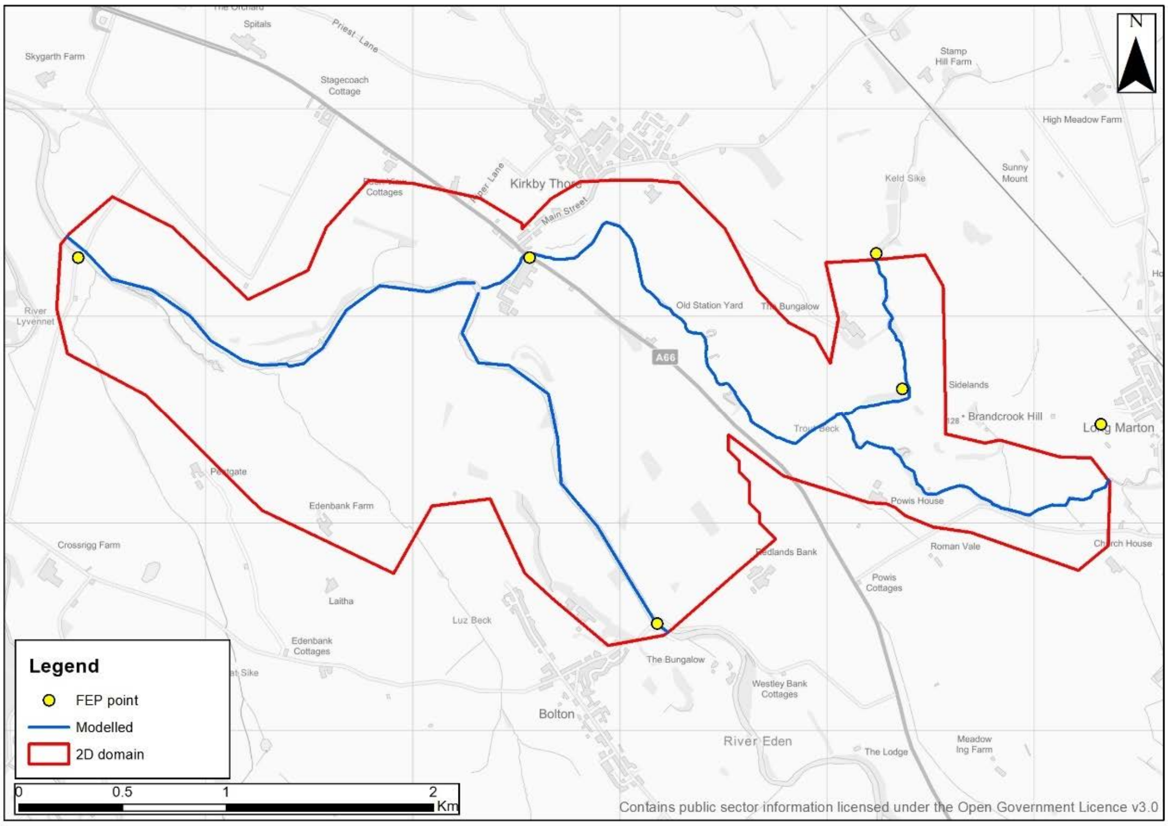


Plate 2: FEP locations

14.9.2.17 To ensure appropriate flows were generated along Trout Beck and River Eden, a joint probability analysis was carried out. Table 2: Joint probability analysis shows the combination of events recommended for both River Eden and Trout Beck dominated events and events suitable for the geomorphological assessment.

Table 2: Joint probability analysis

River Eden	Trout Beck	Storm duration
River Eden dominating events		
20yr	2yr	10.5
100yr	20yr	10.5
100yrCC94	20yrCC94	10.5
100yrCC61	20yrCC61	10.5
100yrCC47	20yrCC47	10.5
1000yr	100yr	10.5
20yr	2yr	10.5
Trout Beck dominating events		
2yr	20yr	4.5
20ry	100yr	4.5
20yrCC94	100yrCC94	4.5
20yrCC61	100yrCC61	4.5

River Eden	Trout Beck	Storm duration
20yrCC47	100yrCC47	4.5
100yr	1000yr	4.5
20yrCC94	20yr	4.5
Geomorphology simulations		
2yr	20y	4.5
2yr	10yr	4.5
2yr	2y	4.5

Flood defences

14.9.2.18 It is understood that there is a flood defence along the right bank of Trout Beck, upstream of the existing A66 and is shown in Plate 3: Flood defence location on Trout Beck. This was included in the model using a Z-line and Z-points to enforce the height of the defence. The height of the flood defences has been derived from survey data collected by JBA Consulting site surveyors.

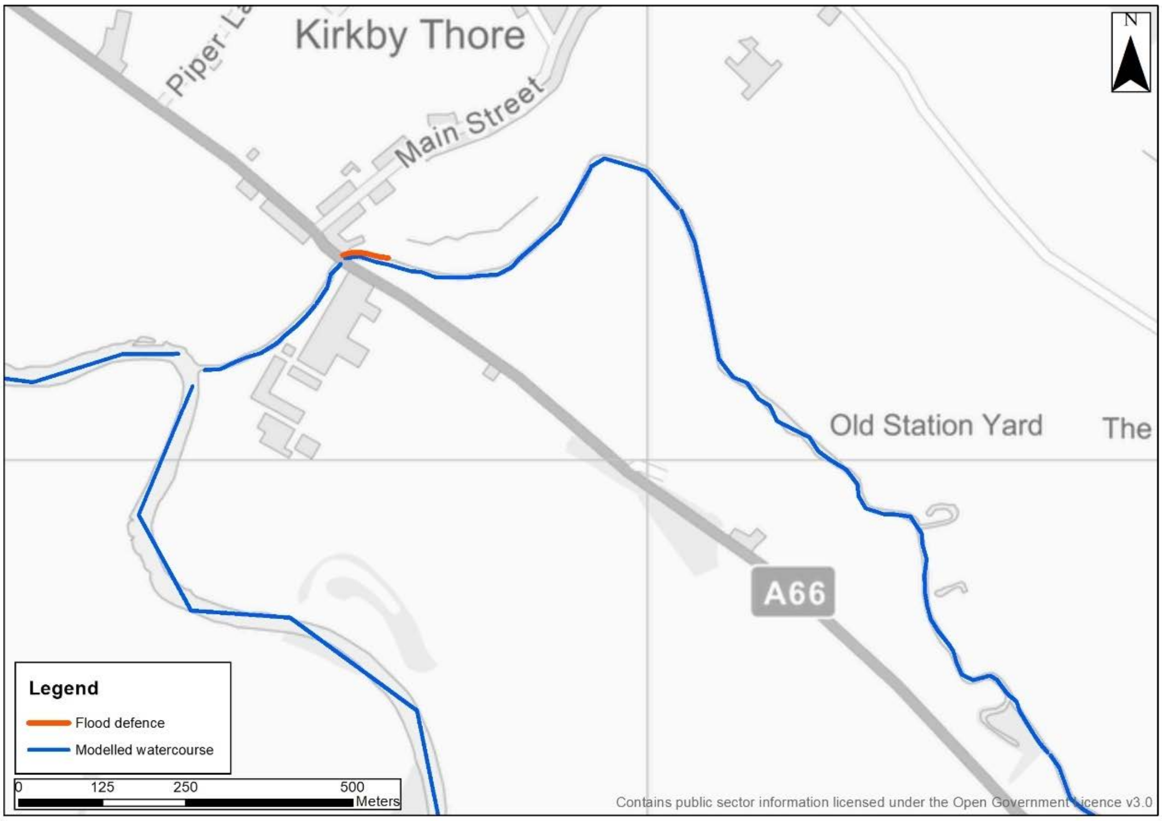


Plate 3: Flood defence location on Trout Beck

Model proving

14.9.2.19 Formal calibration of the hydraulic model could not be completed as there was no relevant gauge data available. Therefore, model verification took place in the form of sensibility checking the model outlines to the Environment Agency flood zones.

14.9.2.20 A comparison of the modelled 1% Annual Exceedance Period (AEP) events, for both the River Eden and Trout Beck dominated events, with Environment Agency Flood Zone 3 is shown on Plate 4: Comparison of 1% AEP event outlines with Environment Agency Flood Zone 3.

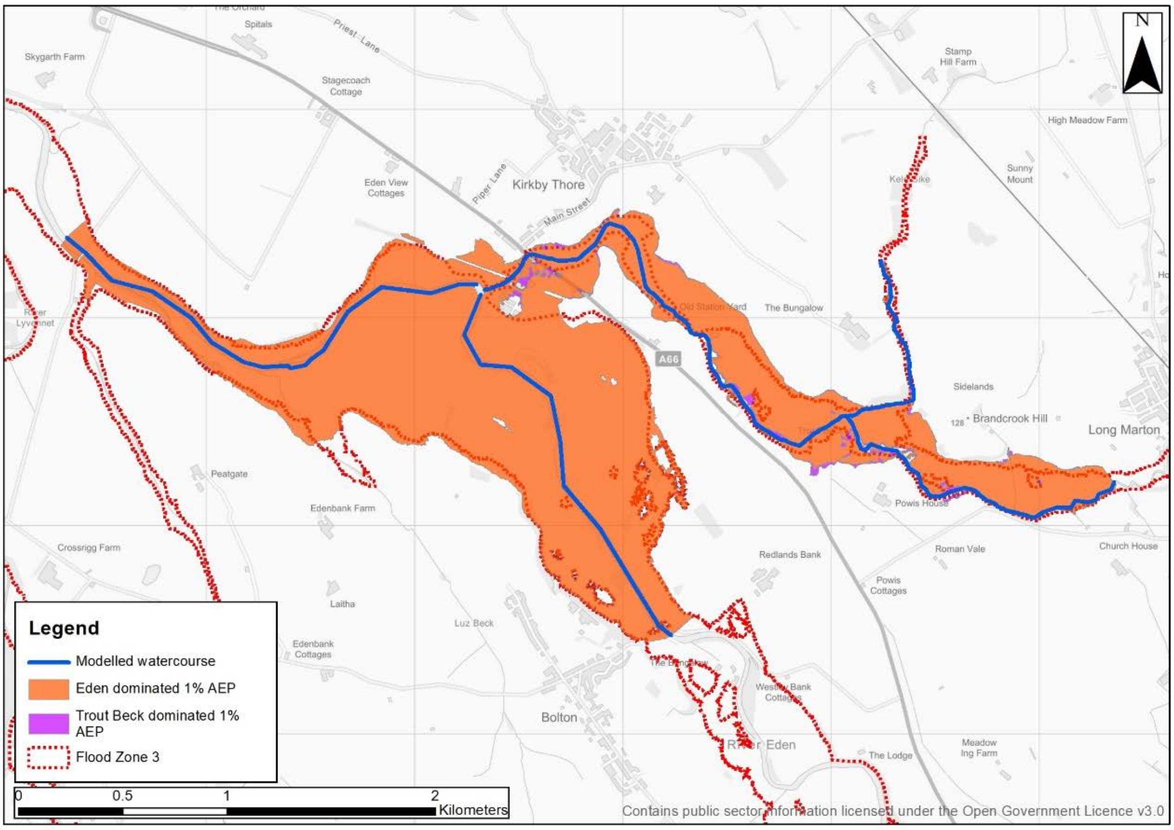


Plate 4: Comparison of 1% AEP event outlines with Environment Agency Flood Zone 3

14.9.2.21 Plate 4: Comparison of 1% AEP event outlines with Environment Agency Flood Zone 3 shows that the modelled 1% AEP event outline matches well with Flood Zone 3 along the River Eden, but there are some differences along Trout Beck where the modelled outline covers a larger area than Flood Zone 3. This is particularly true in the area of the River Eden/Trout Beck confluence.

Hydraulic modelling - scheme alignment

14.9.2.22 The model schematisation for the scheme alignment is shown in Plate 5: Scheme alignment relative to the model extents.

14.9.2.23 The proposed alignment was modelled in the 2D domain using 2D Flow Constriction Polygons to represent the obstructions within the floodplain caused by the viaduct piers. As the viaduct soffit levels were designed to be a minimum of 600mm above the 1% AEP with climate change flood level, there was no need to include the viaduct deck in the model. The main alignment embankment, a flood plain attenuation pond and ditches on the flood plain were included within the model using a DTM.

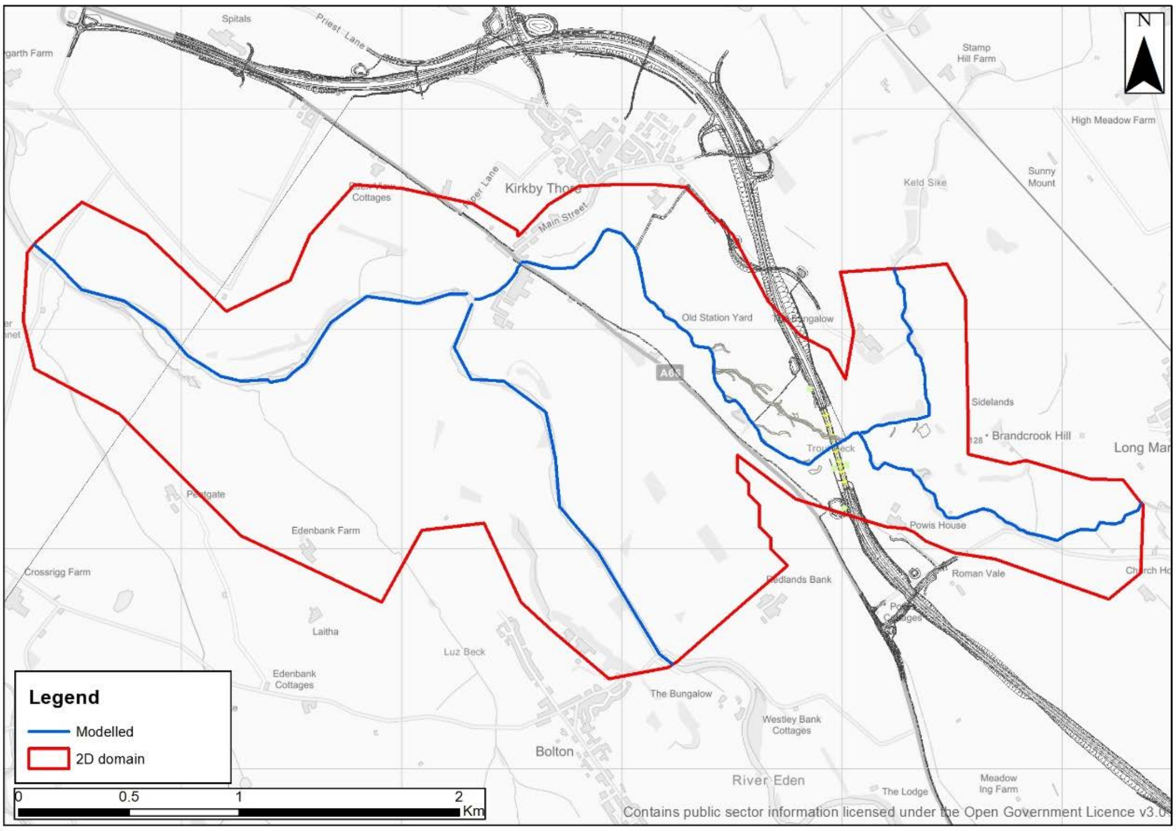


Plate 5: Scheme alignment relative to the model extents

Model runs

14.9.2.24 The following flood scenarios were simulated:

- [Baseline Scenario] –River Eden 20-year (5% AEP) / Trout Beck 2-year (50% AEP) flood event
- [Baseline Scenario] – River Eden 100-year (1% AEP) / Trout Beck 20-year (5% AEP) flood event
- [Baseline Scenario] – River Eden 100-year (1% AEP) with (+94%) climate change / Trout Beck 20-year (5% AEP) with (+94%) climate change flood event
- [Baseline Scenario] – River Eden 100-year (1% AEP) with (+61%) climate change / Trout Beck 20-year (5% AEP) with (+61%) climate change flood event
- [Baseline Scenario] – River Eden 100-year (1% AEP) with (+47%) climate change / Trout Beck 20-year (5% AEP) with (+47%) climate change flood event
- [Baseline Scenario] – River Eden 1000-year (0.1% AEP) / Trout Beck 100-year (1% AEP) flood event
- [Baseline Scenario] – River Eden 2-year (50% AEP) / Trout Beck 20-year (5% AEP) flood event
- [Baseline Scenario] – River Eden 20-year (5% AEP) / Trout Beck 100-year (1% AEP) flood event

- [Baseline Scenario] – River Eden 20-year (5% AEP) with (+94%) climate change / Trout Beck 100-year (1% AEP) with (+94%) climate change flood event
- [Baseline Scenario] – River Eden 20-year (5% AEP) with (+61%) climate change / Trout Beck 100-year (1% AEP) with (+61%) climate change flood event
- [Baseline Scenario] – River Eden 20-year (5% AEP) with (+47%) climate change / Trout Beck 100-year (1% AEP) with (+47%) climate change flood event
- [Baseline Scenario] – River Eden 100-year (1% AEP) / Trout Beck 1000-year (0.1% AEP) flood event
- [Baseline Scenario] – River Eden 2-year (50% AEP) / Trout Beck 10-year (10% AEP) flood event
- [Baseline Scenario] – River Eden 2-year (50% AEP) / Trout Beck 2-year (50% AEP) flood event
- [Scheme 4/5 Scenario] – River Eden 2-year (50% AEP) / Trout Beck 2-year (50% AEP) flood event
- [Scheme 4/5 Scenario] – River Eden 2-year (50% AEP) / Trout Beck 10-year (10% AEP) flood event
- [Scheme 4/5 Scenario] – River Eden 2-year (50% AEP) / Trout Beck 20-year (5% AEP) flood event
- [Scheme 4/5 Scenario] – River Eden 20-year (5% AEP) with (+94%) climate change / Trout Beck 100-year (1% AEP) with (+94%) climate change flood event

Desk-based assessment

Overview

14.9.2.25 This section presents the findings of a geomorphology assessment of Trout Beck and Keld Sike. The geomorphology assessment has been carried out to support the analysis of the scheme.

14.9.2.26 The assessment uses information gathered from desk-based resources (LiDAR, historic Ordnance Survey (OS) maps, and literature, etc.) to provide an understanding of local geomorphological controls influenced by catchment characteristics.

Wider catchment characteristics

14.9.2.27 Trout Beck is located in Eden District, Cumbria where it rises at Murton Fell, to the North of the village of Murton. Trout Beck flows in a generally north-westerly direction towards Kirkby Thore, where it ultimately discharges into the River Eden. Three tributaries discharge into Trout Beck, including the Burthwaite Beck, which rises at Narrowgate Beacon to the north-west of Keisley and joins Trout Beck at Brampton, the Swindale Beck, which rises at Knock Fell to the north of Knock and joins Trout Beck at Broom, and the Keld Sike, which rises at Marton Moor and joins Trout Beck to the west of Long Marton. Trout Beck flows through rural landscapes, where land use is dominated by livestock, arable farming and isolated areas of woodland. The most notable settlements in the vicinity of Trout Beck include Kirkby Thore, Long Marton and Broom.

14.9.2.28 The bedrock geology of Trout Beck is varied, with a complex system of limestone, mudstone and slate formations occupying the headwaters of Trout Beck at Murton Fell. Downstream of Murton to the confluence with the River Eden, the bedrock geology is dominated by the Penrith Sandstone Formation. In terms of superficial deposits, Trout Beck flows over a mixture of silt sands and gravels.

Historic trend analysis

14.9.2.29 Historic OS mapping has been used to examine the extent of historic channel change across Trout Beck. The planform of Trout Beck in 1897 and 1957 has been compared to the current planform to identify areas of channel migration and realignment. The mapping from 1897 is the earliest OS mapping available. The 1897 and 1957 planforms have been overlaid on top of current OS mapping of the study area in Plate 6: Assessment of historic planform change on Trout Beck. Three areas of interest have been selected for discussion in this section, based on a prevalence, or lack, of historic planform change. The areas of interest have been marked with black circles in Plate 6: Assessment of historic planform change on Trout Beck.

14.9.2.30 In Area 1, the channel planform has remained the same since at least 1897, as the historic planforms of Trout Beck derived from the 1897 and 1957 historic OS mapping are the same as the existing channel planform. The channel planform through Area 1 is very straight and lacks natural meander bends or sinuosity. As such, it is probable that the channel planform has been artificially modified and straightened in the past. The evidence presented in Plate 6: Assessment of historic planform change on Trout Beck suggests that this channel modification occurred before 1897, before the earliest available historic OS mapping records available online.

14.9.2.31 In Area 2, historic mapping reveals that the channel sinuosity has reduced over time. The 1897 historic planform passes through a number of palaeo channels identified on the left and right bank floodplain. By 1957, all three of the palaeo channels are no longer connected to Trout Beck, and the channel sinuosity significantly decreases as a result. The channel planform of 1957 largely follows the present-day planform of Trout Beck. It is suspected that the meanders have been lost due to anthropogenic modification (i.e. straightening) rather than a natural process of meander cut-through and channel migration. The channel straightening has resulted in channel incision as the river used the excess energy, generated by the shortening of the planform and increase in its gradient, to cut down into its river bed. This process of incision has left the palaeo channels isolated and raised above the existing bed level, creating the floodplain features that are observed at present.

14.9.2.32 In Area 3, an old mill leet was previously connected to Trout Beck upstream of the A66 bridge. Observed in both the 1897 and 1957 historic OS mapping, the mill leet previously entered the right bank floodplain of Trout Beck at the location of the disused weir (as indicated on Plate 6: Assessment of historic planform change on Trout Beck). The mill leet continued for approximately 450m before re-joining Trout Beck directly downstream of the A66 bridge. This mill leet previously serviced a mill located on the right bank of Trout Beck directly upstream of the A66 road bridge (as indicated on Plate 6: Assessment of historic planform change on Trout Beck). The mill leet is no longer connected to Trout Beck, the mill is no longer active and only remnants of the weir still exist today, suggesting that all three features were removed between 1957 and the present day.

Analysis of LiDAR data

14.9.2.33 1m resolution LiDAR data has been analysed to examine historic geomorphological processes and function on Trout Beck, to improve understanding of Trout Beck’s current conditions and to support the above findings. 1m LiDAR data across the study extent is presented in Plate 7: Analysis of LiDAR data and floodplain features on Trout Beck. The six areas of interest shown circled in red are discussed.

14.9.2.34 A number of palaeo channels have been identified on the right bank floodplain adjacent to the existing channel planform in Area 1. This suggests the planform of Trout Beck previously meandered across the open floodplain to the right of the existing planform, and that channel sinuosity throughout this area was greater than the current level of sinuosity. The palaeo channels on the right bank floodplain are no longer connected to the main channel and sit at a higher level on the floodplain than the existing level of Trout Beck. It is likely that channel planform modification has occurred in this area in an attempt to maintain the agricultural land available on the right bank floodplain and keep the channel to the left of the valley. As such, channel sinuosity has been reduced, increasing the gradient of the river and focusing more of the channel energy on the riverbed. This has encouraged bed incision in this reach and has gradually led to the palaeo channels on the floodplain becoming disconnected from the channel and subsequently isolated.

14.9.2.35 In Area 2, the left bank floodplain of Trout Beck contains a number of visible palaeo channels. The presence of these palaeo channels adjacent to the artificially straightened reach of Trout Beck provides further evidence that historically this reach was significantly more sinuous. It is highly likely that the channel previously cut across the left bank floodplain and contained a number of meanders typical of an active river system. Modification of the channel through this reach has since reduced channel sinuosity and increased the gradient of the river. As such, bed incision in this reach has gradually led to a reduction in bed elevations, and the palaeo channels on the left bank floodplain remain disconnected above the main channel.

14.9.2.36 In Area 3, the right bank floodplain of Trout Beck contains a complex series of palaeo channels across a wide area of the floodplain. The visibility of many of these palaeo channels is poor in the LiDAR, suggesting that the palaeo channels are comparatively older than those observed in Area 2. The floodplain elevation in the vicinity of Area 3 is approximately 1m lower than the floodplain elevation in the vicinity of the existing channel in Area 2. The existing channel is therefore perched above the natural valley bottom, due to the historic realignment and straightening that has taken place. It is likely that Trout Beck previously meandered freely across the right bank floodplain in the space between the A66 to the south and the area of high ground to the north. The detailed network of palaeo channels suggests that the river system through this area may have been a multi-threaded, braided system. The catchment has been adjusting to non-glacial conditions following the end of the last glaciation. During this transition period, a large volume of sediment would have been available in the catchment as the glaciers retreated. This would have provided suitable conditions for Trout Beck to adopt a braided or multi-threaded channel planform in some reaches.

14.9.2.37 A comparison of palaeo channels has been undertaken in Areas 4 and 5. The palaeo channel identified in Area 4 appears much more defined and clearer compared to the palaeo channels identified in Area 5. The difference in definition between these two palaeo channels is a direct function of their age. As identified in the historic trend analysis, it has been confirmed that the palaeo channel in Area 4 formed part of Trout Beck channel planform between 1897 and 1957, and subsequently became disconnected from the channel between 1957 and the present day. The palaeo channel identified in Area 5 is not observed to be part of Trout Beck planform in the 1897 historic mapping, and as such must pre-date 1897.

14.9.2.38 The mill leet previously identified in the historic trend analysis is visible in the LiDAR data, identified in Area 6 on the right bank floodplain of Trout Beck.

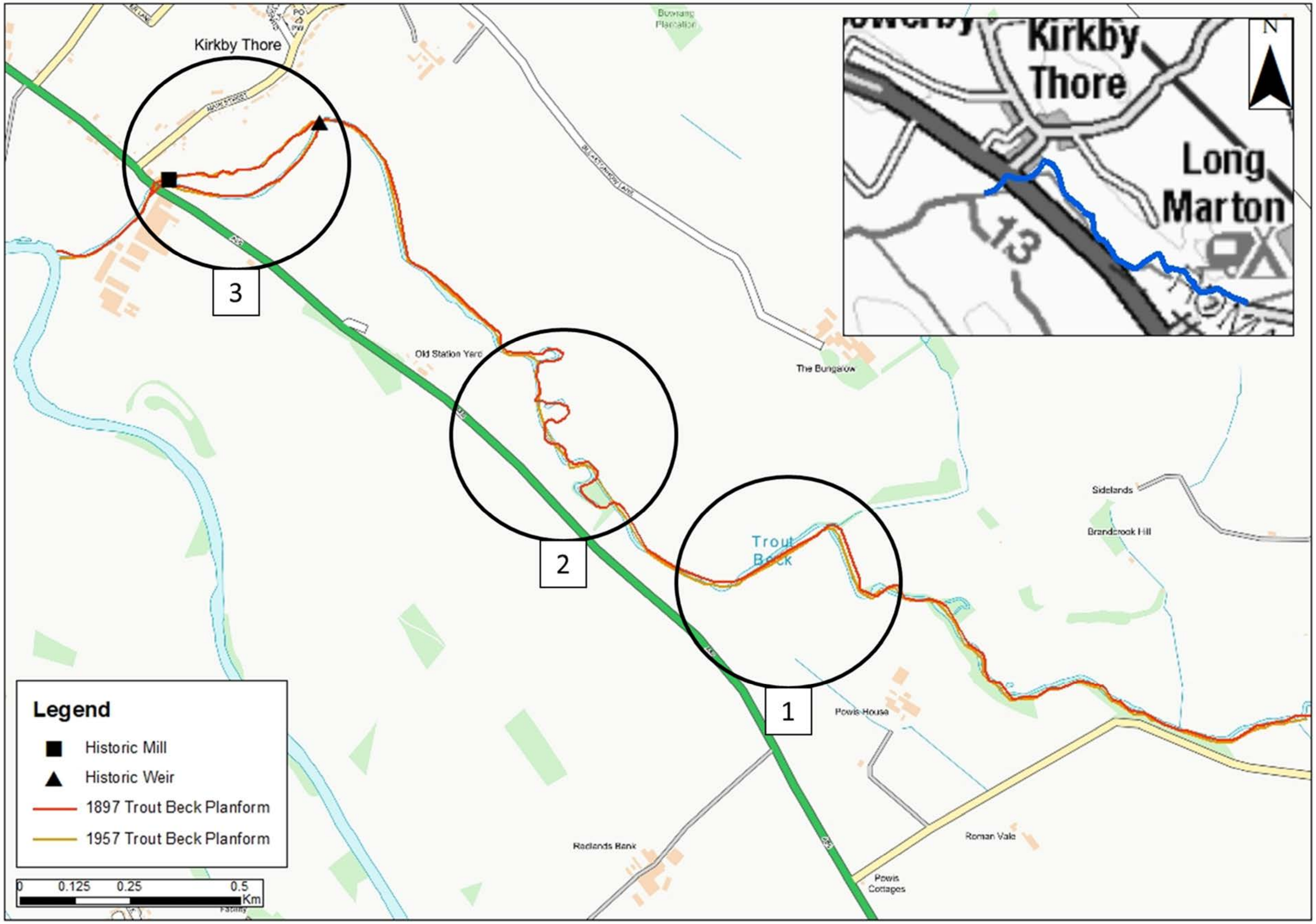

Kirkby Thore
Old Station Yard
The Bungalow
Trout Beck
Sidelands
Brandsrook Hill
Powis House
Roman Vale
Radlands Bank
Powis Cottages
3
2
1
Legend
Historic Mill
Historic Weir
1897 Trout Beck Planform
1957 Trout Beck Planform
0 0.125 0.25 0.5 Km
Kirkby Thore
Long Marton
N

Plate 6: Assessment of historic planform change on Trout Beck

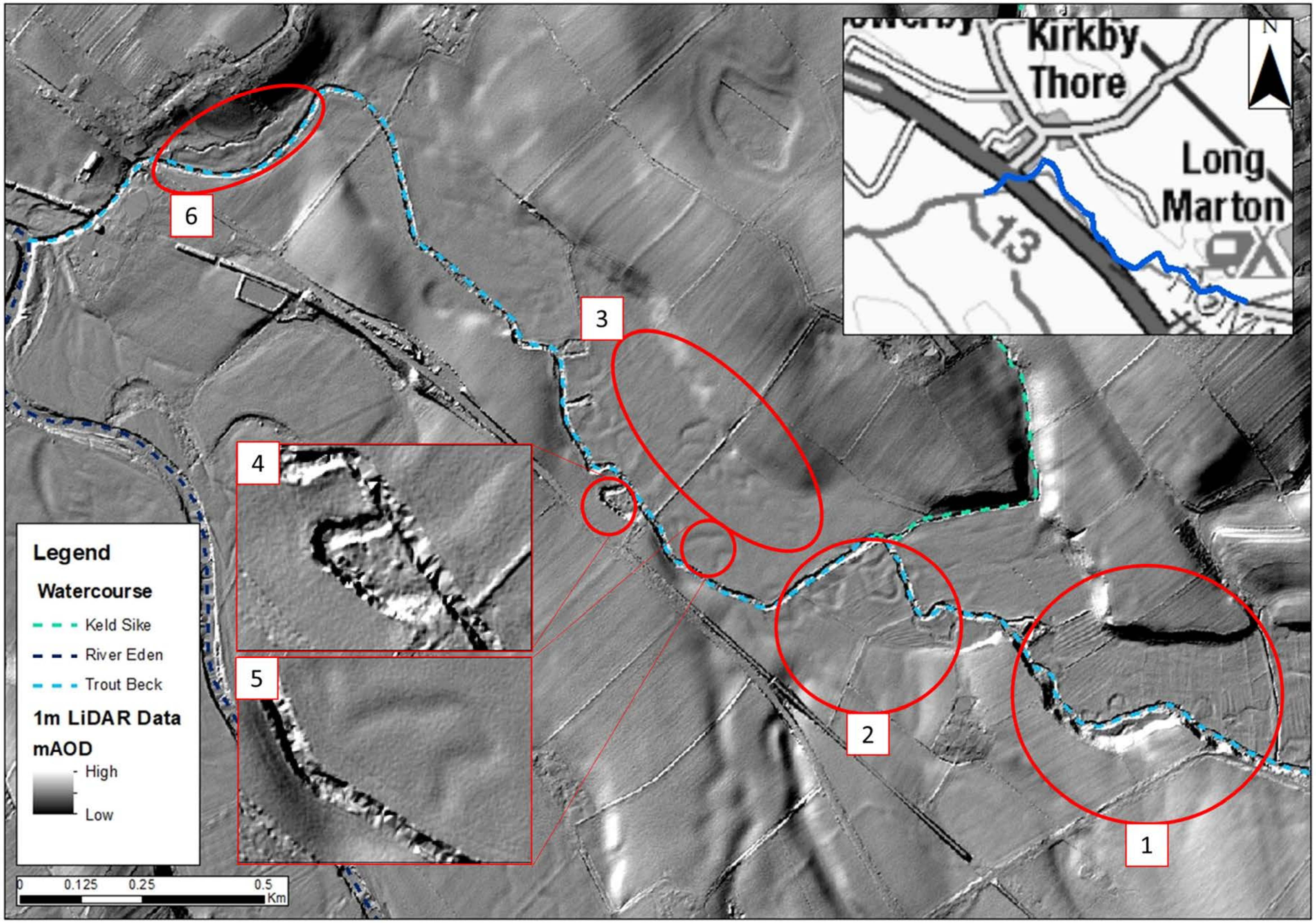


Plate 7: Analysis of LiDAR data and floodplain features on Trout Beck

Site-based assessment

Overview

14.9.2.39 To support the desk-based assessment, a site visit was conducted between 5 May 2021 and 7 May 2021 to gain a comprehensive understanding of morphological processes occurring within the vicinity of Trout Beck, Keld Sike and the River Eden where the proposed road crossing is located. The walkover extent of Trout Beck and Keld Sike is shown in Plate 8: Walkover extent and reaches of Trout Beck.

14.9.2.40 The Trout Beck has been divided into eight distinct reaches, each characterised by variations in morphological function and processes. The extent of these reaches is also highlighted in Plate 8: Walkover extent and reaches of Trout Beck.

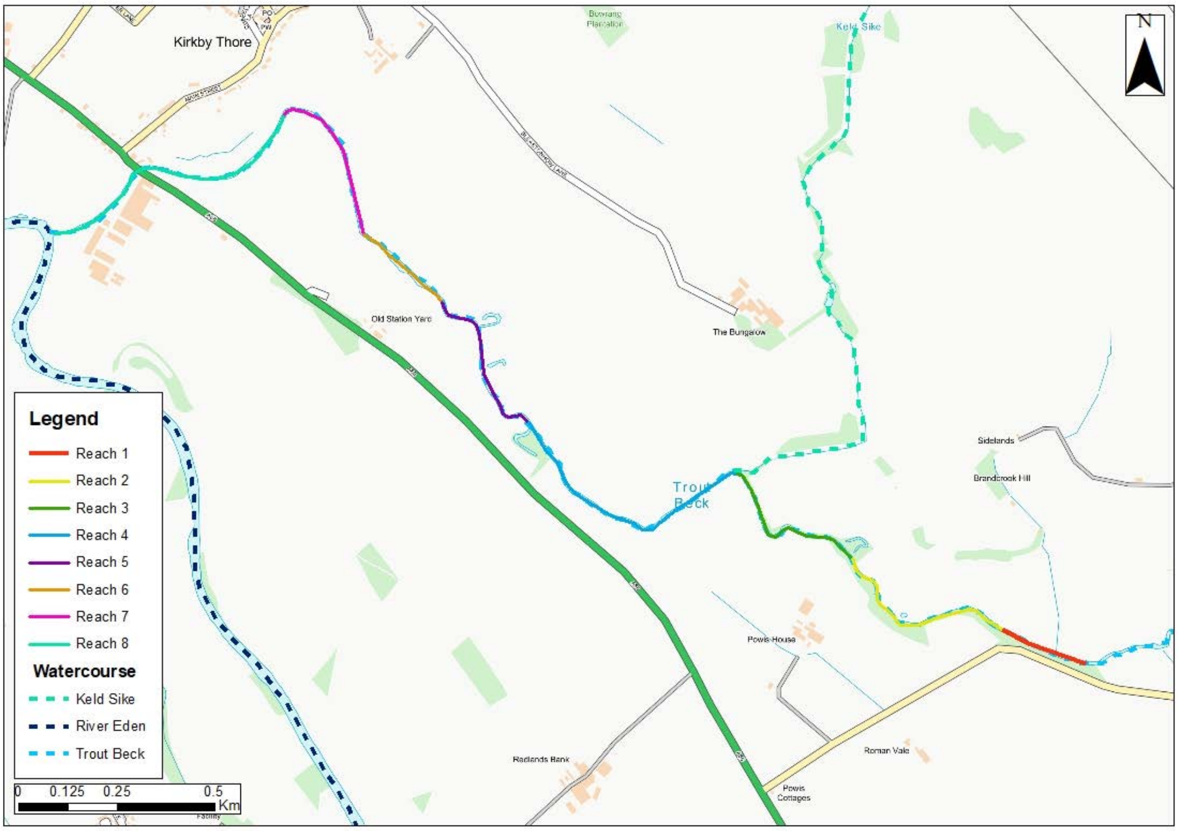


Plate 8: Walkover extent and reaches of Trout Beck

14.9.2.41 The Keld Sike has been divided into two distinct reaches, and the extent of these reaches is highlighted in Plate 9: Walkover extent and reaches of Keld Sike.

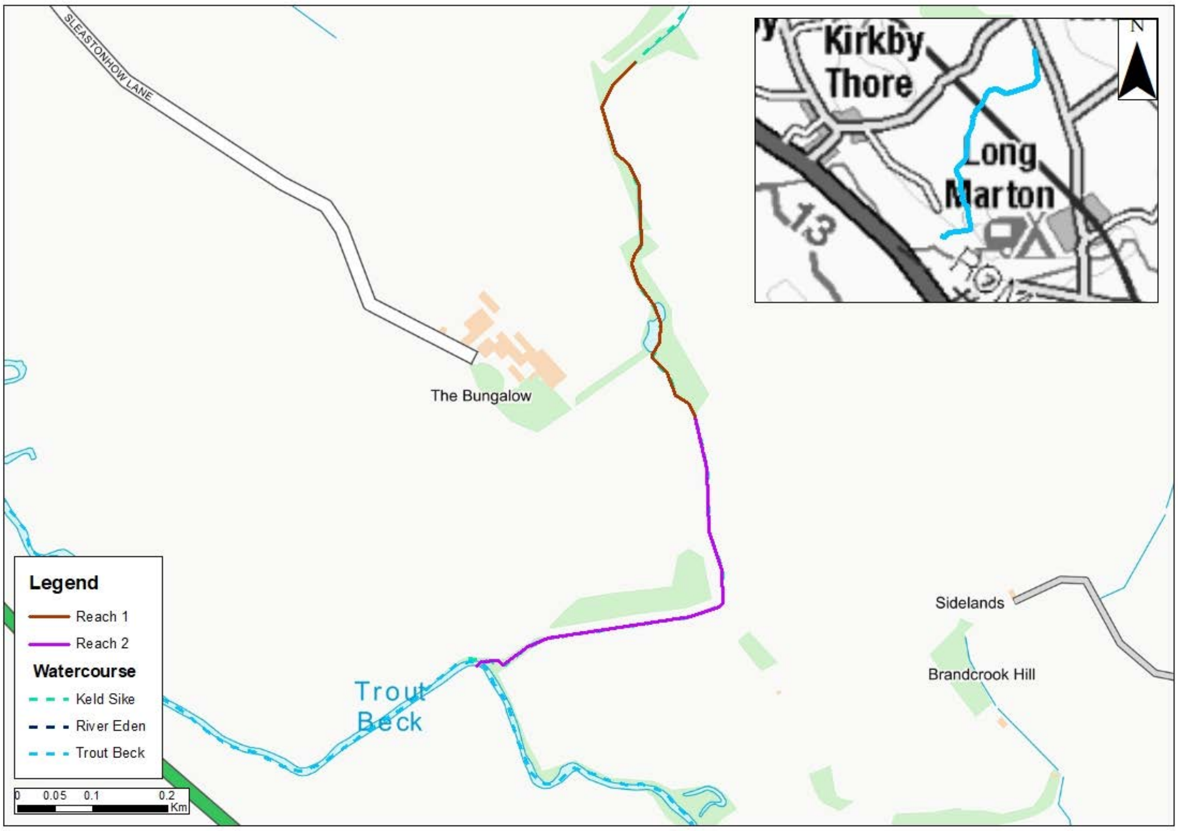


Plate 9: Walkover extent and reaches of Keld Sike

Trout Beck Reach 1

14.9.2.42 Plate 10: Map of flow biotopes within Trout Beck Reach 1, Plate -11: Map of observed bank erosion pressures within Trout Beck Reach 1, Plate 12: Map of bank modifications within Trout Beck Reach 1 and Plate 13: Map of the dominant bed substrate type within Trout Beck Reach 1 provide an overview of the morphological characteristics observed on site, including flow biotopes, bank erosion pressures, bank modifications and typical bed substrate in Reach 1.

14.9.2.43 Photographs of the reach are presented in Plate 98: Location of photos taken during the survey of Trout Beck Reach 1 in Annex A: Temple Sowerby to Appleby site photographs.

14.9.2.44 The river is confined against high ground on the left bank in Reach 1, and consequently, the relief of the left bank is steep between the road and the riverbank (Photo 1, Plate 98: Location of photos taken during the survey of Trout Beck Reach 1). The water column is relatively clear and devoid of suspended fine sediment, facilitating observations of the riverbed substrate and bedforms.

14.9.2.45 The steep gradient of the watercourse through this reach combined with the straight channel planform provides the river with high flow energy, which is sufficient to mobilise fine material such as silts and sands, and re-work coarser bed material such as gravels and cobbles. The result is the development of alternating sequences of riffle / rapid and run features. During low (normal) flows, flow energy is greatest over the riffle / rapid features, with run features representing lower flow energy (Photo 2, Plate 98: Location of photos taken during the survey of Trout Beck Reach 1). River width through the reach varies between 5-7m, approximately. In locations where riffle features have developed, the bed level is higher due to the accumulation of coarse bed material, leading to reduced water depths (Photo 3, Plate 98: Location of photos taken during the survey of Trout Beck Reach 1). Divergent flows around the riffle features lead to bank erosion and subsequent widening of the channel. This pattern is confirmed by observations of bank erosion, bank slumping and cuspate-shaped erosion between riparian trees at the site of riffle features (Photo 4, Plate 98: Location of photos taken during the survey of Trout Beck Reach 1). Conversely, bed levels are lower where run features have developed, and bank erosion is less prominent.

14.9.2.46 Riparian vegetation is mixed throughout the reach. Land cover on the lower right bank is mainly agricultural with patchy riparian tree cover (Photo 5, Plate 98: Location of photos taken during the survey of Trout Beck Reach 1). This has led to the exposed earth between existing riparian trees being eroded by the watercourse and has generated the cuspate erosion observed on site. On the steep left bank, a thick buffer of tree cover occupies the space between the left bank and the road to the south (Photo 6, Plate 98: Location of photos taken during the survey of Trout Beck Reach 1.

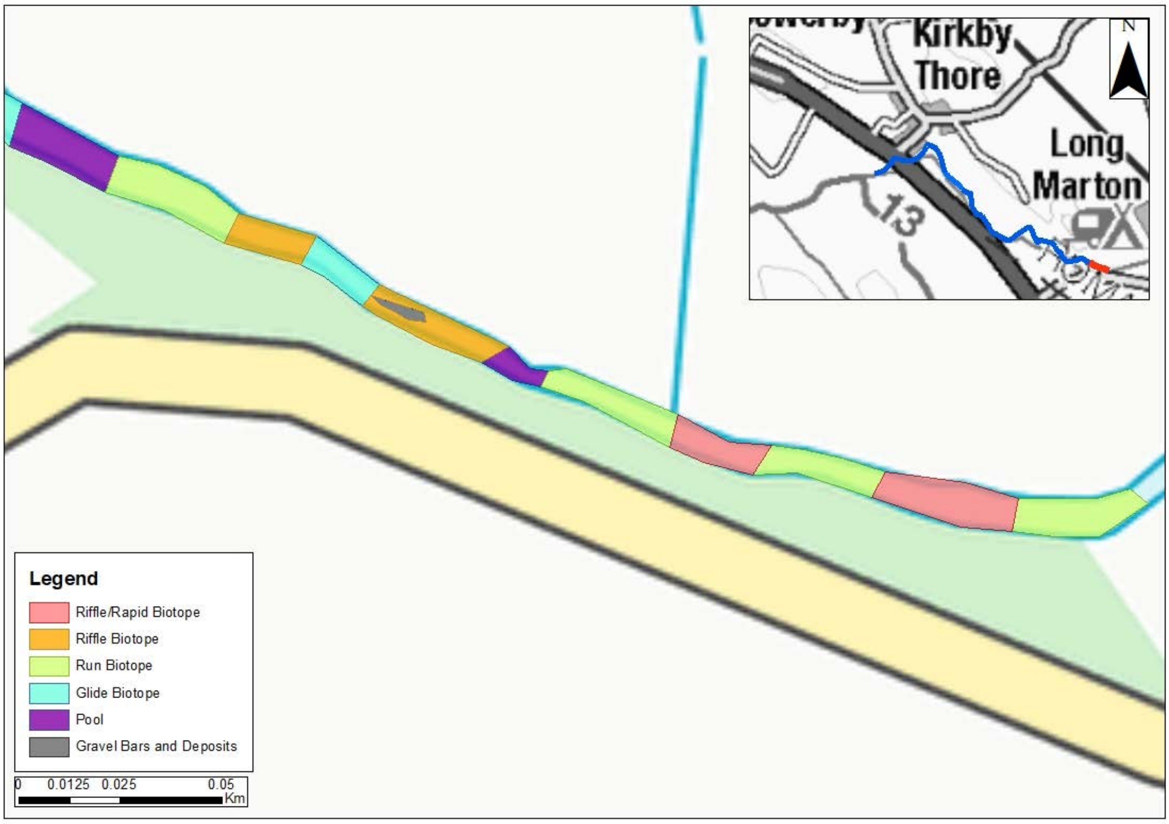


Plate 10: Map of flow biotopes within Trout Beck Reach 1

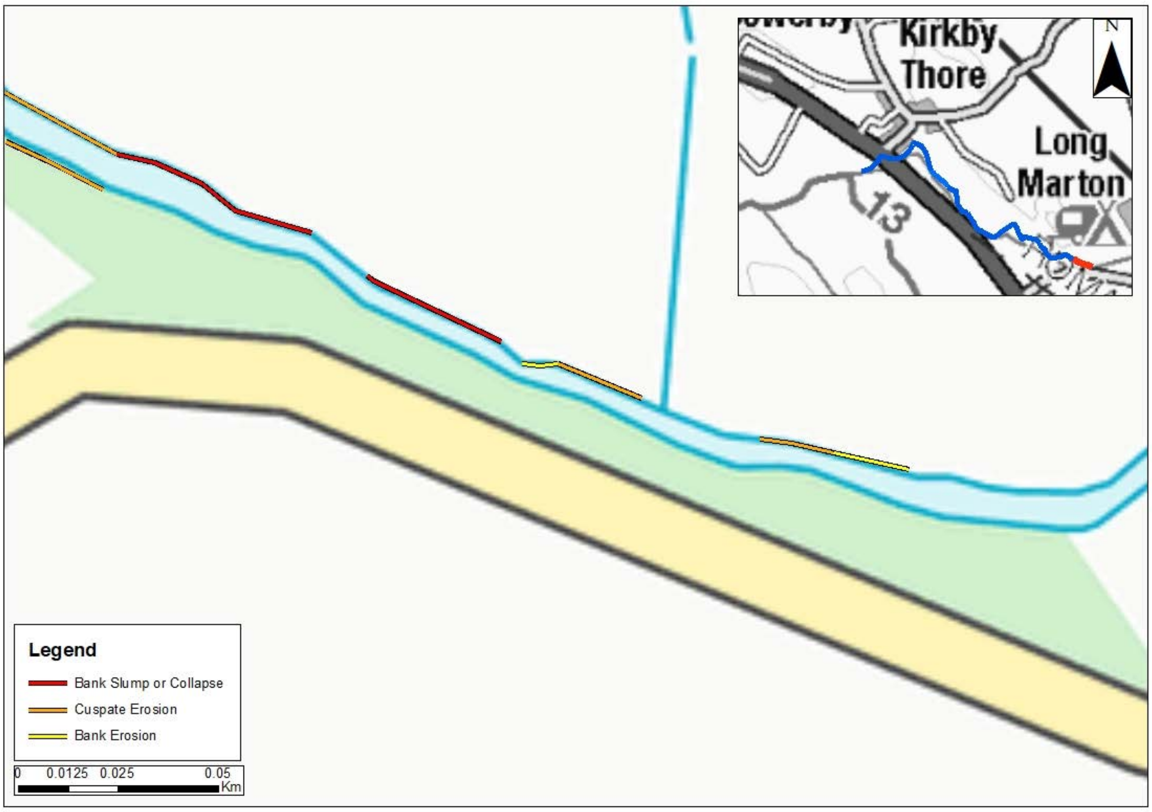


Plate -11: Map of observed bank erosion pressures within Trout Beck Reach 1

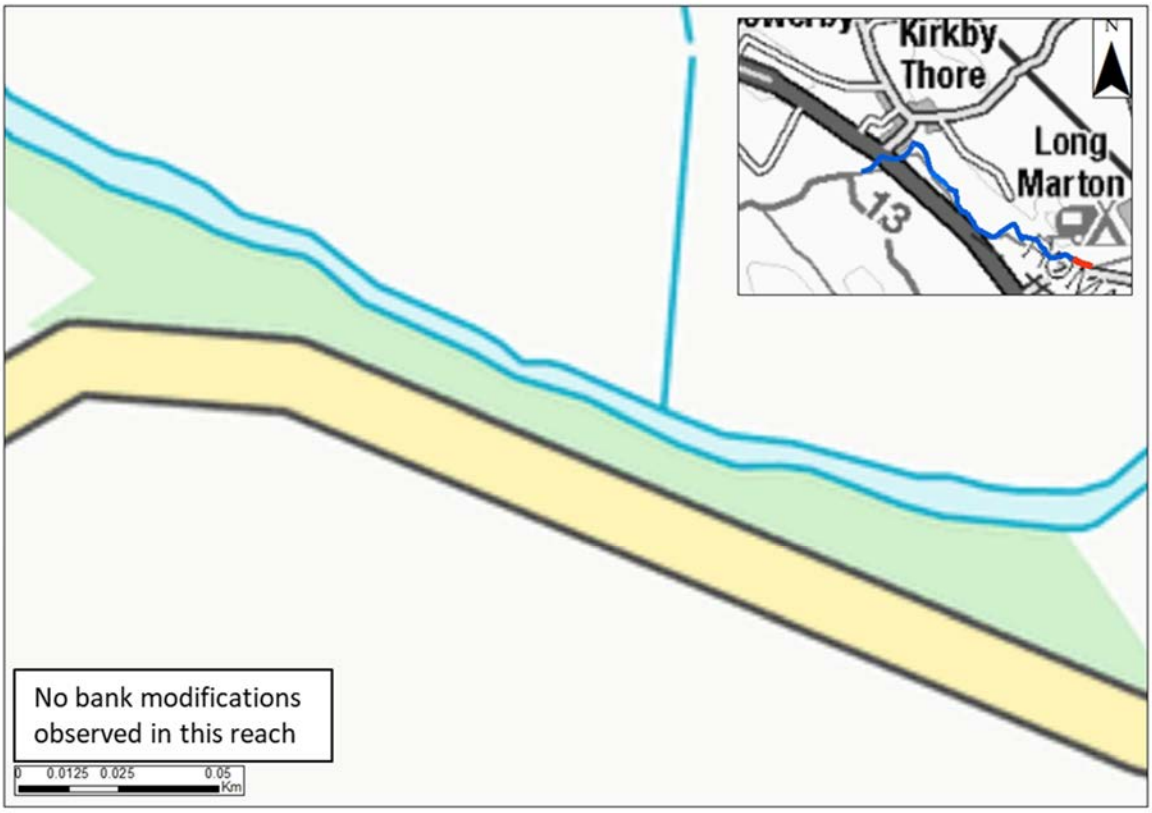


Plate 12: Map of bank modifications within Trout Beck Reach 1

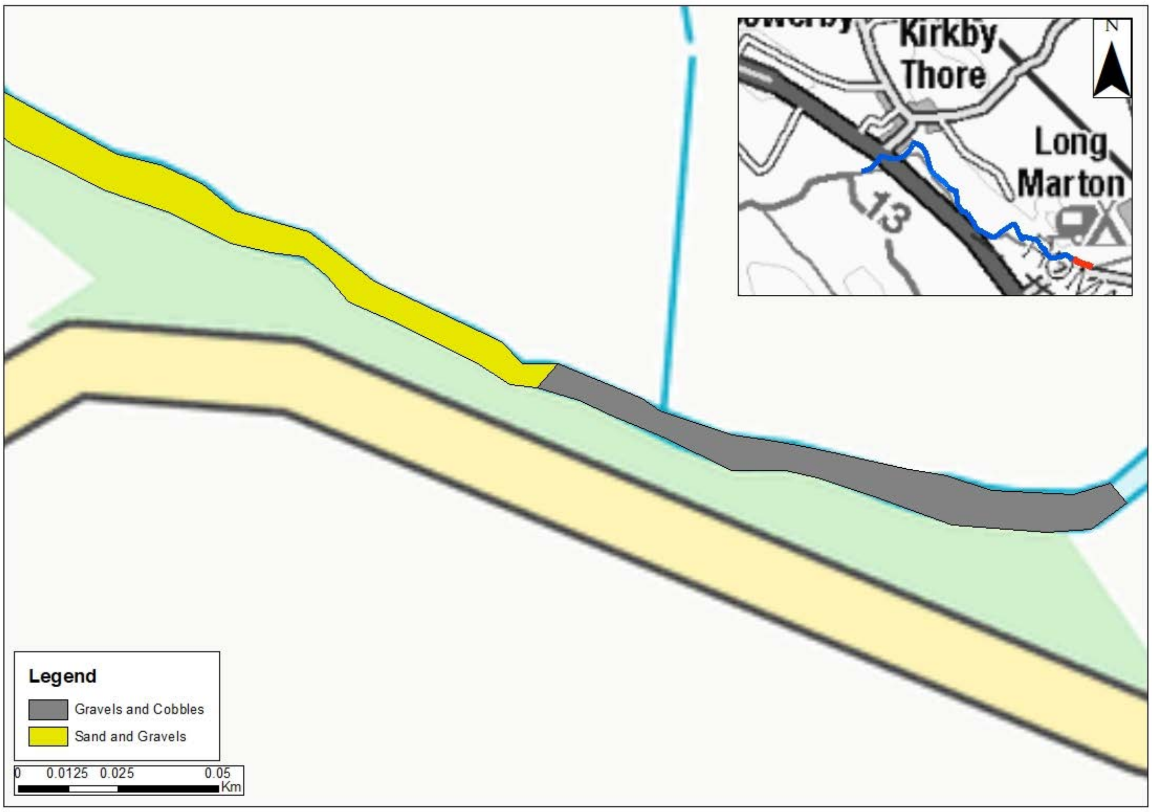


Plate 13: Map of the dominant bed substrate type within Trout Beck Reach 1

Trout Beck Reach 2

14.9.2.47 Plate 14: Map of flow biotopes within Trout Beck Reach 2, Plate 15: Map of observed bank erosion pressures within Trout Beck Reach 2, Plate 16: Map of bank modifications within Trout Beck Reach 2 and Plate 17: Map of the dominant bed substrate type within Trout Beck Reach 2 provide an overview of the morphological characteristics observed on site, including flow biotopes, bank erosion pressures, bank modifications and typical bed substrate in Reach 2.

14.9.2.48 Photographs of the reach are presented in Plate 99: Location of photos taken during the survey of Trout Beck Reach 2 in Annex A: Temple Sowerby to Appleby site photographs.

14.9.2.49 In Reach 2 the gradient, and therefore flow energy, of the channel decreases marginally. Flow biotopes associated with lower flow energy are observed such as pools and glides, with intermittent riffle features (Photo 1, Plate 99: Location of photos taken during the survey of Trout Beck Reach 2). The bed substrate transitions from predominantly sands and gravels to gravels and cobbles (Photo 2,). Depositional features comprised of coarse gravels and cobbles such as point bars and mid-channel deposits have formed. At the location of low energy areas such as pools and glides, finer material can drop out of the water column, covering the existing bed substrate with a layer of fine sediment (Photo 3, Plate 99: Location of photos taken during the survey of Trout Beck Reach 2). Despite this, very little fine material is suspended within the water column suggesting that the flow energy is still sufficient to mobilise a large volume of fine material to downstream reaches.

14.9.2.50 Riparian cover on the left bank is patchy, whereas the riparian cover on the right bank is extremely sparse to non-existent in places. The unconsolidated soil banks lack binding by tree roots and are easily eroded during high flows. The result is a continuation of cuspate erosion between riparian trees and bank slumping along both riverbanks (Photo 4 and Photo 5, Plate 99: Location of photos taken during the survey of Trout Beck Reach 2). In areas where sections of the riverbank have slumped into the channel, recirculating currents reinforce erosion patterns (Photo 6, Plate 99: Location of photos taken during the survey of Trout Beck Reach 2). Bank erosion and collapse, combined with the cattle poaching and surrounding agricultural land use has led to an increase in fine sediment in this area. Fine material is also likely to be carried by surface water flows from the surrounding agricultural fields and transported into the river. The low riverbank stability coupled with a lack of valley confinement has enabled the channel planform to adopt a more sinuous course compared to upstream areas; gentle meander bends were observed within this area of Trout Beck. (Photo 7, Plate 99: Location of photos taken during the survey of Trout Beck Reach 2).

14.9.2.51 The dominant flow biotope subsequently transitions to an alternating series of riffle and runs (Photo 8, Plate 99: Location of photos taken during the survey of Trout Beck Reach 2). The increase in flow energy mobilises and transports finer bed substrates such as silts and sands to downstream reaches, leaving gravels and cobbles on the riverbed (Photo 9, Plate 99: Location of photos taken during the survey of Trout Beck Reach 2). Riparian cover on the left bank improves considerably, with a thick riparian corridor of tree cover present (Photo 10, Plate 99: Location of photos taken during the survey of Trout Beck Reach 2). However, the right bank of the channel is still devoid of riparian cover, and the topsoil bank material remains unconsolidated. This has resulted in significant bank collapse on the right bank through this area (Photo 11, Plate 99: Location of photos taken during the survey of Trout Beck Reach 2).

Plate 14: Map of flow biotopes within Trout Beck Reach 2

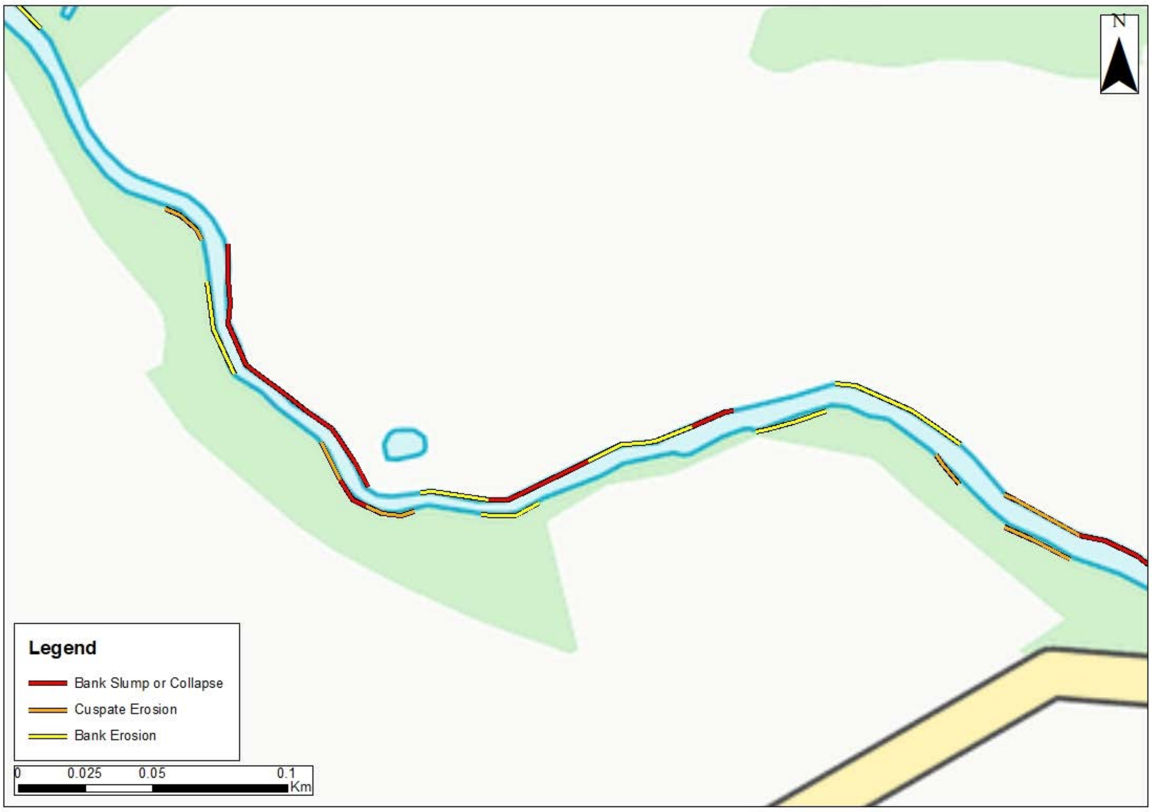


Plate 15: Map of observed bank erosion pressures within Trout Beck Reach 2

Plate 16: Map of bank modifications within Trout Beck Reach 2

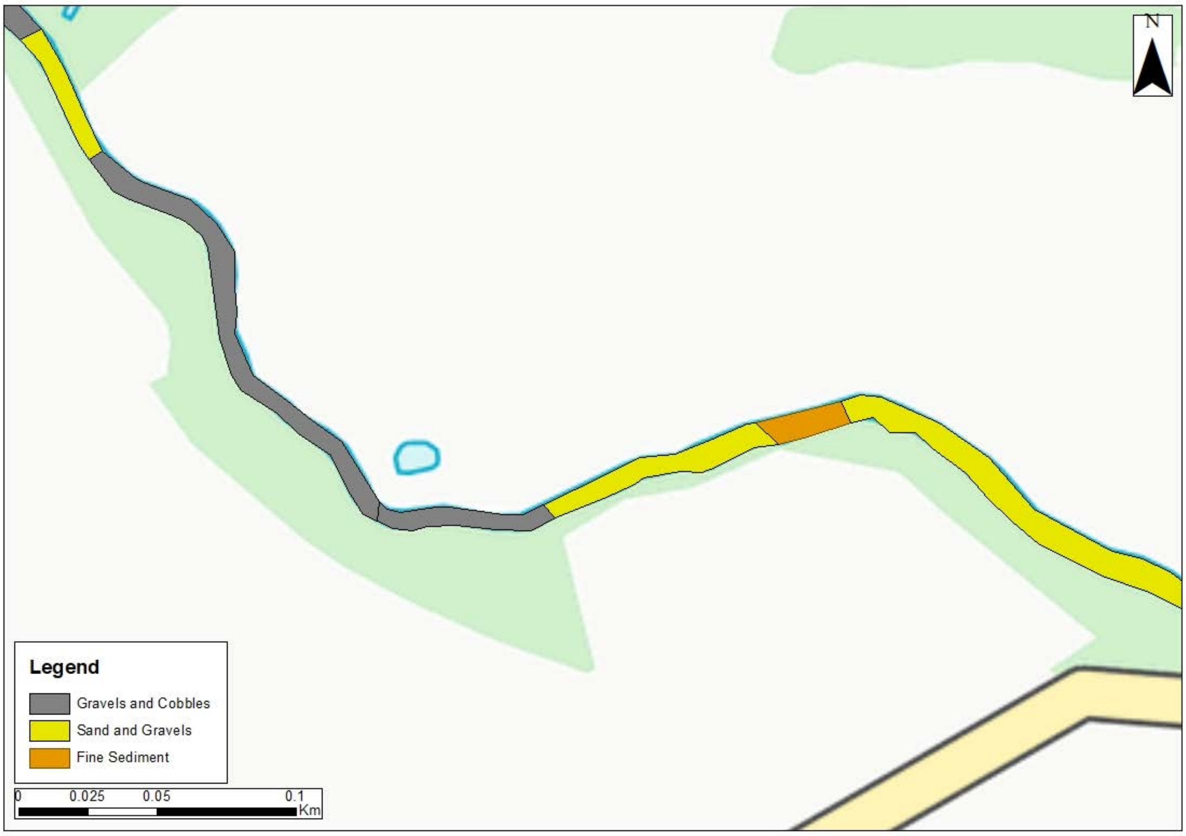


Plate 17: Map of the dominant bed substrate type within Trout Beck Reach 2

Trout Beck Reach 3

14.9.2.52 Plate 18: Map of flow biotopes within Trout Beck Reach 3, Plate 19: Map of observed bank erosion pressures within Trout Beck Reach 3, Plate 20: Map of bank modifications within Trout Beck Reach 3 and Plate 21: Map of the dominant bed substrate type within Trout Beck Reach 3 provide an overview of the morphological characteristics observed on site, including flow biotopes, bank erosion pressures, bank modifications and typical bed substrate in Reach 3.

14.9.2.53 Photographs of the reach are presented in Plate 100: Location of photos taken during the survey of Trout Beck Reach 3 in Annex A: Temple Sowerby to Appleby site photographs.

14.9.2.54 At the start of Reach 3 geomorphological complexity increases. On the right bank floodplain, a palaeo channel is creating an offline backwater region (Photo 1, Plate 100: Location of photos taken during the survey of Trout Beck Reach 3). The palaeo channel is at a higher elevation on the floodplain than the existing channel planform, indicating that Trout Beck has incised downwards over time. An agricultural drainage ditch joins the paleo channel from the northeast and discharges limited flow into it (Photo 2, Plate 100: Location of photos taken during the survey of Trout Beck Reach 3). On the day of the site visit the water within the paleo channel was stagnant, and it is likely that this backwater area is only connected to the watercourse during flood events.

14.9.2.55 In the main channel, alternating riffle, pool and run sequences return (Photo 3 and Photo 4, Plate 100: Location of photos taken during the survey of Trout Beck Reach 3). River width varies between 5 and 7 metres approximately. As seen upstream, riffles are generally associated with flow divergence and increased bank erosion. Sediment deposition occurs through the reach in the form of mid-channel gravel bars (Photo 5, Plate 100: Location of photos taken during the survey of Trout Beck Reach 3).

14.9.2.56 In the vicinity of the confluence with the Keld Sike where Reach 3 ends, large woody material is present across both Trout Beck and the Keld Sike, generating localised flow diversity (Photo 6, Plate 100: Location of photos taken during the survey of Trout Beck Reach 3). Velocities are reduced upstream of the woody material and deposition of sediment occurs (Photo 7, Plate 100: Location of photos taken during the survey of Trout Beck Reach 3). Flow diversion around the woody material focuses flow energy on the riverbanks and bed, leading to bank erosion and bed scour (Photo 8, Plate 100: Location of photos taken during the survey of Trout Beck Reach 3).

14.9.2.57 Sporadic wooden toe boards (some in a poor condition) have been observed in the vicinity of the confluence, presumably installed to limit of bank scour and channel migration (Photo 9, Plate 100: Location of photos taken during the survey of Trout Beck Reach 3). A narrow riparian corridor is present on both of the riverbanks which acts as a source of woody debris for the channel. Large volumes of coarse material have been deposited in the channel and channel margins around the confluence, leading to the formation of large riffle features, mid channel deposits and marginal deposits of gravels and cobbles (Photo 10, Plate 100: Location of photos taken during the survey of Trout Beck Reach 3). This has diverted the flow around the features, encouraging scour on both the riverbanks, and resulting in an increase in channel width at this location compared to the river further upstream.

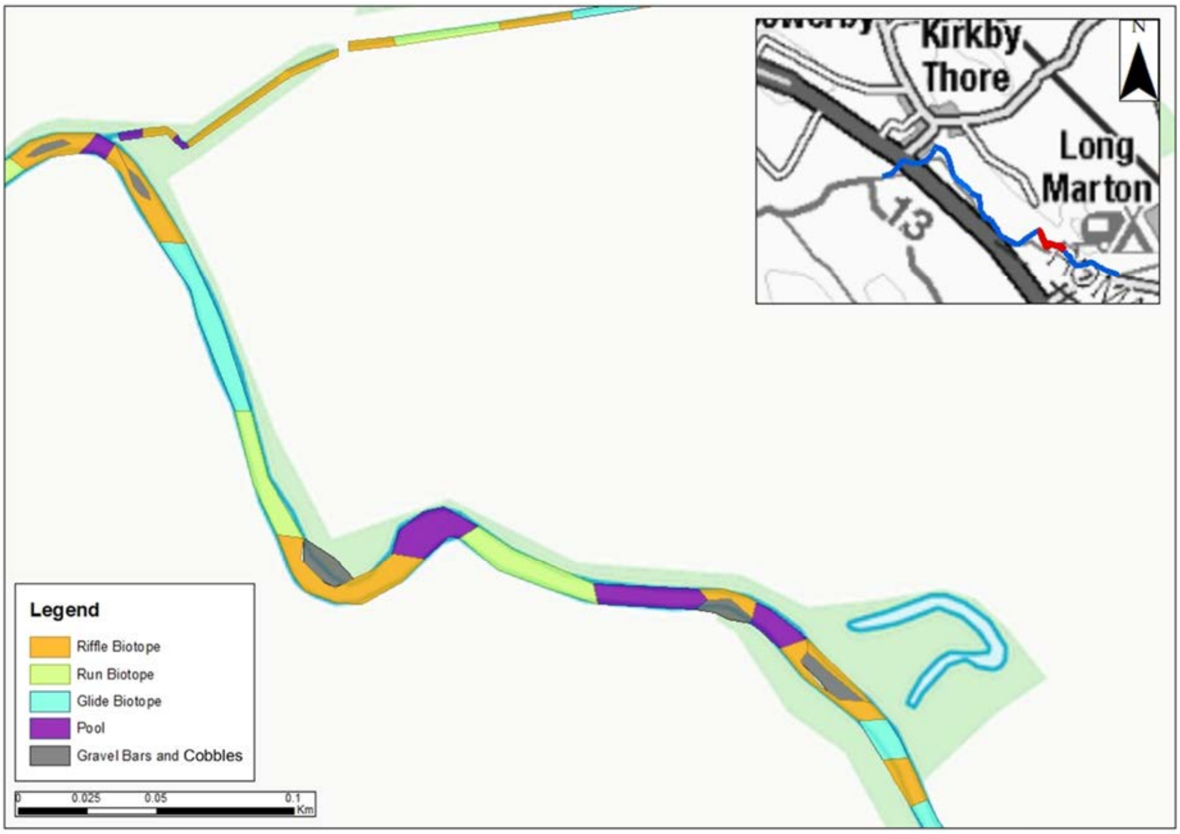


Plate 18: Map of flow biotopes within Trout Beck Reach 3

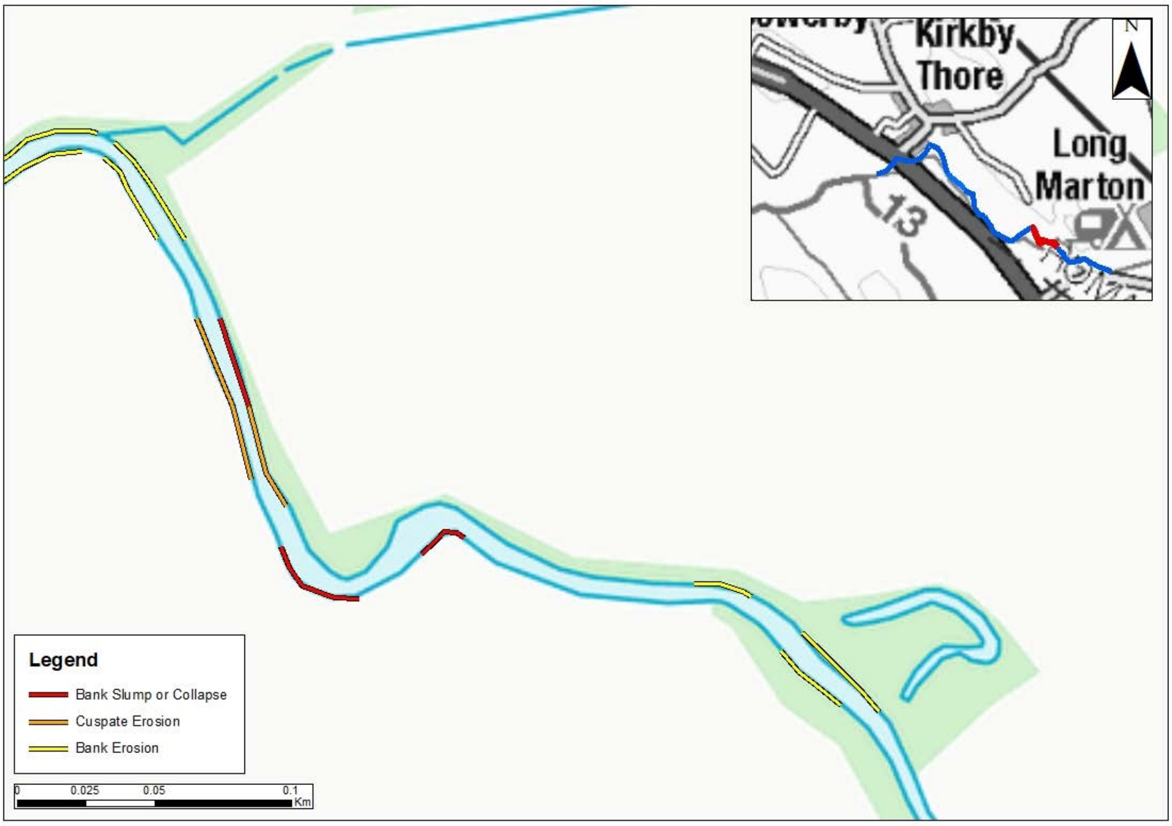


Plate 19: Map of observed bank erosion pressures within Trout Beck Reach 3

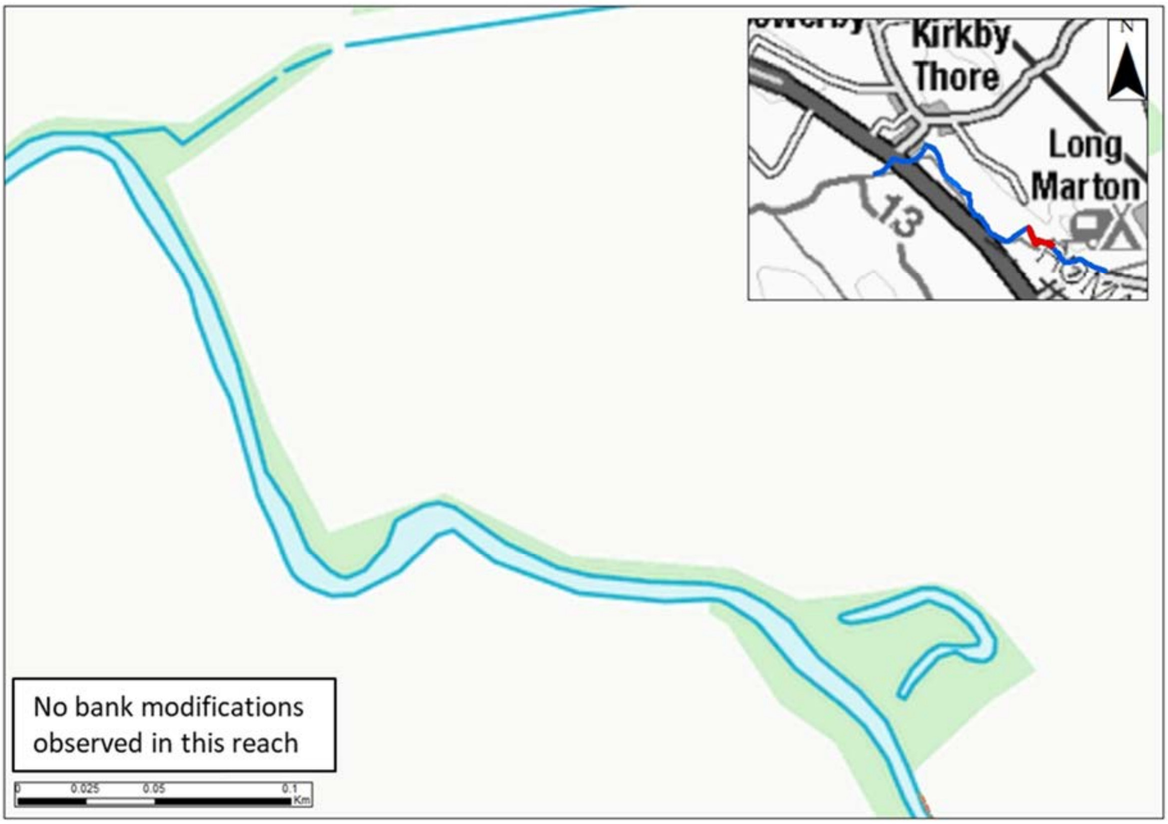


Plate 20: Map of bank modifications within Trout Beck Reach 3

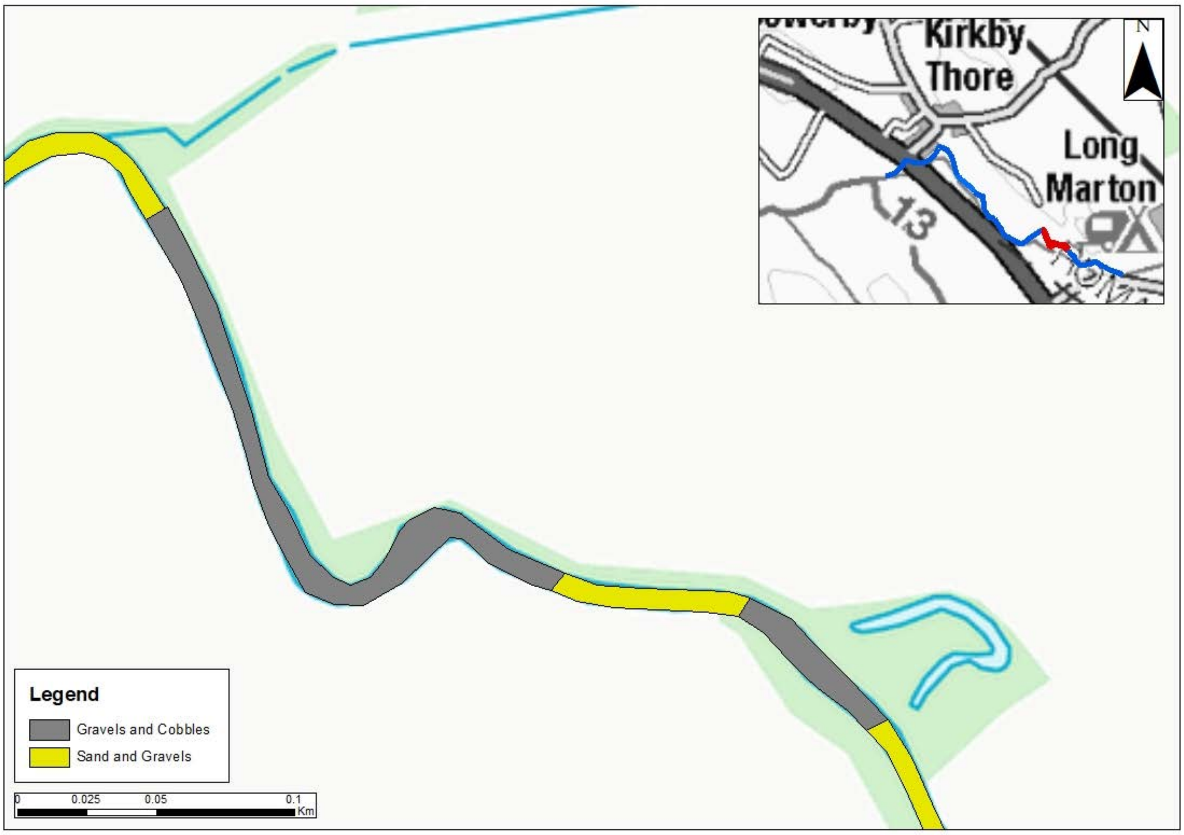


Plate 21: Map of the dominant bed substrate type within Trout Beck Reach 3

Trout Beck Reach 4

14.9.2.58 Plate 22: Map of flow biotopes within Trout Beck Reach 4, Plate 23: Map of observed bank erosion pressures within Trout Beck Reach 4, Plate 24: Map of bank modifications within Trout Beck Reach 4 and Plate 25: Map of the dominant bed substrate type within Trout Beck Reach 4 provide an overview of the morphological characteristics observed on site, including flow biotopes, bank erosion pressures, bank modifications and typical bed substrate in Reach 4.

14.9.2.59 Photographs of the reach are presented in Plate 101: Location of photos taken during the survey of Trout Beck Reach 4 in Annex A: Temple Sowerby to Appleby site photographs.

14.9.2.60 Downstream of the confluence with the Keld Sike, the planform of Trout Beck is straight for approximately 300m as a result of historic realignment (Photo 1, Plate 101: Location of photos taken during the survey of Trout Beck Reach 4). Channel straightening has resulted in a reduction in channel length and corresponding increase in channel gradient. These anthropogenic changes have increased in-channel energy, causing the river to cut down into its bed, resulting in channel incision through this reach. The floodplain is disconnected from the channel, and the tops of the riverbanks sit approximately 2m above the water level.

14.9.2.61 Riparian vegetation on both sides of the bank through this straightened area is mixed, with a thick buffer of tree cover on the left bank, but sporadic tree cover on the right bank. As such, bank stability on the left bank was substantial and the banks exhibited less signs of bank erosion. On the right bank areas of bank erosion, bank toe undercutting, and bank slumping were identified. It is likely that these erosional pressures on the riverbanks were triggered as a consequence of the channel straightening and has been further compounded by the lack of riparian vegetation (Photo 2, Plate 101: Location of photos taken during the survey of Trout Beck Reach 4). In-channel hydromorphic diversity is reduced within the straightened section compared to morphological diversity observed in upstream reaches, with a dominance of alternating run and glide biotopes.

14.9.2.62 Approximately 300m downstream of the Keld Sike confluence, Trout Beck flows to the right at a sharp right-angle and continues in a generally north-western direction (Photo 3, Plate 101: Location of photos taken during the survey of Trout Beck Reach 4). At the location of the bend the flow energy is sufficient to cause erosion on the left bank on the outside of the bend. At this location the riverbank has collapsed into the river (Photo 4, Plate 101: Location of photos taken during the survey of Trout Beck Reach 4). The bank has retreated some distance into the left bank floodplain, with the existing fence line on the riverbank now exposed and overhanging into the channel (Photo 5, Plate 101: Location of photos taken during the survey of Trout Beck Reach 4). The development of a riffle feature at this bend is further encouraging bank erosion on the outside of the bend; flow is diverted to the left and right of the riffle, focusing flow energy on the riverbanks and increasing bank erosion (Photo 6, Plate 101: Location of photos taken during the survey of Trout Beck Reach 4). Wooden toe boards have been installed on the outside of the bend directly downstream of the observed bank collapse, but the river has eroded around them and their condition is degraded (Photo 7, Plate 101: Location of photos taken during the survey of Trout Beck Reach 4).

14.9.2.63 Downstream of the bend, the historic channel realignment and straightening persists. The river has incised downwards over time and the floodplain remains disconnected from the channel (Photo 8, Plate 101: Location of photos taken during the survey of Trout Beck Reach 4), resulting in bank instability and collapse (Photo 9, Plate 101: Location of photos taken during the survey of Trout Beck Reach 4). Tree cover on both banks is sporadic, further encouraging band erosion and collapse due to the lack of binding provided by the tree roots (Photo 10, Plate 101: Location of photos taken during the survey of Trout Beck Reach 4). Wooden toe boards have been installed in an attempt to reduce toe erosion and prevent bank collapse, present within the channel sporadically over the next 300m.

14.9.2.64 An alternating sequence of riffles and runs have developed with clear water and clean gravels on the riverbed. A farm access bridge spans the watercourse at OS NGR 364598 524566. At the location of the farm access bridge the channel is overwide and very incised and the riverbanks are very step and vertical in some locations (Photo 11, Plate 101: Location of photos taken during the survey of Trout Beck Reach 4). Wooden toe boards have been placed on both banks in the vicinity of the farm access bridge in an attempt to prevent further bank erosion and collapse, although many of the observed wooden toe boards are now failing.

14.9.2.65 Downstream of the farm access bridge on the left bank floodplain a palaeo channel has created an offline backwater region (Photo 12, Plate 101: Location of photos taken during the survey of Trout Beck Reach 4). The palaeo channel is at a higher elevation on the floodplain than the existing channel planform, indicating the level of incision that has taken place. The outfall from the palaeo channel discharges into Trout Beck approximately 100m downstream of the farm access bridge. On the day of the site visit the water within the paleo channel was stagnant, and it is likely that this backwater area is only connected to the watercourse during moderate to high flood events (Photo 13 and Photo 14, Plate 101: Location of photos taken during the survey of Trout Beck Reach 4). A woodland area has developed in the vicinity of the palaeo backwater area, which has deposited a large amount of woody material into the palaeo channel itself.

14.9.2.66 'J' shaped trees lining the riverbank of Trout Beck downstream of the farm access bridge provides further evidence to support conclusions that the watercourse has undergone bed incision (Photo 15, Plate 101: Location of photos taken during the survey of Trout Beck Reach 4).

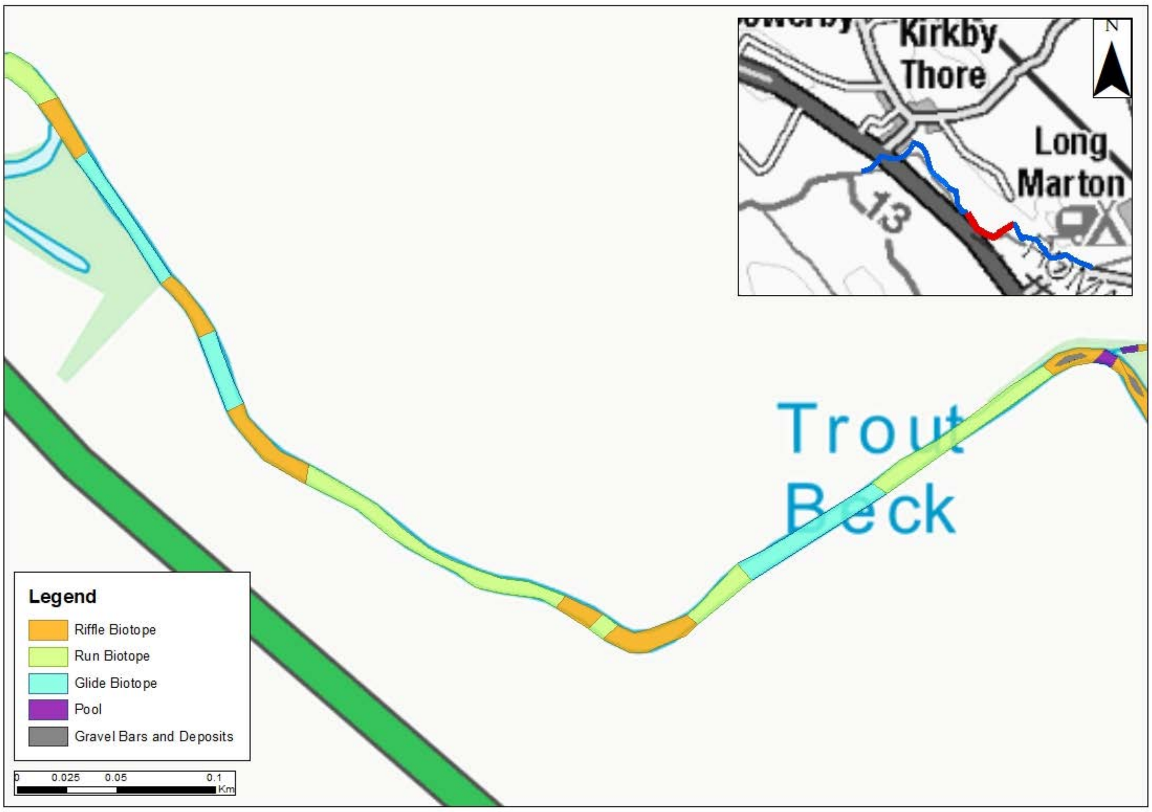


Plate 22: Map of flow biotopes within Trout Beck Reach 4

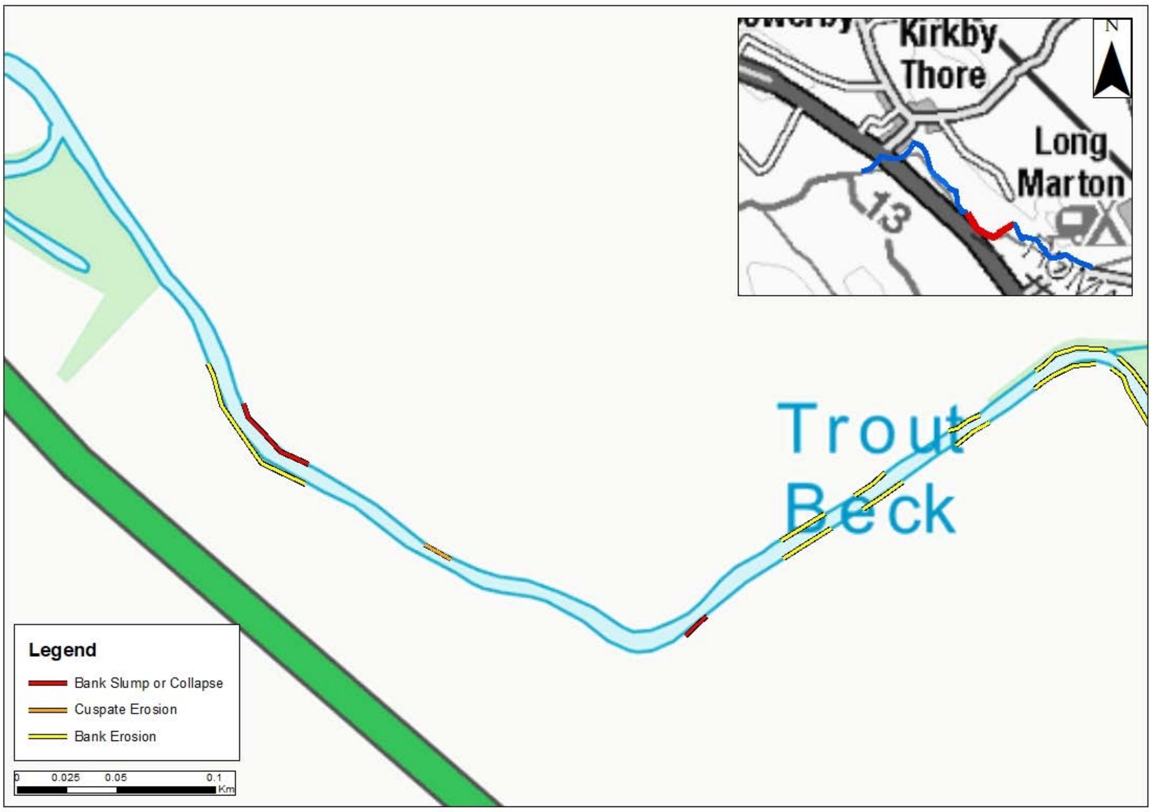


Plate 23: Map of observed bank erosion pressures within Trout Beck Reach 4

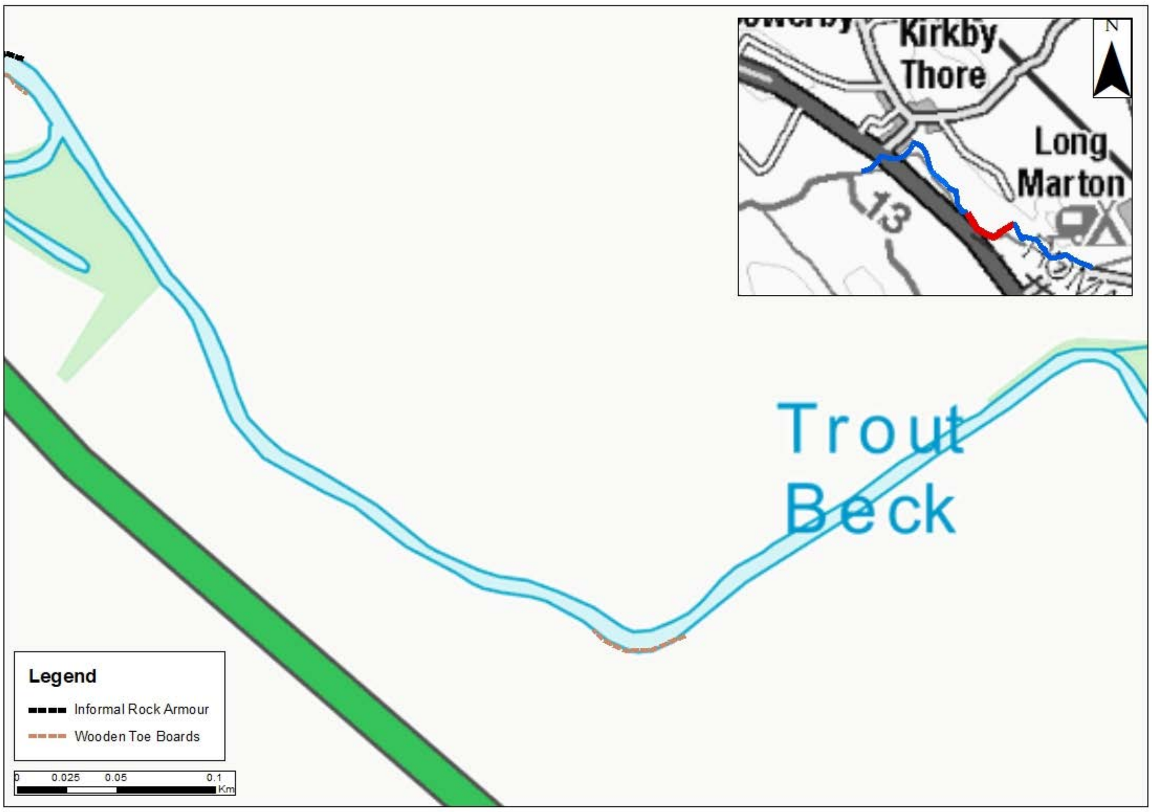


Plate 24: Map of bank modifications within Trout Beck Reach 4

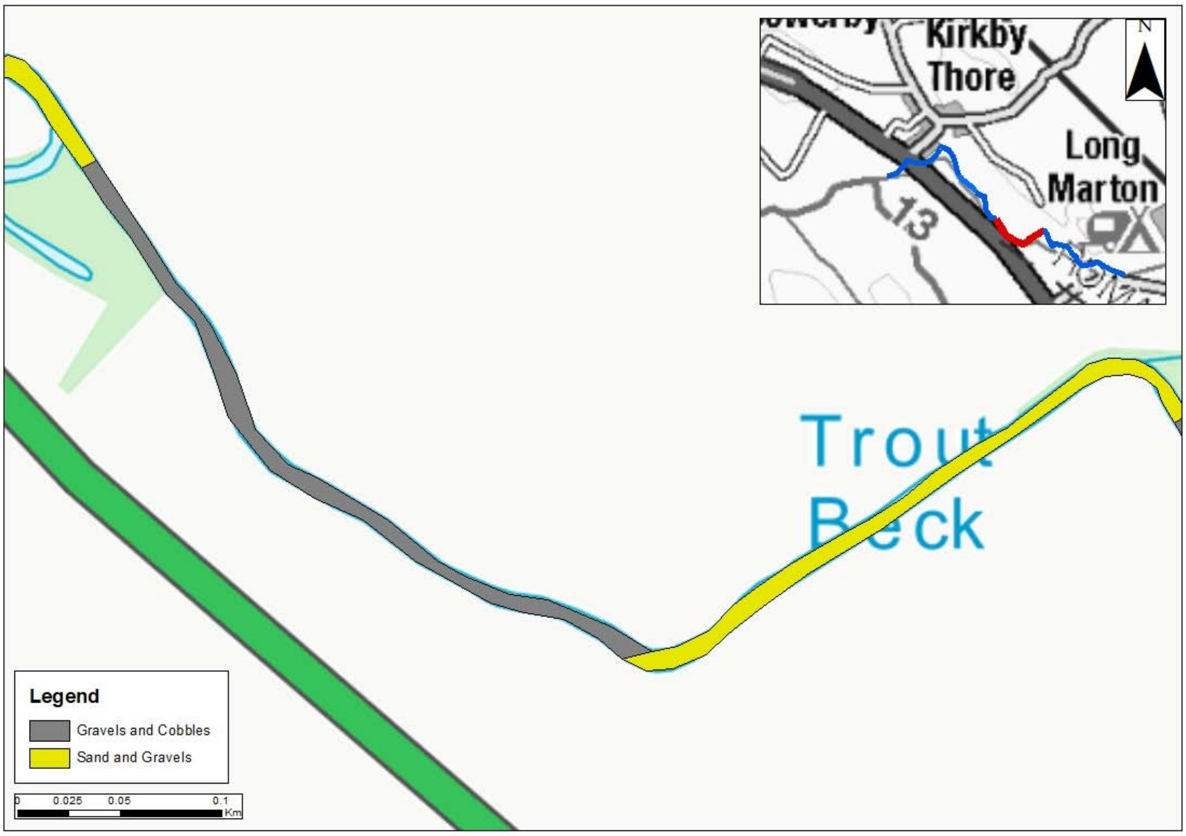


Plate 25: Map of the dominant bed substrate type within Trout Beck Reach 4

Trout Beck Reach 5

14.9.2.67 Plate 26: Map of flow biotopes within Trout Beck Reach 5, Plate 27: Map of observed bank erosion pressures within Trout Beck Reach 5, Plate 28: Map of bank modifications within Trout Beck Reach 5 and Plate 29: Map of the dominant bed substrate type within Trout Beck Reach 5 provide an overview of the morphological characteristics observed on site, including flow biotopes, bank erosion pressures, bank modifications and typical bed substrate in Reach 5.

14.9.2.68 Photographs of the reach are presented in Plate 102: Location of photos taken during the survey of Trout Beck Reach 5 in Annex A: Temple Sowerby to Appleby site photographs.

14.9.2.69 The channel sinuosity through Reach 5 increases marginally and consequently the morphological diversity of the watercourse increases (Photo 1, Plate 102: Location of photos taken during the survey of Trout Beck Reach 5). A diverse range of alternating flow biotopes has developed ranging from riffles and runs to glides (Photo 2, Photo 3 and 4, Plate 102: Location of photos taken during the survey of Trout Beck Reach 5).

14.9.2.70 Multiple locations of bank collapse are identified on both the left and right bank of the channel, which have created marginal deposits of fine soil material (Photo 5, Plate 102: Location of photos taken during the survey of Trout Beck Reach 5). In areas where the riverbanks have collapsed, the watercourse is exhibiting natural signs of recovery in response to the overwide nature of the channel. Where slumped banks have come to rest on the channel margins, this topsoil material has been colonised by marginal vegetation, leading to the retention of material in the channel margins and the gradual reduction in channel width over time (Photo 6, Plate 102: Location of photos taken during the survey of Trout Beck Reach 5).

14.9.2.71 Bank modifications such as wooden toe boards and informal rock armour have been installed sporadically throughout this reach (Photo 7, Plate 102: Location of photos taken during the survey of Trout Beck Reach 5); however, in many instances these measures are degraded.

14.9.2.72 The incised nature of Trout Beck through this reach accelerates the processes bank erosion and collapse due to the vertical nature of the banks (Photo 8 and Photo 9, Plate 102: Location of photos taken during the survey of Trout Beck Reach 5). Riparian vegetation and tree cover remains sporadic, further reducing the resistance of the banks to erosion.

14.9.2.73 Additional palaeo channels are identified on the right bank of channel (Photo 10, Plate 102: Location of photos taken during the survey of Trout Beck Reach 5). A woodland area has developed in the vicinity of both these palaeo backwater areas, which has deposited a large amount of woody material into the palaeo channel itself. The palaeo channels on the right bank cut through higher ground and remain elevated above the height of the riverbed by approximately 2-3m (Photo 11, Plate 102: Location of photos taken during the survey of Trout Beck Reach 5), indicative of the former pre-incision level of the river.

Plate 26: Map of flow biotopes within Trout Beck Reach 5

Plate 27: Map of observed bank erosion pressures within Trout Beck Reach 5

Plate 28: Map of bank modifications within Trout Beck Reach 5

Plate 29: Map of the dominant bed substrate type within Trout Beck Reach 5

Trout Beck Reach 6

14.9.2.74 Plate 30: Map of flow biotopes within Trout Beck Reach 6, Plate 31: Map of observed bank erosion pressures within Trout Beck Reach 6, Plate 32: Map of bank modifications within Trout Beck Reach 6 and Plate 33: Map of the dominant bed substrate type within Trout Beck Reach 6 provide an overview of the morphological characteristics observed on site, including flow biotopes, bank erosion pressures, bank modifications and typical bed substrate in Reach 6.

14.9.2.75 Photographs of the reach are presented in Plate 103: Location of photos taken during the survey of Trout Beck Reach 6 in Annex A: Temple Sowerby to Appleby site photographs.

14.9.2.76 The river is relatively morphologically active through Reach 6. Large riffle features spanning between 10 to 15 metres in length occur throughout the reach and are comprised of a range of sediment clasts, from sands to gravels with occasional cobbles (Photo 1, Plate 103: Location of photos taken during the survey of Trout Beck Reach 6). Sediment deposition is present in the form of mid-channel deposits (Photo 2, Plate 103: Location of photos taken during the survey of Trout Beck Reach 6). These features create flow divergence, focussing flows on both the left and right riverbanks and encouraging bank erosion (Photo 3, Plate 103: Location of photos taken during the survey of Trout Beck Reach 6). The sparsity of riparian vegetation is also enabling bank erosion processes to be widespread through the reach. In particular, areas of cuspate-shaped bank erosion were prevalent throughout this reach where bank erosion had occurred between trees (Photo 4, Plate 103: Location of photos taken during the survey of Trout Beck Reach 6). In areas where the riverbanks had collapsed, flow recirculation is occurring, which further reinforces bank erosion and bed erosion processes (Photo 5, Plate 103: Location of photos taken during the survey of Trout Beck Reach 6). These areas of cuspate-shaped erosion and recirculation of flow have encouraged the channel to develop a more sinuous planform on a local scale, with smaller meander bends occurring along the length of this reach (Photo 6, Plate 103: Location of photos taken during the survey of Trout Beck Reach 6). The ongoing erosional processes of the channel, combined with the sinuous planform of Trout Beck in this reach suggests that the channel planform is relatively active, and is liable to migrate across the floodplain in this reach in the future.

14.9.2.77 The localised flow complexity described above has encouraged areas of very high and low flow energy. In areas where flow energy is low, fine material as deposited on the bed of the channel, whereas areas of high flow energy have left just coarse material such as gravels and some cobbles (Photo 7 and Photo 8, Plate 103: Location of photos taken during the survey of Trout Beck Reach 6). The result is a very wide range of sediment clasts over a relatively short area of watercourse. It is likely that the continued patten of bank erosion, collapse and retreat will see this localised sinuosity develop into a reach scale pattern of sinuosity. The result of this widespread bank erosion and collapse is a river channel which as a very wide variety of channel widths, ranging between 5m to 20m in some areas.

Plate 30: Map of flow biotopes within Trout Beck Reach 6

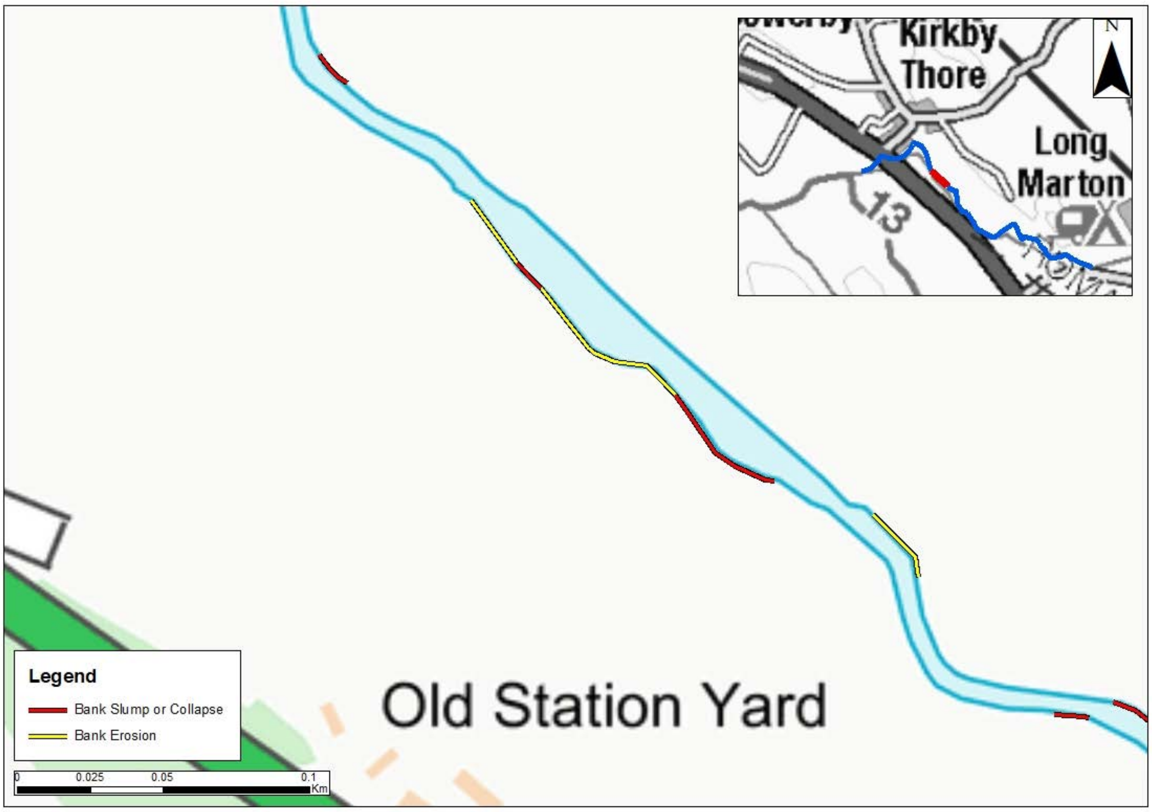


Plate 31: Map of observed bank erosion pressures within Trout Beck Reach 6

Plate 32: Map of bank modifications within Trout Beck Reach 6

Plate 33: Map of the dominant bed substrate type within Trout Beck Reach 6

Trout Beck Reach 7

14.9.2.78 Plate 34: Map of flow biotopes within Trout Beck Reach 7, Plate 35: Map of observed bank erosion pressures within Trout Beck Reach 7, Plate 36: Map of bank modifications within Trout Beck Reach 7 and Plate 37: Map of the dominant bed substrate type within Trout Beck Reach 7 provide an overview of the morphological characteristics observed on site, including flow biotopes, bank erosion pressures, bank modifications and typical bed substrate in Reach 7.

14.9.2.79 Photographs of the reach are presented in Plate 104: Location of photos taken during the survey of Trout Beck Reach 7 in Annex A: Temple Sowerby to Appleby site photographs.

14.9.2.80 The watercourse transitions from a very active channel dominated by riffles and significant bank erosion to a straighter channel planform dominated by gliding flows and homogeneous bed features (Photo 1, Plate 104: Location of photos taken during the survey of Trout Beck Reach 7). The right bank is embanked along some of its length, and both the riverbanks are lined with riparian tree cover, although there is little in terms of understory foliage coverage. The flow energy through this section of the watercourse is significantly reduced. It is likely that the coarse riffle/rapid feature observed beneath the farm access track bridge located approximately 300m downstream is influencing the flow dynamics and energy within this reach (Photo 2, Plate 104: Location of photos taken during the survey of Trout Beck Reach 7). The flow is impounded by this riffle / rapid feature, which has led to a reduction in flow energy. As such, the channel lacks the energy to generate a range of flow biotopes and bedforms, resulting in a reduction in morphological diversity compared to upstream reaches (Photo 3, Plate 104: Location of photos taken during the survey of Trout Beck Reach 7). Some of the material of which the riffle/rapid feature is composed is angular / artificial and could have been sourced by erosion of the abutments of the farm access track bridge.

14.9.2.81 The gradient of the channel downstream of the riffle/rapid feature downstream of the farm access track becomes much steeper compared to upstream reaches, and the watercourse has significant flow energy. As such, the bed substrate transitions from gravels, sands and fines observed upstream of the farm access track to gravels and cobbles downstream (Photo 4, Plate 104: Location of photos taken during the survey of Trout Beck Reach 7). Material finer than gravels is transported to downstream reaches leaving the bed gravels and cobbles clean of fine sediment, and no fine material suspended within the water column. The flow biotope over the next 250m alternates between riffle/rapid features and runs, in line with the high flow energy of the watercourse (Photo 5, Plate 104: Location of photos taken during the survey of Trout Beck Reach 7). Riparian tree cover within this reach is mixed; tree cover is sporadic, with a single line of trees occupying the riverbank edge (Photo 6, Plate 104: Location of photos taken during the survey of Trout Beck Reach 7). Cuspate-shaped erosion is prevalent through this reach, where the watercourse has eroded unconsolidated topsoil bank material between trees.

14.9.2.82 Approximately 150m downstream of the farm access track, Trout Beck bends sharply to the south-west at an almost 45-degree angle, before continuing in a generally south-westerly direction. Directly downstream of the meander bend, an old structure is present on the riverbanks and across the bed of the channel. Due to the degraded nature of the structure, its purpose was difficult to ascertain on site, but an analysis of historic mapping (Plate 104: Location of photos taken during the survey of Trout Beck Reach 7) reveals that the structure was previously a weir, constructed to service a mill race that has since been infilled (Photo 7, Plate 104: Location of photos taken during the survey of Trout Beck Reach 7). Despite the presence of this dilapidated weir structure within the channel, there are no obvious signs of impoundment upstream of the weir; the steep gradient of the channel combined with the very shallow weir apron and weir crest height compared to the bed levels has significantly reduced the control of the weir on water levels (Photo 8, Plate 104: Location of photos taken during the survey of Trout Beck Reach 7). At the location of the weir the channel is overwide, and the riverbanks have scoured the left bank of the weir (Photo 9, Plate 104: Location of photos taken during the survey of Trout Beck Reach 7). Recirculation of flow at the point of scour on the riverbank has further exacerbated the bank erosion, and a weir pool has scoured the riverbed (Photo 10,

Plate 104: Location of photos taken during the survey of Trout Beck Reach 7).

Plate 34: Map of flow biotopes within Trout Beck Reach 7

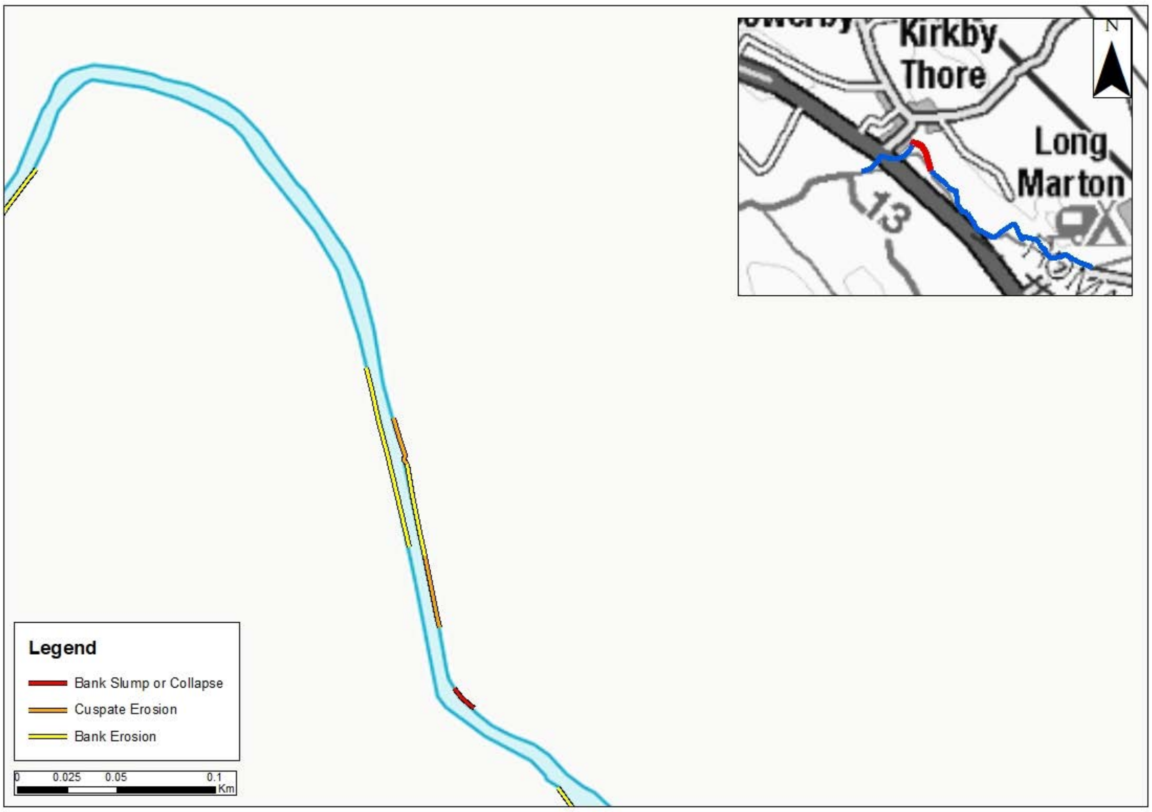


Plate 35: Map of observed bank erosion pressures within Trout Beck Reach 7

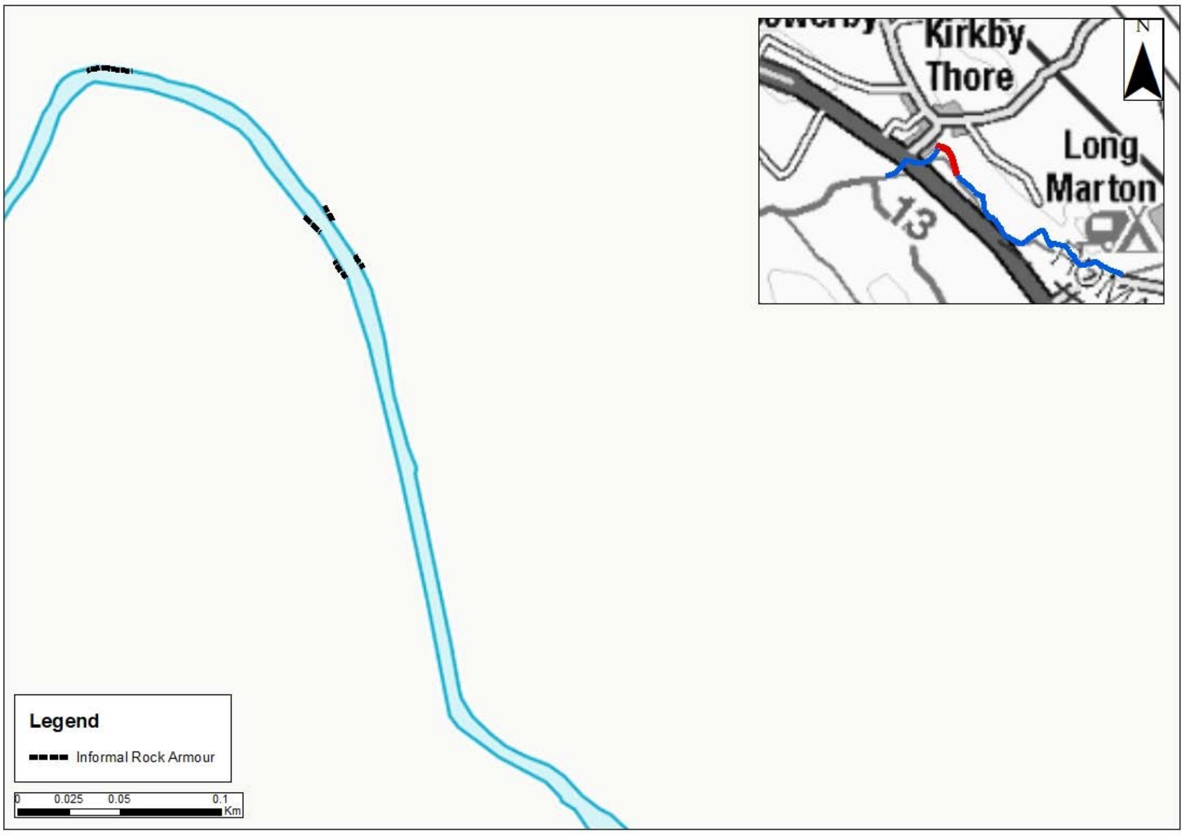


Plate 36: Map of bank modifications within Trout Beck Reach 7

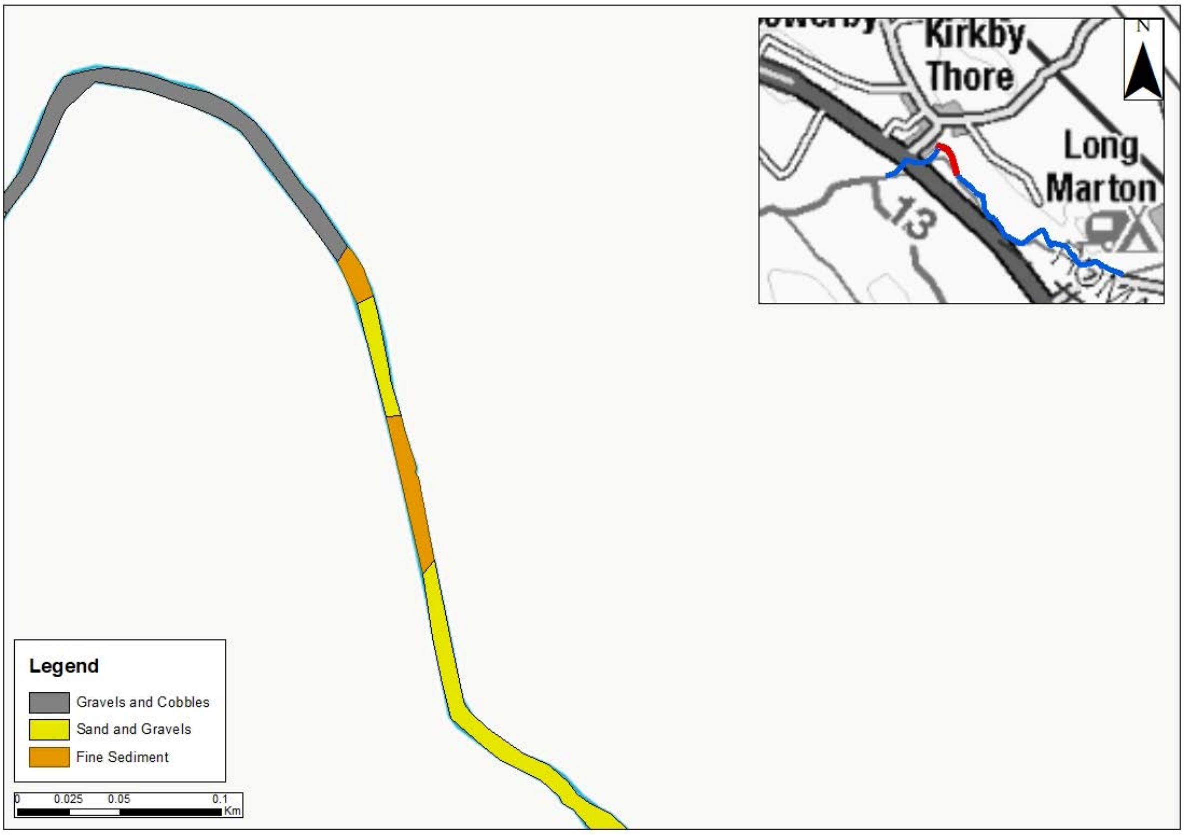


Plate 37: Map of the dominant bed substrate type within Trout Beck Reach 7

Trout Beck Reach 8

14.9.2.83 Plate 38: Map of flow biotopes within Trout Beck Reach 8, Plate 39: Map of observed bank erosion pressures within Trout Beck Reach 8, Plate 40: Map of bank modifications within Trout Beck Reach 8 and Plate 41: Map of the dominant bed substrate type within Trout Beck Reach 8 provide an overview of the morphological characteristics observed on site, including flow biotopes, bank erosion pressures, bank modifications and typical bed substrate in Reach 8.

14.9.2.84 Photographs of the reach are presented in Plate 105: Location of photos taken during the survey of Trout Beck Reach 8 in Annex A: Temple Sowerby to Appleby site photographs.

14.9.2.85 Within this reach, the channel is characterised by processes of incision, as indicated by the J-shaped trees (Photo 1, Plate 105: Location of photos taken during the survey of Trout Beck Reach 8) and vertical banks. In locations where riparian tree cover is sparse or patchy, the bare topsoil bank material has been eroded by the flow; bank toe erosion has resulted in many areas of the riverbank slumping or collapsing into the channel (Photo 2, Plate 105: Location of photos taken during the survey of Trout Beck Reach 8). This pattern of bed incision, bank collapse and retreat has led to an overwide channel and has contributed to the reductions in flow energy observed during low (i.e. normal) flows (Photo 3, Plate 105: Location of photos taken during the survey of Trout Beck Reach 8). In the channel margins where collapsed banks have settled, marginal vegetation has colonised the material which has led to the retention of marginal sediment deposits (Photo 4, Plate 105: Location of photos taken during the survey of Trout Beck Reach 8) leading to variations in channel width.

14.9.2.86 The gradient of the channel between the weir and the A66 road bridge reduces and becomes less steep compared to the start of Reach 8. As such, the flow energy of Trout Beck reduces. As the flow energy reduces, the size of material that can be mobilised and transported further downstream is reduced significantly; this results in the bed substrate being comprised of a range of material from fine sediment to sands and gravels, compared to the gravel and cobble bed substrate identified further upstream (Photo 5, Plate 105: Location of photos taken during the survey of Trout Beck Reach 8). The diversity of bed formations reduces within this reach with the only bedform diversity occurring via the marginal deposits of bank slump material. Despite the reduction in flow energy, the flow biotopes are largely similar to those upstream with alternating sequences of riffles and runs (Photo 6, Plate 105: Location of photos taken during the survey of Trout Beck Reach 8).

14.9.2.87 Downstream of the A66 road bridge the channel planform has been modified historically, leading to a relatively straight channel. A combination of retaining walls relating to the adjacent agricultural land, and relic rail embankments and bank protection from when the

Eden Valley Branch of the North Eastern Railway crossed Trout Beck at this location (Photo 7 and Photo 8, Plate 105: Location of photos taken during the survey of Trout Beck Reach 8). As such, the watercourse is unable to develop a more sinuous planform. The result is a steep channel gradient between the A66 Road bridge and the confluence with the River Eden which increases flow velocities within the channel significantly. The flow has sufficient energy to mobilise and transport material such as fine sediment and sands, leaving just coarser material such as gravels and cobbles on the riverbed (Photo 9, Plate 105: Location of photos taken during the survey of Trout Beck Reach 8) and a plane riffle morphology. Bank erosion through this reach is often associated with flow divergence around riffles (Photo 10 and Photo 11, Plate 105: Location of photos taken during the survey of Trout Beck Reach 8). Attempts have been made to mitigate the erosion of adjacent farmland in places by placing loose, coarse brickwork and rubble against the riverbank (Photo 12, Plate 105: Location of photos taken during the survey of Trout Beck Reach 8).

14.9.2.88 Bed incision in the area between the A66 road bridge and the confluence of the watercourse with the River Eden. The riverbanks are 2m to 3m above the height of the riverbed in some locations. Bank slumping and collapse are prevalent throughout the reach and the channel is generally overwide compared to upstream reaches (Photo 13 and Photo 14, Plate 105: Location of photos taken during the survey of Trout Beck Reach 8).

14.9.2.89 As Trout Beck approaches the confluence with the River Eden, flow energy reduces as the flow becomes impounded by the water level on the River Eden. This causes finer material such as sands and fine sediment to drop out of transportation, and a fine layer of material was observed to be covering the coarse bed material (Photo 15, Plate 105: Location of photos taken during the survey of Trout Beck Reach 8). Tree cover between the rail embankment and the confluence is sporadic, and any trees on the riverbanks in this area have slumped into the river because of riverbank toe erosion and bank collapse (Photo 16, Plate 105: Location of photos taken during the survey of Trout Beck Reach 8).

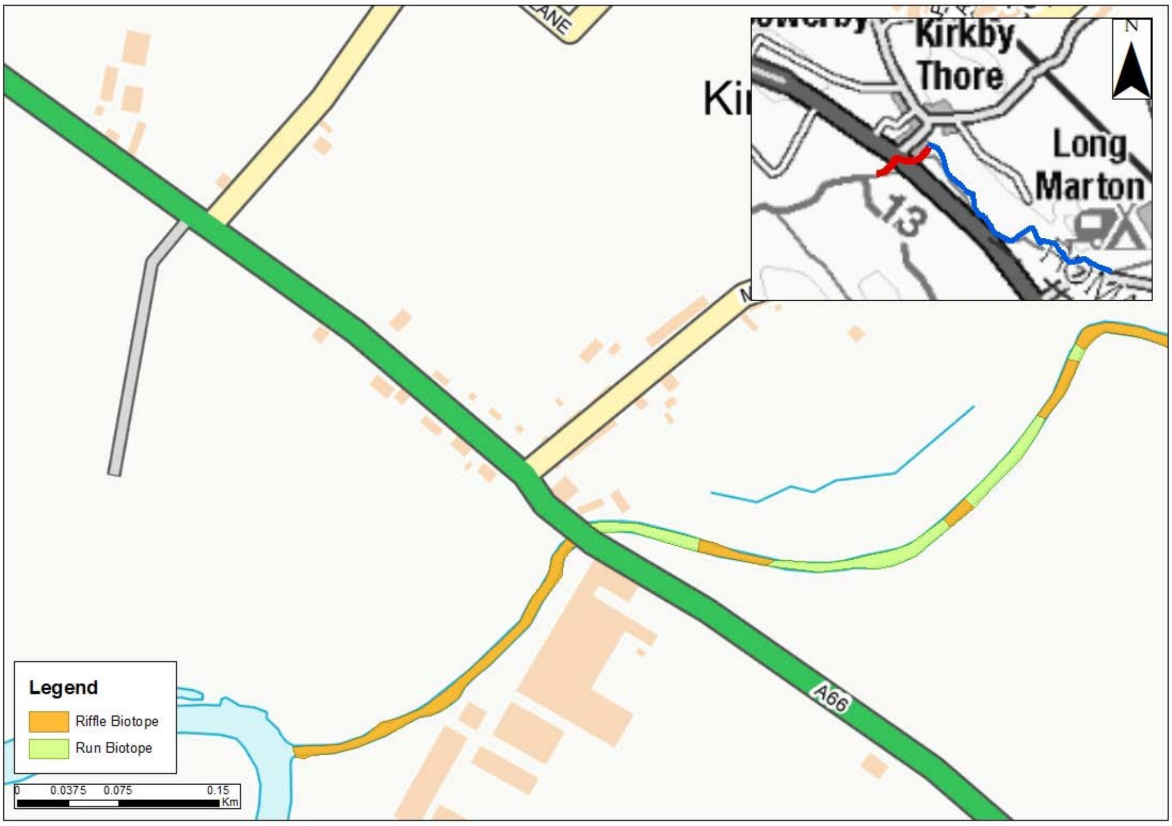


Plate 38: Map of flow biotopes within Trout Beck Reach 8

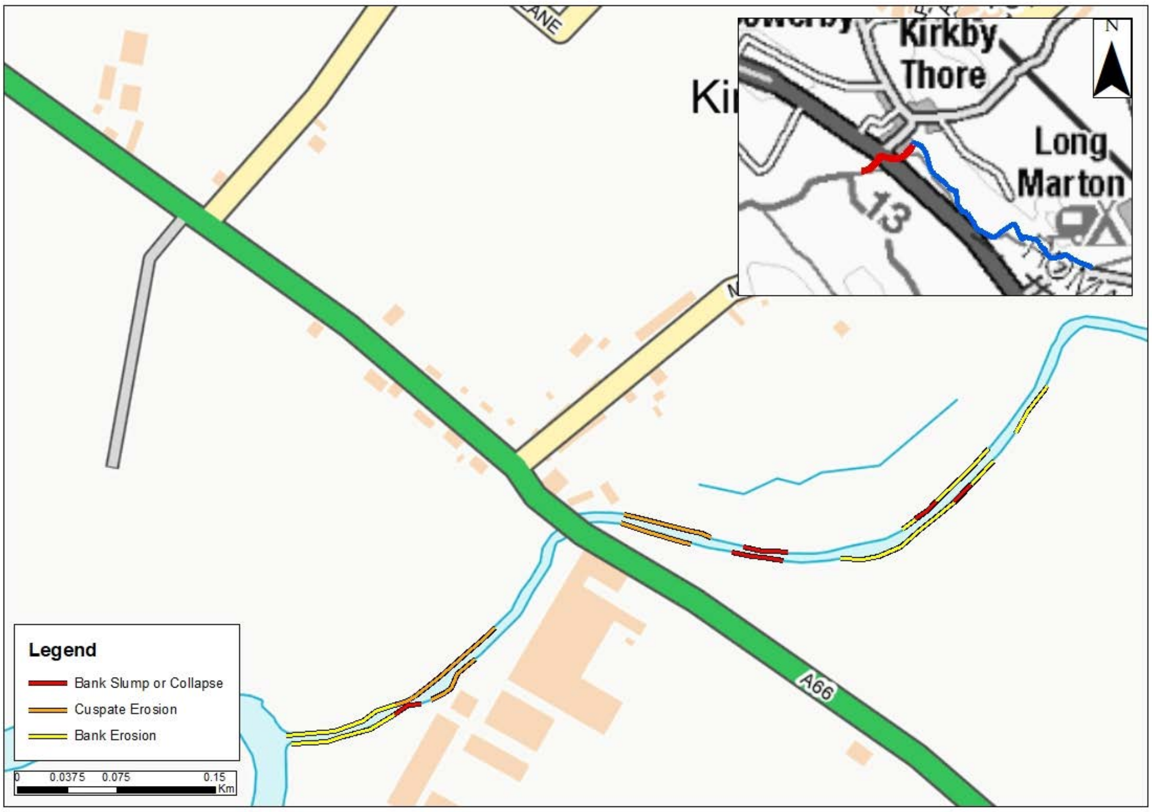


Plate 39: Map of observed bank erosion pressures within Trout Beck Reach 8

Plate 40: Map of bank modifications within Trout Beck Reach 8

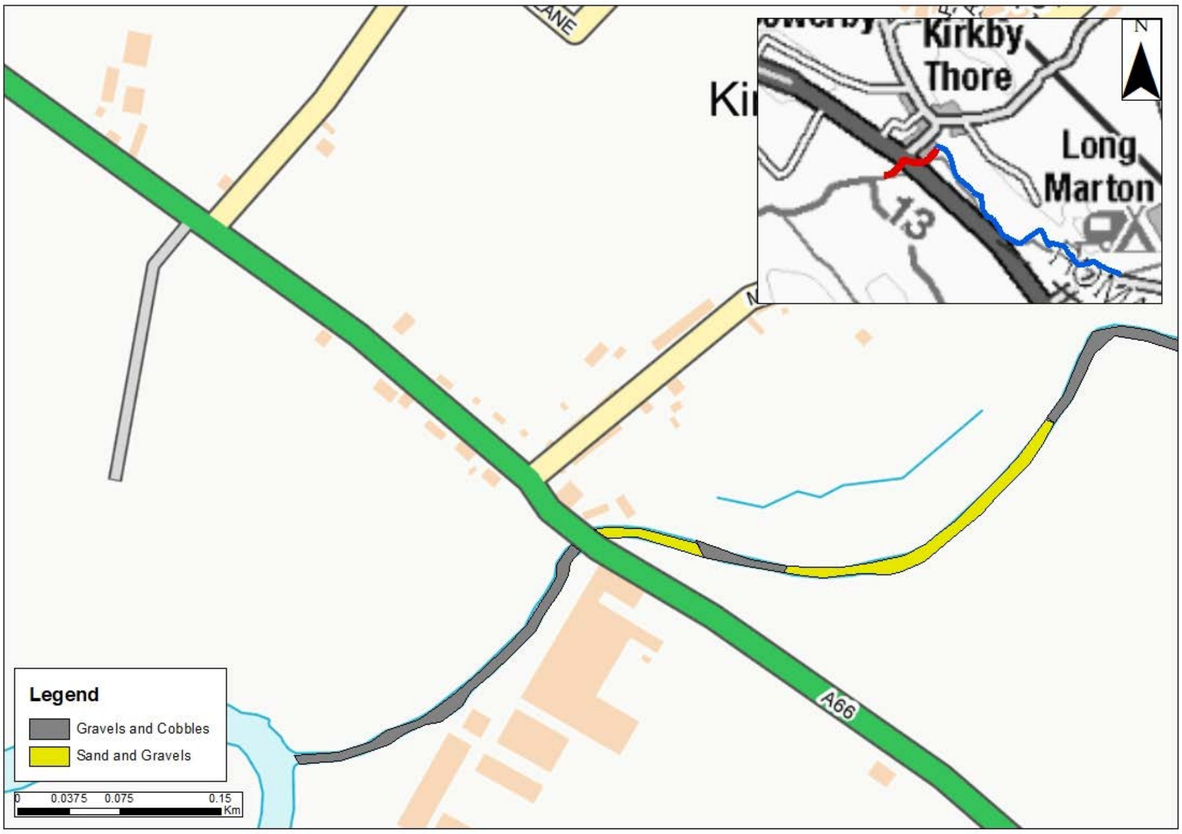


Plate 41: Map of the dominant bed substrate type within Trout Beck Reach 8

Keld Sike Reach 1

14.9.2.90 Plate 42: Map of flow biotopes within Keld Sike Reach 1, Plate 43: Map of observed bank erosion pressures within Keld Sike Reach 1, Plate 44: Map of bank modifications within Keld Sike Reach 1 and Plate 45: Map of the dominant bed substrate type within Keld Sike Reach 1 provide an overview of the morphological characteristics observed on site, including flow biotopes, bank erosion pressures, bank modifications and typical bed substrate along Keld Sike Reach 1.

14.9.2.91 Photographs of the reach are presented in Plate 106: Location of photos taken during the survey of Keld Sike Reach 1 in Annex A: Temple Sowerby to Appleby site photographs.

14.9.2.92 Keld Sike is confined within a relatively steep side v-shaped valley. The upstream limit of Reach 1 of the Keld Sike is characterised by a small, single thread channel system with a predominantly fine bed is relatively shallow, which limits the energy available to the water column to entrain, transport and erode bed and bank material. As such the predominant flow biotope in the upstream section of reach 1 is gliding flow, with the occasional run or riffle where there is localised variation in channel gradient or channel width (Photo 1 and Photo 2, Plate 106: Location of photos taken during the survey of Keld Sike Reach 1). The result is a predominantly fine bed substrate, limited channel sinuosity and stable riverbanks (Photo 3, Plate 106: Location of photos taken during the survey of Keld Sike Reach 1). During heavy rainfall events, it is likely that overland surface water flow conveys large volumes of fine material from the surrounding arable and livestock agricultural land, and inputs this into the Keld Sike. The riverbanks are relatively stable, with a thick riparian buffer strip of trees flanking both the left and right riverbank (Photo 4, Plate 106: Location of photos taken during the survey of Keld Sike Reach 1).

14.9.2.93 A bridge supporting a farm access track crosses the Keld Sike influencing the flow and sediment transfer dynamics both upstream and downstream (Photo 5, Plate 106: Location of photos taken during the survey of Keld Sike Reach 1). The bridge is supported by a circular culvert which conveys the Keld Sike beneath the bridge. The invert of the culvert was noted to be at a greater elevation than the bed level of the Keld Sike immediately upstream (Photo 6, Plate 106: Location of photos taken during the survey of Keld Sike Reach 1Plate 106). As such, the invert of the culvert impounds the flow upstream, reducing flow energy for approximately 30 meters. This further reduces the sediment transport capacity of the watercourse during low to moderate flows, with more fine sediment dropping out of the water column and being deposited on the riverbed (Photo 7, Plate 106: Location of photos taken during the survey of Keld Sike Reach 1). The channel planform on the approach to the culvert appears to have been straightened, as the limited channel sinuosity observed upstream has been replaced with a straight planform (Photo 8, Plate 106: Location of photos taken during the survey of Keld Sike Reach

1). The channel planform has likely been modified to improve the conveyance of flow through the culvert, reduce flood risk and limit bank erosion downstream of the culvert. Downstream of the culvert, a pool has developed. Flow velocities increase through the culvert, which increases the erosional pressure on the bed of the channel as the flow is discharged from the culvert (Photo 9, Plate 106: Location of photos taken during the survey of Keld Sike Reach 1). Informal rock armour bank protection has been installed on the left bank of the channel in an attempt to limit bank erosion in the vicinity of the culvert outfall (Photo 10, Plate 106: Location of photos taken during the survey of Keld Sike Reach 1).

14.9.2.94 Downstream of the culvert, the conditions of the Keld Sike change significantly. The gradient of the channel increases, which provides the watercourse with sufficient energy to develop a diverse range of flow biotopes, including riffles and runs, as well as some limited sinuosity. The increase in flow energy is sufficient enough to mobilise and transfer finer material to downstream reaches, leaving a bed composed of sands gravels and cobbles (Photo 11, Plate 106: Location of photos taken during the survey of Keld Sike Reach 1). The alternating sequence of riffles and runs facilitates the development of marginal sediment deposits, variations in bed morphology and channel sinuosity. Channel sinuosity is further improved by the presence of a thick riparian woodland flanking the Keld Sike on both the left and right bank floodplain. This woodland area provides a source of woody material to the channel, generating localised variations in flow and sediment transfer (Photo 12, Plate 106: Location of photos taken during the survey of Keld Sike Reach 1).

14.9.2.95 A former pond area is located in the centre of the riparian woodland, and the route of the existing channel planform passes through this (Photo 13, Plate 106: Location of photos taken during the survey of Keld Sike Reach 1). The channel has successfully carved out a path through the former pond area and has developed a series of alternating riffle and run sequences. The result is a series of isolated wetted areas occupying former palaeo channels on the left and right bank of the channel, which have become heavily overgrown with vegetation (Photo 14, Plate 106: Location of photos taken during the survey of Keld Sike Reach 1). Isolated fluvial sediments were observed on the floodplain through the former pond area, suggesting that the area is activated by out of bank flows during heavy rainfall events (Photo 15, Plate 106: Location of photos taken during the survey of Keld Sike Reach 1).

14.9.2.96 Reach 1 of Keld Sike ends at a second farm access bridge, where the woodland area ends and the morphological characteristics of the Keld Sike change.

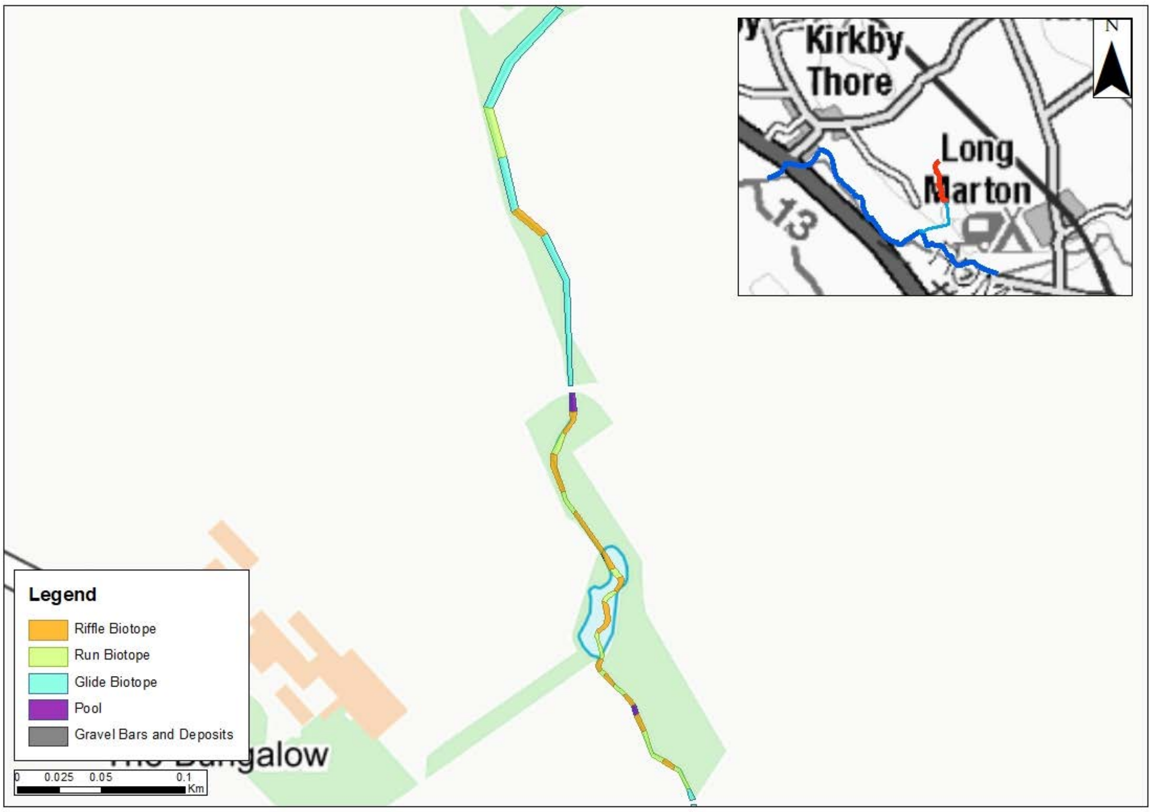


Plate 42: Map of flow biotopes within Keld Sike Reach 1

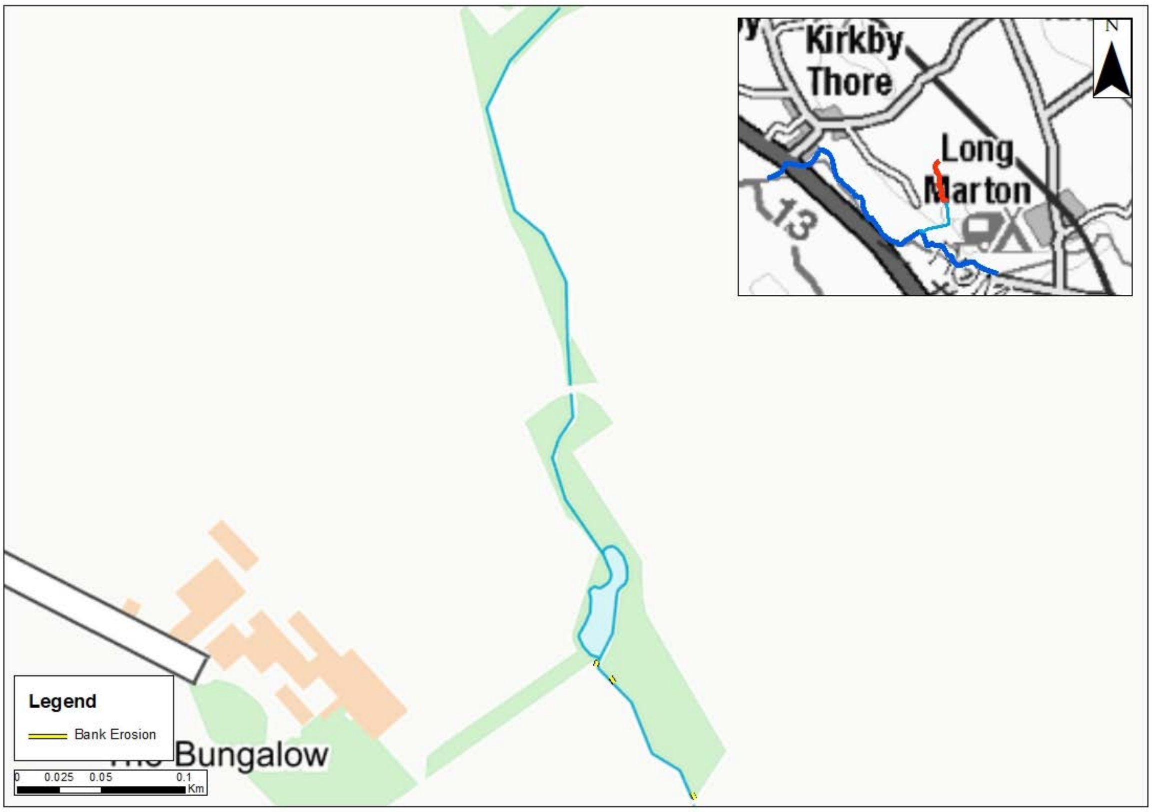


Plate 43: Map of observed bank erosion pressures within Keld Sike Reach 1

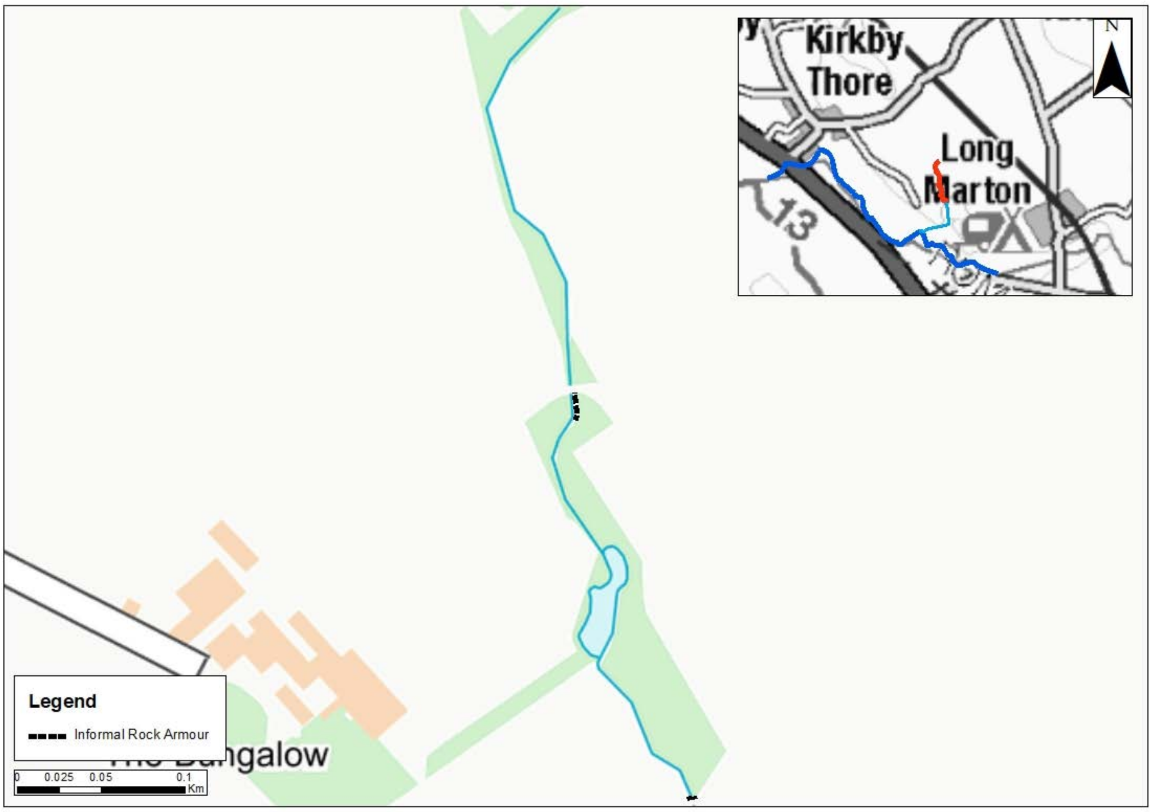


Plate 44: Map of bank modifications within Keld Sike Reach 1

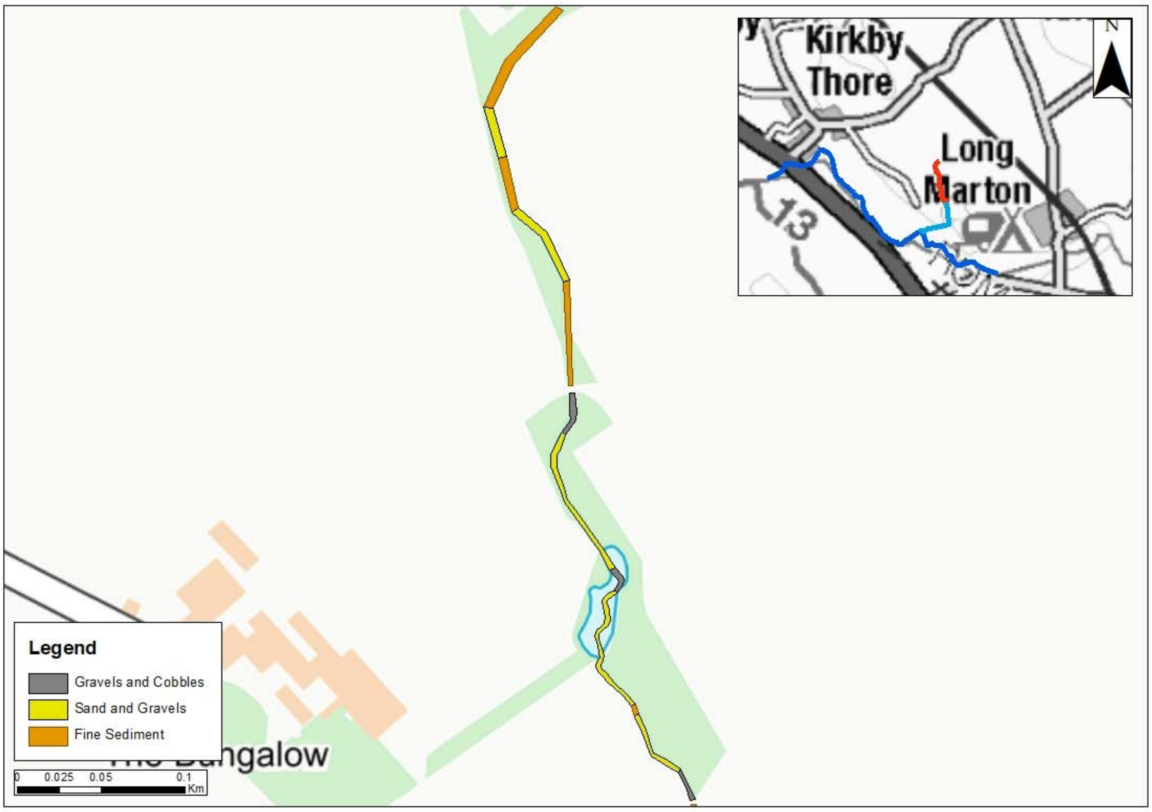


Plate 45: Map of the dominant bed substrate type within Keld Sike Reach 1

Keld Sike Reach 2

14.9.2.97 Plate 46: Map of flow biotopes within Keld Sike Reach 2, Plate 47: Map of observed bank erosion pressures within Keld Sike Reach 2, Plate 48: Map of bank modifications within Keld Sike Reach 2 and Plate 49: Map of the dominant bed substrate type within Keld Sike Reach 2 provide an overview of the morphological characteristics observed on site, including flow biotopes, bank erosion pressures, bank modifications and typical bed substrate along Keld Sike Reach 2.

14.9.2.98 Photographs of the reach are presented in Plate 107: Location of photos taken during the survey of Keld Sike Reach 2 in Annex A: Temple Sowerby to Appleby site photographs.

14.9.2.99 Downstream of the farm access bridge and culvert, the morphology of the Keld Sike changes significantly compared to conditions observed in Reach 1 (Photo 1, Plate 107: Location of photos taken during the survey of Keld Sike Reach 2). The channel planform becomes very straight, and as such the channel gradient increases. The Keld Sike remains confined within a relatively narrow v-shaped valley. As such, there is limited space for the Keld Sike to adopt a more sinuous planform at the start of Reach 2. This linear channel planform provides the watercourse with significant flow energy, which ensures that fine material is mobilised and transported to reaches further downstream with less energy. As such, the predominant bed substrate ranges from cobbles to gravels to sands (Photo 2, Plate 107: Location of photos taken during the survey of Keld Sike Reach 2). The width of the channel remains relatively homogeneous, estimated between 1 to 1.5m in width. Despite this area being largely a sediment transfer zone, a localised area of shallow gradient results in a reduction in flow energy and the deposition of fine material on the bed (Photo 3, Plate 107: Location of photos taken during the survey of Keld Sike Reach 2). This is further compounded by an increase in channel width compared to other sections of Reach 2, increasing to 2-3m in localised areas. This further reduces flow energy and encourages the deposition of fine material. Due to the straight channel planform, flow biotope diversity is limited, and as such the dominant flow biotope is a riffle, which gradually transitions to a run as the channel gradient reduces further downstream (Photo 4, Plate 107: Location of photos taken during the survey of Keld Sike Reach 2).

14.9.2.100 This straight channel planform persists for approximately 250m, before the Keld Sike sharply changes direction and continues in a westerly direction towards the confluence with Trout Beck (Photo 5, Plate 107: Location of photos taken during the survey of Keld Sike Reach 2). Despite the sharp change in direction, there is little evidence of bank erosion on the outside bend. Downstream of this sharp bend, the valley of the Keld Sike opens up, with flat arable land occupying the left bank of the watercourse (Photo 6, Plate 107: Location of photos taken during the survey of Keld Sike Reach 2).

Despite this, the Keld Sike is confined to the field boundary, and the channel planform retains its linear route. It is likely that this is the result of anthropogenic pressures, and the channel planform has been moved for field drainage purposes in the past. Despite the straight channel planform, the gradient of the Keld Sike is relatively shallow on the approach to the Trout Beck confluence, The result is a reduction in the flow energy of the watercourse, which has led to a degradation of the riverbed. A layer of fine material covers the existing bed substrate for the majority of the Keld Sike between the sharp bend at the upstream limit and the confluence at the downstream limit (Photo 6, Plate 107: Location of photos taken during the survey of Keld Sike Reach 2). The Keld Sike has insufficient energy to mobilise fine material, and the result is fine material dropping out of the water column and depositing on the existing bed substrate, covering material ranging from gravels to cobbles. The issue of fine sediment deposition on the bed is further compounded by the lack of riparian vegetation in this reach to consolidate bank material and provide a buffer for overland flows (Photo 7, Plate 107: Location of photos taken during the survey of Keld Sike Reach 2).

14.9.2.101 On the approach to Trout Beck confluence the planform of Keld Sike becomes more sinuous, with two sharp meanders identified (Photo 8, Plate 107: Location of photos taken during the survey of Keld Sike Reach 2). There is evidence of bank erosion in the vicinity of these meander bends (Photo 9, Plate 107: Location of photos taken during the survey of Keld Sike Reach 2). Attempts have been made to mitigate the erosion using wooden toe boards (Photo 10, Plate 107: Location of photos taken during the survey of Keld Sike Reach 2). However, many are in poor condition and have been degraded by the watercourse over time. The introduction of planform sinuosity at this location improves the morphological diversity of the Keld Sike, with alternating sequences of riffles and pools developing (Photo 11 and Photo 12, Plate 107: Location of photos taken during the survey of Keld Sike Reach 2).

14.9.2.102 The riparian vegetation on both banks of the Keld Sike improves on the approach to the Trout Beck confluence, with a think buffer strip of trees flanking the watercourse (Photo 13, Plate 107: Location of photos taken during the survey of Keld Sike Reach 2). The surrounding woodland area serves as a source of woody material to the Keld Sike, which further enhances morphological diversity. Woody material has become lodged at the mouth of the Keld Sike, significantly reducing flow velocities directly upstream (Photo 14, Plate 107: Location of photos taken during the survey of Keld Sike Reach 2). This has resulted in the deposition of fine material as flow fine material drops out of suspension of the watercourse.

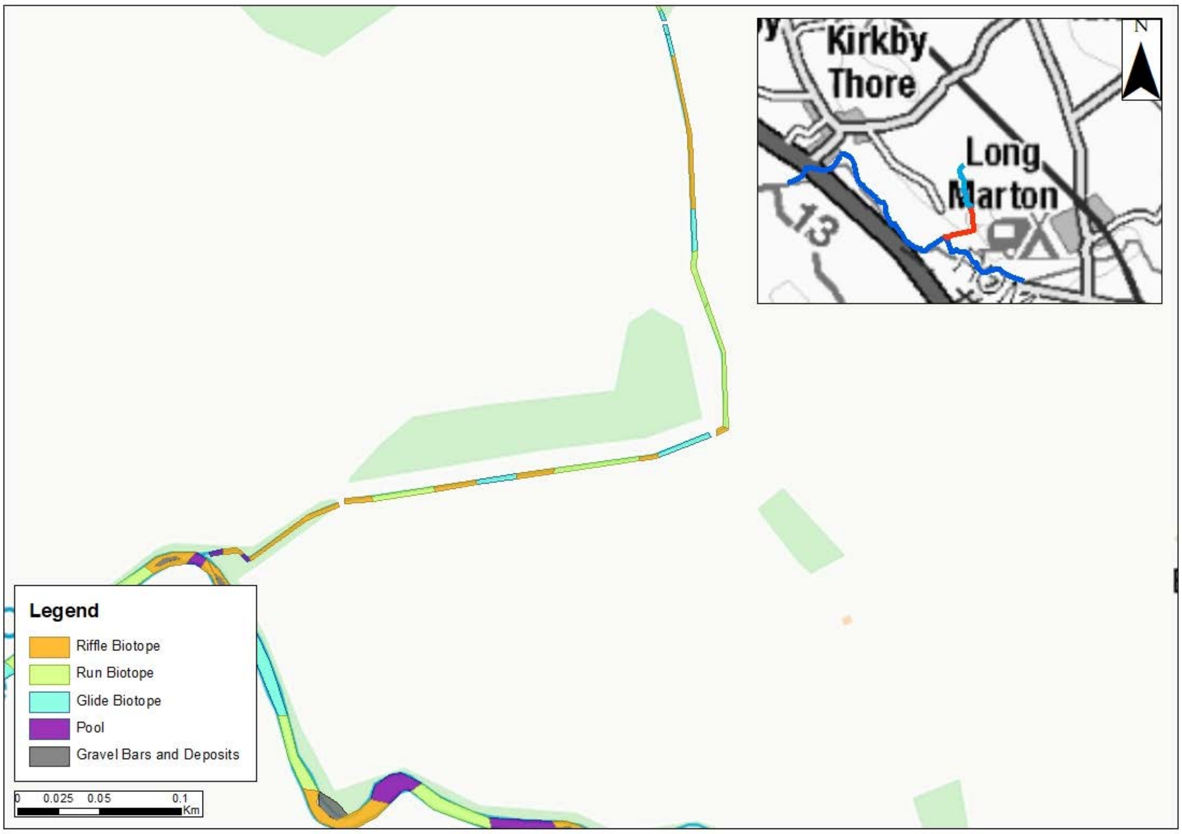


Plate 46: Map of flow biotopes within Keld Sike Reach 2

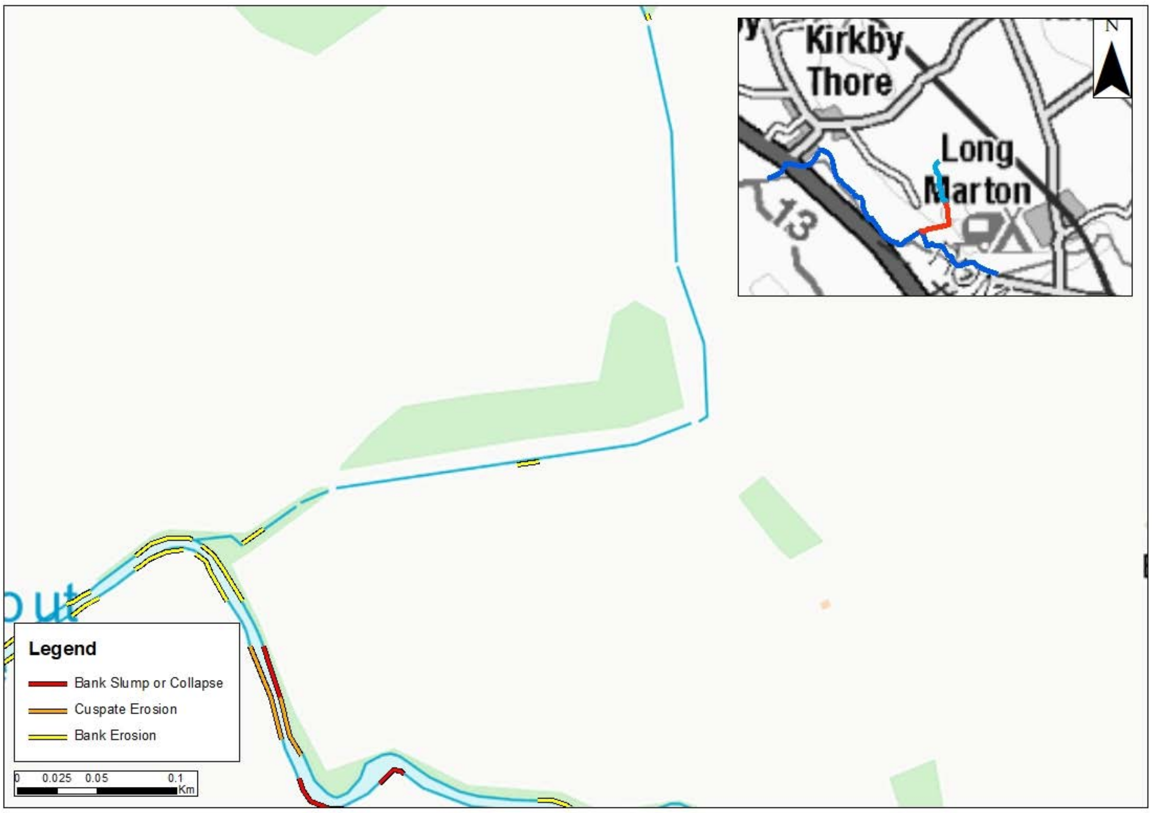


Plate 47: Map of observed bank erosion pressures within Keld Sike Reach 2

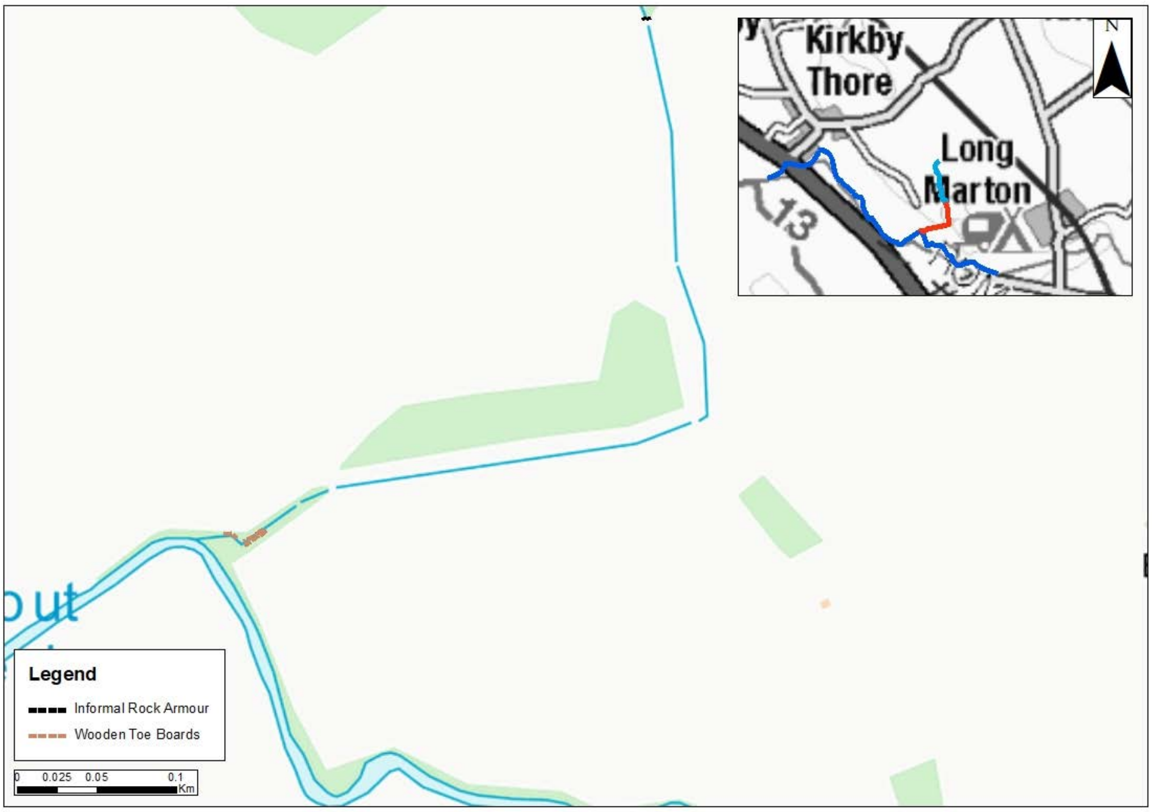


Plate 48: Map of bank modifications within Keld Sike Reach 2

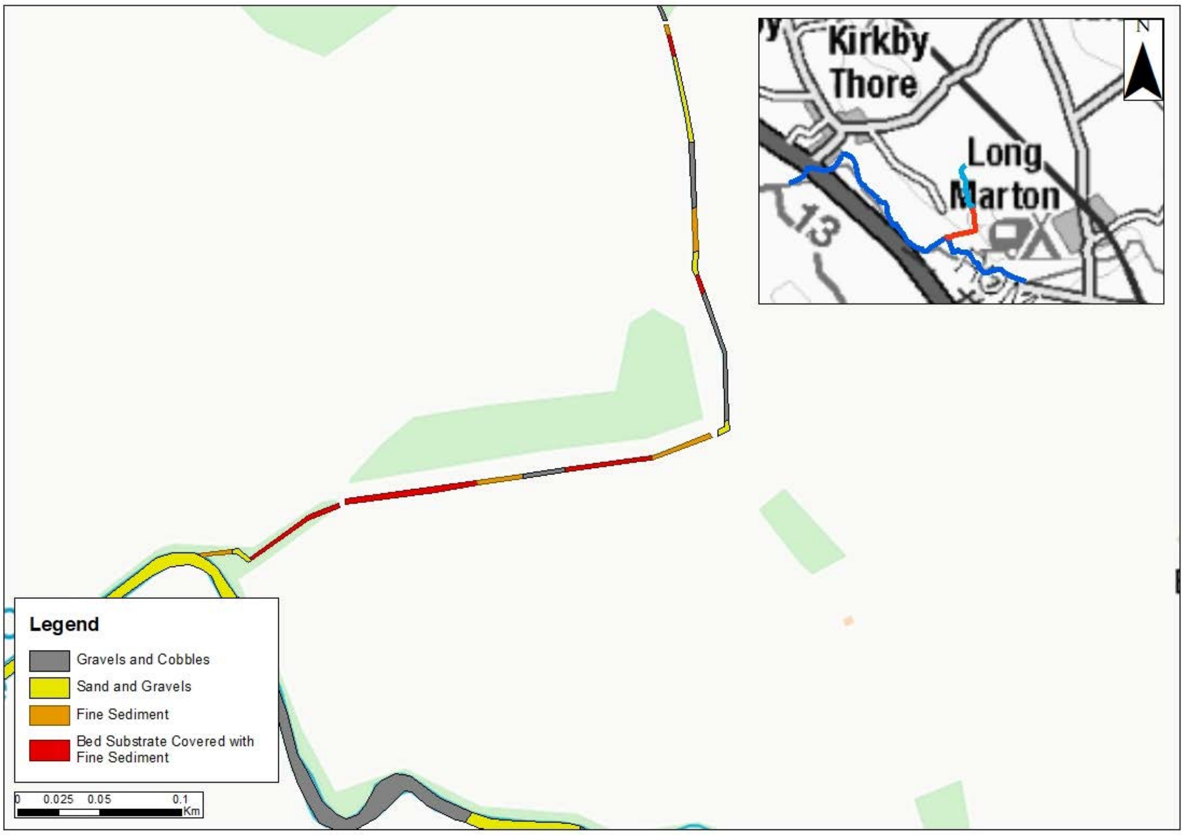


Plate 49: Map of the dominant bed substrate type within Keld Sike Reach 2

Sediment sampling

14.9.2.103 Sampling of the main active gravel bar features within Trout Beck and Keld Sike was undertaken during the site walkover. Plate 50: Sediment sampling locations along Trout Beck and Keld Sike shows the locations of the seven sampling locations. Gravel bars were selected for sampling based on safe access to the channel.

14.9.2.104 Wolman Pebble Count sampling across each of the selected gravel bars was undertaken, recording the intermediate axis of each sediment clast using a gravelometer. The procedure for undertaking Wolman Pebble Count sampling is detailed in Appendix A. This methodology is known to minimise operator error compared to measuring the intermediate axis of clasts using a ruler. The sampling size data has been analysed to produce Particle Size Distribution curves at each sample site, allowing an assessment of the range of particle sizes within each sample. A separate assessment of sediment sizes on Trout Beck and Keld Sike have been undertaken to facilitate a more appropriate comparison between gravel bars. The Calculated D50 (median), D10 and D90 particle size distribution values are displayed in the following sections.

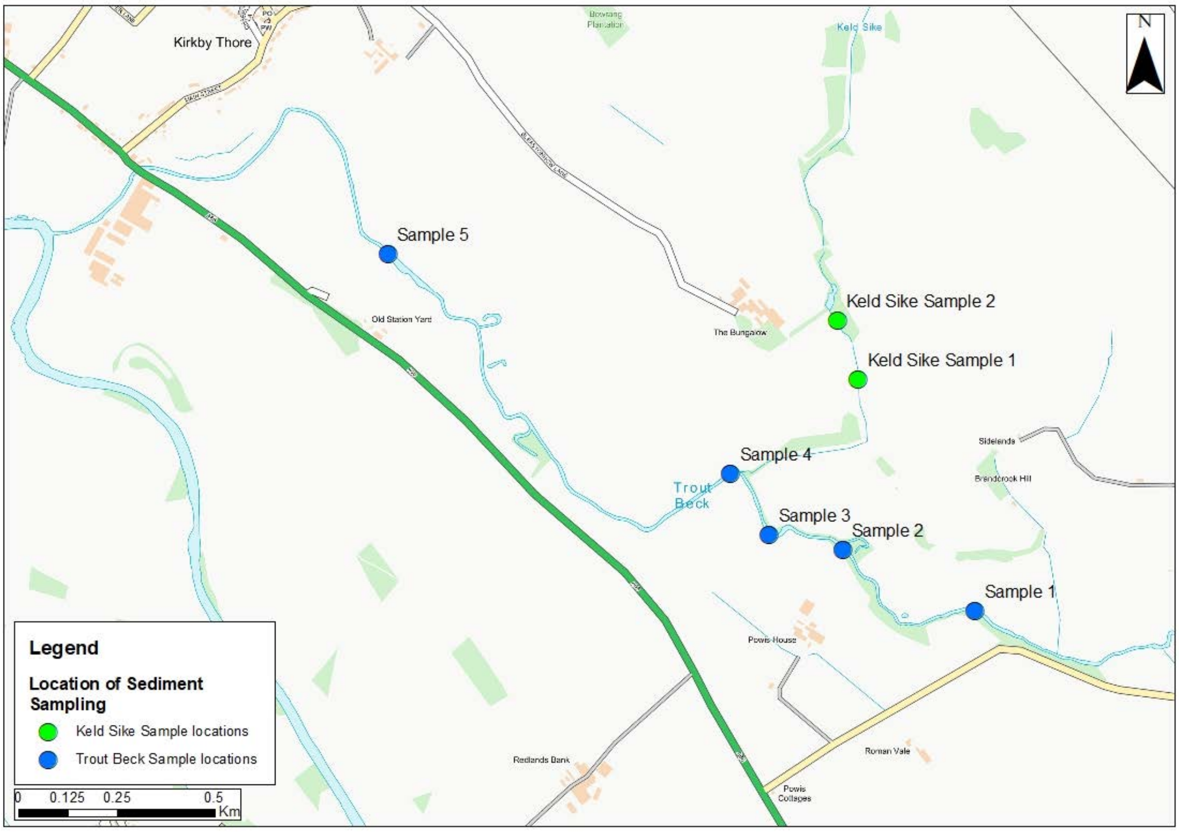


Plate 50: Sediment sampling locations along Trout Beck and Keld Sike

Trout Beck sediment sample analysis

14.9.2.105 Based on the D10, D50 and D90 values for each sample on Trout Beck, it is apparent that Sample Locations 1 and 2 have the coarsest particle size distribution, with 90% of the samples measuring <90mm and <64mm respectively (Table 3: D10, D50 and D90 particle size distribution values for each gravel bar sampling site on Trout Beck). In comparison the particle size distribution at Sample Locations 4 and 5 are finer, with 90% of the samples measuring <32mm at both locations (Table 3: D10, D50 and D90 particle size distribution values for each gravel bar sampling site on Trout Beck). As observed in Plate 51: Combined Particle Size Distribution curves for each gravel sampling site on Trout Beck, the particle size distribution at Sample Location 3 is somewhat coarser than Sample Location 2, with 90% of the samples measuring <90mm.

14.9.2.106 The analysis of particle size distribution data within each of the sampled gravels bars on Trout Beck indicate a broad trend of particle size reductions as distance downstream on the watercourse increases. Coarser ranges of particle sizes are typically found in upstream gravel bars where channel sinuosity and activity is minimal. These less active reaches typically have higher flow energy as a result of a steeper channel gradient. In-channel velocities are maintained high enough in these upstream reaches to ensure that fine material remains in suspension and is transported to reaches further downstream. This leaves only the coarsest material left to populate the gravel bars in upstream reaches, where the material is too large to be mobilised and transported to downstream reaches.

14.9.2.107 Conversely, finer material is found in more active, sinuous reaches where channel planform migration is observed. The flow energy in these downstream reaches is lower, as the channel gradient is much shallower as Trout Beck approaches the confluence with the River Eden. In channel velocities are no longer high enough to maintain sediment transport processes, and as such finer material drops out of the suspension in the water column and deposits on the bed of the channel and gravel bars. To further compound the build-up of fine material in this downstream reaches, processes of bank erosion and bank slumping provide a major source of local fine sediment to Trout Beck. Inputs of fine material from Keld Sike, as well as inputs from surface water flow routes during heavy rainfall events also contribute finer material to Trout Beck, which cumulatively increase the volume of finer material in downstream reaches.

14.9.2.108 Gravel bars with a finer particle size are predicted to represent areas of continued deposition and bar growth, as lower velocities allow finer particles to drop out of suspension and accumulate on the bar features. As such, the gravel bars at Sample Locations 4 and 5 are predicted to continue to grow in size over short-term timescales.

14.9.2.109 The confluence with Keld Sike is located directly upstream of Sample Location 4, which provides a source of finer material into Trout Beck. It is likely that this continuous supply of material from Keld Sike will continue to accumulate on the gravel bar at this location. Continued growth of the gravel bar on the inside of this meander bend will exert more erosive pressure on the outside meander bend, which will likely affect channel planform change in the future and could pose a threat to the scheme at Trout Beck located directly downstream of Sample Location 4 (Plate 51: Combined Particle Size Distribution curves for each gravel sampling site on Trout Beck).

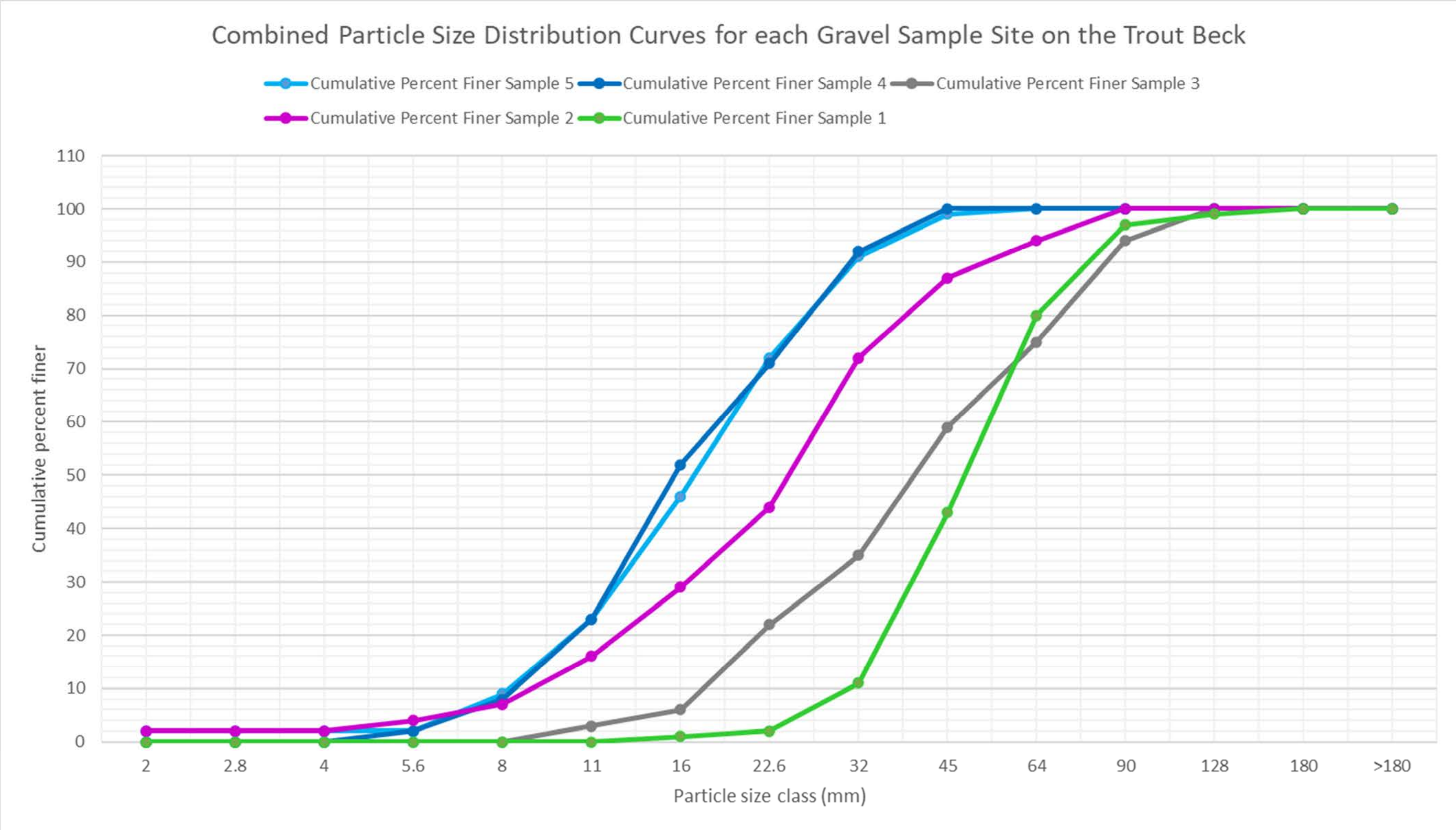


Plate 51: Combined Particle Size Distribution curves for each gravel sampling site on Trout Beck

Table 3: D10, D50 and D90 particle size distribution values for each gravel bar sampling site on Trout Beck

Sample No.	D10 (mm)	D50 (median) (mm)	D90 (mm)
Sample 1	32	64	90
Sample 2	8	22.6	64
Sample 3	16	45	90
Sample 4	8	16	32
Sample 5	8	16	32

Table 4: D10, D50 and D90 particle size distribution classes for each gravel bar sampling site on Trout Beck

Sample No.	D10 (mm)	D50 (median) (mm)	D90 (mm)
Sample 1	Coarse Gravel	Very Coarse Gravel	Small Cobble
Sample 2	Fine Gravel	Coarse Gravel	Very Coarse Gravel
Sample 3	Medium Gravel	Very Coarse Gravel	Small Cobble
Sample 4	Fine Gravel	Medium Gravel	Coarse Gravel
Sample 5	Fine Gravel	Medium Gravel	Coarse Gravel

Table 5: Millimetre size ranges for different sediment sizes

Sediment description	Size (mm)
Coarse Sand	0.5 to 2.0
Gravel	2.0 to 16.0
Pebbles	16.0 to 64.0
Cobbles	64.0 to 256.0
Boulders	>256.0

Keld Sike sediment sample analysis

14.9.2.110 Based on the D10, D50 and D90 values for both sample locations on the Keld Sike, a pattern in sediment size distribution across the watercourse is discernible. The most upstream sample site, Sample Location 2 has the coarsest particle size distribution, with 90% of the samples measuring <90mm, 50% measuring 45mm and 10% measuring 5.6mm (Table 6). In comparison the particle size distribution at Sample Location 1 is much finer, with 90% of the samples measuring <45mm, 50% measuring and 10% measuring 5.6mm (Table 6). This pattern is reinforced by the cumulative particle size plots displayed in Plate 52, which illustrates that particle sizes in the upstream sample location (Sample Location 2) are generally coarser than Sample Location 1. Despite the variation in particle size, the range of sediment clasts at both locations shows little variation. Table 6 reveals that the D90 and D10 for both sample locations range from Very Coarse Gravel to Medium Gravel. As such, whilst the particle size distribution identifies variations in the size of material, the general composition of gravels bars at both sample locations is broadly similar.

14.9.2.111 Sample Location 2 is located within the woodland area in Reach 1 of the Keld Sike. The site based morphological assessment of Reach 1 identified this reach to have a steep channel gradient and a relatively stable channel planform. This ensures that in-channel velocities are maintained high enough to keep fine material in suspension and transported to downstream reaches where in-channel velocities reduce.

14.9.2.112 Conditions at Sample Location 1 are largely similar to morphological conditions identified in Sample Location 2. The site based morphological assessment of Reach 2 identified this reach to have a steep channel gradient and a relatively stable, straight channel planform, as a result of a confined valley. This ensures that in-channel velocities are maintained high enough to keep fine material in suspension and transported to downstream reaches where in-channel velocities reduce. This leaves only the coarsest material left to populate the gravel bars in upstream reaches, where the material is too large to be mobilised and transported to downstream reaches.

14.9.2.113 The similar morphological conditions identified at Sample Locations 1 and 2 ensure that the composition and range of sediment sizes at gravel bars are broadly similar, ranging from Very Coarse Gravel to Medium Gravel.

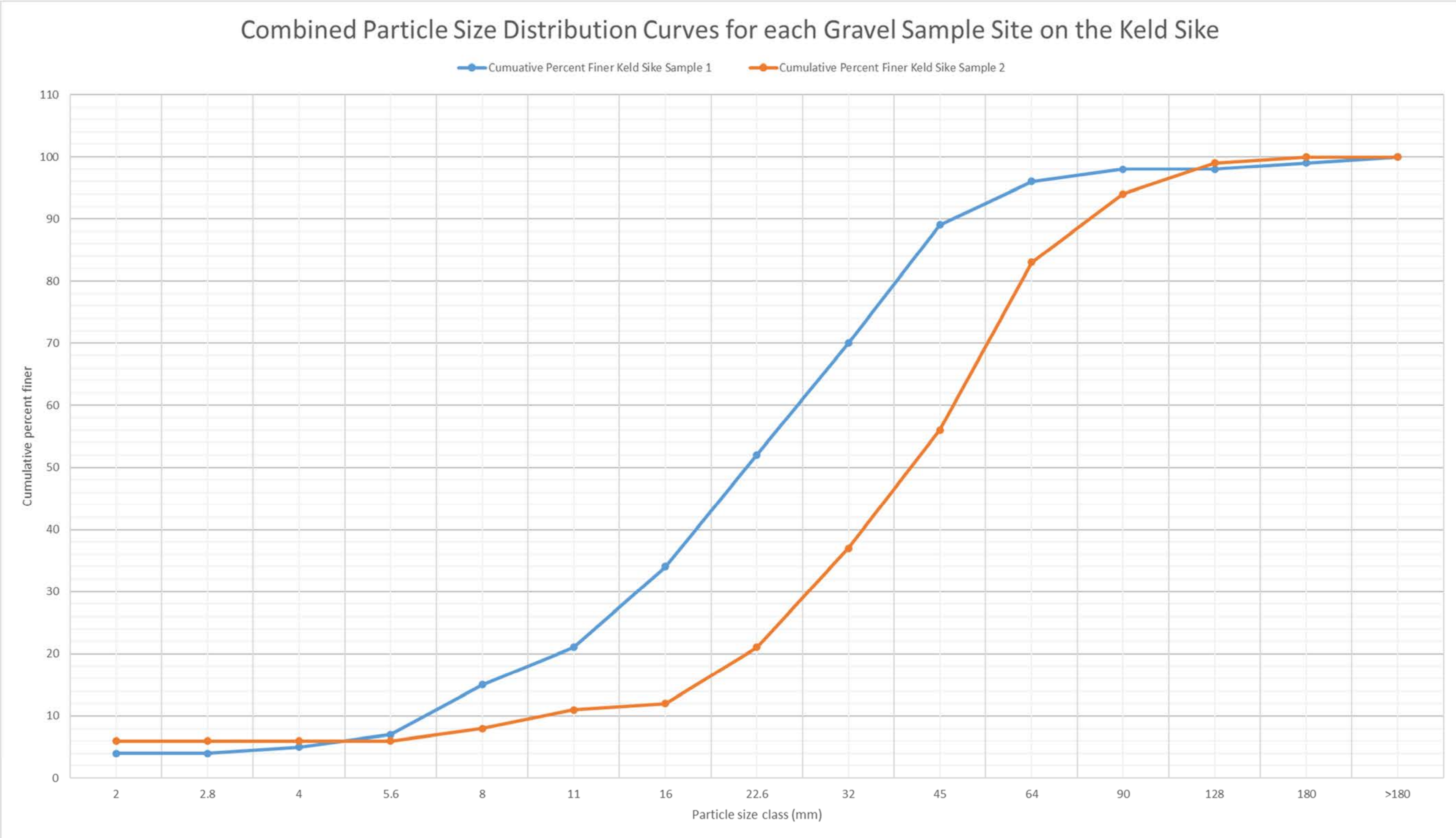


Plate 52: Combined Particle Size Distribution curves for each gravel sampling site on Keld Sike

Table 6: D10, D50 and D90 particle size distribution values for each gravel bar sampling sites on the Keld Sike

Sample No.	D10 (mm)	D50 (median) (mm)	D90 (mm)
Sample 1	5.6	22.6	45
Sample 2	11	45	90

Table 7: D10, D50 and D90 particle size distribution classes for each gravel bar sampling sites on the Keld Sike

Sample No.	D10 (mm)	D50 (median) (mm)	D90 (mm)
Sample 1	Medium Gravel	Coarse Gravel	Very Coarse Gravel
Sample 2	Medium Gravel	Very Coarse Gravel	Very Coarse Gravel

Table 8: Millimetre size ranges for different sediment sizes

Sediment description	Size (mm)
Coarse Sand	0.5 to 2.0
Gravel	2.0 to 16.0
Pebbles	16.0 to 64.0
Cobbles	64.0 to 256.0
Boulders	>256.0

Risk to the Trout Beck Viaduct from existing geomorphological processes

14.9.2.114 Plate 53: Analysis of potential risk posed to the scheme by local geomorphological processes provides an overview of the risks associated with existing geomorphological processes to the Trout Beck Viaduct. Existing bank instability, erosion and active zones on the Trout Beck in the vicinity of the structure increase the likelihood of channel planform migration in the future.

14.9.2.115 Appropriate mitigation and monitoring measures have been stipulated in the mitigation measures section.

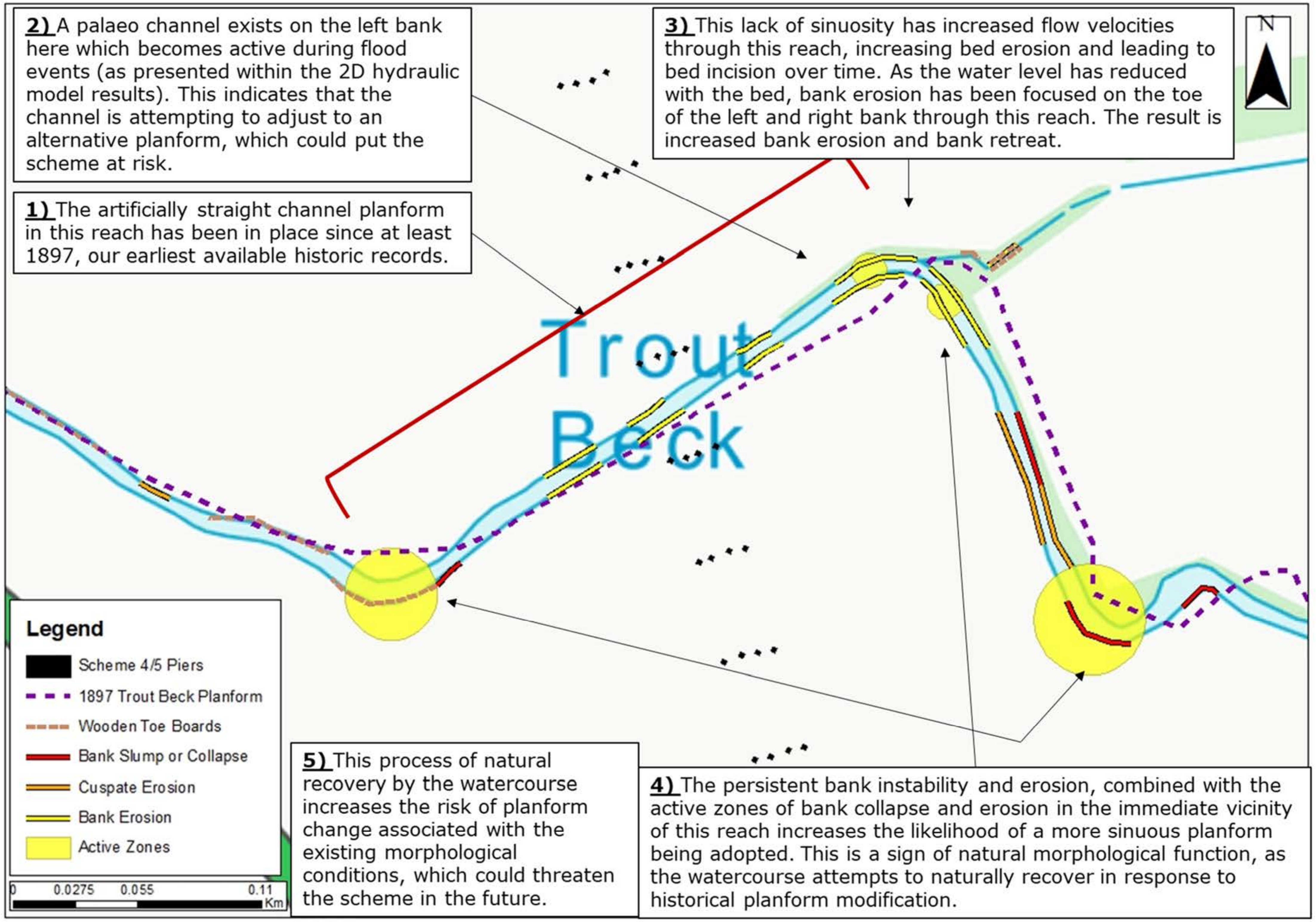


Plate 53: Analysis of potential risk posed to the scheme by local geomorphological processes

Analysis of hydraulic model results

Overview

14.9.2.116 A hydraulic model of Trout Beck, Keld Sike and the River Eden was developed for the purposes of this study.

14.9.2.117 Two scenarios have been modelled to assist with the geomorphological analysis, outlined below:

- Baseline scenario – existing conditions on Trout Beck, Keld Sike and the River Eden have been replicated
- Post Development scenario – representation of the scheme on the floodplain of Trout Beck

14.9.2.118 For the purposes of the geomorphological assessment of the hydraulic model results, the model has been run for the combined flood event scenarios outlined in Table 9: List of the Flood Event Scenarios simulated in the hydraulic model for geomorphological analyses. For each flood return period combination used for the hydraulic model analysis, a 1-in-2 year flood return period was maintained on the River Eden to minimise the influence of the River Eden on flood depths, velocities and shear stress in Trout Beck.

Table 9: List of the Flood Event Scenarios simulated in the hydraulic model for geomorphological analyses

Flood Event on Trout Beck	Flood Event on the River Eden	Name of the combined Flood Event Scenario simulated in the hydraulic model
1-in-2 Year	1-in-2 Year	Trout Beck 1-in-2 Year and River Eden 1-in-2 Year Scenario
1-in-10 Year	1-in-2 Year	Trout Beck 1-in-10 Year and River Eden 1-in-2 Year Scenario
1-in-20 Year	1-in-2 Year	Trout Beck 1-in-20 Year and River Eden 1-in-2 Year Scenario

14.9.2.119 In order to gain an understanding of how the scheme will impact geomorphological function and processes of Trout Beck and Keld Sike, comparisons between existing conditions and post development conditions on Trout Beck were completed to gauge how the watercourse is likely to change. An assessment of shear stress, mobile grain sizes, velocities and depth were undertaken to understand how sediment transport dynamics, riverbed scour and deposition, riverbank erosion and channel planform change is likely to change following the completion of the scheme.

Analysis of in-channel shear stress and mobile grain sizes

14.9.2.120 A comparison of hydraulically modelled sediment entrainment sizes was undertaken assess the potential impact to the riverbed substrate on Trout Beck and Keld Sike in the vicinity of the scheme.

14.9.2.121 Plate 54: Comparison of hydraulically modelled sediment entrainment size for the River Eden 1-in-2 Year and Trout Beck 1-in-2 Year Flood Event, Plate 55: Comparison of hydraulically modelled sediment entrainment size for the River Eden 1-in-2 Year and Trout Beck 1-in-10 Year Flood Event and Plate 56: Comparison of hydraulically modelled sediment entrainment size for the River Eden 1-in-2 Year and Trout Beck 1-in-20 Year Flood Event, provide a comparison of hydraulically modelled entrained sediment sizes within the channel of Trout Beck and the Keld Sike, for existing baseline conditions and predicted future change in the vicinity of the scheme. This comparison facilitates an assessment of the potential impacts on the riverbed substrate and sediment transport dynamics to assess the potential impact to the riverbed substrate.

14.9.2.122 The in-channel sediment entrainment sizes analysed between Plate 54: Comparison of hydraulically modelled sediment entrainment size for the River Eden 1-in-2 Year and Trout Beck 1-in-2 Year Flood Event, Plate 55: Comparison of hydraulically modelled sediment entrainment size for the River Eden 1-in-2 Year and Trout Beck 1-in-10 Year Flood Event and Plate 56: Comparison of hydraulically modelled sediment entrainment size for the River Eden 1-in-2 Year and Trout Beck 1-in-20 Year Flood Event have been calculated using the following flood return period combinations:

- Trout Beck 1-in-2 Year and River Eden 1-in-2 Year scenario (Plate 54: Comparison of hydraulically modelled sediment entrainment size for the River Eden 1-in-2 Year and Trout Beck 1-in-2 Year Flood Event)
- Trout Beck 1-in-10 Year and River Eden 1-in-2 Year scenario (Plate 55: Comparison of hydraulically modelled sediment entrainment size for the River Eden 1-in-2 Year and Trout Beck 1-in-10 Year Flood Event)
- Trout Beck 1-in-20 Year and River Eden 1-in-2 Year scenario (Plate 56: Comparison of hydraulically modelled sediment entrainment size for the River Eden 1-in-2 Year and Trout Beck 1-in-20 Year Flood Event)

14.9.2.123 Maximum velocity and depth outputs from the hydraulic model have been used, along with a roughness estimate (Manning's n) [1] to calculate an effective bed shear derived from the following quadratic expression (Lane and Ferguson, 2005) [2]:

$$\tau_o = \rho g \frac{n^2}{d^{1/3}} v^2$$

[1] Manning, R. (1889), On the flow of water in open channels and pipes. Transactions of the Institution of Civil Engineers of Ireland, 20, 161-195.
[2] Lane, S.N. and Ferguson, R.I. (2005), Modelling reach-scale fluvial flows. In Computational Fluid Dynamics: Applications in Environmental Hydraulics. Paul. D. Bates, Stuart N. Lane, Robert I. Ferguson (eds). John Wiley and Sons Ltd. ISBN 13 978-0-470-84359-8 (HB)

14.9.2.124 Where τ_0 is effective shear stress (N/m^2), ρ is density of water (kg/m^3), g is acceleration due to gravity (m/s^2), n is the Manning's coefficient (s/m$^{1/3}$), d is depth (m) and V is depth averaged velocity (m/s). This relation gives a very similar functional relationship to shear stresses derived on integrating flows assuming a logarithmic law of the wall.

14.9.2.125 The calculated bed shear stress can be used to predict the mobile sediment size when used in conjunction with Shield's (1936)[3] entrainment function, derived from the following expression:

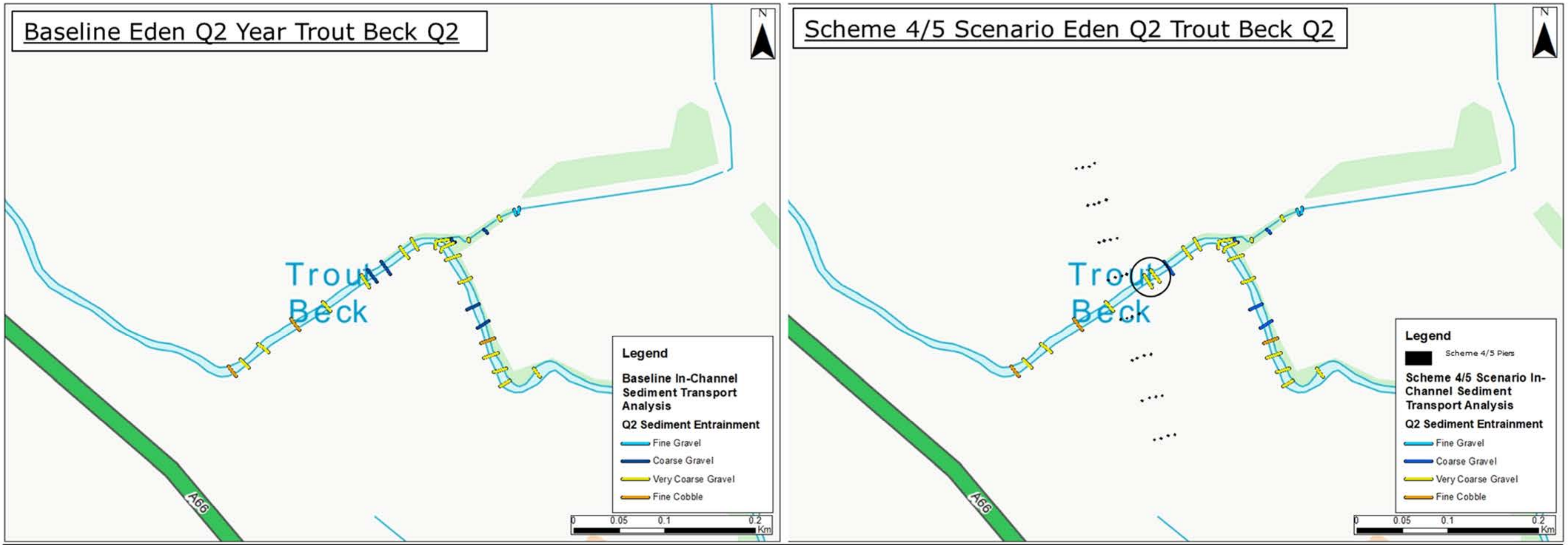
$$\tau_{0c} = \theta(\rho_s - \rho_w)gD$$

14.9.2.126 Where τ_{0c} is the critical shear stress (N/m^2), θ is the Shields parameter (non-dimensional), ρ_s is the density of sediment (kg/m^3), ρ_w is the density of water (kg/m^3) and, g is acceleration due to gravity (m/s^2) and D is a characteristic diameter of the sediment (mm). On hydraulically rough beds (the common condition in natural rivers), the Shields parameter rapidly attains a constant value (reported values range from 0.03 to 0.06), with 0.045 now accepted as a good approximation (Komar, 1988) [4].

14.9.2.127 Mobile grain sizes were calculated for the flood return period combinations highlighted in Table 9 using the method described above are presented in Plate 54 to Plate 56. Mobile grain sizes are banded according to the Wentworth (1922) classification.

[3] Shields, A. (1936), Anwendung der Aehnlichkeitsmechanik und der Turbulenzforschung auf die Geschiebebewegung, Mitt. Preuss. Versuchsanst. Wasserbau Schiffbau, 26, 36 pp.

[4] Komar, P.D. (1987) Selective entrainment by a current from a bed of mixed sizes: A reanalysis. Journal of Sedimentary Petrology, 57(2), 203-211.



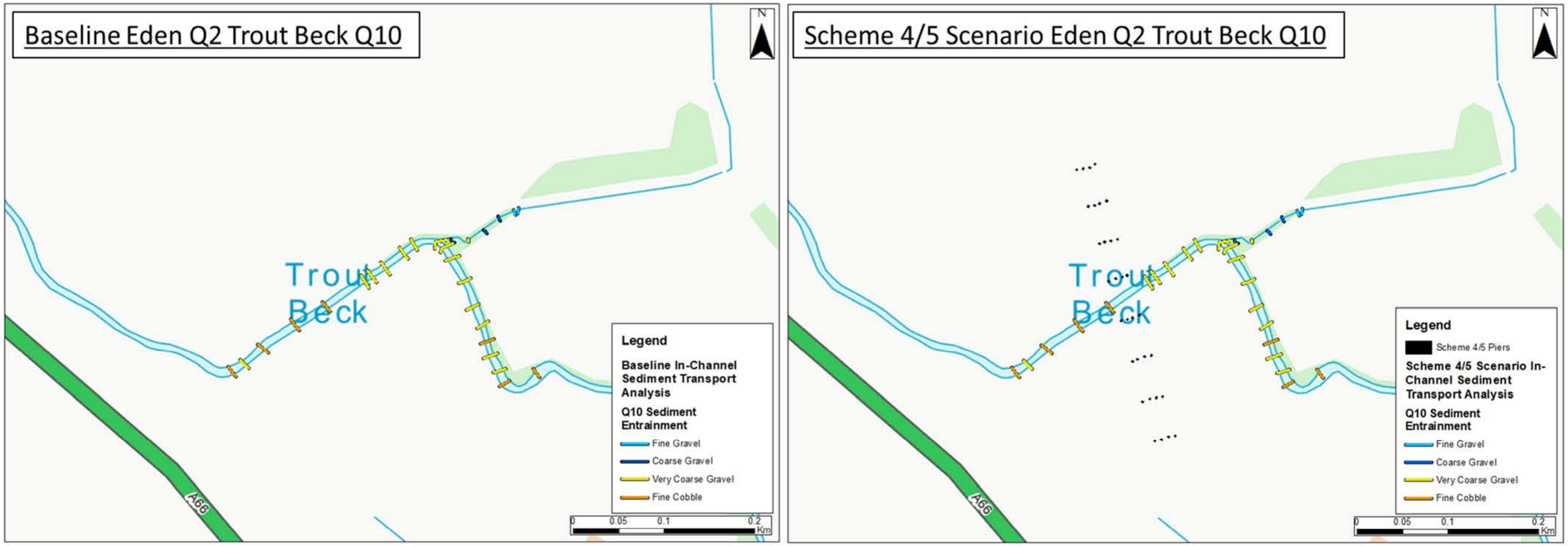
Key Changes in the Scheme 4/5 Scenario Compared to the Baseline

- Increase in the maximum size of sediment that can be entrained at one cross section located upstream of the scheme. Maximum sediment size that can be entrained increases from Coarse Gravel to Very Coarse Gravel. Indicated by black circle on map.

Implications for Riverbed Substrate Composition

- Site observations revealed that the typical bed substrate within the vicinity of the scheme piers ranges from gravels to cobbles. The hydraulic model results for this reach indicate that the maximum sediment size that can be entrained ranges between coarse gravels to fine cobbles. As there is minimal change to the maximum sediment size that can be entrained in the Scheme 4/5 Scenario compared to the Baseline Scenario, there is unlikely to be any change to the bed substrate composition within the vicinity of the scheme.

Plate 54: Comparison of hydraulically modelled sediment entrainment size for the River Eden 1-in-2 Year and Trout Beck 1-in-2 Year Flood Event



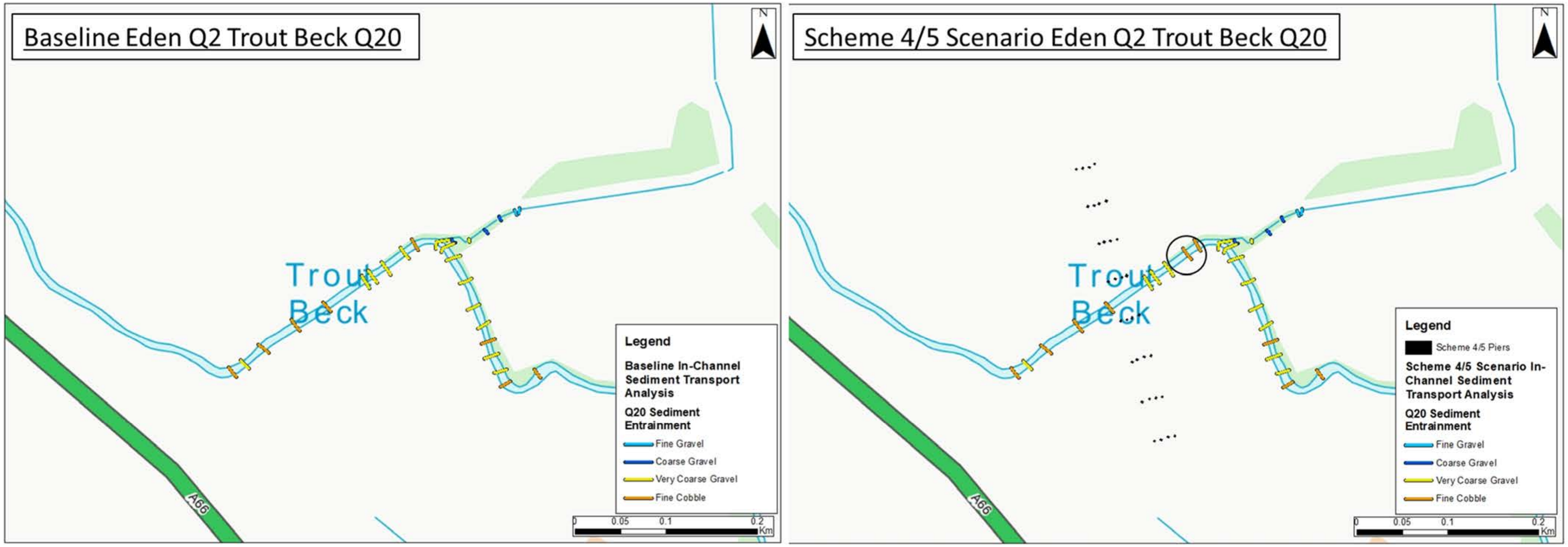
Key Changes in the Scheme 4/5 Scenario Compared to the Baseline

- Negligible.

Implications for Riverbed Substrate Composition

- Site observations revealed that the typical bed substrate within the vicinity of the scheme piers ranges from gravels to cobbles. The hydraulic model results for this reach indicate that the maximum sediment size that can be entrained ranges between coarse gravels to fine cobbles. As there is negligible change to the maximum sediment size that can be entrained in the Scheme 4/5 Scenario compared to the Baseline Scenario, there is unlikely to be any change to the bed substrate composition within the vicinity of the scheme.

Plate 55: Comparison of hydraulically modelled sediment entrainment size for the River Eden 1-in-2 Year and Trout Beck 1-in-10 Year Flood Event



Key Changes in the Scheme 4/5 Scenario Compared to the Baseline

- Increase in the maximum size of sediment that can be entrained at one cross section located upstream of the scheme. Maximum sediment size that can be entrained increases from Very Coarse Gravel to Fine Cobble. Indicated by black circle on map.

Implications for Riverbed Substrate Composition

- Site observations revealed that the typical bed substrate within the vicinity of the scheme piers ranges from gravels to cobbles. The hydraulic model results for this reach indicate that the maximum sediment size that can be entrained ranges between coarse gravels to fine cobbles. As there is minimal change to the maximum sediment size that can be entrained in the Scheme 4/5 Scenario compared to the Baseline Scenario, there is unlikely to be any change to the bed substrate composition within the vicinity of the scheme.

Plate 56: Comparison of hydraulically modelled sediment entrainment size for the River Eden 1-in-2 Year and Trout Beck 1-in-20 Year Flood Event

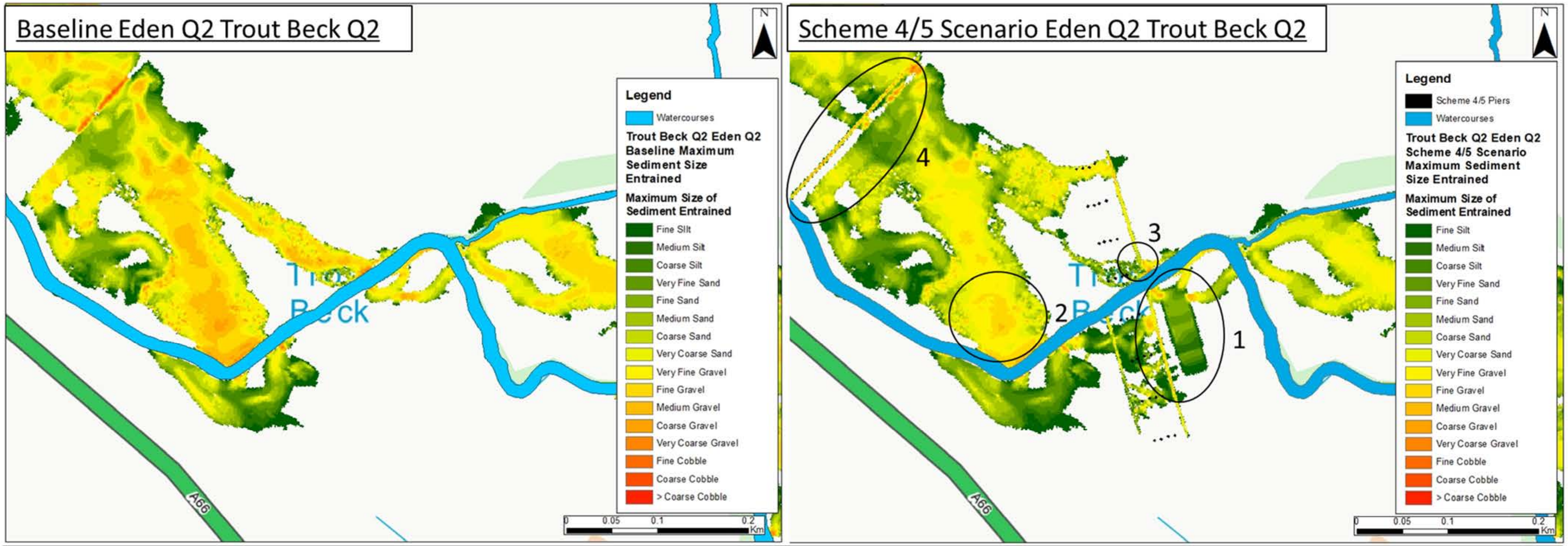
Analysis of floodplain shear stress and mobile grain sizes

14.9.2.128 Plate 57: Comparison of hydraulically modelled sediment entrainment size on the floodplain for the River Eden 1-in-2 Year and Trout Beck 1-in-2 Year Flood Event, Plate 58: Comparison of hydraulically modelled sediment entrainment size on the floodplain for the River Eden 1-in-2 Year and Trout Beck 1-in-10 Year Flood Event and Plate 59: Comparison of hydraulically modelled sediment entrainment size on the floodplain for the River Eden 1-in-2 Year and Trout Beck 1-in-20 Year Flood Event provide a comparison of hydraulically modelled entrained sediment sizes on the floodplain of Trout Beck and Keld Sike, for existing baseline conditions and predicted future change in the vicinity of the at scheme. This comparison facilitates an assessment of the potential impacts on floodplain erosional and depositional processes as a result of the scheme's viaduct piers.

14.9.2.129 The floodplain sediment entrainment sizes analysed between Plate 57: Comparison of hydraulically modelled sediment entrainment size on the floodplain for the River Eden 1-in-2 Year and Trout Beck 1-in-2 Year Flood Event, Plate 58: Comparison of hydraulically modelled sediment entrainment size on the floodplain for the River Eden 1-in-2 Year and Trout Beck 1-in-10 Year Flood Event and Plate 59: Comparison of hydraulically modelled sediment entrainment size on the floodplain for the River Eden 1-in-2 Year and Trout Beck 1-in-20 Year Flood Event have been calculated using the following flood return period combinations:

- Trout Beck 1-in-2 Year and River Eden 1-in-2 Year scenario (Plate 57: Comparison of hydraulically modelled sediment entrainment size on the floodplain for the River Eden 1-in-2 Year and Trout Beck 1-in-2 Year Flood Event)
- Trout Beck 1-in-10 Year and River Eden 1-in-2 Year scenario (Plate 58: Comparison of hydraulically modelled sediment entrainment size on the floodplain for the River Eden 1-in-2 Year and Trout Beck 1-in-10 Year Flood Event)
- Trout Beck 1-in-20 Year and River Eden 1-in-2 Year scenario (Plate 59: Comparison of hydraulically modelled sediment entrainment size on the floodplain for the River Eden 1-in-2 Year and Trout Beck 1-in-20 Year Flood Event)

14.9.2.130 Mobile grain sizes were calculated for the flood return period combinations highlighted in the list above. Mobile grain sizes are banded according to the Wentworth (1922) classification.



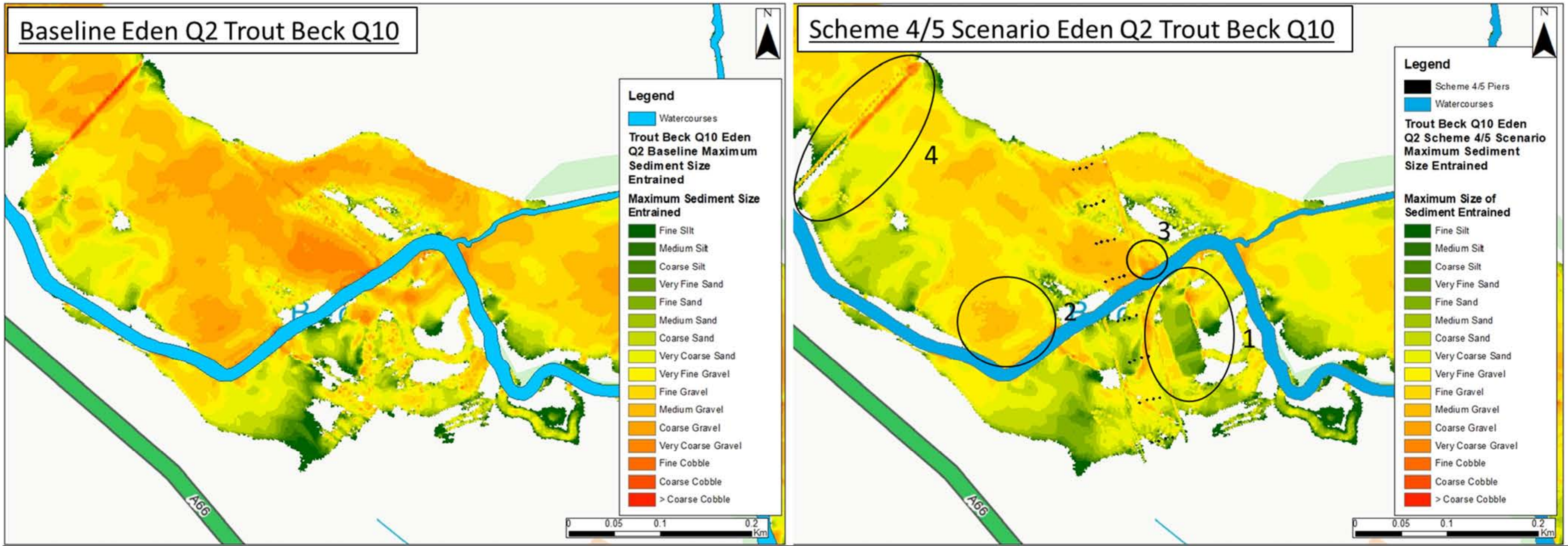
Key Changes in the Scheme 4/5 Scenario Compared to the Baseline

- The installation of a flood compensation structure on the left bank floodplain (identified in black circle 1) generates a new overland flow route and variations in the size of material that can be mobilised. The typical sizes of material that can be entrained in the new overland flow route on the left bank floodplain range from silts to sands. The establishment of this new overland flow route on the left bank means that more water is conveyed and stored on the left bank. The increased conveyance of water onto the left bank floodplain reduces the total volume of water conveyed on the right bank (identified in black circle 2). The result is reductions in the size of material that can be mobilised reducing from Coarse to Medium Gravel in the baseline scenario to Very Fine Gravel to Very Coarse Sand.
- Water that previously spilled directly from the Trout Beck channel into the right bank floodplain now enters the drainage channel discharging from the right bank first (identified in black circle 3), leading to a reduction in flow velocities in the existing overland flow route. A new overland flow route is established further to the north. As a result, there are changes in the size of material that can be mobilised on the right bank floodplain of the Trout Beck, reducing from Coarse to Medium Gravel in the baseline scenario to Very Fine Gravel to Very Coarse Sand.
- The drainage channel that has been installed along the access track in the north west (identified in black circle 4) disrupts overland flow routes. Water that previously spilled directly across the access track now enters this drainage channel first, which conveys more water back into the Trout Beck. This further contributes to the reduction in the sizes of material that can be mobilised.

Predicted Geomorphological Change

- No detrimental impacts. The right bank floodplain remains active during the Eden Q2 Trout Beck Q2 flood event across a broadly similar extent. Therefore the changes to sediment entrainment dynamics are unlikely to significantly impact existing geomorphological processes on the floodplain or in the channel.

Plate 57: Comparison of hydraulically modelled sediment entrainment size on the floodplain for the River Eden 1-in-2 Year and Trout Beck 1-in-2 Year Flood Event



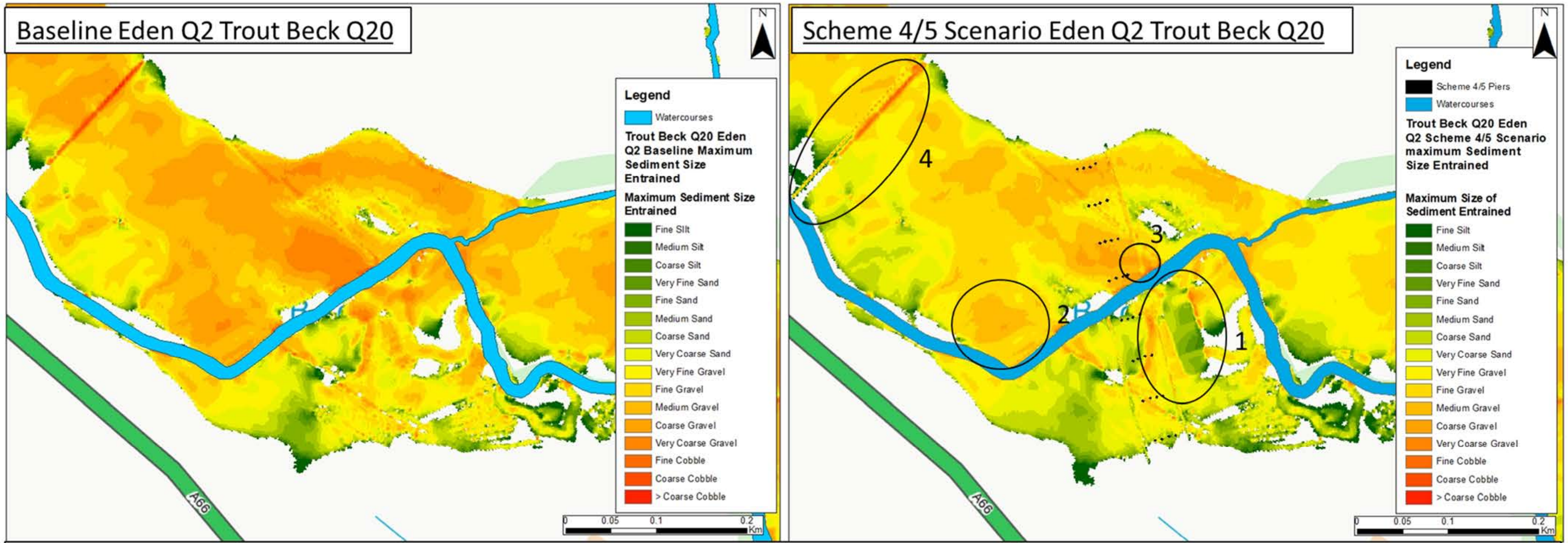
Key Changes in Scheme 4/5 Scenario Compared to the Baseline

- The installation of the flood compensation structure on the left bank floodplain (identified in black circle 1) encourages more water to enter the left bank and a new overland flow route is created. The establishment of this new overland flow route on the left bank means that more water is conveyed and stored on the left bank. The increased conveyance of water onto the right bank reduces the total volume of water conveyed on the right bank (identified in black circle 2). The result is reductions in the size of material that can be mobilised reducing from Fine Cobble and Very Coarse Gravel in the baseline scenario to Medium Gravel and Fine Gravel.
- The drainage channel discharging into the right bank of the Trout Beck (identified in black circle 3) disrupts the existing overland flow route. Water that previously spilled directly from the Trout Beck channel into the right bank floodplain now enters this drainage channel first, leading to the reduction in shear stresses in the existing overland flow route.
- The installation of a drainage channel along the access track in the north west (identified in black circle 4) disrupts the existing overland flow route across the right bank floodplain of the Trout Beck. Water that previously spilled directly across the access track now enters this drainage channel first, which conveys more water back into the Trout Beck, and less water is conveyed across the floodplain to the west of the access road. This results in a reduction in shear stress values and the size of material that can be mobilised, reducing from Fine Cobble and Very Coarse Gravel in the baseline scenario to Medium Gravel to Very Fine Gravel.

Predicted Geomorphological Change

- No detrimental impacts. The right bank floodplain remains active during the Eden Q2 Trout Beck Q10 flood event across a broadly similar footprint. Therefore the changes to sediment entrainment dynamics are unlikely to significantly impact existing geomorphological processes on the floodplain or in the channel.

Plate 58: Comparison of hydraulically modelled sediment entrainment size on the floodplain for the River Eden 1-in-2 Year and Trout Beck 1-in-10 Year Flood Event



Key Changes in the Scheme 4/5 Scenario Compared to the Baseline

- The installation of the flood compensation structure on the left bank floodplain (identified in black circle 1) encourages more water to enter the left bank and a new overland flow route is created. The establishment of this new overland flow route on the left bank means that more water is conveyed and stored on the left bank. The increased conveyance of water onto the right bank reduces the total volume of water conveyed on the right bank (identified in black circle 2). The result is reductions in the size of material that can be mobilised reducing from Fine Cobble and Very Coarse Gravel in the baseline scenario to Medium Gravel and Coarse Sand.
- The drainage channel discharging into the right bank of the Trout Beck (identified in black circle 3) disrupts the existing overland flow route. Water that previously spilled directly from the Trout Beck channel into the right bank floodplain now enters this drainage channel first, leading to the reduction in shear stresses in the existing overland flow route.
- The installation of a drainage channel along the access track in the north west (identified in black circle 4) disrupts the existing overland flow route across the right bank floodplain of the Trout Beck. Water that previously spilled directly across the access track now enters this drainage channel first, which slows the flow down and conveys more water back into the Trout Beck. This impounds water to the east of the drainage channel, resulting in a reduction in shear stress values and the size of material that can be mobilised.

Predicted Geomorphological Change

- No detrimental impacts. Whilst there will be changes to the size of material that can be mobilised in overland flow routes, the right bank floodplain remains active during the Eden Q2 Trout Beck Q20 flood event across a broadly similar footprint. Therefore the changes to sediment entrainment dynamics are unlikely to significantly impact existing geomorphological processes on the floodplain or in the channel.

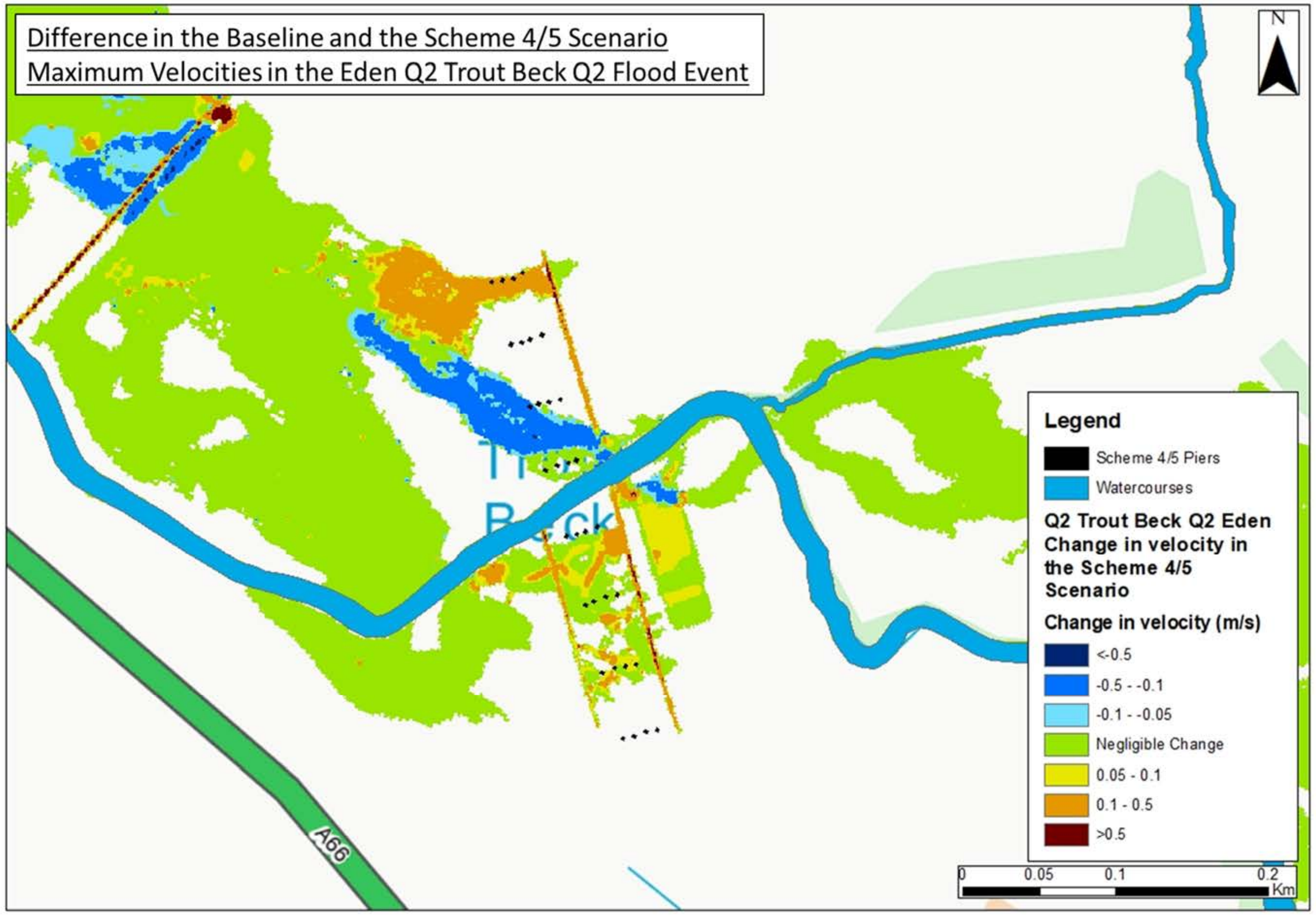
Plate 59: Comparison of hydraulically modelled sediment entrainment size on the floodplain for the River Eden 1-in-2 Year and Trout Beck 1-in-20 Year Flood Event

Analysis of floodplain velocities

14.9.2.131 Plate 60: Comparison of hydraulically modelled velocities size on the floodplain for the River Eden 1-in-2 Year and Trout Beck 1-in-2 Year Flood Event, Plate 61: Comparison of hydraulically modelled velocities size on the floodplain for the River Eden 1-in-2 Year and Trout Beck 1-in-10 Year Flood Event and Plate 62: Comparison of hydraulically modelled velocities size on the floodplain for the River Eden 1-in-2 Year and Trout Beck 1-in-20 Year Flood Event provide a comparison of hydraulically modelled velocities to assess the potential impact erosion and scour on the floodplain, for existing baseline conditions and predicted future change. in the vicinity of the scheme. The maximum velocities in the scheme (post-development) hydraulic model scenario were subtracted from the maximum velocities in the baseline hydraulic model scenario, to provide a velocity difference grid. This comparison allows an assessment of the potential impacts on floodplain erosional and depositional processes as a result of the scheme's viaduct piers. The velocity comparison figures presented below only include comparisons in areas of flooding present in both the baseline and post-development scenarios.

14.9.2.132 The differences in floodplain velocities analysed between Plate 60: Comparison of hydraulically modelled velocities size on the floodplain for the River Eden 1-in-2 Year and Trout Beck 1-in-2 Year Flood Event, Plate 61: Comparison of hydraulically modelled velocities size on the floodplain for the River Eden 1-in-2 Year and Trout Beck 1-in-10 Year Flood Event and Plate 62: Comparison of hydraulically modelled velocities size on the floodplain for the River Eden 1-in-2 Year and Trout Beck 1-in-20 Year Flood Event have been calculated using the following flood return period combinations:

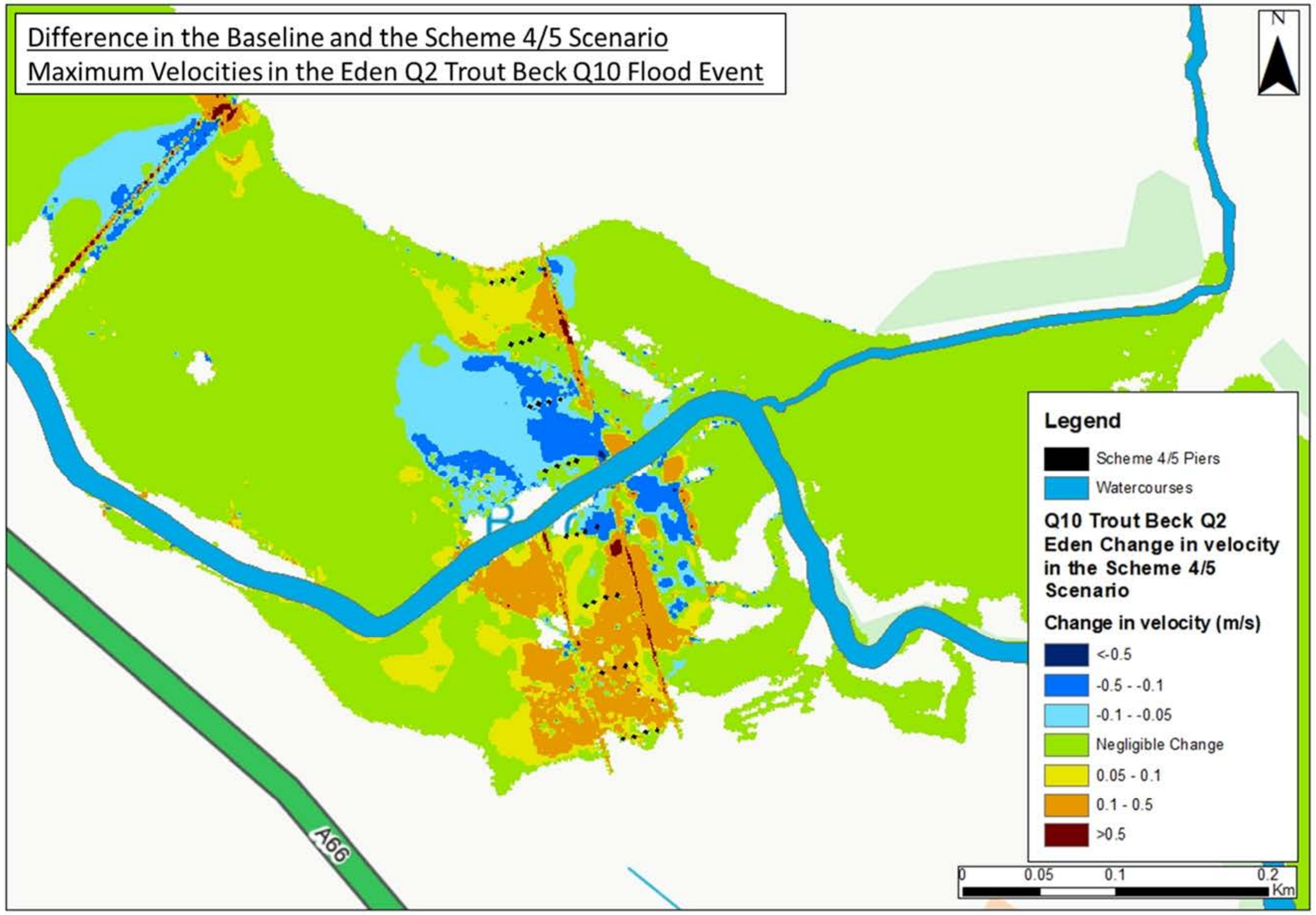
- Trout Beck 1-in-2 Year and River Eden 1-in-2 Year Scenario (Plate 60: Comparison of hydraulically modelled velocities size on the floodplain for the River Eden 1-in-2 Year and Trout Beck 1-in-2 Year Flood Event)
- Trout Beck 1-in-10 Year and River Eden 1-in-2 Year Scenario (Plate 61: Comparison of hydraulically modelled velocities size on the floodplain for the River Eden 1-in-2 Year and Trout Beck 1-in-10 Year Flood Event)
- Trout Beck 1-in-20 Year and River Eden 1-in-2 Year Scenario (Plate 62: Comparison of hydraulically modelled velocities size on the floodplain for the River Eden 1-in-2 Year and Trout Beck 1-in-20 Year Flood Event)



Key Changes in the Scheme 4/5 Scenario Compared to the Baseline

- There are localised changes in flow velocities in the vicinity of the flood compensation structure on the left bank of the Trout Beck. Velocities increase as more water spills into the flood compensation structure from the channel, and subsequently decrease as water pools in the structure.
- On the right bank of the Trout Beck, flow velocities reduce significantly. The drainage channel discharging into the right bank of the Trout Beck disrupts the existing overland flow route. Water that previously spilled directly from the Trout Beck channel into the right bank floodplain now enters this drainage channel first, leading to the reduction in flow velocities in the existing overland flow route.
- The installation of a drainage channel along the access track in the north west of the map disrupts the existing overland flow route across the right bank floodplain of the Trout Beck. Water that previously spilled directly across the access track now enters this drainage channel first, which conveys more water back into the Trout Beck. The result is a reduction in flow velocities in the existing overland flow route.
- **Predicted Geomorphological Change**
- No detrimental impacts. Whilst there will be changes to flow velocities in overland flow routes, the right bank floodplain remains active during the Eden Q2 Trout Beck Q2 flood event across a broadly similar footprint. Therefore the changes to sediment entrainment dynamics are unlikely to impact existing geomorphological processes on the floodplain or in the channel.

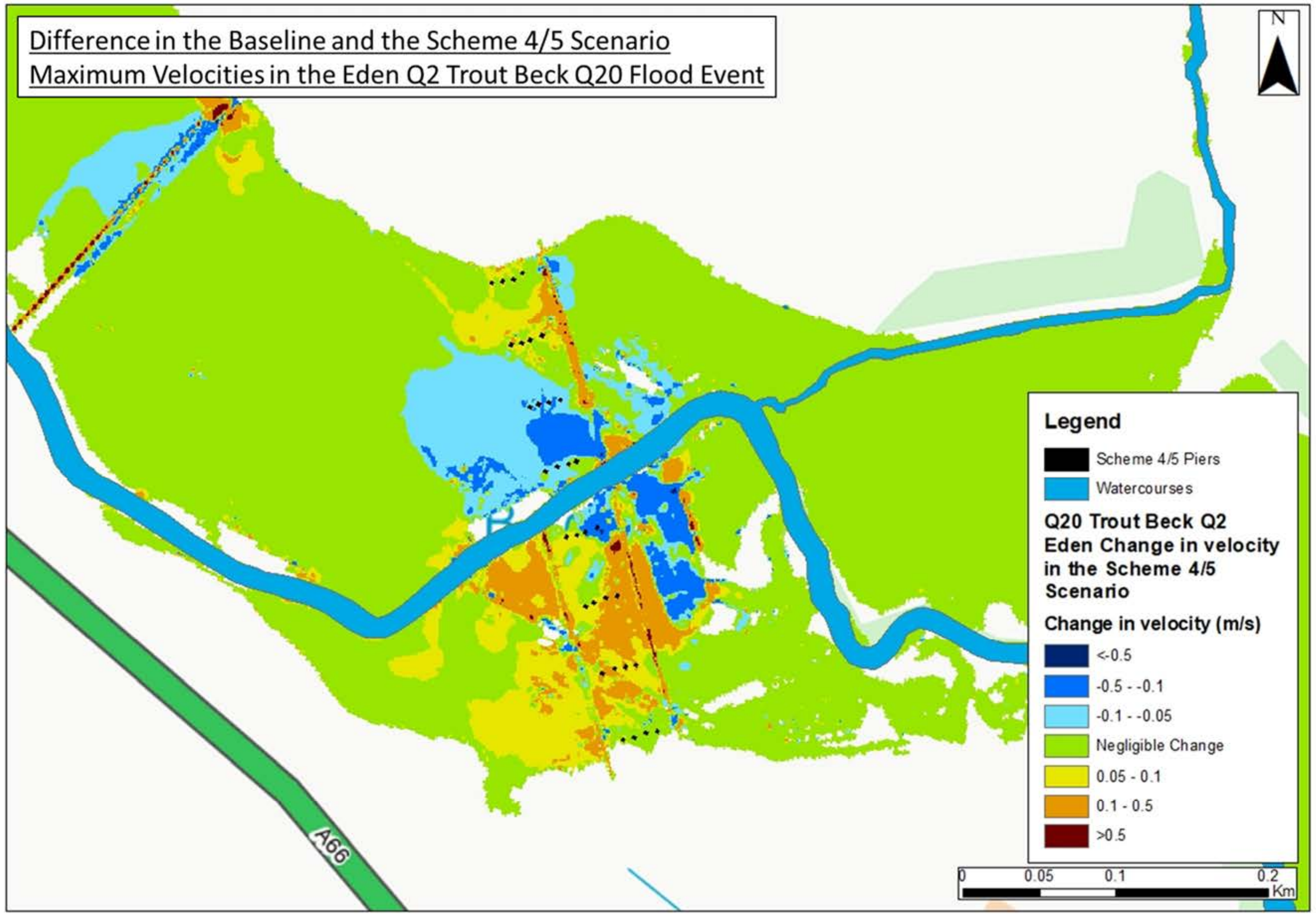
Plate 60: Comparison of hydraulically modelled velocities size on the floodplain for the River Eden 1-in-2 Year and Trout Beck 1-in-2 Year Flood Event



Key Changes in the Scheme 4/5 Scenario Compared to the Baseline

- There are significant changes in flow velocities in the vicinity of the flood compensation structure on the left bank of the Trout Beck. Velocities increase as more water spills into the flood compensation structure from the channel, and subsequently decrease as water pools in the structure. A new overland flow route is established to the west and south of the flood compensation structure, leading to increases in velocities on the left bank floodplain in this area.
- On the right bank of the Trout Beck, flow velocities change significantly. The drainage channel discharging into the right bank of the Trout Beck disrupts the existing overland flow route. Water that previously spilled directly from the Trout Beck channel into the right bank floodplain now enters this drainage channel first, leading to the reduction in flow velocities in the existing overland flow route. A new overland flow route is established further to the north, leading to increases in flow velocities in this area.
- The installation of a drainage channel along the access track in the north west of the map disrupts the existing overland flow route across the right bank floodplain of the Trout Beck. Water that previously spilled directly across the access track now enters this drainage channel first, which conveys more water back into the Trout Beck. The result is a reduction in flow velocities in the existing overland flow route.
- **Predicted Geomorphological Change**
- No detrimental impacts. Whilst there will be changes to flow velocities in overland flow routes, the right bank floodplain remains active during the Eden Q2 Trout Beck Q10 flood event across a broadly similar footprint. Therefore the changes to sediment entrainment dynamics are unlikely to impact existing geomorphological processes on the floodplain or in the channel.

Plate 61: Comparison of hydraulically modelled velocities size on the floodplain for the River Eden 1-in-2 Year and Trout Beck 1-in-10 Year Flood Event



Key Changes in the Scheme 4/5 Scenario Compared to the Baseline

- There are significant changes in flow velocities in the vicinity of the flood compensation structure on the left bank of the Trout Beck. Velocities increase as more water spills into the flood compensation structure from the channel, and subsequently decrease as water pools in the structure. A new overland flow route is established to the west and south of the flood compensation structure, leading to increases in velocities on the left bank floodplain in this area.
- On the right bank of the Trout Beck, flow velocities change significantly. The drainage channel discharging into the right bank of the Trout Beck disrupts the existing overland flow route. Water that previously spilled directly from the Trout Beck channel into the right bank floodplain now enters this drainage channel first, leading to the reduction in flow velocities in the existing overland flow route. A new overland flow route is established further to the north, leading to increases in flow velocities in this area.
- The installation of a drainage channel along the access track in the north west of the map disrupts the existing overland flow route across the right bank floodplain of the Trout Beck. Water that previously spilled directly across the access track now enters this drainage channel first, which conveys more water back into the Trout Beck. The result is a reduction in flow velocities in the existing overland flow route.
- **Predicted Geomorphological Change**
- No detrimental impacts. Whilst there will be changes to flow velocities in overland flow routes, the right bank floodplain remains active during the Eden Q2 Trout Beck Q20 flood event across a broadly similar footprint. Therefore the changes to sediment entrainment dynamics are unlikely to impact existing geomorphological processes on the floodplain or in the channel.

Plate 62: Comparison of hydraulically modelled velocities size on the floodplain for the River Eden 1-in-2 Year and Trout Beck 1-in-20 Year Flood Event

Analysis of flood depths

14.9.2.133 Plate 63: Change in flood depths in the post-development scenario during Trout Beck 100-year plus 94% climate change event shows the change in flood depth between the baseline and post-development option for the River Eden 20-year plus 94% climate change event combined with the Trout Beck 100-year plus 94% climate change event.

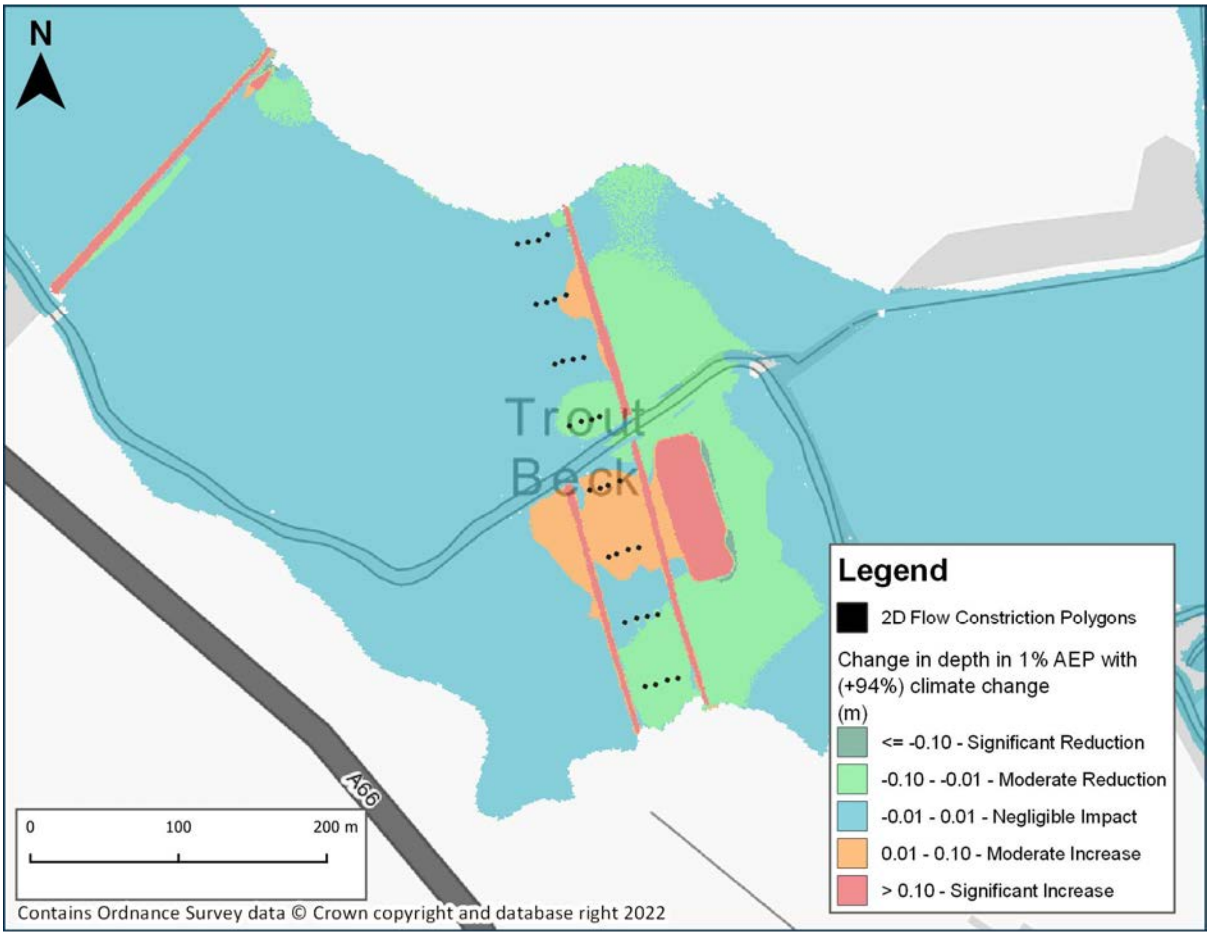


Plate 63: Change in flood depths in the post-development scenario during Trout Beck 100-year plus 94% climate change event

14.9.2.134 Plate 63: Change in flood depths in the post-development scenario during Trout Beck 100-year plus 94% climate change event shows that during the Trout Beck 100-year plus 94% climate change event, the post-development scenario is predicted to result in negligible changes in flood depths across the majority of the floodplain. Moderate increases are predicted in the vicinity of the proposed flood attenuation pond and ditches, this is likely to be a result of water being drawn in by the lowered ground levels. However, predicted increases in flood depths during the 100-year plus 94% climate change event are localised, within areas already at flood risk and within the Order Limits.

Conclusions from hydraulic model analysis

14.9.2.135 Based on the analyses presented in the previous chapters, the conclusions outlined below can be drawn regarding sediment transport dynamics, geomorphological function and implications for the scheme.

14.9.2.136 Comparison between the baseline and post development scenarios indicates that the typical range of sediment sizes that can be entrained in the channel are coarse gravels to fine cobbles. This is validated by the sediment sampling undertaken at Sample Location 4, located approximately 100m upstream of scheme, which indicated that 90% of material is coarse gravels or smaller. Not only does this provide more confidence in the hydraulic model results, but also indicates that there is unlikely to be a change to the bed substrate composition within the vicinity of scheme.

14.9.2.137 Existing overland flow routes on the floodplain in the vicinity of Trout Beck observed in the baseline scenario are disrupted by ground level changes in the post-development scenario. The flood compensation structure on the left bank floodplain captures more water on the left bank floodplain, and releases this to the south west of the flood compensation structure, establishing a new overland flow route which is capable of entraining material ranging from silts to sands. This reduces the total volume of water conveyed on the right bank floodplain, resulting in a reduction in the size of sediment that can be entrained, from Coarse Gravel and Medium Gravel to Very Fine Gravel and Very Coarse Sand.

14.9.2.138 Water that previously spilled directly from Trout Beck channel into the right bank floodplain now enters the drainage channel discharging from the right bank first, leading to a reduction in flow velocities in the existing overland flow route. A new overland flow route is established further to the north. Typical reductions in the size of material that can be mobilised on the right bank floodplain range from Coarse Gravel and Medium Gravel to Very Fine Gravel and Very Coarse Sand. The drainage channel that has been installed along the access track in the north west disrupts overland flow routes. Water that previously spilled directly across the access track now enters this drainage channel first, which conveys more water back into Trout Beck. This further contributes to the reduction in the sizes of material that can be mobilised on the right bank floodplain.

14.9.2.139 Despite these changes to sediment transport dynamics on the floodplain, existing geomorphological processes are unlikely to be significantly impacted and there is unlikely to be a detrimental impact to the composition of the floodplain. The right bank floodplain remains active during all assessed flood events across a broadly similar extent. Therefore, the changes to sediment entrainment dynamics are unlikely to impact existing geomorphological processes on the floodplain or in the channel.

14.9.2.140 Changes in flow velocities between the baseline and post development scenarios were identified in the vicinity of the flood compensation structure on the left bank of Trout Beck. Velocities increase as more water spills into the flood compensation structure from the channel, and subsequently decrease as water pools in the structure. A new overland flow route is established to the west and south of the flood compensation structure, leading to increases in velocities on the left bank floodplain in this area. As the severity of the flood event increases, the greater the extent of velocity variation across the left bank floodplain.

14.9.2.141 The drainage channel discharging into the right bank of Trout Beck disrupts the existing overland flow route. Water that previously spilled directly from Trout Beck channel into the right bank floodplain now enters this drainage channel first, leading to the reduction in flow velocities in the existing overland flow route. A new overland flow route is established further to the north, leading to increases in flow velocities in this area.

14.9.2.142 The installation of a drainage channel along the access track in the north west of the map disrupts the existing overland flow route across the right bank floodplain of Trout Beck. Water that previously spilled directly across the access track now enters this drainage channel first, which conveys more water back into Trout Beck. The result is a reduction in flow velocities in the existing overland flow route.

14.9.2.143 Despite these changes to velocities on the floodplain, variations in velocities are insufficient to effect changes to the floodplain through erosion or deposition in the events analysed. The right bank floodplain remains active during all assessed flood events across a broadly similar extent. Therefore, the changes to flow velocities are unlikely to impact existing geomorphological processes on the floodplain or in the channel.

14.9.2.144 Comparisons of flood depths between the baseline and post development scenario show that during Trout Beck 100-year plus 94% climate change event, the scheme is predicted to result in moderate increases in the vicinity of the proposed flood attenuation pond and ditches, this is likely to be a result of water being drawn in by the lowered ground levels. However, predicted increases in flood depths during the 100-year plus 94% climate change event are localised, within areas already at flood risk and within the Order Limits.

Conclusions

14.9.2.145 Following the analysis of morphological conditions on Trout Beck and Keld Sike in the desk-based assessment, site-based assessment and hydraulic modelling analysis, the following key conclusions can be drawn in relation to the scheme:

- There is evidence to suggest that Trout Beck in the vicinity of the scheme has been artificially straightened in the past and is undergoing natural recovery to restore a more natural, sinuous channel planform. This increases the risk of channel planform migration in the future, which could threaten the viaduct pier locations at Trout Beck crossing.

- The scheme is unlikely to generate significant morphological change within the river channel of Trout Beck and the Keld Sike. Small changes immediately upstream of the scheme are observed in the flood return period combination River Eden 1-in-2 Year and Trout Beck 1-in-2 Year. However, this is not significant enough to effect changes in the riverbed substrate composition, or in sediment transport dynamics in the immediate vicinity of the scheme.
- The scheme is unlikely to generate significant morphological change on Trout Beck floodplain. Variations in the shear stress and velocities were observed on the floodplain as a result of ground level changes including a flood compensation structure and two drainage channels. Despite this, variations in shear stress and flow velocities are not significant enough to effect changes to the floodplain composition through erosion or deposition in the events analysed, and overland flow routes observed in the baseline scenario remain across a broadly similar extent in the post-development scenario in all assessed flood events
- There is moderate impact on flood depths along Trout Beck as a result of the scheme. However, predicted increases in flood depths during the 100-year plus 94% climate change event are localised, within areas already at flood risk and within the Order Limits.

Mitigation Measures

14.9.2.146 The assessment reported in this assessment is based on a precautionary worst case scenario. As such, the mitigation identified in this assessment as being required to mitigate the likely significant effects reported are based on this worst case scenario. It may be the case that as detailed design of the Project evolves, it becomes apparent that a lesser form of mitigation is required to achieve the same outcome. As such, the EMP secures the ‘maximum’ extent of mitigation required (as identified in this assessment) but also, where appropriate, includes mechanisms (e.g. by way of further surveys or modelling) to establish, pre-construction and during detailed design, whether the identified mitigation can be refined such that a lesser extent is required to achieve the outcome reported in this assessment. The fundamental point is that the mitigation identified in this assessment is secured by the EMP, where required to achieve the outcome reported in this assessment.

14.9.2.147 In light of the conclusions drawn from the evidence base, the following mitigation measures, secured by the Project Design

Principles (Application Document 5.11) and the Environmental Management Plan (Application Document 2.7), which are certified documents under DCO, have been stipulated:

- Hydraulic modelling to understand the impact on quantity and dynamics of flow and structure and substrate of the river bed
- Channel realignment
- Continued monitoring of the Trout Beck Viaduct crossing will be required to assess the rate of scour to the piers. At detailed design, further modelling of the proposed bridge crossing piers and refinement of design will be required to ensure no change in potential effect on geomorphology. Details of this mitigation are outlined in ES Appendix 14.9: Detailed Geomorphological Modelling (Application Document 3.4)
- As part of National Highways' maintenance, inspections of potential scour on the Trout Beck Viaduct crossing piers will be conducted. Should any adverse changes be reported, appropriate mitigation plans to address this will be developed and implemented by National Highways. The Environment Agency and Natural England will be consulted on impacts to geomorphology.
- Refinements to the design and hydraulic modelling of the proposed viaduct crossing piers will be required at detailed design stage to ensure no impact on flood depths or extent to third party land.

14.9.3 Appleby to Brough

Introduction

Objectives

14.9.3.1 An understanding of geomorphological function of the watercourses within the vicinity of Warcop is required, in order to provide a comprehensive assessment of the constraints that local morphological function will have on the scheme, and to assess the potential impacts that the scheme will have on morphological function. The primary study objectives are as follows:

- Undertake a geomorphological analysis of the Moor Beck/Hayber Beck, Moor Beck (Offtake), Eastfield Sike and Crooks Beck, using desk-based and field-based sources.
- Develop a hydraulic model within the study area and analyse the results of this modelling study to provide further evidence to support the geomorphological analysis in the first objective.
- Identify any constraints that local morphological function will have on the delivery of the proposed route for the project.
- Identify any potential impacts of the scheme on local morphological function.

Study approach

Overview

14.9.3.2 A spatially integrated study has been conducted to gain the understanding necessary to describe system form and behaviour and predict future fluvial change. This assessment has been combined with an analysis of hydraulic model results, to provide a comprehensive assessment of the implications of developing the scheme in Warcop. This study combines desk-based and field-based components, to deliver the geomorphological analysis of the watercourses in the vicinity of Warcop. The watercourses that are to be assessed as part of this site-specific study at Warcop are as follows:

- Moor Beck/Hayber Beck
- Moor Beck (Offtake)
- Eastfield Sike
- Crooks Beck

14.9.3.3 The extent of the study area and the watercourses to be investigated as part of this assessment are presented in Plate 64: Study extent and watercourses to be investigated.

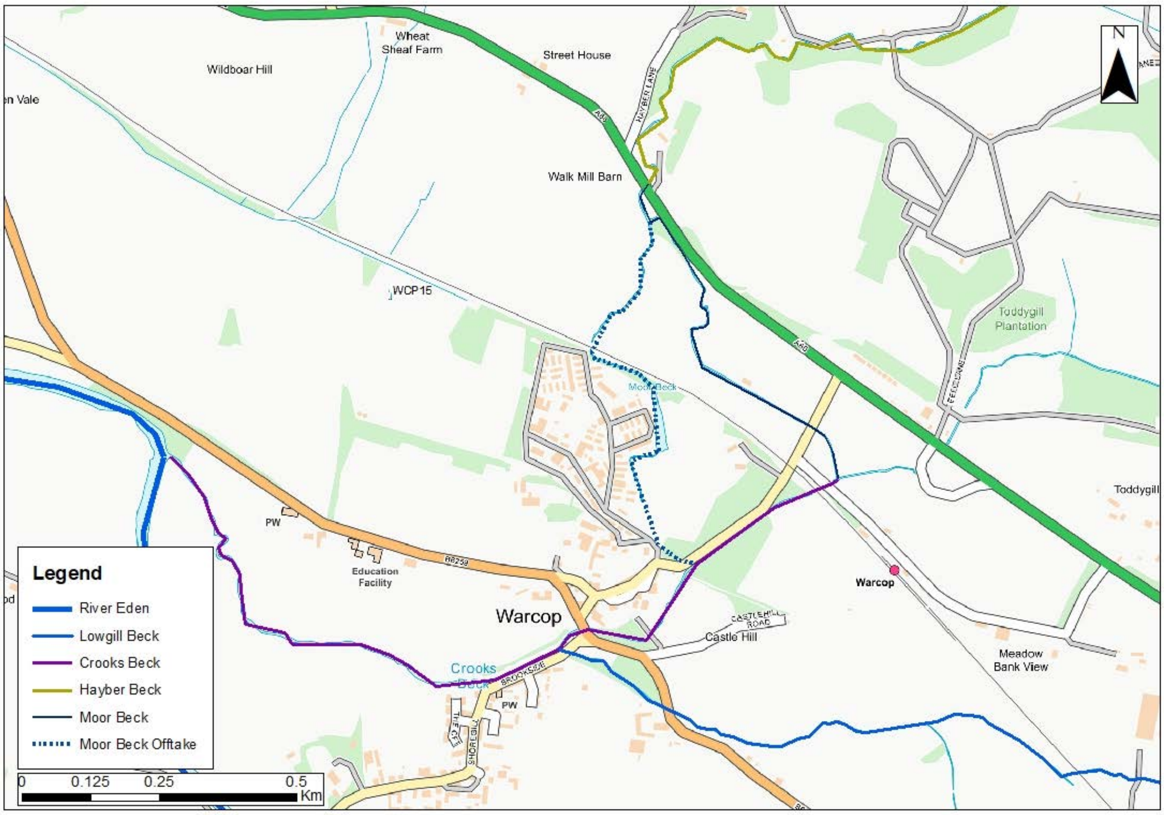


Plate 64: Study extent and watercourses to be investigated

Desk-based assessment

14.9.3.4 The desk-based components included review of a wide range of information provided for this study, as well as other sources openly available through the internet (LiDAR, historical maps, literature). The desk-based component of the study is essential to gain understanding of the wider context of the catchment and its waterbodies, in order to appreciate the local and catchment-wide controls that are influencing geomorphology on the watercourses in the vicinity of Warcop.

Site-based assessment

14.9.3.5 A complete walkover of the watercourses in the vicinity of Warcop was undertaken by suitably qualified geomorphologists. Morphological features of the watercourses, the riparian strip and the associated floodplain were recorded, to provide a detailed understanding of the functioning of the river system and how this influences the geomorphology of the river, banks and floodplain.

14.9.3.6 Following completion of the field-based surveys, the desk-based component was re-visited, and the various sources of information were linked. Channel change, morphological evolution, river engineering, historic system functioning and wider catchment influences were assessed and placed within the context of the development of the proposed route as part of the scheme.

Hydraulic modelling

14.9.3.7 A linked 1D-2D hydraulic model including the Moor Beck/Hayber Beck, Moor Beck (Offtake) Eastfield Sike and Crooks Beck was developed, to further supplement the analysis of morphological function undertaken in the desk-based and site-based assessment. Hydraulic model results were analysed to determine the likely impact that the proposed scheme will have on morphological function in the channel and on the floodplain.

Hydraulic modelling approach

Model approach

14.9.3.8 A combined 1D-2D hydraulic model was developed to investigate the flood risk and geomorphological implications of the scheme. Plate 65: Overview of the model schematisation for the Appleby to Brough scheme provides an overview of the model schematisation. The watercourses in the vicinity of Warcop are labelled.

14.9.3.9 The software used in each domain was as follows:

- 1D: Flood Modeller (FM) and Estry
- 2D: TUFLOW

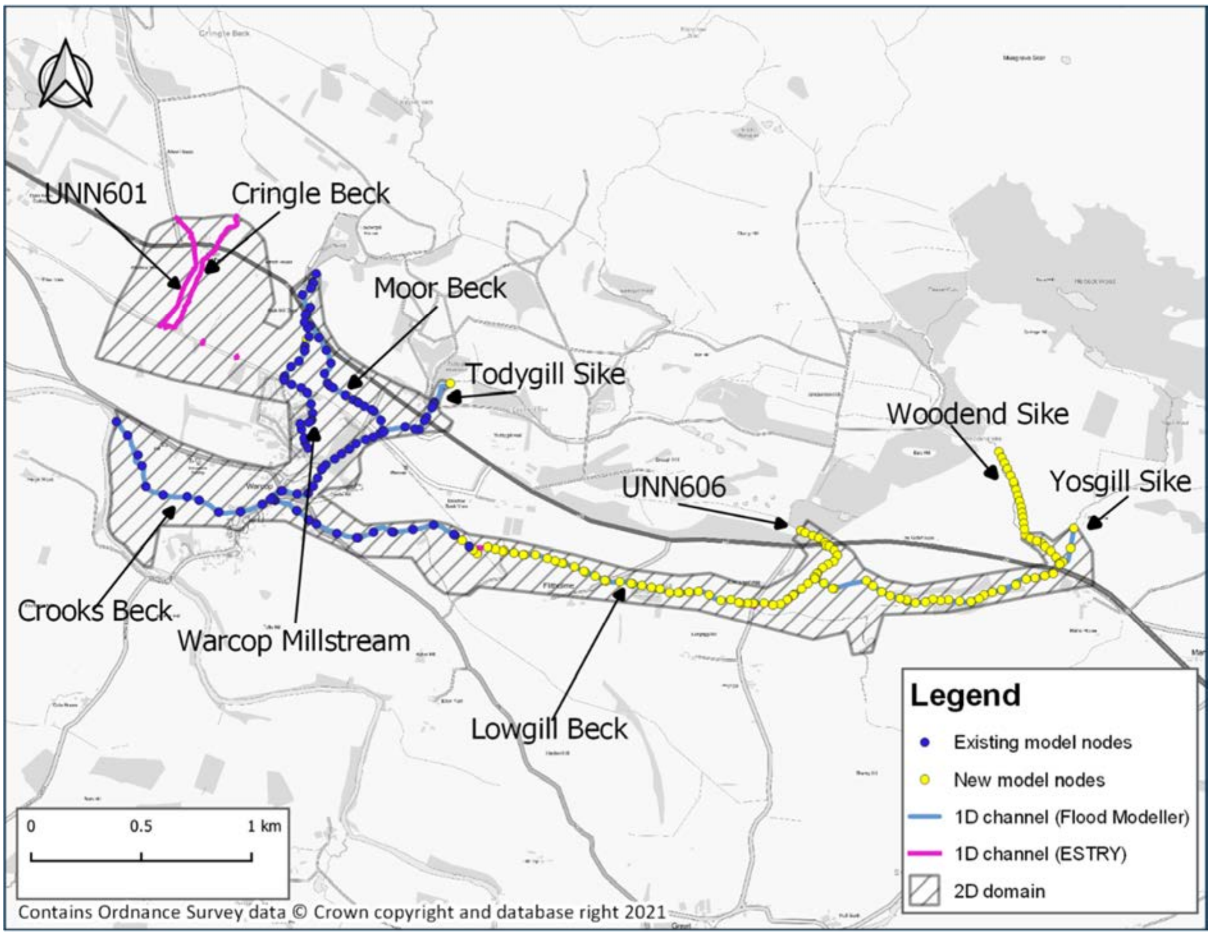


Plate 65: Overview of the model schematisation for the Appleby to Brough scheme

Hydrological inflows

14.9.3.10 The following flood return periods simulated within the hydraulic model were used to support the hydromorphological assessment of the watercourses in the vicinity of Warcop:

- 1-in-2 Year Flood Return Period
- 1-in-20 Year Flood Return Period
- 1-in-100 Year + 94% Climate Change Flood Return Period

Model scenarios

14.9.3.11 Two scenarios were constructed within the hydraulic model to assess the impacts arising from the proposed route for the scheme:

- Baseline: Existing conditions across all watercourses within the hydraulic model
- Post Development: Conditions following the installation of the proposed route and all associated structures within the hydraulic model.

14.9.3.12 Comparison of hydraulic model results across a range of flood return periods between the Baseline and Post Development scenarios yields an understanding of the implications to both flood risk and geomorphological conditions in the vicinity of Warcop following the completion of the proposed route.

Model simulations

14.9.3.13 The following model simulations were run and subsequently assessed to support the hydromorphological assessment of watercourses in the vicinity of Warcop:

- Baseline 1-in-2 Year Flood Event
- Post Development 1-in-2 Year Flood Event
- Baseline 1-in-20 Year Flood Event
- Post Development 1-in-20 Year Flood Event
- Baseline 1-in-100 Year +94% Climate Change Flood Event
- Post Development 1-in-100 Year +94% Climate Change Flood Event

14.9.3.14 The information presented in this chapter provides an overview of the hydraulic model build. For more detailed information on the hydraulic model build, please refer to ES Appendix 14.2: Flood Risk Assessment and Outline Drainage Strategy (Application Document 3.2).

Desk-based assessment

Overview

14.9.3.15 This section presents the findings of a geomorphology assessment of the watercourses in the vicinity of Warcop. The geomorphology assessment has been carried out to support the analysis of the scheme.

14.9.3.16 The assessment uses information gathered from desk-based resources (LiDAR, historic OS maps, and literature, etc.) to provide an understanding of local geomorphological controls influenced by catchment characteristics.

Wider catchment characteristics

14.9.3.17 The Hayber Beck rises on the foothills of Musgrave Scar, to the north of Warcop at an approximate elevation of 305mAOD. The Hayber Beck flows in a southerly direction for approximately 5.6km before meeting the existing A66 carriageway, and being conveyed beneath the road. Downstream of the road, the Hayber Beck is renamed the Moor Beck, which continues to flow in an easterly direction for approximately 0.7km before forming into the Crooks Beck at the confluence with the Eastfield Sike. The Crooks Beck flows in an easterly direction through Warcop for approximately 1.3km before discharging into the River Eden.

14.9.3.18 The Moor Beck (Offtake) splits downstream of the existing A66 carriageway and flows in a southern direction towards the rail line. The watercourse is subsequently culverted beneath the rail embankment and flows around the northern outskirts of Warcop Training Centre, before being culverted. The watercourse is culverted to the confluence with the Crooks Beck to the south east of Warcop Training Centre.

14.9.3.19 The Eastfield Sike rises on the southern slopes of Middle Fell and flows in a generally southern direction through Warcop Training Centre, before joining the Moor Beck to the north of Warcop. Downstream of the confluence with the Moor Beck the watercourse is renamed the Crooks Beck.

14.9.3.20 The Lowgill Beck rises at the confluence between the Yosgill Sike and the Woodend Sike, directly upstream of the existing A66 north-west of Brough. The Lowgill Beck is immediately culverted beneath the A66 before flowing in a generally western direction towards Warcop for approximately 5km, passing through Flitholme and beneath the rail line on the route. The Lowgill Beck discharges into the Crooks Beck in the centre of Warcop.

14.9.3.21 The Hayber Beck, Moor Beck, Moor Beck (Offtake), Eastfield Sike and Lowgill Beck all fall within the Low Gill (Crooks Beck) Water Framework Directive waterbody catchment.

14.9.3.22 The Crooks Beck rises at the confluence between the Moor Beck and the Eastfield Sike, directly north east of Warcop. The Crooks Beck is immediately culverted beneath the rail line before flowing in a generally western direction through Warcop. The Crooks Beck discharges into the River Eden to the west of Warcop.

Historic trend analysis

14.9.3.23 Historic OS mapping has been used to examine the extent of historic channel change within the water body catchment. The watercourse routes illustrated in the 1888 OS mapping (the earliest OS mapping available online) have been compared to current watercourses to identify areas of channel migration and realignment.

Moor Beck/Hayber Beck

14.9.3.24 There has been little change upstream to the Moor Beck/Hayber Beck in the *c.*130 years since the earliest mapping available online (Plate 66: Assessment of historic planform change on the Moor Beck/Hayber Beck). The watercourse has largely remained in the same location since 1899. The upstream reach of the Hayber Beck can be characterised by a steep, upland river. As such, the narrow valley shape limits lateral channel planform migration.

14.9.3.25 The extent of anthropogenic modification to the Hayber Beck and Moor Beck watercourses has changed over time (Plate 66: Assessment of historic planform change on the Moor Beck/Hayber Beck). Upstream of Warcop in Area 1, historic mapping identifies a weir structure and mill race along the Hayber Beck that is no longer in operation Further downstream, the flow in the Moor Beck channel continues to be controlled by a weir structure which directs flow to a mill race. In Area 2, the planform of the Moor Beck mill race has changed since 1899. In 1899, the Moor Beck mill race distributed water to the Warcop Mill. The mill is no longer in operation and the course of the mill race has changed over time.

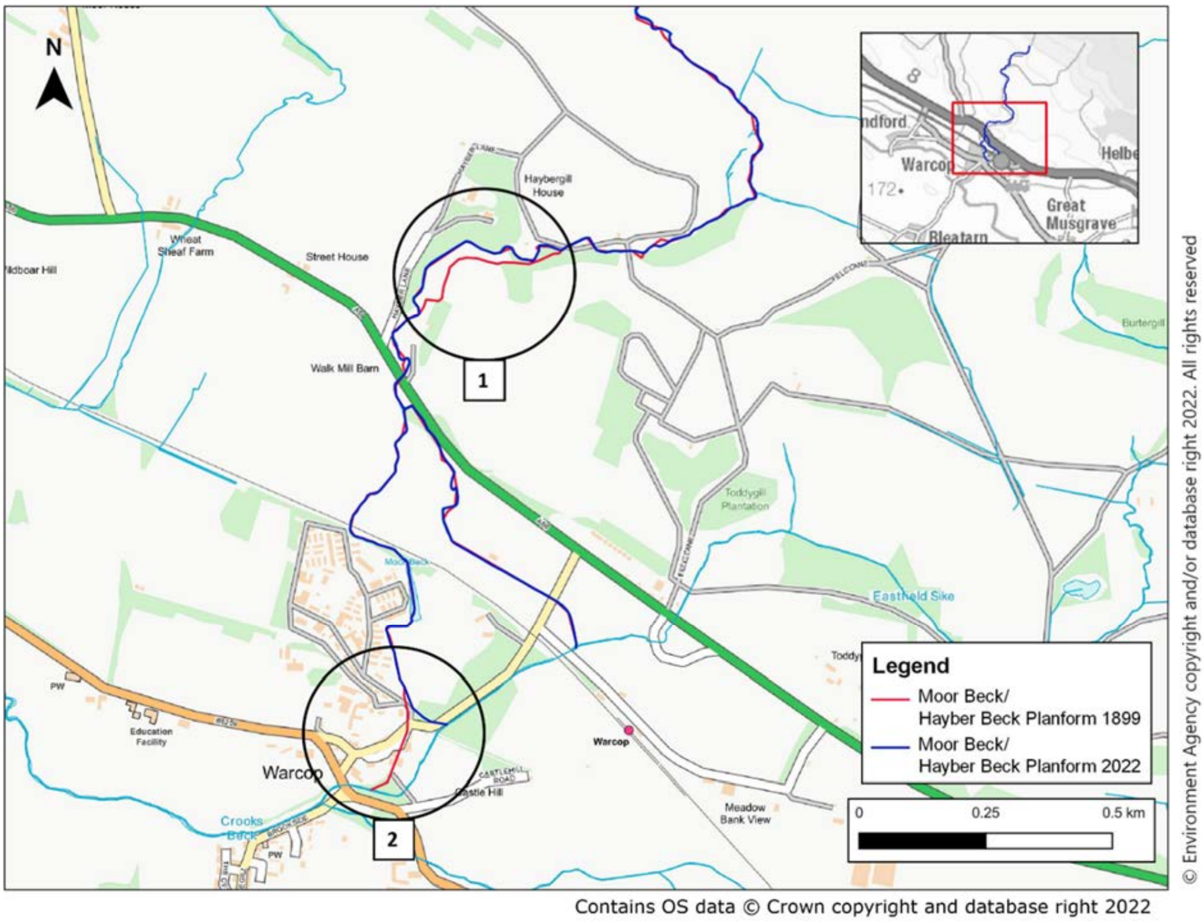


Plate 66: Assessment of historic planform change on the Moor Beck/Hayber Beck

Lowgill Beck

14.9.3.26 There has been significant planform change to the Lowgill Beck watercourse in the *c.*130 years since the earliest mapping available online (Plate 67: Assessment of historic planform change on the Lowgill Beck). To the east of Warcop, the Lowgill Beck appears to have been managed sometime after 1956. In Area 1, a meander bend on the left bank floodplain has been cut off from the channel. In Area 2, near the hamlet of Flitholme, the Lowgill Beck planform has been straightened. These changes are most likely to be a result of anthropogenic modification and historic channel straightening.

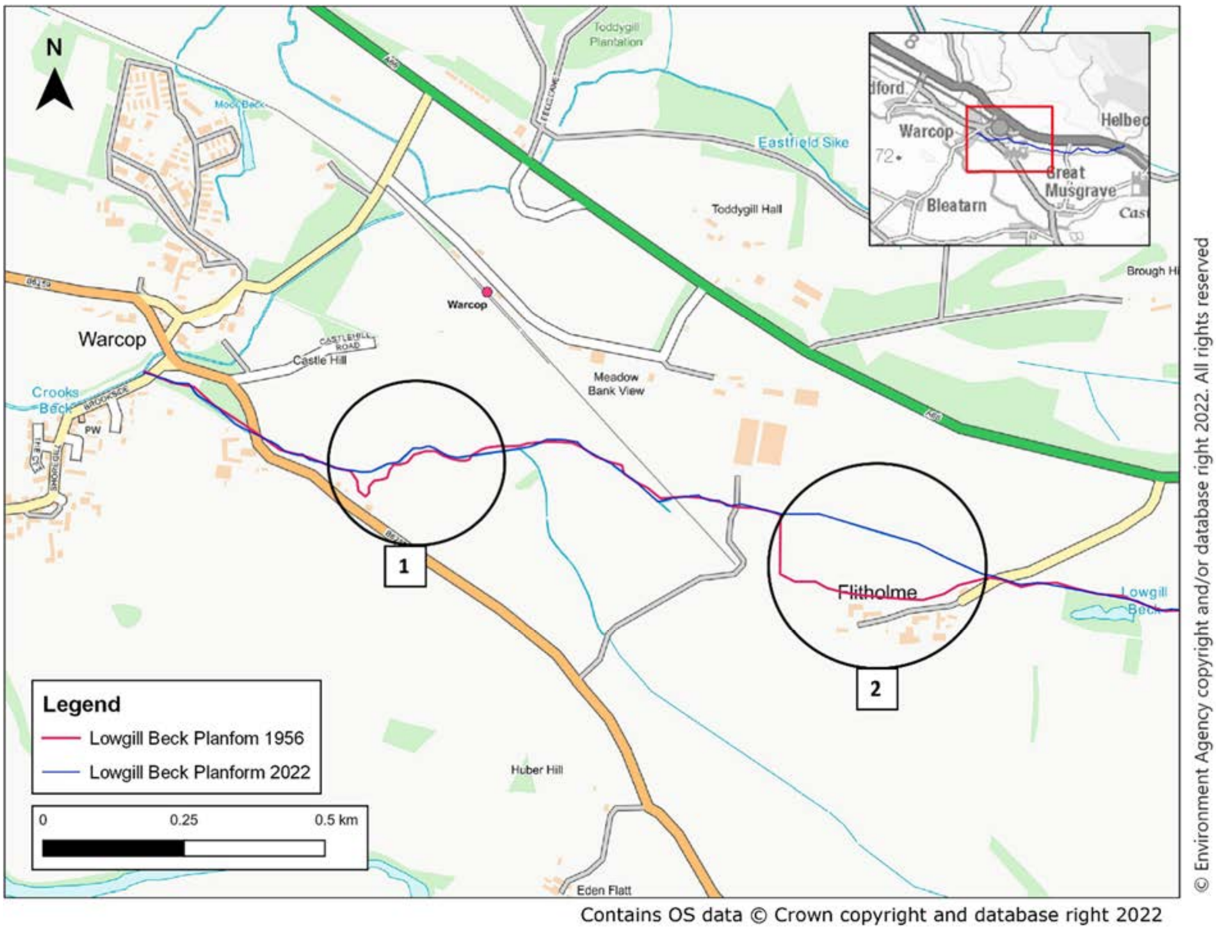


Plate 67: Assessment of historic planform change on the Lowgill Beck

Eastfield Sike

14.9.3.27 There has been little change to the Eastfield Sike in the c. 130 years since the earliest mapping available online (Plate 68: Assessment of historic planform change on the Eastfield Sike). The watercourse has largely remained in the same location since 1899. The downstream extent of the Eastfield Sike has been historically managed and flows beneath the A66 road network. Further upstream, the Eastfield Sike is confined by steep topography that limits lateral channel planform migration.

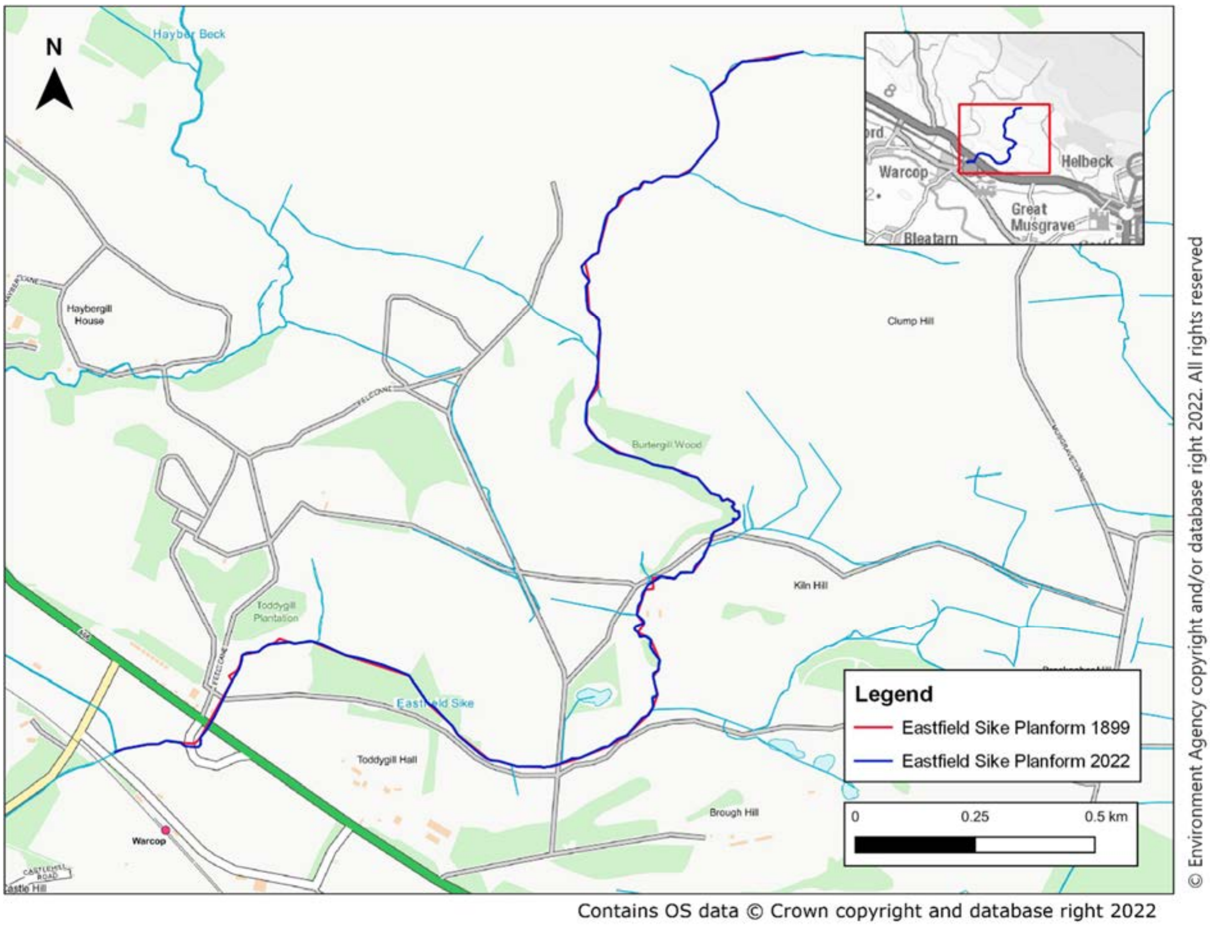


Plate 68: Assessment of historic planform change on the Eastfield Sike

Crooks Beck

14.9.3.28 There has been some change to the Crooks Beck in the c. 130 years since the earliest mapping available online (Plate 69: Assessment of historic change on the Crooks Beck). Downstream of Warcop, the planform of the Crooks Beck has largely remained in the same location since 1899. The watercourse flows through an area of agricultural land and is situated along a number of field boundaries. There has been a slight increase in sinuosity further downstream at Area 1. In this location, the watercourse does not flow along a field boundary and has migrated laterally across the floodplain. In Area 2, the Crooks Beck planform has reduced in sinuosity since 1899 and appears to have been straightened. It is likely that the channel has been modified in this location to prevent lateral migration towards road infrastructure in Warcop.

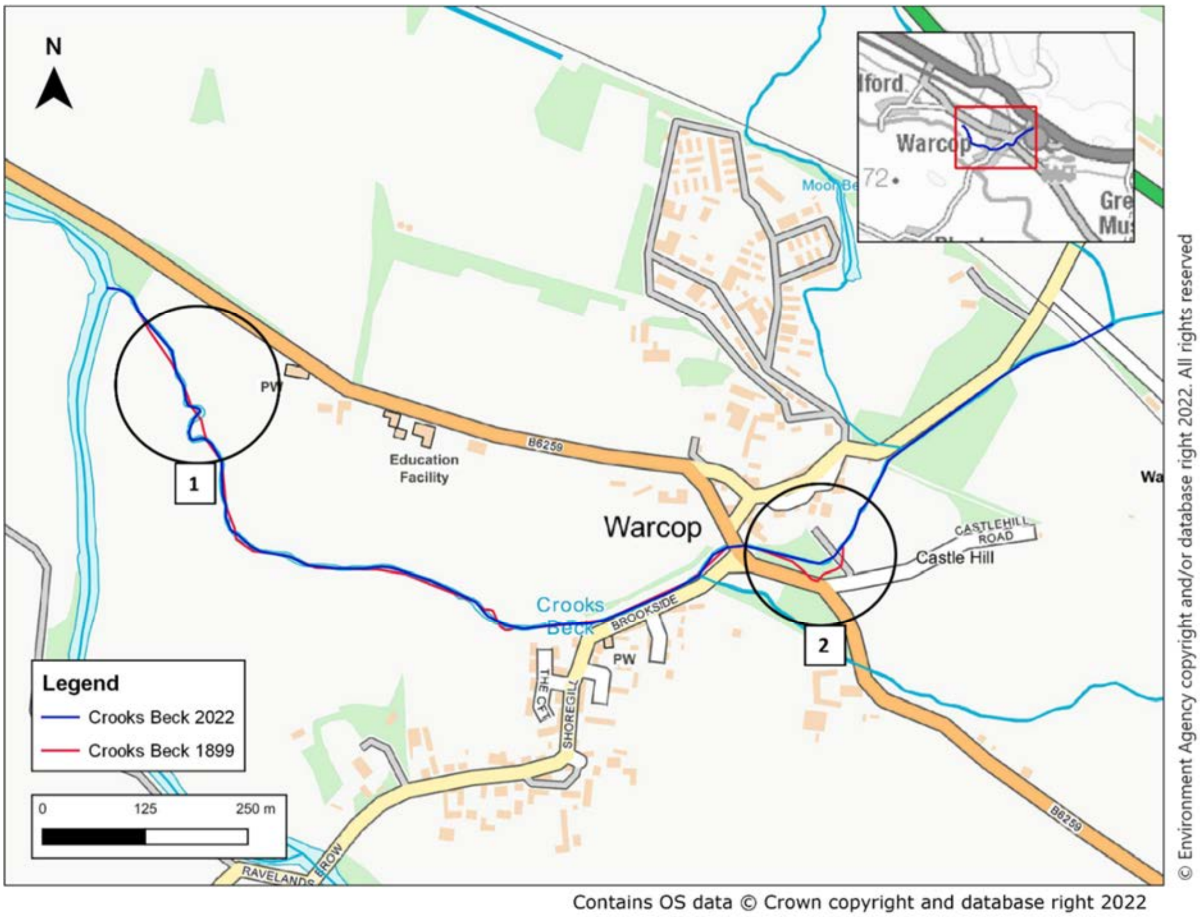


Plate 69: Assessment of historic change on the Crooks Beck

Assessment of LiDAR data

14.9.3.29 2m resolution LiDAR data has been analysed to examine historic geomorphological processes and function of the scheme watercourses, to improve understanding of current channel conditions.

Moor Beck/Hayber Beck

14.9.3.30 In Area 1 (Plate 70: Assessment of LiDAR data in the vicinity of the Moor Beck/Hayber Beck), there are palaeo channels on the floodplain of the Hayber Beck, suggesting that the channel has migrated over time. This can be attributed to the high-energy nature of the upstream reach. In Area 2 (Plate 70: Assessment of LiDAR data in the vicinity of the Moor Beck/Hayber Beck), a palaeo channel on the right bank floodplain of the Moor Beck suggests a reduction in sinuosity and channel complexity over time. The meander bend is not visible in historic mapping, and as such likely pre-dates 1899, the earliest available historic mapping online.

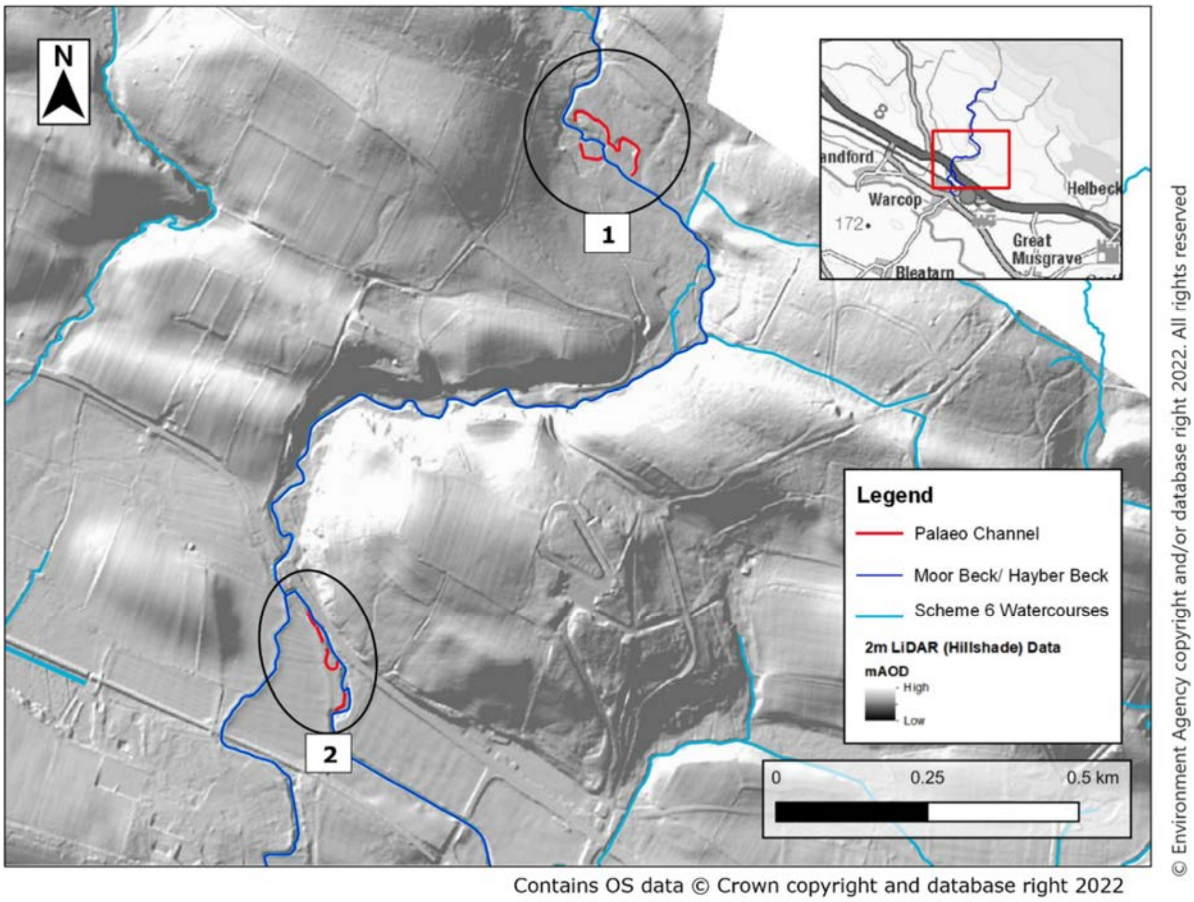
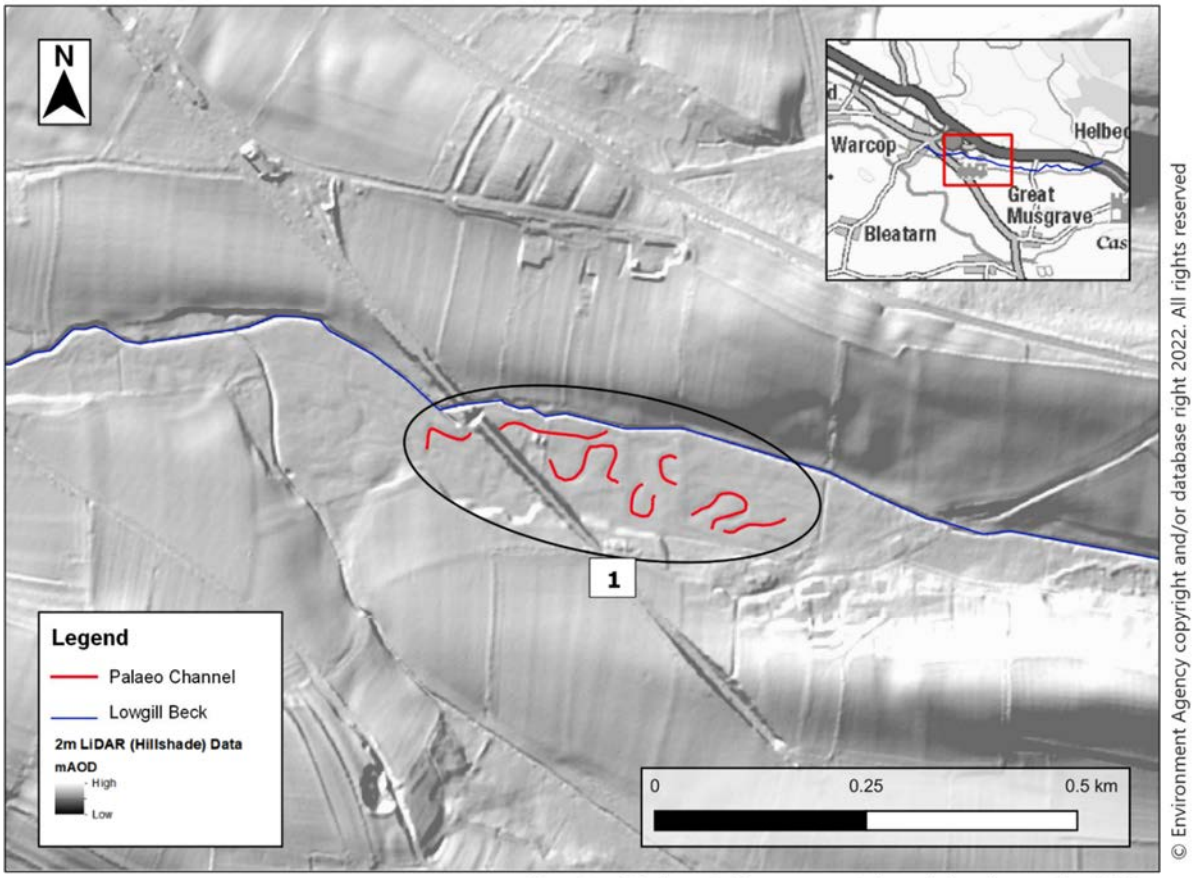


Plate 70: Assessment of LiDAR data in the vicinity of the Moor Beck/Hayber Beck

Lowgill Beck

14.9.3.31 In Area 1 (Plate 71: Assessment of LiDAR data on the Lowgill Beck) a palaeo channel can be observed on the floodplain of the Lowgill Beck. This suggests that the Lowgill Beck previously meandered across the open floodplain. It is likely that the channel has been straightened and moved to the right side of the floodplain to increase the amount of agricultural land available on the left bank floodplain. Alteration of the watercourse planform has reduced sinuosity and increased the river gradient. Over time, the channel sinuosity has significantly decreased.



Contains OS data © Crown copyright and database right 2022

Plate 71: Assessment of LiDAR data on the Lowgill Beck

Eastfield Sike

14.9.3.32 The palaeo channels identified in Area 1 (Plate 72: Assessment of LiDAR data on the Eastfield Sike) indicate that the Eastfield Sike has migrated across the right bank floodplain in the past. Historic mapping does not indicate any channel migration. This suggests that the watercourse is not actively migrating and any changes in the channel form of the Eastfield Sike occurred prior to 1899.

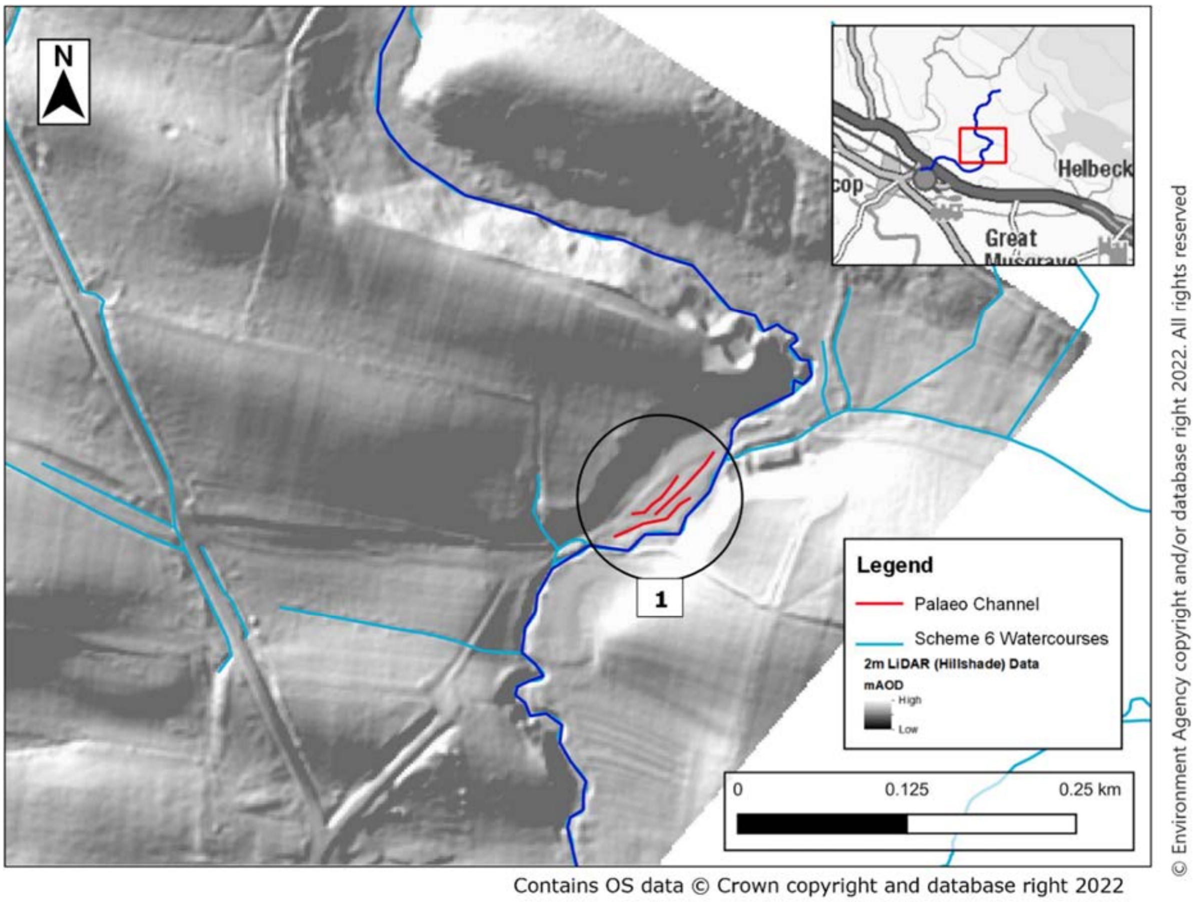


Plate 72: Assessment of LiDAR data on the Eastfield Sike

Crooks Beck

14.9.3.33 In Area 1 (Plate 73: Assessment of LiDAR data on the Crooks Beck) palaeo channels can be observed on the right bank floodplain of the Crooks Beck. This suggests that the Crooks Beck previously meandered across the floodplain and has decreased in sinuosity. It is likely that the channel has been realigned to increase the amount of agricultural land available. In Area 2, the left bank floodplain of the Crooks Beck contains a number of visible palaeo channels. The existing channel planform is relatively straight in this location and lacks in sinuosity. The presence of palaeo channels suggests that the Crooks Beck previously migrated across the left bank floodplain and may have been modified in the past. Historic map analysis did not reveal any changes to the planform of the Crooks Beck at Area 1 and Area 2 between 1899 and 2022. This implies that the palaeo channels identified by LiDAR data pre-date 1899.

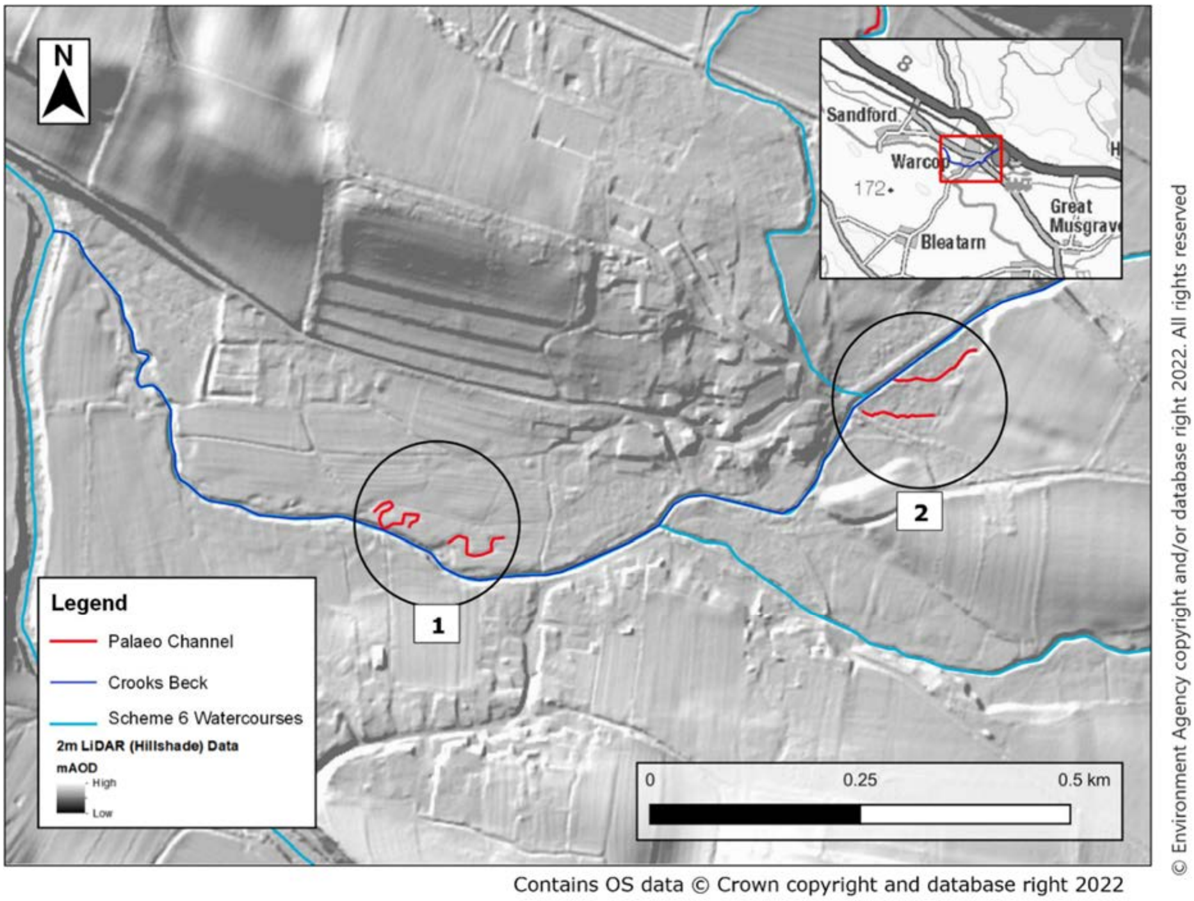


Plate 73: Assessment of LiDAR data on the Crooks Beck

Site-based assessment

Overview

14.9.3.34 To support the desk-based assessment, a site visit was conducted to gain a comprehensive understanding of morphological processes occurring on the watercourses in the vicinity of Warcop. An individual assessment of morphological processes was undertaken at each of the following watercourses:

- Hayber Beck/Moor Beck
- Moor Beck (Offtake)
- Eastfield Sike
- Lowgill Beck
- Crooks Beck

Hayber Beck/Moor Beck

14.9.3.35 Annex B: Appleby to Brough site photographs provides photographs of site conditions of the Hayber Beck and Moor Beck respectively to support the site-based assessment of geomorphological conditions.

14.9.3.36 Where the Hayber Beck rises the watercourse can be characterised as an upland river, with a steep channel gradient, narrow valley geometry and high energy flow biotopes. The steep upland nature of the Hayber Beck means that the valley is naturally narrow, and the channel gradient is steep, and as such the watercourse is naturally confined in the narrow space within the valley. Riparian cover is excellent in the upland reaches, with a forest present on both the left and right bank of the channel. This riparian cover provides enhanced structural integrity for the riverbanks, mitigating against bank erosion, slumping and failure in the narrow valley. Flow velocities within the channel are very high as a result of the steep channel gradient, and as such typical flow biotopes vary between long riffle features and a limited number of rapid features. The typical bed substrate is coarse, ranging between coarse cobbles to boulders.

14.9.3.37 On the approach to the A66 carriageway, the gradient begins to reduce, and as such the flow energy of the watercourse reduces. This facilitates the development of alternating riffle and glide sequences, as local variations in channel sinuosity generate flow biotope diversity. Downstream of the A66 Road, the alternating sequences of riffles and glides continue to the confluence with the Eastfield Sike. The reduction in flow velocities within the channel results in the deposition of finer riverbed substrate, with the typical riverbed composition ranging between cobbles and gravels at riffle features and gravels and sands in glide biotopes. A rectangular box culvert conveys the Hayber Beck beneath the A66 carriageway, and the watercourse is subsequently renamed the Moor Beck downstream of the structure. Approximately 60m downstream of the culvert outfall, a series of three weir structures regulate the flows within the channel and encourages flow into the Moor Beck Offtake channel, situated on the right bank of the Moor Beck. The reduction in channel gradient, combined with the transition from a narrow valley geometry to a wider floodplain, has facilitated the development of a more sinuous channel planform. Despite this, there is evidence of channel realignment and straightening, particularly in the vicinity of the road bridge. This has led to riverbed incision as a result of increases in channel gradient and subsequent increase in channel energy, leaving the floodplain disconnected from the channel. Areas of fresh bank collapse and bank slumping were observed during the site visit, indicating that the riverbanks are unstable as a result of the bed incision that has occurred in this reach. Incidences of riverbank erosion and slumping are exacerbated by the lack of riparian tree cover and buffer strip in this reach of the Moor Beck. The unvegetated riparian zone has resulted in the riverbanks being unstable and prone to erosion. Flow velocities within the channel remain moderate, and the typical range of flow biotopes are diverse, ranging from glides to runs and riffles. The range of flow biotopes across this reach have resulted in a diverse structure of the riverbed substrate. Finer material such as sands and silts have deposited within glides, where flow velocities are reduced; conversely coarser material has deposited at riffle features, as a result of the higher flow velocities. These conditions continue to the confluence with the Eastfield Sike.

Moor Beck (Offtake)

14.9.3.38 Annex B: Appleby to Brough site photographs site photographs provides photographs of site conditions of the Moor Beck (Offtake) respectively to support the site-based assessment of geomorphological conditions.

14.9.3.39 The Moor Beck (Offtake) is an artificial channel, with flow diverted from the Moor Beck directly downstream of the A66 Road. A series of three weir structures control the flow on the Moor Beck and convey flow from the Moor Beck to the Moor Beck (Offtake). The Moor Beck (Offtake) flows in a generally southern direction towards Warcop and flows beneath the rail bridge. The Moor Beck (Offtake) subsequently flows around northern perimeter of Warcop Training Centre, before being culverted and ultimately discharging into the Crooks Beck.

14.9.3.40 The reach of the channel between the main Moor Beck and Warcop Training Centre has a relatively shallow channel gradient compared to other watercourses surveyed across the scheme, and as such flow velocities within the channel are moderate to low. This is further compounded by the regulated quantity of flow that is discharged from the Moor Beck to the Moor Beck (Offtake), which further limits flow velocities. Due to the low flow conveyance to the Moor Beck (Offtake), combined with the low flow velocities, the channel has not undergone bed incision. The result is the water level of the Moor Beck (Offtake) being close to the top of the riverbank. It is likely during higher flow events or heavy rainfall events that flow is able to spill into the floodplain and connectivity is moderate. The presence of rushes on the floodplain suggests that the floodplain becomes regularly inundated during heavy rainfall events. Riparian cover on both banks of the Moor Beck (Offtake) is poor, with a very limited riparian buffer zone and minimal riparian tree coverage. The flow within the Moor Beck (Offtake) on the day of the site visit was very low, resulting in low flow energy. This was further compounded by the overgrown nature of the channel, which further reduced flow velocities in the channel. As such typical flow biotopes observed within the channel were glides. The low flow velocities within the channel result in fine material suspended in the water column dropping out of transport and depositing on the riverbed. The result is the accumulation of fine material on the riverbed. On the approach to Warcop Training Centre, the watercourse is conveyed beneath the rail embankment via a bridge.

14.9.3.41 Downstream of the rail bridge, connectivity to the floodplain reduces. The right bank of the channel has been raised to protect the training centre from flooding, and as such the right bank floodplain is disconnected from the Moor Beck (Offtake). Further downstream, a wet woodland area exists in the north eastern corner of the training centre. Floodplain connectivity is excellent, and water is able to regularly enter the woodland from the channel throughout the year. As a result of this, riparian tree cover and the condition of the riparian zone improves significantly compared to upstream reaches of the

Moor Beck (Offtake). flow within the Moor Beck (Offtake) increases compared to upstream; it is likely that additional discharges from local field drains and drainage outfalls supplement the flow within the channel. Despite the increase in flow, the flow velocity remains low, with gliding flows being the predominant flow biotope. It is likely a number of structures within the channel, such as culverts and access tracks within the grounds of the Training Centre impound the water and reduce the flow velocity. In addition, the impoundment on the flow encourages water to enter the wet woodland to the north east of Warcop Training Centre. The watercourse is subsequently culverted before discharging into the Crooks Beck to the south east of Warcop Training Centre.

Eastfield Sike

14.9.3.42 Annex B: Appleby to Brough site photographs photographs provides photographs of site conditions of the Eastfield Sike to support the site-based assessment of geomorphological conditions.

14.9.3.43 The Eastfield Sike upstream of the A66 road can be characterised as an upland river, with a steep channel gradient and a narrow valley geometry. In upstream reaches on the southern slopes of the Middle Fell and in the Warcop Training Centre, riparian tree cover is very limited, and large stretches of the riverbanks are unvegetated. The steep channel gradient of this upland reach provides the watercourse with high flow energy, leading to the development of high energy flow biotopes such as riffles. is dominated by very coarse bed material, ranging from coarse cobbles to gravels. The steep channel gradient and high flow energy transfers smaller material to downstream reaches where flow energy is reduced. As such this upstream reach can be categorised as a sediment transport reach. On the approach to the A66 Road, the channel gradient reduces, and as such the flow energy reduces. This reduction in flow energy is further compounded by a series of culverts that convey the Eastfield Sike beneath an access road within Warcop Training Ground, the A66 Road and the tank turning junction. These structures likely have an impounding effect on the flow within the channel; however, given the relative steepness of the channel still, the extent of this impoundment is likely very limited. The changes in flow velocities has led to the development of alternating riffle and run sequences.

14.9.3.44 Downstream of the A66 carriageway and associated culvert, the channel gradient reduces further, and the steep sided valley observed upstream gives way to a more open floodplain on both banks of the Eastfield Sike. Realignment and straightening of the channel has led to riverbed incision as a result of increased in-channel energy, leaving the floodplain disconnected from the channel. Incidences of riverbank erosion and slumping are exacerbated by the lack of riparian tree cover and buffer strip in this reach of the Moor Beck. The unvegetated riparian zone has resulted in the riverbanks being unstable and prone to erosion and unchecked livestock poaching has occurred, leading to further deterioration of the riverbanks. Flow velocities within the channel reduce further between the A66 carriageway and the confluence with the Moor Beck, as the channel gradient reduces compared to upstream reaches. Typical flow biotopes range from glides to riffles. The typical size of bed substrate reduces compared to upstream reaches, as the channel gradient and flow energy decreases. This provides an opportunity for finer material to drop out of the water column and deposit on the riverbed. As such, the bed material ranges from gravels to sands. Finer material such as silts continues to be transported to downstream reaches downstream of the confluence with the Moor Beck.

Lowgill Beck

14.9.3.45 Annex B: Appleby to Brough site photographs site photographs provides photographs of site conditions of the Lowgill Beck to support the site-based assessment of geomorphological conditions.

14.9.3.46 Across the Lowgill Beck floodplain connectivity is generally poor. The steep narrow valley shape of the Lowgill Beck immediately downstream of the existing A66, combined with the steep channel gradient naturally confines the watercourse to the narrow space. Through the woodland area to the north of Lowgill Farm, connectivity is improved, with wet woodland areas identified during the site visit suggesting connectivity to some areas of the floodplain for the channel. As a result of the steep channel gradient in this reach, a continuous riffle feature exists. The high flow in the upper part of this reach conveys finer material such as sands and silts to downstream reaches, leaving behind a riverbed composed of coarser material. As such, this reach of the Lowgill Beck can be categorised as a transfer reach.

14.9.3.47 In the reach of the Lowgill Beck between the Unnamed Tributary of Lowgill Beck 6.1 and Flitholme, riparian vegetation cover on the riverbank decreases significantly. As such, bank stability reduces, and the riverbanks are prone to erosion, undercutting and slumping. The result is an active channel planform that has been controlled with informal bank engineering methods to limit the loss of surrounding agricultural land and maintain a straight channel planform. In addition, the lack of riparian tree cover has resulted in livestock poaching of the riverbanks, which has led to the degradation of the riverbanks and fine material input into the river system. The channel planform of the Lowgill Beck becomes artificially straightened through the agricultural fields. Despite the straightened channel planform, flow diversity increases in this reach, ranging from high flow velocity biotopes such as riffles, to runs and glides. Localised variation in flow is generated by woody material in the channel and informal structures in the channel such as culverts and farm access tracks. The volume of fine material on the riverbed increases significantly. In areas of low flow velocity, the bed is composed almost entirely of fine sandy material, or a layer of fine material covers the existing coarse bed substrate. It is likely that a lower channel gradient, and therefore lower flow energy, combined with input of fine material from the surrounding agricultural land through pathways such as cattle poaching, riverbank erosion and overland flow routes during heavy rainfall events contributes to this increased volume of fine material. As such this reach can be categorised as a sediment storage reach.

14.9.3.48 In the reach between Flitholme and Warcop, the channel gradient increases and sinuosity decreases, likely a result of historic channel realignment and straightening. Riparian vegetation within this reach is poor and limited, and cattle poaching is widespread. In some areas a riparian corridor has been established, with the use of fencing prohibiting the poaching of riverbanks. Despite the straightened channel planform, flow diversity increases in this reach, ranging from high flow velocity biotopes such as riffles, to runs and glides. Localised variation in flow is generated by woody material in the channel and informal structures in the channel such as culverts and farm access tracks. Structures in the channel, such as the culvert beneath the rail embankment and farm access tracks impound the flow in some areas, leading to a reduction in flow velocities. The size of material increases from the finer bed substrate observed upstream to coarse material ranging from cobbles to gravels. The steeper channel gradient in this reach results in higher flow velocities, which are able to mobilise and transport finer bed material such as sands and silts to downstream reaches, leaving coarser bed substrate such as cobbles and gravels in situ. Fine sediment input into the river system in this reach is still high, from pathways such as cattle poaching, riverbank erosion and overland flow routes during heavy rainfall events. The result is fine material choking the riverbed substrate in some areas. On the approach to the confluence with the Crooks Beck, the riverbed becomes armoured. Finer material is transported to downstream reaches on the Crooks Beck, and the coarser material

Crooks Beck

14.9.3.49 Annex B: Appleby to Brough site photographs site photographs provides photographs of site conditions of the Crooks Beck to support the site-based assessment of geomorphological conditions.

14.9.3.50 The Crooks Beck is conveyed beneath an arched bridge structure at Warcop, directly upstream of the Lowgill Beck confluence. At Warcop, the floodplain is disconnected and the channel is managed to prevent flooding of the village. In this reach, the channel gradient is steep and high energy flow biotopes are present. A long riffle feature occupies the channel and the typical bed substrate ranges between coarse cobbles and gravels. The riverbed is armoured in this location and the water column is clear as there is sufficient flow energy to transport fine sediment downstream.

14.9.3.51 Floodplain connectivity improves downstream but not to a large extent. The watercourse has been straightened alongside Brookside

Road and there is limited riparian cover on the left bank. Grass vegetation lines both riverbanks, with a forest present on the right bank floodplain. There is a decline in channel gradient downstream of the bridge and the flow energy of the watercourse decreases. The channel is characterised by alternating riffle and glide features. Cobbles and gravels continue to be the typical riverbed substrate in this reach. At glide features, reduced flow velocity has resulted in the deposition of finer sand material.

14.9.3.52 Downstream of Brookside Road, the Crooks Beck flows through an area of agricultural land. A mini dam comprised of fence material has impounded flow upstream. The channel planform remains relatively straight, although there is a slight increase in sinuosity. Palaeo channels observed on site suggest that the channel has previously migrated across the left and right bank floodplain. It is likely that the channel has been realigned in the past to increase the amount of land available for farming. The riparian zone is poor, with a limited riparian buffer zone and minimal riparian tree coverage. Flow velocities within the channel remain moderate, and riffle-glide sequences are present. Reduced flow velocities at the channel margins have resulted in the deposition of fine material. The water column remains clear in this reach and the typical bed substrate is gravel.

14.9.3.53 A footbridge spans across the Crooks Beck approximately 2km downstream of Brookside Road. Riparian cover remains poor downstream of the footbridge and nettle vegetation occupies the riverbanks. Areas of bank collapse and bank slumping along the right bank indicate that the riverbank is unstable and prone to erosion. Unchecked livestock poaching has occurred on the left bank, leading to further deterioration of the riverbanks. Glide flows are the main flow biotope on approach to the River Eden confluence.

Sediment sampling

14.9.3.54 Sampling of the main active gravel bar features within the Low Gill (Crooks Beck) was undertaken during the site walkover. Plate 74: Sediment sampling locations in the vicinity of Warcop shows the location of the six samples. Gravel bars were selected for sampling based on safe access to the channel.

14.9.3.55 Wolman Pebble Count sampling across each of the selected gravel bars was undertaken, recording the intermediate axis of each sediment clast using a gravelometer. The procedure for undertaking Wolman Pebble Count sampling is detailed in Annex C: Sediment sampling methodology. This methodology is known to minimise operator error compared to measuring the intermediate axis of clasts using a ruler. The sampling size data has been analysed to produce Particle Size Distribution curves at each sample site, allowing an assessment of the range of particle sizes within each sample. A separate assessment of sediment sizes on the Hayber Beck / Moor Beck / Crooks Beck, Eastfield Sike and Low Gill Beck has been undertaken to facilitate a more appropriate comparison between gravel bars.

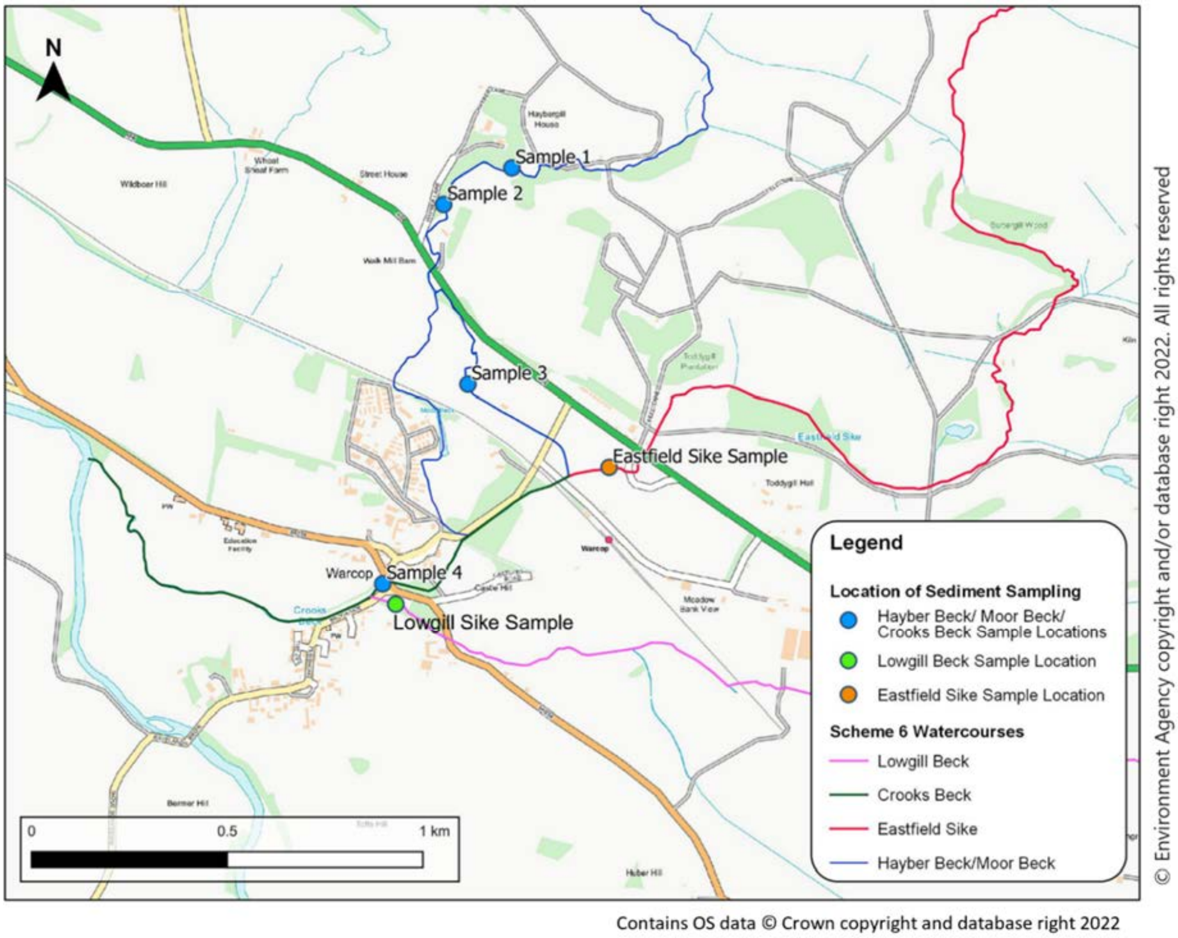


Plate 74: Sediment sampling locations in the vicinity of Warcop

Hayber Beck / Moor Beck / Crooks Beck sediment sample analysis

14.9.3.56 Based on the D10, D50 and D90 values for each sample on the Hayber Beck/ Moor Beck/ Crooks Beck, it is apparent that sample locations 1 and 4 have the coarsest particle size distribution. In sample location 1, 90% of the samples measure <180mm (Table 10: D10, D50 and D90 particle size distribution values for each gravel bar sample site on the Hayber Beck / Moor Beck / Crooks Beck). In comparison, the particle size distribution at Sample Locations 2 and 3 are finer, with 90% of the samples measuring <128mm Table 10: D10, D50 and D90 particle size distribution values for each gravel bar sample site on the Hayber Beck / Moor Beck / Crooks Beck). As observed in Plate 75: Combined particle size distribution curves for gravel sample locations on the Hayber Beck, Moor Beck and Crooks Beck, the particle size distribution at Sample 4 is somewhat coarser than sample locations 1, 2 and 3, with 90% of the samples measuring >180mm.

14.9.3.57 The analysis of particle size distribution data within each of the sampled gravels bars on the Moor Beck/ Crooks Beck indicate a broad trend of particle size reductions as distance downstream on the watercourse increases. At the sample 1 location, the Moor Beck is characterised as a steep, upland river that flows within a narrow valley. Coarser ranges of particle sizes are typically found in upstream gravel bars where channel sinuosity and activity is minimal. These less active reaches typically have higher flow energy as a result of a steeper channel gradient. In-channel velocities are maintained high enough in these upstream reaches to ensure that fine material remains in suspension and is transported to reaches further downstream. This leaves only the coarsest material left to populate the gravel bars in upstream reaches, where the material is too large to be mobilised and transported to downstream reaches.

14.9.3.58 Conversely, finer material is found in downstream gravel bars where there is a shallower gradient and flow energy is lower. There is a reduction in channel gradient at sample locations 2 and 3, as the Moor Beck approaches Warcop. On the approach to the Eastfield Sike confluence, the size of the bed substrate decreases, as the flow energy decreases. In this location, channel velocities have reduced capacity to maintain sediment transport processes. Finer material transported from the upstream reaches drops out of suspension in the water column and deposits on the bed of the channel and gravel bars.

14.9.3.59 At sample location 4, the particle sizes were found to be the coarsest (Table 10: D10, D50 and D90 particle size distribution values for each gravel bar sample site on the Hayber Beck / Moor Beck / Crooks Beck). The armoured bed of the Crooks Beck in this reach indicates that coarse sediment is stored within the channel. Sample location 4 is downstream of the Eastfield Sike confluence. Inputs of material from the Eastfield Sike have increased the volume of coarser material in the Crooks Beck reach. The downstream Crooks Beck reach is situated in the village of Warcop. The channel in this location appears to be managed and is relatively straight. The straight planform in this reach results in an increase in channel gradient and flow velocity. Finer material is entrained and transported downstream.

14.9.3.60 The calculated D50 (median), D10 and D90 particle size distribution values are presented in Table 10: D10, D50 and D90 particle size distribution values for each gravel bar sample site on the Hayber Beck / Moor Beck / Crooks Beck, Table 11: D10, D50 and D90 particle size distribution classes for each gravel bar sample site on the Hayber Beck / Moor Beck / Crooks Beck and Table 12: Millimetre size ranges for different sediment sizes.

Table 10: D10, D50 and D90 particle size distribution values for each gravel bar sample site on the Hayber Beck / Moor Beck / Crooks Beck

Sample Location	D10 (mm)	D50 (median) (mm)	D90 (mm)
Sample 1	32	90	180
Sample 2	22.6	64	128
Sample 3	2.8	45	128

Sample Location	D10 (mm)	D50 (median) (mm)	D90 (mm)
Sample 4	32	64	>180

Table 11: D10, D50 and D90 particle size distribution classes for each gravel bar sample site on the Hayber Beck / Moor Beck / Crooks Beck

Sample Location	D10 (mm)	D50 (median) (mm)	D90 (mm)
Sample 1	Coarse Gravel	Fine Cobble	Coarse Cobble
Sample 2	Coarse Gravel	Very Coarse Gravel	Fine Cobble
Sample 3	Very Fine Gravel	Very Coarse Gravel	Fine Cobble
Sample 4	Coarse Gravel	Very Coarse Gravel	Coarse Cobble

Table 12: Millimetre size ranges for different sediment sizes

Description	Size (mm)
Coarse Sand	0.5 to 2.0
Gravel	2.0 to 16.0
Pebbles	16.0 to 64.0
Cobbles	64.0 to 256.0
Boulders	> 256

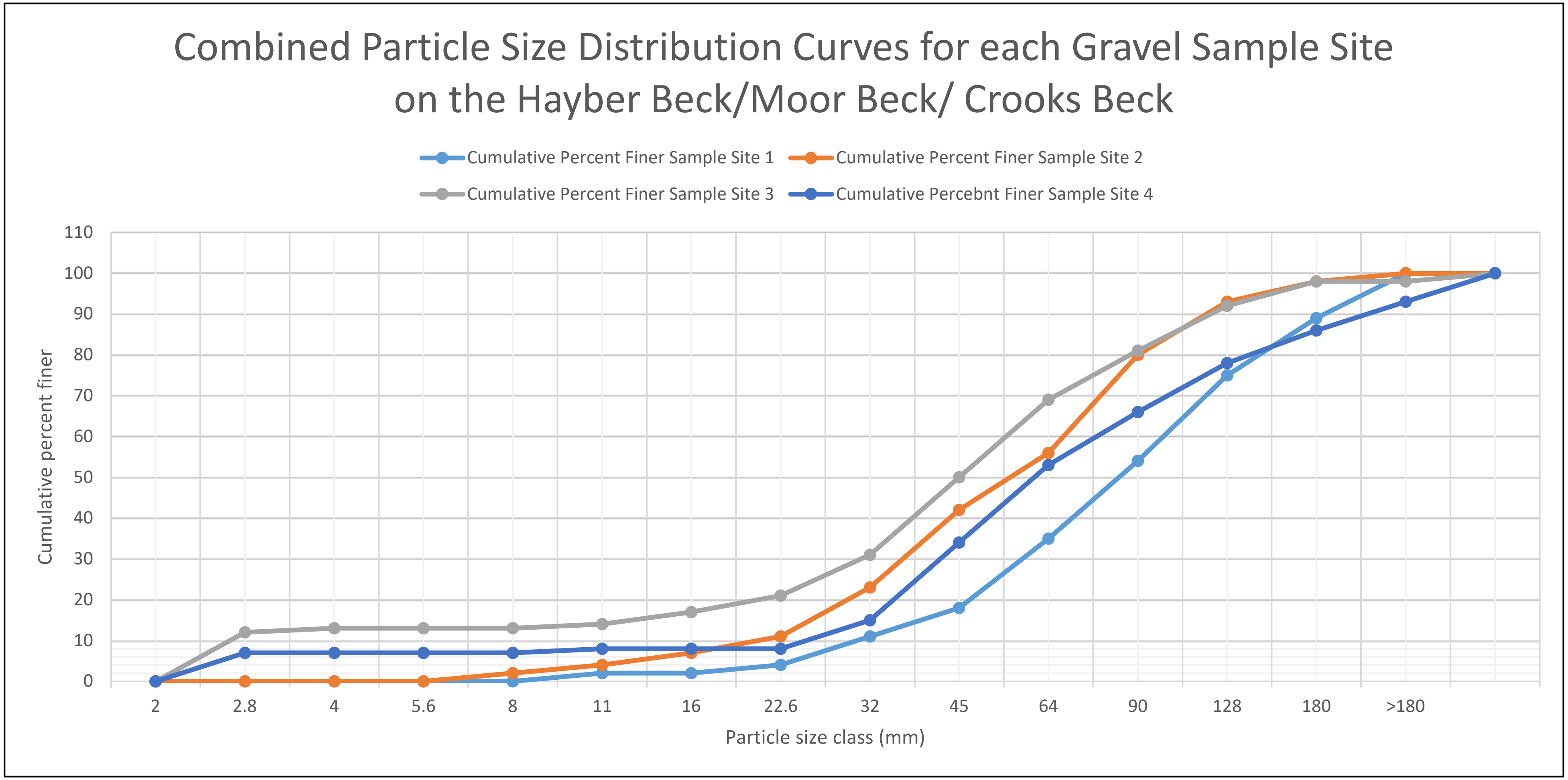


Plate 75: Combined particle size distribution curves for gravel sample locations on the Hayber Beck, Moor Beck and Crooks Beck

Eastfield Sike sediment sample analysis

14.9.3.61 Table 13: D10, D50 and D90 particle size distribution values for each gravel bar sample site on the Eastfield Sike and Table 14: D10, D50 and D90 particle size distribution classes for each gravel bar sample site on the Eastfield Sike present the particle size distribution values and classes across Sample Location 1 on the Eastfield Sike respectively. The calculated D50 (median), D10 and D90 particle size distribution values are displayed below.

14.9.3.62 Table 15: Millimetre size ranges for different sediment sizescompares the typical particle size values to the corresponding particle size classification.

14.9.3.63 Plate 76: Particle size distribution curve for the gravel sampling site on Eastfield Sike presents the particle distribution curve for Eastfield Sike.

Table 13: D10, D50 and D90 particle size distribution values for each gravel bar sample site on the Eastfield Sike

Sample Location	D10 (mm)	D50 (median) (mm)	D90 (mm)
Sample 1	5.6	45	90

Table 14: D10, D50 and D90 particle size distribution classes for each gravel bar sample site on the Eastfield Sike

Sample Location	D10 (mm)	D50 (median) (mm)	D90 (mm)
Sample 1	Fine Gravel	Very Coarse Gravel	Fine Cobble

Table 15: Millimetre size ranges for different sediment sizes

Description	Size (mm)
Coarse Sand	0.5 to 2.0
Gravel	2.0 to 16.0
Pebbles	16.0 to 64.0
Cobbles	64.0 to 256.0
Boulders	> 256

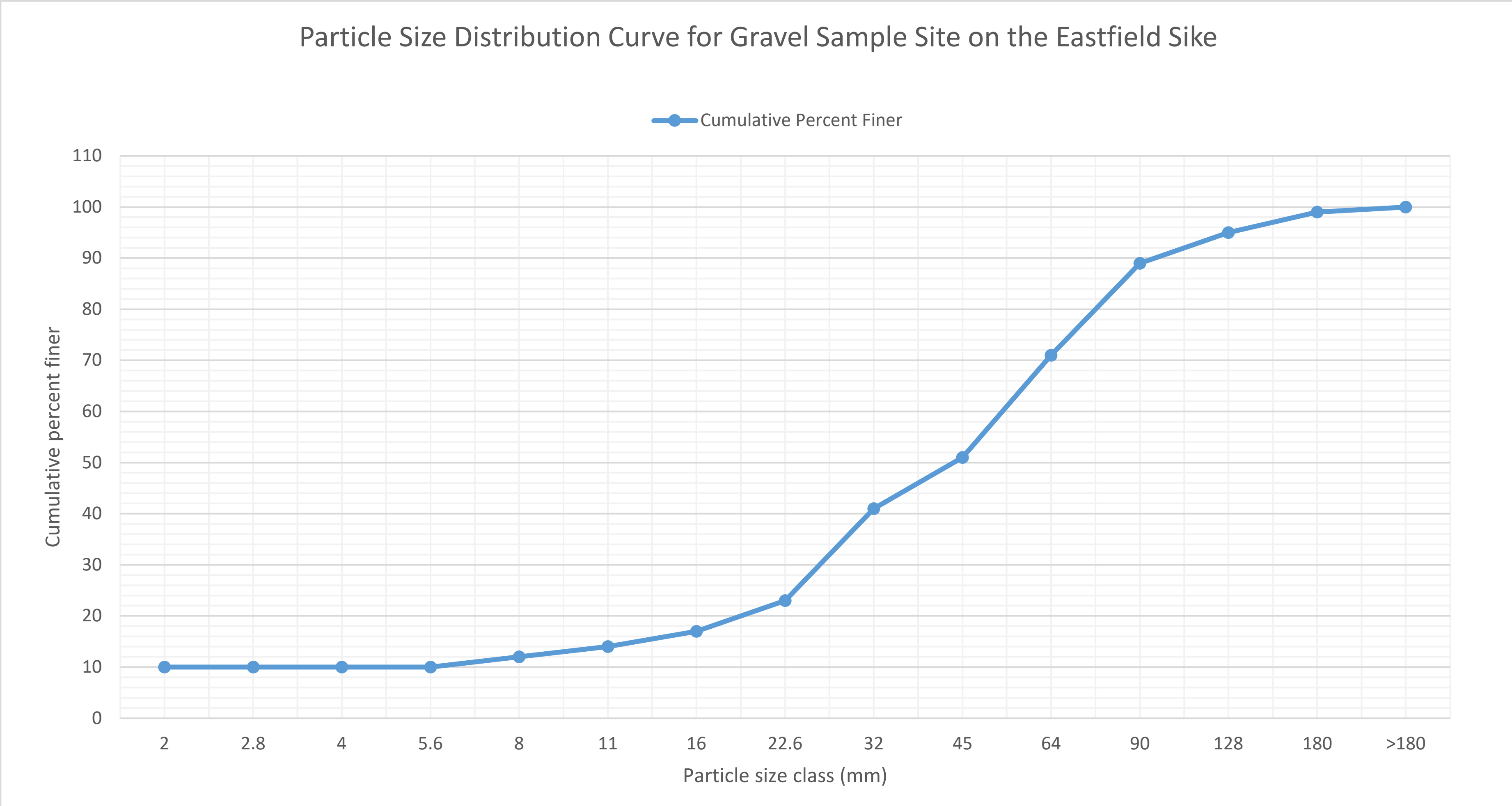


Plate 76: Particle size distribution curve for the gravel sampling site on Eastfield Sike

Lowgill Beck sediment sample analysis

14.9.3.64 Table 16: D10, D50 and D90 particle size distribution values for each gravel bar sample site on Lowgill Beck and Table 17: D10, D50 and D90 particle size distribution classes for each gravel bar sample site on the Lowgill Beck present the particle size distribution values and classes across Sample Location 1 on the Lowgill Beck respectively. The calculated D50 (median), D10 and D90 particle size distribution values are displayed below.

14.9.3.65 Table 18: Millimetre size ranges for different sediment sizes compares the typical particle size values to the corresponding particle size classification.

14.9.3.66 Plate 77: Particle size distribution curve for the gravel sampling site on the Lowgill Beck presents the particle distribution curve for the Lowgill Beck.

Table 16: D10, D50 and D90 particle size distribution values for each gravel bar sample site on Lowgill Beck

Sample Location	D10 (mm)	D50 (median) (mm)	D90 (mm)
Sample 1	11	32	64

Table 17: D10, D50 and D90 particle size distribution classes for each gravel bar sample site on the Lowgill Beck

Sample Location	D10 (mm)	D50 (median) (mm)	D90 (mm)
Sample 1	Medium Gravel	Coarse Gravel	Very Coarse Gravel

Table 18: Millimetre size ranges for different sediment sizes

Description	Size (mm)
Coarse Sand	0.5 to 2.0
Gravel	2.0 to 16.0
Pebbles	16.0 to 64.0
Cobbles	64.0 to 256.0
Boulders	> 256

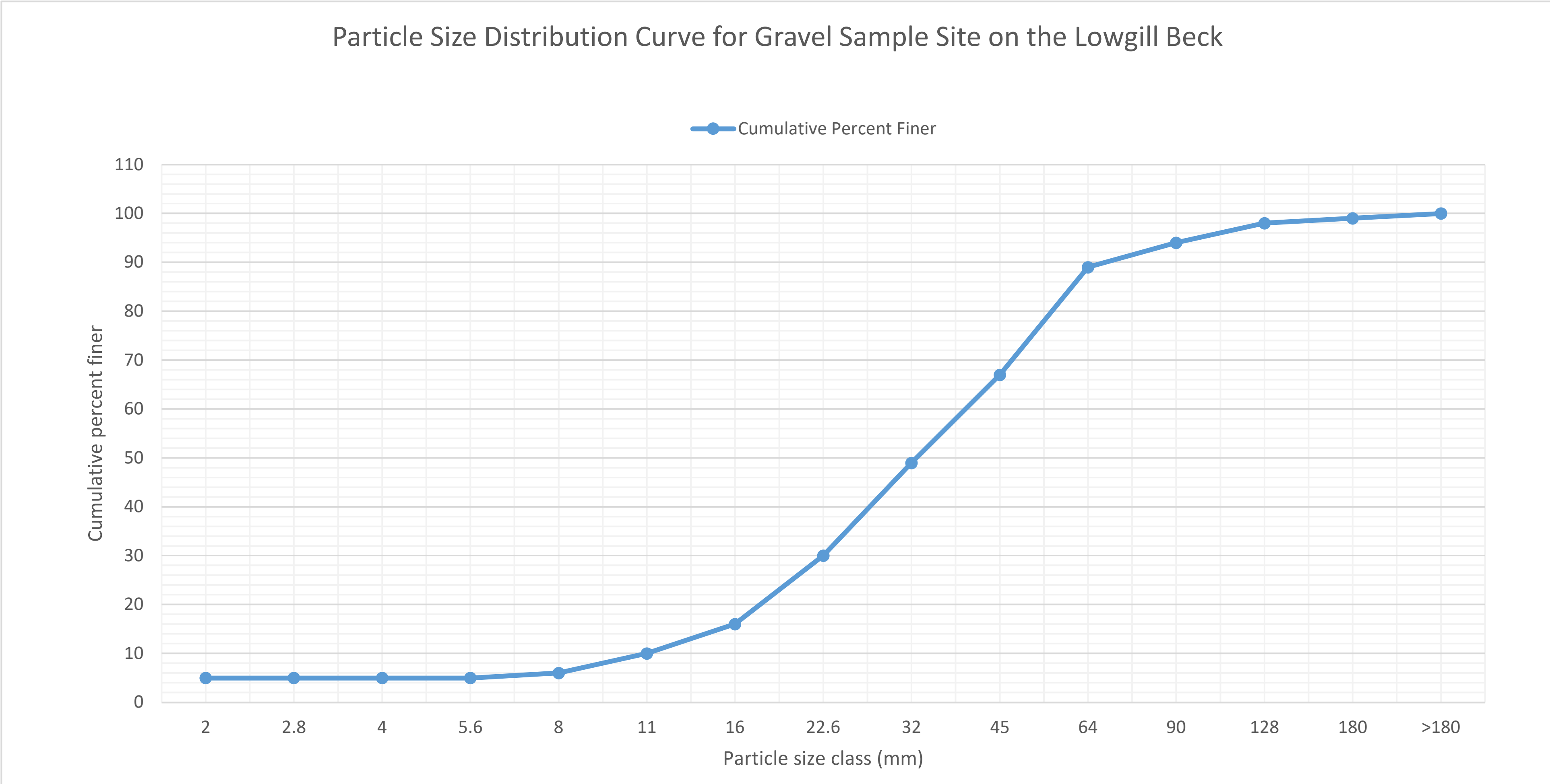


Plate 77: Particle size distribution curve for the gravel sampling site on the Lowgill Beck

Proposed works in the vicinity of Warcop

Overview

14.9.3.67 Plate 78: Overview of the proposed works in the vicinity of Warcop provides detail on the proposed works at each watercourse crossing point in Warcop.

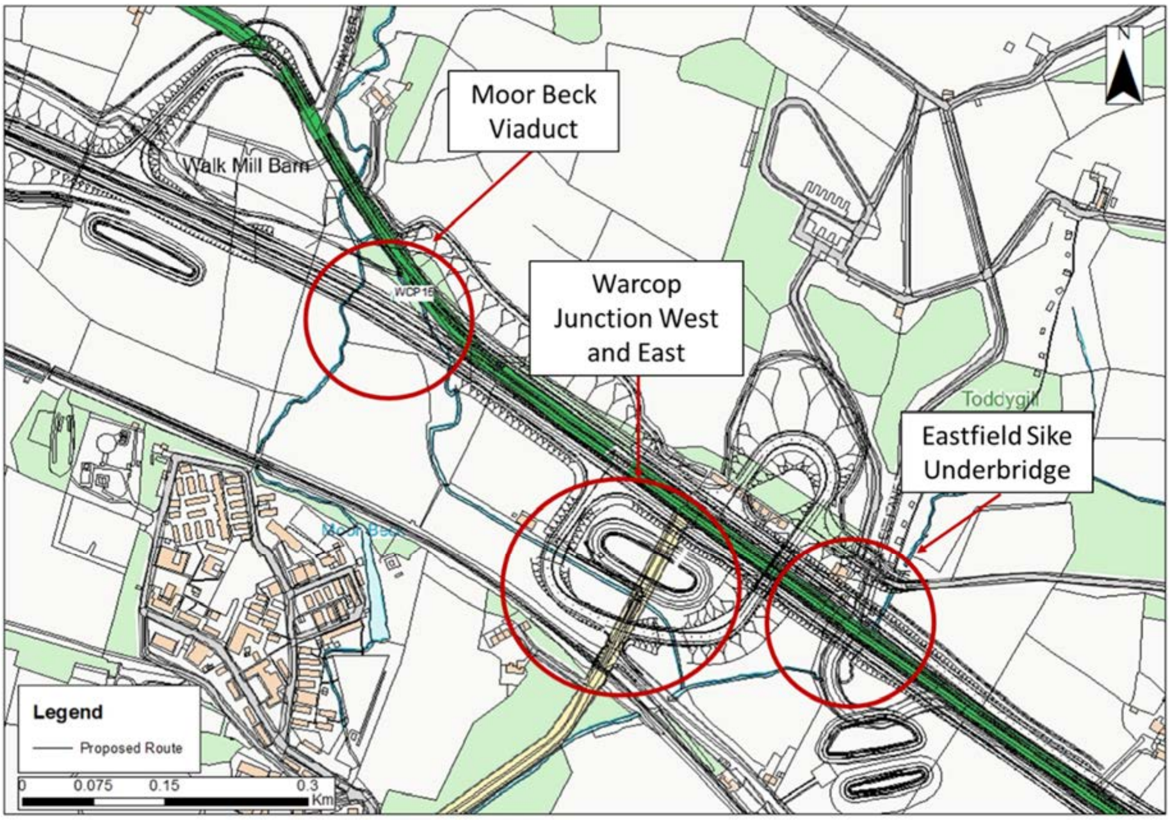


Plate 78: Overview of the proposed works in the vicinity of Warcop

Warcop Viaduct

14.9.3.68 There is an existing box culvert of 3.77m width and 1.45m height which conveys the Hayber Beck (before the watercourse splits into the Moor Beck and Moor Beck (Offtake)) beneath the existing A66.

14.9.3.69 The proposed structures involve the installation of a viaduct structure spanning 259.75m across the Moor Beck and the Moor Beck (Offtake), approximately 100m downstream of the existing box culvert on the existing A66.

14.9.3.70 Six pier locations are proposed across the span of the viaduct, with five bridge openings between each of the pier locations. From east to west, an opening width of 63m will be available over the Moor Beck; an opening of 49m occupying the floodplain between the Moor Beck and Moor Beck (Offtake); and an opening of 49.25m will be available over the Moor Beck (Offtake); and two openings of 49.25m will be available on the right bank floodplain of the Moor Beck (Offtake).

14.9.3.71 At each pier location, five plinths will be installed across the width of the bridge deck to support the viaduct. These will be spaced at 32.5m intervals across the bridge soffit.

14.9.3.72 The viaduct deck width will be 32.69m.

14.9.3.73 Attenuation ponds will be installed within the perimeter of the Warcop Junction structure and to the south east of the Eastfield Sike Underbridge structure.

Warcop Junction West

14.9.3.74 There is an existing road bridge which crosses the Moor Beck approximately 100m downstream of Watercourse Crossing Point 51. This structure will remain *in situ* following the completion of the works in the vicinity of Warcop.

14.9.3.75 The proposed structure involves the installation of an underbridge structure spanning 25m across the width of the Moor Beck for a total length of 25m, to convey the A66 junction carriageway across the Moor Beck.

14.9.3.76 Road embankments occupying the left and right bank of the Moor Beck will tie into the left and right extent of the underbridge structure. Reinforced earth granular backfill will be used to fill the space between the end of the road embankment and the underbridge structure. This will leave a 25m wide combined area of channel and floodplain for the Moor Beck to utilise.

14.9.3.77 A flood compensation structure will be added on the floodplain area between the left bank of the Moor Beck and the right bank of the Moor Beck offtake, and on the left bank floodplain of the Moor Beck. Water will be captured and stored within this structure across a range of flood events, reducing the conveyance of flood water across the floodplain on the left bank of the Moor Beck on the approach to the embankments associated with Warcop Junction.

14.9.3.78 An embankment will be installed on the eastern extent of the flood compensation structure to improve retention of flood waters. Stored flood water will be conveyed back into the Moor Beck on the right bank of the channel, directly upstream of the embankment associated with the flood compensation structure. The existing banks of the Moor Beck will not be modified to facilitate the installation of the flood compensation structure.

14.9.3.79 An overview of the flood compensation structure is presented in Plate 79: Overview of the flood compensation structure associated with Warcop Junction.

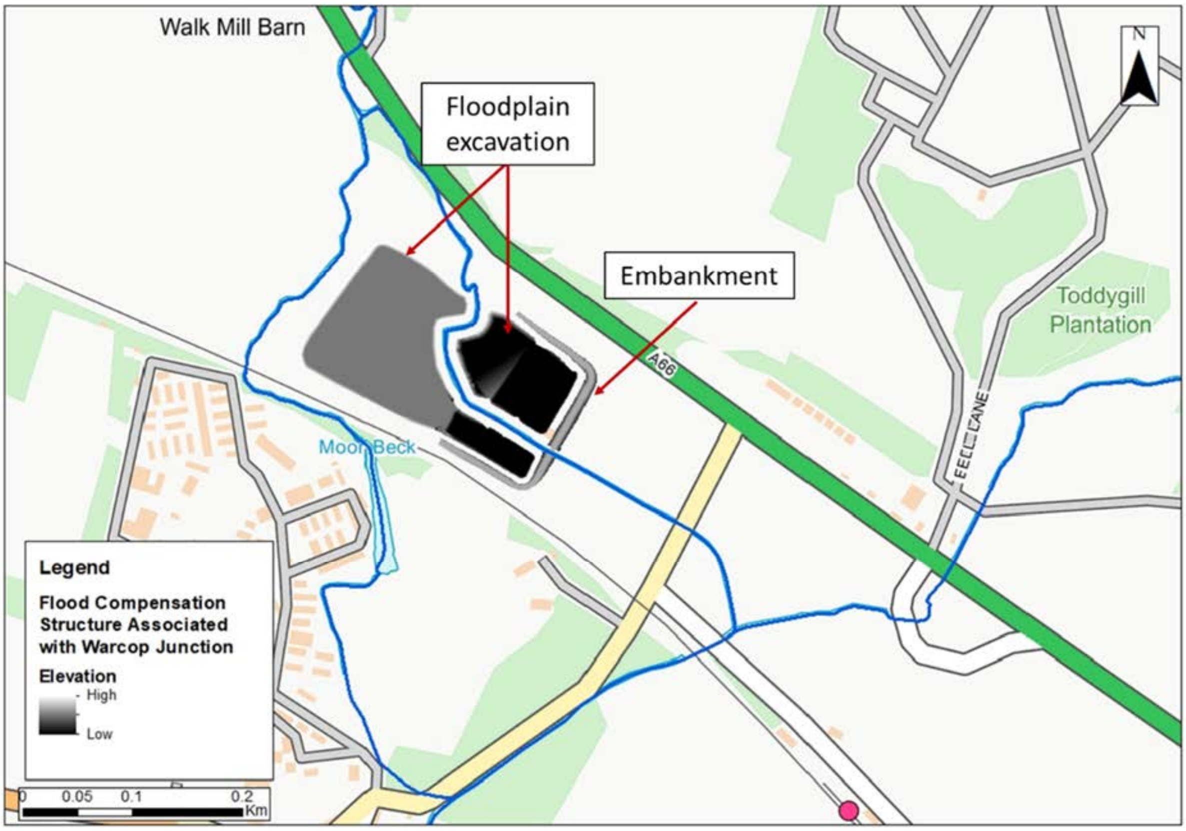


Plate 79: Overview of the flood compensation structure associated with Warcop Junction

Warcop Junction East

14.9.3.80 There is an existing road bridge which crosses the Moor Beck approximately 60m upstream of Watercourse Crossing Point 52. This structure will remain *in situ* following the completion of the works in the vicinity of Warcop.

14.9.3.81 The proposed structure involves the installation of an underbridge structure spanning 25m across the width of the Moor Beck for a total length of 19.6m, to convey the A66 junction carriageway across the Moor Beck.

14.9.3.82 Road embankments occupying the left and right bank of the Moor Beck will tie into the left and right extent of the underbridge structure. Reinforced earth granular backfill will be used to fill the space between the end of the road embankment and the underbridge structure. This will leave a 25m wide combined area of channel and floodplain for the Moor Beck to utilise.

14.9.3.83 A flood compensation structure will be added on the floodplain area between the left bank of the Moor Beck and the right bank of the Moor Beck offtake, and on the left bank floodplain of the Moor Beck. Water will be captured and stored within this structure across a range of flood events, reducing the conveyance of flood water across the floodplain on the left bank of the Moor Beck on the approach to the embankments associated with Warcop Junction.

14.9.3.84 An embankment will be installed on the eastern extent of the flood compensation structure to improve retention of flood waters. Stored flood water will be conveyed back into the Moor Beck on the right bank of the channel, directly upstream of the embankment associated with the flood compensation structure. The existing banks of the Moor Beck will not be modified to facilitate the installation of the flood compensation structure.

Eastfield Sike Underbridge

14.9.3.85 There is an existing culvert structure conveying the Eastfield Sike beneath the existing A66 road. This is comprised of two circular culvert barrels with a diameter of 1.05m for a total length of 18m. Another structure conveys the Eastfield Sike beneath the access road located approximately 50m upstream of the existing A66 road.

14.9.3.86 The proposed structure involves the replacement of the existing culvert structure beneath the A66 with an underbridge structure spanning 19m across the width of the Eastfield Sike for a total length of 50.6m to convey the A66 carriageway across the Eastfield Sike.

14.9.3.87 Road embankments occupying the left and right bank of the Eastfield Sike will tie into the left and right extent of the underbridge structure. Reinforced earth granular backfill will be used to fill the space between the end of the road embankment and the underbridge structure. This will leave a 19m wide combined area of channel and floodplain for the Eastfield Sike to utilise.

Analysis of hydraulic model results

Overview

14.9.3.88 A combined hydraulic model of the Hayber Beck / Moor Beck, Moor Beck (Offtake), Eastfield Sike, Lowgill Beck and Crooks Beck was developed for the purposes of this study (detailed in previously).

14.9.3.89 Two scenarios have been modelled to assist with the geomorphological analysis, outlined below:

- Baseline Scenario – Existing conditions on Hayber Beck/Moor Beck, Moor Beck (Offtake), Eastfield Sike, Lowgill Beck and Crooks Beck have been replicated
- Post Development Scenario – Representation of the scheme on the floodplain of the Hayber Beck / Moor Beck, Moor Beck (Offtake), Eastfield Sike, Lowgill Beck and Crooks Beck.

14.9.3.90 The analysis of hydraulic model results has been undertaken for the following flood return periods:

- 1-in-2 Year Flood Event
- 1-in-20 Year Flood Event
- 1-in-100 Year +94% Climate Change Flood Event

14.9.3.91 The following results have been analysed to provide a holistic understanding of the geomorphological processes occurring within the channel and on the floodplain in the Baseline and Post Development scenario on the Hayber Beck/Moor Beck, Moor Beck (Offtake), Eastfield Sike, Lowgill Beck and Crooks Beck.

- Floodplain (2D) maximum sediment entrainment comparison
- Floodplain (2D) maximum velocity comparison
- In channel (1D) maximum sediment entrainment comparison

14.9.3.92 Analysis has been undertaken on the following watercourses:

- Hayber Beck / Moor Beck
- Moor Beck (Offtake)
- Eastfield Sike
- Crooks Beck

14.9.3.93 Analysis has not been undertaken on the Lowgill Beck, as there are no proposed works as part of the scheme in the vicinity of Warcop.

14.9.3.94 For analysis of flood depths and pass forward flow, refer to ES Appendix 14.2: Flood Risk Assessment and Outline Drainage Strategy (Application Document 3.2).

Shear stress analysis calculations

Derivation of 1D shear stress, critical shear stress and mobile grain sizes

14.9.3.95 Bed load movement and sediment transport is a function of shear stress. When the drag force of flowing water against a particle is greater than the gravitational force holding it in place it begins to move. The moment when the directive forces (shear forces) overcome restrictive forces (inertia, friction) is known as the moment of incipient motion and is the threshold of particle entrainment. The shear stress at this threshold is known as the critical shear stress.

14.9.3.96 The wetted perimeter, wetted area and velocity outputs from the hydraulic model have been used, along with a roughness estimate (Manning's n)[1] to calculate bed shear stress derived from the following expression:

(Eq.1)

$$\tau = \frac{\rho\, g\, n^2\, V^2}{\left(\frac{A}{P}\right)^{\left(\frac{1}{3}\right)}}$$

14.9.3.97 Where τ is shear stress (N/m^2), ρ is the density of water (kg/m^3), *g* is acceleration due to gravity (m/s^2), *n* is the Manning's coefficient (s/m$^{1/3}$), V is the depth averaged velocity (m/s), *A* is the wetted area (m^2) and *P* is the wetted perimeter (m).

14.9.3.98 The calculated bed shear stress can be used to predict the mobile sediment size when used in conjunction with Shields (1936)[3] entrainment function, derived from the following expression:

(Eq.2)

$$\tau_{0c} = \theta(\rho_s - \rho_w)gD$$

14.9.3.99 Where τ_{0c} is the critical shear stress (N/m^2), θ is the Shields parameter (non-dimensional), ρ_s is the density of sediment (kg/m^3), ρ_w is the density of water (kg/m^3) and, g is acceleration due to gravity (m/s^2) and D is a characteristic diameter of the sediment (mm). On hydraulically rough beds (the common condition in natural rivers), the Shields parameter rapidly attains a constant value (reported values range from 0.03 to 0.06), with 0.045 now accepted as a good approximation (Komar, 1988)[4].

Derivation of 2D shear stress, critical shear stress and mobile grain sizes

14.9.3.100 Maximum velocity and depth outputs from the hydraulic model have been used, along with a roughness estimate (Manning's n) to calculate an effective bed shear derived from the following quadratic expression (Lane and Ferguson, 2005)[2]:

(Eq.3)

$$\tau_0 = \rho\, g\, \frac{n^2}{d^{\frac{1}{3}}}\, V^2$$

14.9.3.101 Where τ_0 is effective shear stress (N/m^2), ρ is density of water (kg/m^3), g is acceleration due to gravity (m/s^2), n is the Manning's coefficient (s/m$^{1/3}$), d is depth (m) and, V is depth averaged velocity (m/s). This relation gives a very similar functional relationship to shear stresses derived on integrating flows assuming a logarithmic law of the wall.

14.9.3.102 The calculated bed shear stress can be used to predict the mobile sediment size when used in conjunction with Shields (1936)[3] entrainment function, derived from the following expression:

(Eq.4)

$$\tau_{0c} = \theta(\rho_s - \rho_w)gD$$

14.9.3.103 Where τ_{0c} is the critical shear stress (N/m^2), θ is the Shields parameter (non-dimensional), ρ_s is the density of sediment (kg/m^3), ρ_w is the density of water (kg/m^3) and, g is acceleration due to gravity (m/s^2) and D is a characteristic diameter of the sediment (mm). On hydraulically rough beds (the common condition in natural rivers), the Shields parameter rapidly attains a constant value (reported values range from 0.03 to 0.06), with 0.045 now accepted as a good approximation (Komar, 1987)[4].

1-in-2 year flood event

Floodplain shear stress analysis

14.9.3.104 Under existing conditions in the 1-in-2 Year Flood Event, minimal overland flow routes are observed on the floodplain in the vicinity of Warcop, as much of the flow within this flood return period is contained within the channel in both the baseline and post development scenarios, with the exception of the floodplain between the Moor Beck and Moor Beck (Offtake) (Plate 80: Baseline 1-in-2 Year Flood Event maximum size of sediment entrained).

14.9.3.105 The typical size of material that can be mobilised on the floodplain between the Moor Beck and the Moor Beck (Offtake) ranges between silts to medium gravels.

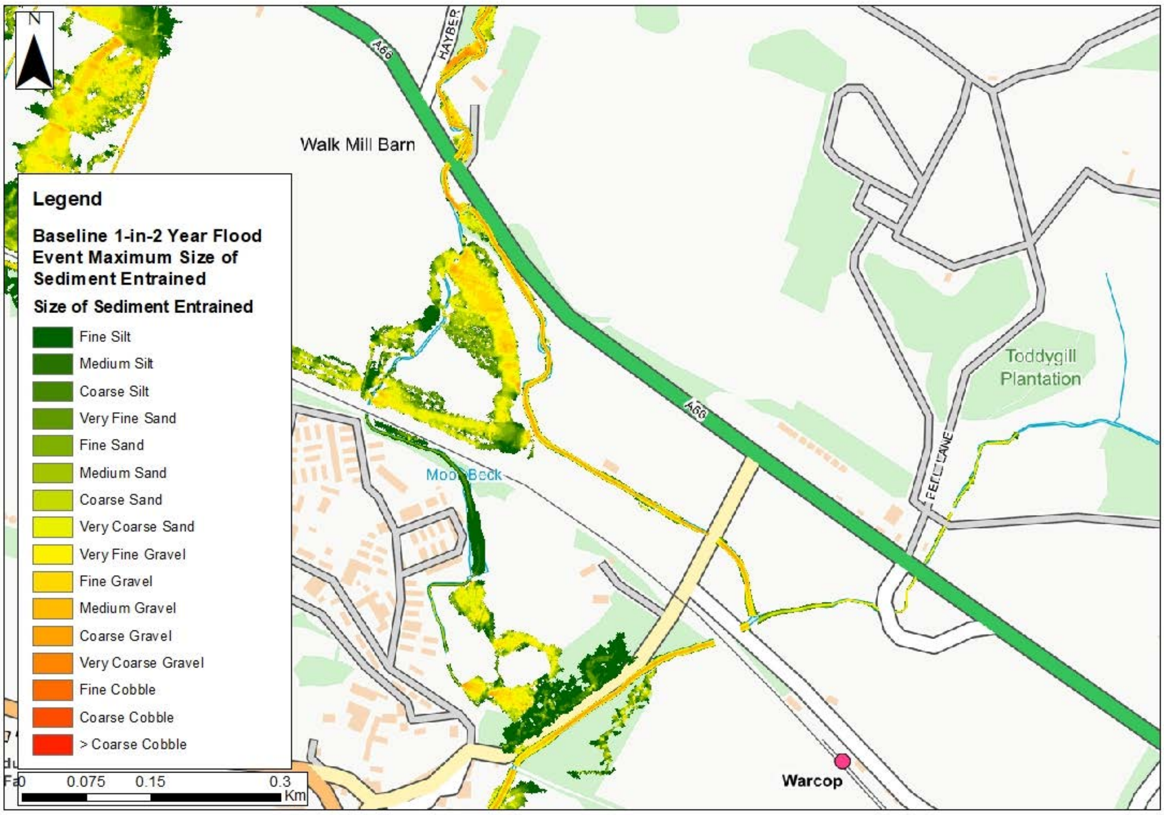


Plate 80: Baseline 1-in-2 Year Flood Event maximum size of sediment entrained

14.9.3.106 In the Post-Development 1-in-2 Year Flood Event, the addition of a flood compensation structure on the left and right bank of the Moor Beck (as indicated in Plate 79: Overview of the flood compensation structure associated with Warcop Junction) generates localised variations in sediment transport dynamics on the floodplain (Plate 81: Post-Development 1-in-2 Year Flood Event maximum size of sediment entrained). The maximum size of material that can be mobilised on the floodplain in the vicinity of the flood compensation structure reduces. The flood compensation structure improves the lateral connectivity between the Moor Beck channel and floodplain, which improves the retention of water on the floodplain. As more flood water is captured and redistributed across the floodplain at the flood compensation structure, water pools and flow velocities reduce significantly.

14.9.3.107 The hydraulic model results suggest that potential retention of fine material, ranging from silts to sands, is possible within the structure. The potential increased retention of fine material on the floodplain would represent improved geomorphological function, as this would limit the conveyance of fine material to downstream reaches on the Moor Beck and Crooks Beck, which could lead to the degradation of the riverbed substrate.

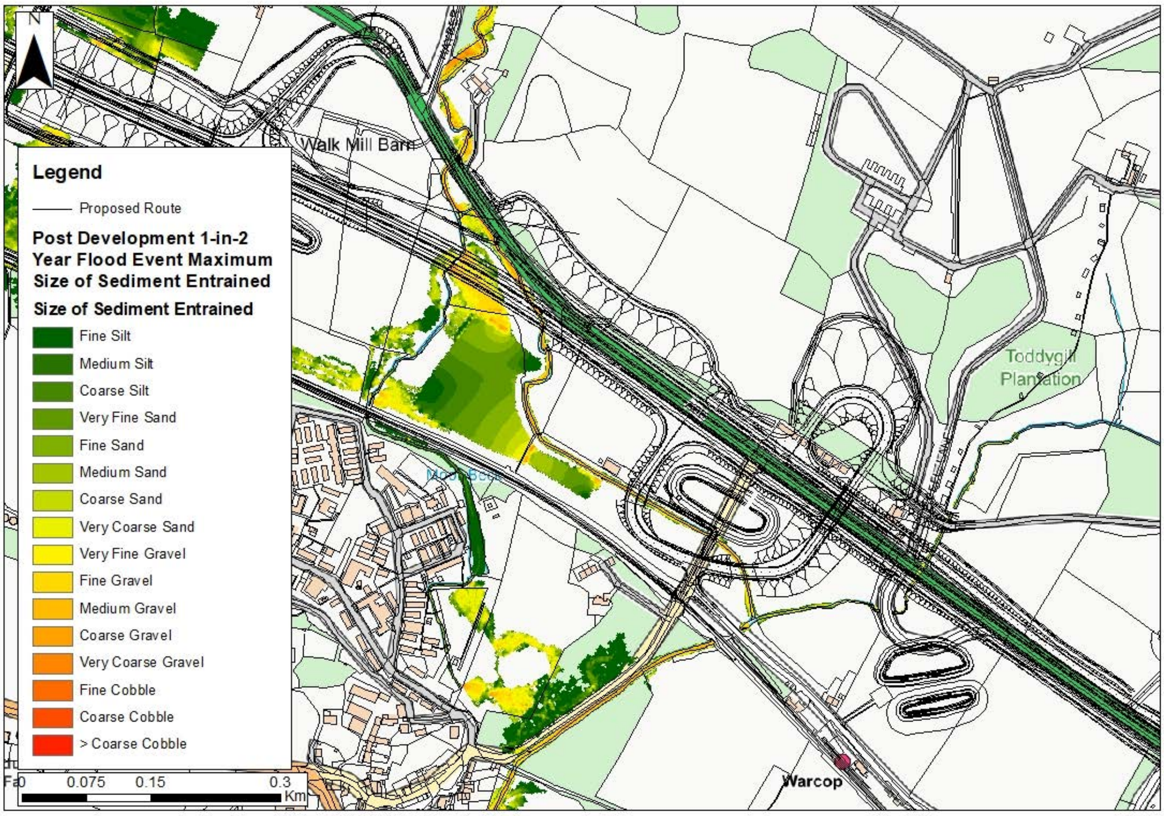


Plate 81: Post-Development 1-in-2 Year Flood Event maximum size of sediment entrained

Floodplain velocity comparison analysis

14.9.3.108 Plate 82: 1-in-2 Year Flood Event Change in velocity in the Post Development Scenario compared to the Baseline Scenario presents a comparison between maximum velocities on the floodplain in the Post Development scenario and the Baseline Scenario.

14.9.3.109 Minimal variations in maximum velocities were identified across the floodplain to the north of Warcop. Much of the flow during the 1-in-2 Year Flood Event in both the Baseline and Post-Development scenarios are contained within the channel, with the exception of the floodplain between the Moor Beck and the Moor Beck (Offtake).

14.9.3.110 The addition of a flood compensation structure on the left and right bank of the Moor Beck (as indicated in Plate 79: Overview of the flood compensation structure associated with Warcop Junction) generates localised variations maximum flow velocities on the floodplain. Maximum flow velocities reduce where water pools within the floodplain structure, and velocities increase where water is conveyed from the south eastern corner of the structure back into the Moor Beck on the right bank. Maximum increases in this area of the right bank of the Moor Beck are between 0.1 and 0.5m/s.

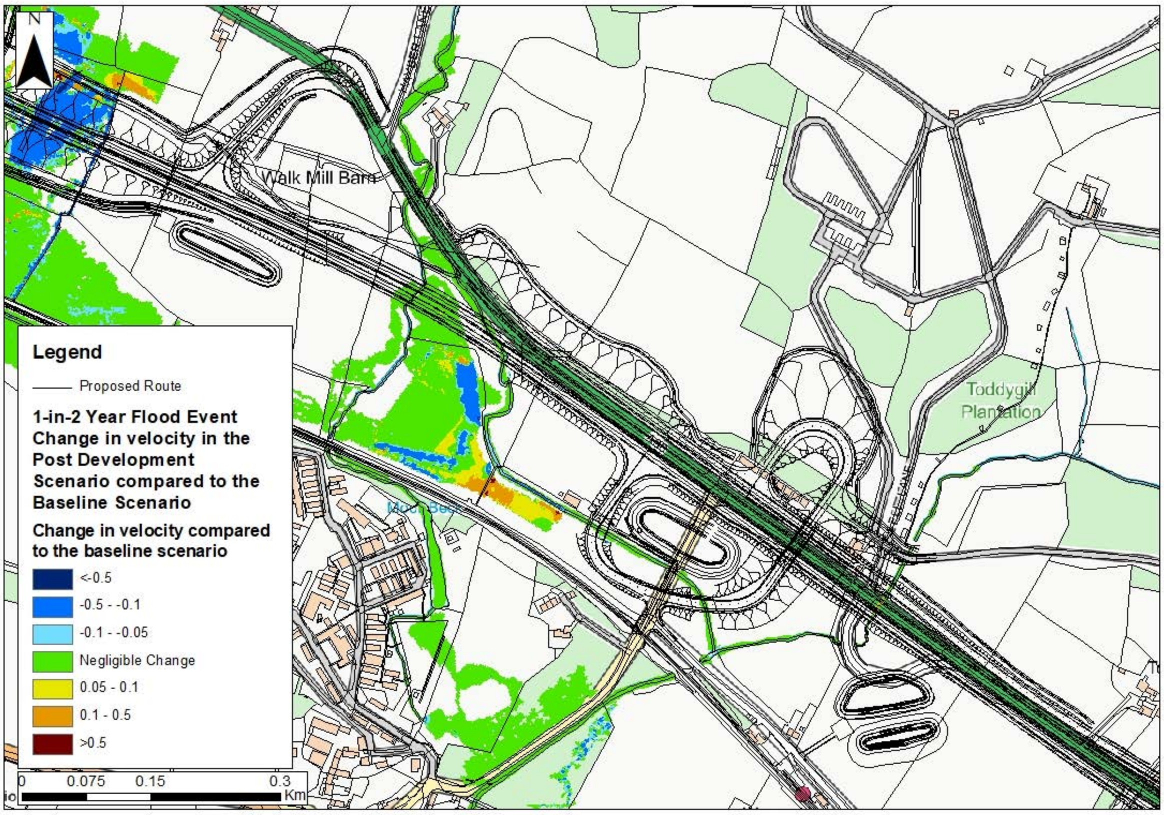


Plate 82: 1-in-2 Year Flood Event Change in velocity in the Post Development Scenario compared to the Baseline Scenario

In-channel shear stress analysis

14.9.3.111 Plate 83: 1-in-2 Year Flood Event comparison of in channel maximum size of sediment entrained on the Moor Beck and Crooks Beck between the Post Development and Baseline Scenarios, Plate 84: 1-in-2 Year Flood Event comparison of in channel maximum size of sediment entrained on the Moor Beck (Offtake) between the Post Development and Baseline Scenarios and Plate 85: 1-in-2 Year Flood Event comparison of in channel maximum size of sediment entrained on the Eastfield Sike between the Post Development and Baseline Scenarios present a comparison of the 1-in-2 Year Flood Event in-channel maximum sizes of sediment entrained between the Post Development and Baseline Scenarios across the Moor Beck, Moor Beck (Offtake), Eastfield Sike and Crooks Beck respectively.

14.9.3.112 The predicted maximum size of material that can be mobilised at each of the cross sections from the hydraulic model has been calculated for the Moor Beck, Moor Beck (Offtake), Eastfield Sike and Crooks Beck. Red circles indicate areas where the size of material that can be mobilised in the channel could increase in the Post Development Scenario. In these locations slight changes to the composition of the riverbed could occur, with a small risk of scour.

14.9.3.113 Green circles indicate areas where the size of the material that can be mobilised in the channel could decrease in the Post Development Scenario. No erosion is likely here, and there is the potential for a small increase in sediment deposition.

14.9.3.114 All other areas have either no change, or changes in shear stress that are negligible meaning that the typical size of material that can be entrained will not change.

14.9.3.115 On the Moor Beck and Crooks Beck, only two cross sections exhibited predicted changes in the maximum size of material that can be mobilised (Plate 83: 1-in-2 Year Flood Event comparison of in channel maximum size of sediment entrained on the Moor Beck and Crooks Beck between the Post Development and Baseline Scenarios). Cross section CROO_01629D, located directly upstream of the confluence with the Eastfield Sike, experienced a small reduction in the size of material that can be entrained, reducing from Coarse Gravel to Medium Gravel. On the Crooks Beck, cross section CR00_01394 experiences a small increase in the potential size of material entrained, increasing from Very Coarse Gravel to Fine Cobble.

14.9.3.116 In summary, no significant changes to the size of sediment that can be entrained are predicted as a result of the proposed works on the Moor Beck and Crooks Beck. The small variations predicted in the size of material that can be entrained at these two locations are unlikely to translate into significant increases to in-channel sediment deposition or erosion. Site observations indicated that the typical size of material present on the riverbed on both the Moor Beck and the Crooks Beck ranged between gravels to cobbles. As changes identified within the hydraulic model in both of these reaches are within the approximate ranges of typical sediment sizes already present on the riverbed, there is unlikely to be a change in the composition and structure of the riverbed.

14.9.3.117 On the Moor Beck (Offtake) only two cross sections exhibited predicted changes in the maximum size of material that can be mobilised (Plate 84: 1-in-2 Year Flood Event comparison of in channel maximum size of sediment entrained on the Moor Beck (Offtake) between the Post Development and Baseline Scenarios). Cross sections CROK_00625 and CROK_00568, both located upstream of the rail embankment, both experienced a small reduction in the size of material that can be entrained, reducing from Fine Gravel to Very Fine Gravel. In summary, there are insignificant changes to the riverbed composition arising from the scheme on the Moor Beck (Offtake).

14.9.3.118 Predicted reductions in the size of material that can be mobilised in the Moor Beck (Offtake) are likely a result of the conveyance of additional flow from the flood compensation structure on the left bank floodplain into the channel. Increased volumes of water in the channel upstream of the structure at the rail embankment is creating flow impoundment, leading to a reduction in velocities and the size of material mobilised. The variations predicted in the size of material that can be entrained at these two locations are unlikely to translate into significant increases to in-channel sediment deposition or erosion. Site observations indicated that the typical size of material present on the riverbed on both the Moor Beck (Offtake) ranged between sands and gravels. As changes identified within the hydraulic model in both of these reaches are within the approximate ranges of typical sediment sizes already present on the riverbed, there is unlikely to be a change in the composition and structure of the riverbed.

14.9.3.119 On the Eastfield Sike, only two cross sections were identified as experiencing changes in the maximum size of material that can be mobilised (Plate 85: 1-in-2 Year Flood Event comparison of in channel maximum size of sediment entrained on the Eastfield Sike between the Post Development and Baseline Scenarios). Cross sections TODDY_00297 and TODDY_00247, both located immediately upstream of the culvert that conveys the Eastfield Sike beneath the access road adjacent to Fell Lane. Both exhibited increases in the size of material that can be entrained, increasing from Coarse Gravel to Very Coarse Gravel and Fine Gravel to Coarse Gravel.

14.9.3.120 Increases in the size of material mobilised marked on the map are likely a result of the replacement of the culvert beneath the existing A66 with a new structure. Removal of impoundment of flow upstream of the A66 improves conveyance within the channel, leading to greater velocities and shear stress values. The predicted increase in the size of material that can be mobilised in this reach is unlikely to significantly impact existing sediment transport dynamics or the composition of the riverbed. Typical sizes of bed material noted on the Eastfield Sike during the site visit were predominantly gravels and some coarser material.

Model Cross Section	Baseline Q2 Sediment Size Moved	PostDev Q2 Sediment Size Moved
CROO_02656	Fine Cobble	Fine Cobble
CROO_02608	Very Coarse Gravel	Very Coarse Gravel
CROO_02605	Fine Cobble	Fine Cobble
CROO_02602	Fine Cobble	Fine Cobble
CROO_02570	Very Coarse Gravel	Very Coarse Gravel
CROO_02567	Very Coarse Gravel	Very Coarse Gravel
CROO_02518	Fine Cobble	Fine Cobble
CROO_02439	Fine Cobble	Fine Cobble
CROO_02408	Very Coarse Gravel	Very Coarse Gravel
CROO_02396	Fine Cobble	Fine Cobble
CROO_02332	Coarse Gravel	Coarse Gravel
CROK_00846B	Very Coarse Gravel	Very Coarse Gravel
CROO_02329	Medium Gravel	Medium Gravel
CROO_02329D	Coarse Gravel	Coarse Gravel
CROO_02324	Coarse Gravel	Coarse Gravel
CROO_02324D	Coarse Gravel	Coarse Gravel
CROO_02318	Fine Cobble	Fine Cobble
CROO_02250	Fine Cobble	Fine Cobble
UNN604_0515	Very Coarse Gravel	Very Coarse Gravel
CROO_02112	Fine Cobble	Fine Cobble
CROO_01997	Very Coarse Gravel	Very Coarse Gravel
CROO_01982	Fine Cobble	Fine Cobble
CROO_01965	Fine Cobble	Fine Cobble
UNN604_0240	Very Coarse Gravel	Very Coarse Gravel
CROO_01859	Very Coarse Gravel	Very Coarse Gravel
CROO_01838	Very Coarse Gravel	Very Coarse Gravel
CROO_01834	Very Coarse Gravel	Very Coarse Gravel
CROO_01834_U	Very Coarse Gravel	Very Coarse Gravel
CROO_01832	Fine Cobble	Fine Cobble
CROO_01765	Very Coarse Gravel	Very Coarse Gravel
CROO_01756	Very Coarse Gravel	Very Coarse Gravel
CROO_01629U	Medium Gravel	Medium Gravel
CROO_01629D	Coarse Gravel	Medium Gravel
CROO_01629D2	Medium Gravel	Medium Gravel
CROO_01629	Coarse Gravel	Coarse Gravel
CROO_01473	Very Coarse Gravel	Very Coarse Gravel
CROO_01394	Very Coarse Gravel	Fine Cobble
CROO_01394U	Medium Gravel	Medium Gravel
CROO_01394D	Medium Gravel	Medium Gravel
CROO_01321	Medium Gravel	Medium Gravel

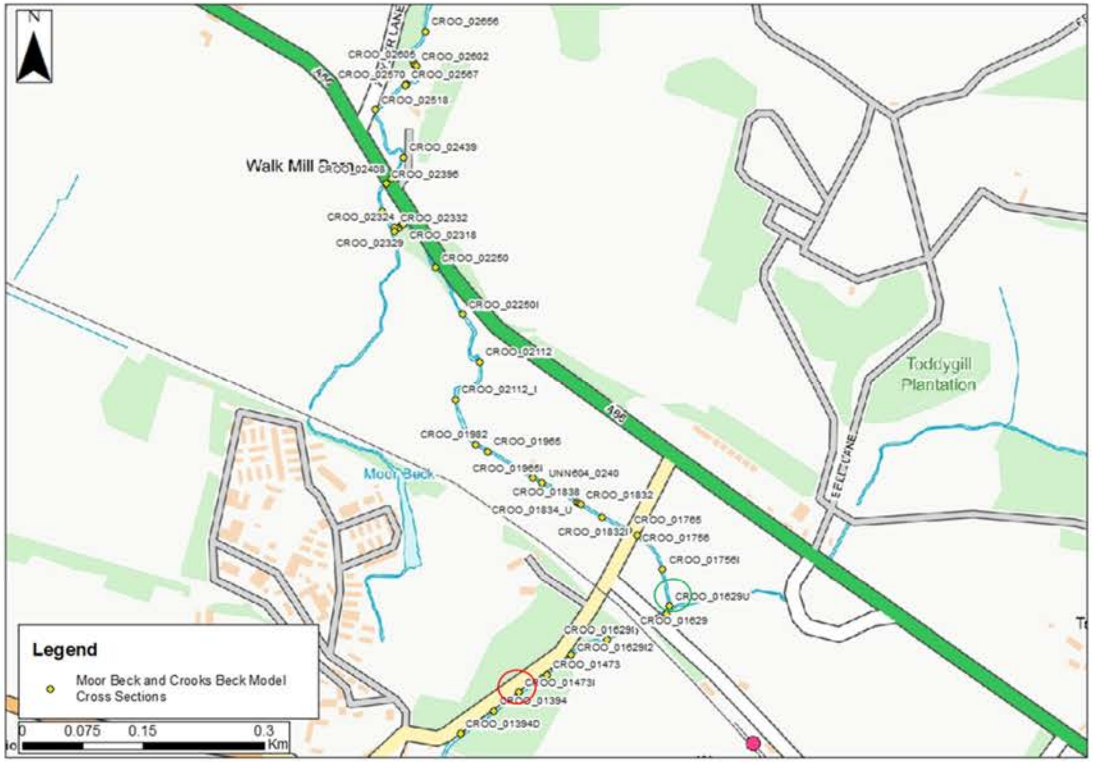


Plate 83: 1-in-2 Year Flood Event comparison of in channel maximum size of sediment entrained on the Moor Beck and Crooks Beck between the Post Development and Baseline Scenarios

Model Cross Sections	Baseline Q2 Sediment Size Moved	PostDev Q2 Sediment Size Moved
CROK_00790	Very Coarse Gravel	Very Coarse Gravel
CROK_00750	Medium Gravel	Medium Gravel
CROK_00731U	Medium Gravel	Medium Gravel
CROK_00731	Medium Gravel	Medium Gravel
CROK_00728	Coarse Gravel	Coarse Gravel
CROK_00625	Fine Gravel	Very Fine Gravel
CROK_00572	Fine Gravel	Fine Gravel
CROK_00568	Fine Gravel	Very Fine Gravel
CROK_00565	Fine Gravel	Fine Gravel
CROK_00560	Fine Gravel	Fine Gravel
CROK_00553	Fine Gravel	Fine Gravel
CROK_00467	Very Coarse Sand	Very Coarse Sand
CROK_00430	Very Coarse Sand	Very Coarse Sand
CROK_00374	Medium Silt	Medium Silt
CROK_00331	Fine Silt	Fine Silt
CROK_00300	Fine Silt	Fine Silt
CROK_00299	Medium Gravel	Medium Gravel
CROK_00296	Very Fine Gravel	Very Fine Gravel
CROK_00292	Fine Gravel	Fine Gravel
CROK_00283	Very Fine Gravel	Very Fine Gravel
CROK_00239U	Coarse Gravel	Coarse Gravel
CROK_00239	Very Coarse Gravel	Very Coarse Gravel
CROK_00213	Coarse Gravel	Coarse Gravel
CROK_00171	Medium Gravel	Medium Gravel
CROK_00164	Very Fine Gravel	Very Fine Gravel
CROK_00150	Fine Gravel	Fine Gravel
CROK_00120	Coarse Gravel	Coarse Gravel

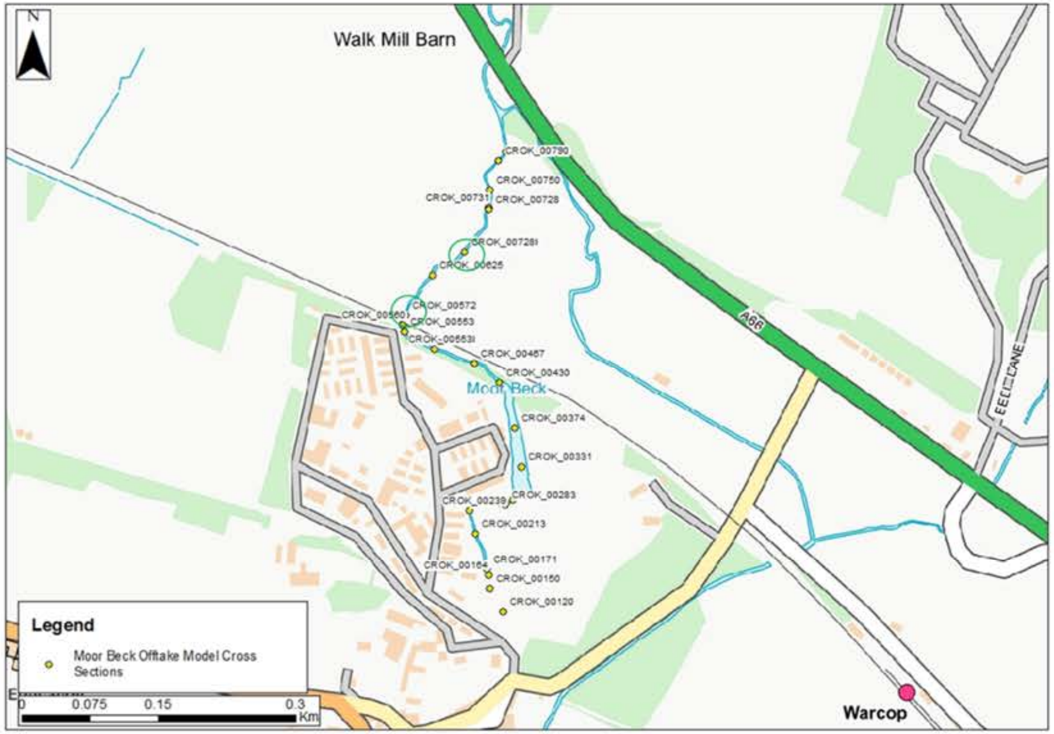


Plate 84: 1-in-2 Year Flood Event comparison of in channel maximum size of sediment entrained on the Moor Beck (Offtake) between the Post Development and Baseline Scenarios

Model Cross Sections	Baseline Q2 Sediment Size Moved	PostDev Q2 Sediment Size Moved
TODY_00446	Fine Cobble	Fine Cobble
TODY_00322U	Coarse Gravel	Coarse Gravel
TODY_00322	Coarse Gravel	Coarse Gravel
TODY_00315	Fine Cobble	Fine Cobble
TODY_00303	Coarse Gravel	Coarse Gravel
TODY_00297	Coarse Gravel	Very Coarse Gravel
TODY_00247	Fine Gravel	Coarse Gravel
TODY_00229	Very Coarse Gravel	Very Coarse Gravel
TODY_00172	Very Coarse Gravel	Very Coarse Gravel
TODY_00154	Fine Cobble	Fine Cobble
TODY_00104	Very Coarse Gravel	Very Coarse Gravel

Plate 85: 1-in-2 Year Flood Event comparison of in channel maximum size of sediment entrained on the Eastfield Sike between the Post Development and Baseline Scenarios

1-in-20 year flood event

Floodplain shear stress analysis

14.9.3.121 Under existing conditions in the 1-in-20 Year Flood Event, an overland flow route is observed on the left bank floodplain, as water spills over the existing A66 carriageway and onto the floodplain. The same overland flow route observed in the 1-in-2 Year flood event between the Moor Beck and Moor Beck (Offtake) is present (Plate 86: Baseline 1-in-20 Year Flood Event Maximum Size of Sediment Entrained).

14.9.3.122 The typical range of material that can be mobilised on the floodplain ranges between sands and coarse gravels.

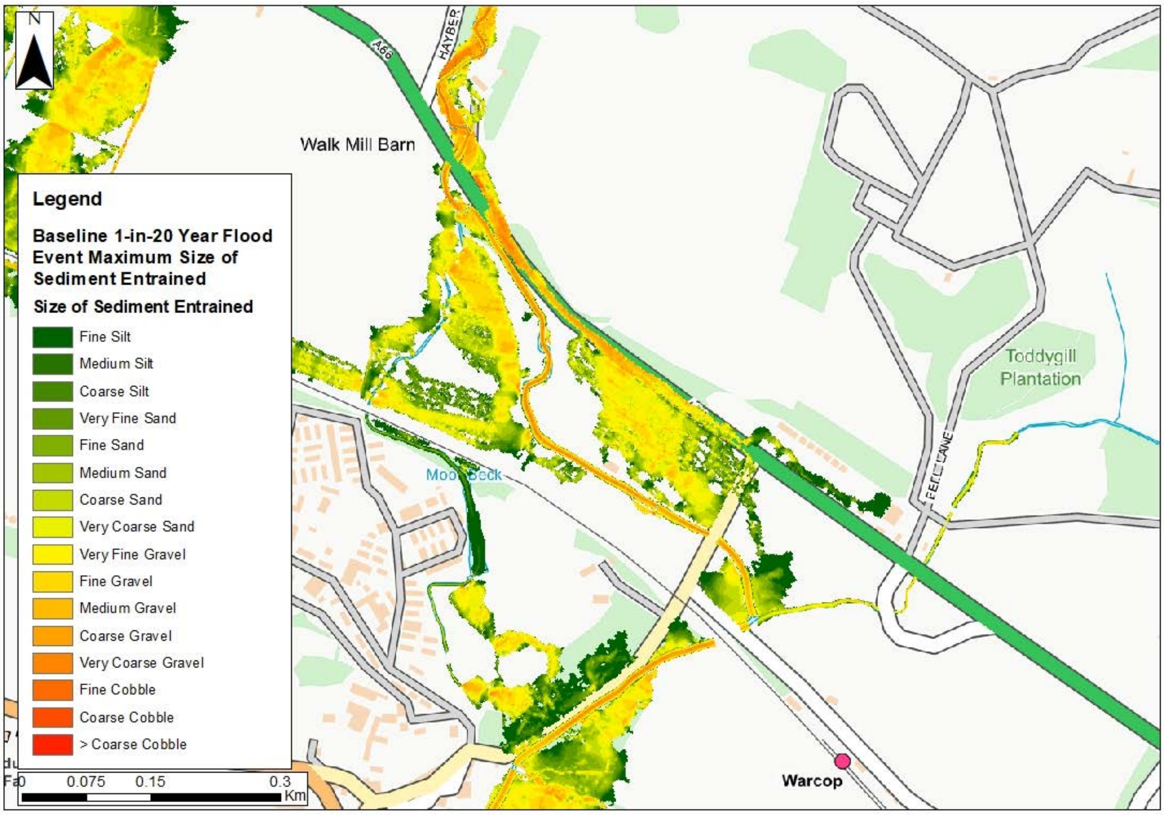


Plate 86: Baseline 1-in-20 Year Flood Event Maximum Size of Sediment Entrained

14.9.3.123 In the Post-Development 1-in-20 Year Flood Event, the addition of a flood compensation structure on the left and right bank of the Moor Beck (as indicated in Plate 79: Overview of the flood compensation structure associated with Warcop Junction) generates localised variations in sediment transport dynamics on the floodplain (Plate 87: Post Development 1-in-20 Year Flood Event Maximum Size of Sediment Entrained). The maximum size of material that can be mobilised on the floodplain in the vicinity of the flood compensation structure reduces. The flood compensation structure improves the lateral connectivity between the Moor Beck channel and floodplain, which improves the retention of water on the floodplain. As more flood water is captured and redistributed across the floodplain at the flood compensation structure, water pools and flow velocities reduce significantly.

14.9.3.124 The hydraulic model results suggest that potential retention of fine material, ranging from silts to sands, is possible within the structure. The potential increased retention of fine material on the floodplain would represent improved geomorphological function, as this would limit the conveyance of fine material to downstream reaches on the Moor Beck and Crooks Beck, which could lead to the degradation of the riverbed substrate.

14.9.3.125 Water that previously spilled along the existing A66 road is diverted onto the floodplain between the Moor Beck and Moor Beck offtake and into the flood compensation area. This removes the overland flow route on the left bank of the Moor Beck, and as a consequence the interaction between the proposed Moor Beck Junction and the overland flow route. This eliminates the risk of water backing up upstream of the junction, and additional water being conveyed through the underbridge structure. Therefore, the risk of scour on the left bank floodplain as a result of the installation of the Warcop Junction structure is significantly reduced. However, the loss of an overland flow route represents a change to the existing flow dynamics on the Moor Beck floodplain.

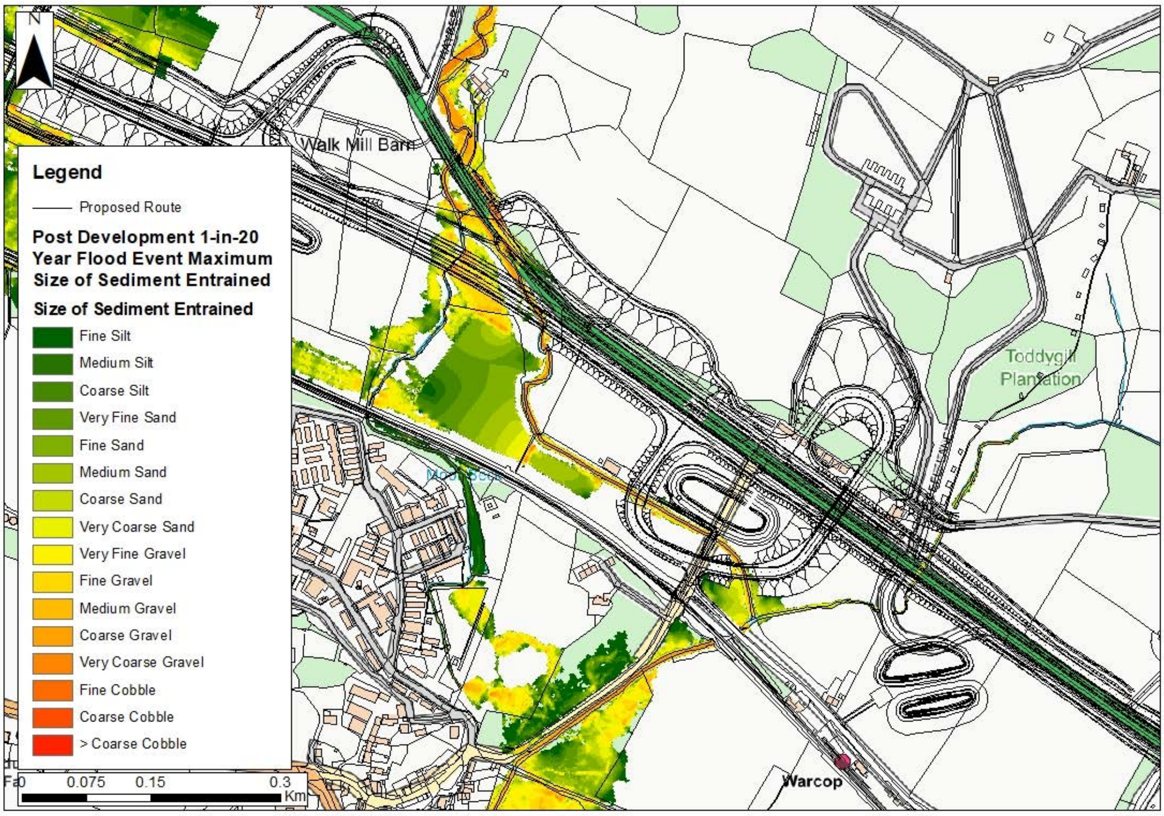


Plate 87: Post Development 1-in-20 Year Flood Event Maximum Size of Sediment Entrained

Floodplain velocity comparison analysis

14.9.3.126 Plate 88: 1-in-20 Year Flood Event Change in Velocity in the Post Development Scenario compared to the Baseline Scenario presents a comparison between maximum velocities on the floodplain in the Post Development scenario and the Baseline Scenario.

14.9.3.127 Significant variations in maximum velocities were identified across the floodplain to the north of Warcop. The most notable changes in flow velocities were identified on the left bank floodplain of the Moor Beck in the vicinity of the proposed Warcop Junction structure (Plate 88: 1-in-20 Year Flood Event Change in Velocity in the Post Development Scenario compared to the Baseline Scenario). Reductions in flow velocities in this area of the floodplain represent the removal of the overland flow route on the left bank of the Moor Beck in the Post Development scenario compared to the Baseline scenario, and the loss of flow in this part of the floodplain. Typical reductions in flow velocities range between 0.1 to 0.5m/s. Changes to the maximum velocities are unlikely to result in significant change to the morphological composition of the left bank floodplain, as these changes largely represent the loss of the overland flow route.

14.9.3.128 The addition of a flood compensation structure on the left and right bank of the Moor Beck generates localised variations in maximum flow velocities on the floodplain. Maximum flow velocities reduce where water pools within the structure, and velocities increase on the right bank floodplain where water is conveyed from the south eastern corner of the structure back into the Moor Beck. Maximum increases on the right bank of the Moor Beck are between 0.1 and 0.5m/s. Whilst it is acknowledged that there is an increase to flow velocities, these changes are unlikely to result in significant change to the morphological composition of the floodplain. However, localised and simple measures can be taken to mitigate increases in flow velocities, such as riparian planting on the floodplain to increase roughness.

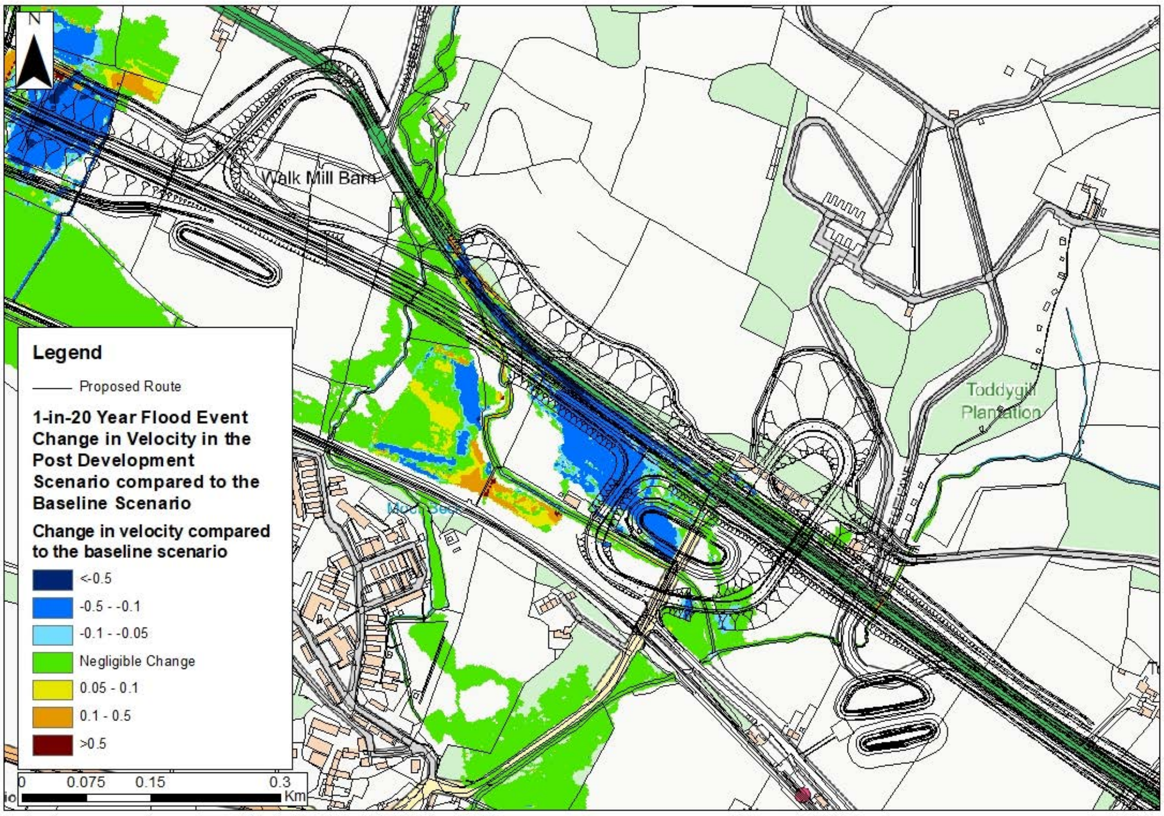


Plate 88: 1-in-20 Year Flood Event Change in Velocity in the Post Development Scenario compared to the Baseline Scenario

In-channel shear stress analysis

14.9.3.129 Plate 89: 1-in-20 Year Flood Event comparison of in channel maximum size of sediment entrained on Moor Beck and Crooks Beck between the Post Development and Baseline Scenarios, Plate 90: 1-in-20 Year Flood Event comparison of in channel maximum size of sediment entrained on Moor Beck (Offtake) between the Post Development and Baseline Scenarios and Plate 91: 1-in-20 Year Flood Event comparison of in channel maximum size of sediment entrained on Eastfield Sike between the Post Development and Baseline Scenarios present a comparison of the 1-in-20 Year Flood Event in-channel maximum sizes of sediment entrained between the Post Development and Baseline Scenarios across the Moor Beck, Moor Beck (Offtake), Eastfield Sike and Crooks Beck respectively.

14.9.3.130 The maximum size of material that can be mobilised at each of the cross sections from the hydraulic model has been calculated for the Moor Beck, Moor Beck (Offtake), Eastfield Sike and Crooks Beck. Red circles indicate areas where the size of material that can be mobilised in the channel could increase in the Post Development Scenario. In these locations slight changes to the composition of the riverbed could occur, with a small risk of scour.

14.9.3.131 Green circles indicate areas where the size of the material that can be mobilised in the channel could decrease in the Post Development

Scenario. No erosion is likely here, and there is the potential for a small increase in sediment deposition.

14.9.3.132 All other areas have either no change, or changes in shear stress that are negligible meaning that the typical size of material that can be entrained will not change.

14.9.3.133 On the Crooks Beck, only one cross section, CR00_01394, exhibited a small change in the maximum size of material that can be mobilised (Plate 89: 1-in-20 Year Flood Event comparison of in channel maximum size of sediment entrained on Moor Beck and Crooks Beck between the Post Development and Baseline Scenarios), increasing from Very Coarse Gravel to Fine Cobble. No changes to the maximum size of material that can be mobilised were observed on the Moor Beck. In summary, no significant changes to the riverbed composition arising from the scheme on the Moor Beck and Crooks Beck are predicted.

14.9.3.134 On the Moor Beck (Offtake) only one cross section was identified as experiencing changes in the maximum size of material that can be mobilised (Plate 90: 1-in-20 Year Flood Event comparison of in channel maximum size of sediment entrained on Moor Beck (Offtake) between the Post Development and Baseline Scenarios). Cross section CROK_00568, located upstream of the rail embankment, exhibited a small reduction in the size of material that can be entrained, reducing from Fine Gravel to Very Fine Gravel. In summary, no significant changes to the riverbed composition arising from the proposed works on the Moor Beck (Offtake) are predicted.

14.9.3.135 Reductions in the size of material that can be mobilised in the Moor Beck (Offtake) are likely a result of the conveyance of additional flow from the flood compensation structure on the left bank floodplain into the channel. Increased volumes of water in the channel upstream of the structure at the rail embankment is causing impoundment, leading to a reduction in velocities and the size of material mobilised. The predicted variations in the size of material that can be entrained at these two locations is unlikely to translate into significant increases to in-channel sediment deposition or erosion. Site observations indicated that the typical size of material present on the riverbed on both the Moor Beck (Offtake) ranged between sands and gravels. As changes identified within the hydraulic model in both of these reaches are within the approximate ranges of typical sediment sizes already present on the riverbed, there is unlikely to be a change in the composition and structure of the riverbed.

14.9.3.136 On the Eastfield Sike, only one cross section was identified as experiencing change in the maximum size of material that can be mobilised (Plate 91: 1-in-20 Year Flood Event comparison of in channel maximum size of sediment entrained on Eastfield Sike between the Post Development and Baseline Scenarios). Cross section TODDY_00297, located immediately upstream of the culvert that conveys the Eastfield Sike beneath the access road adjacent to

Fell Lane, exhibited increases in the size of material that can be entrained, increasing from Very Coarse Gravel to Fine Cobble.

14.9.3.137 Increases in the size of material mobilised marked on the map are likely a result of the replacement of the culvert beneath the existing A66 road with a new structure. Removal of impoundment of flow upstream of the A66 road improves conveyance within the channel, leading to greater velocities and shear stress values. The predicted increase in the size of material that can be mobilised in this reach is unlikely to significantly impact existing sediment transport dynamics or the composition of the riverbed. Typical sizes of bed material noted on the Eastfield Sike during the site visit were predominantly gravels and some coarser material.

Model Cross Section	Baseline Q20 Sediment Size Moved	PostDev Q20 Sediment Size Moved
CROO_02656	Coarse Cobble	Coarse Cobble
CROO_02608	Very Coarse Gravel	Very Coarse Gravel
CROO_02605	Fine Cobble	Fine Cobble
CROO_02602	Coarse Cobble	Coarse Cobble
CROO_02570	Fine Cobble	Fine Cobble
CROO_02567	Very Coarse Gravel	Very Coarse Gravel
CROO_02518	Coarse Cobble	Coarse Cobble
CROO_02439	Fine Cobble	Fine Cobble
CROO_02408	Very Coarse Gravel	Very Coarse Gravel
CROO_02396	Fine Cobble	Fine Cobble
CROO_02332	Coarse Gravel	Coarse Gravel
CROK_00846B	Very Coarse Gravel	Very Coarse Gravel
CROO_02329	Medium Gravel	Medium Gravel
CROO_02329D	Coarse Gravel	Coarse Gravel
CROO_02324	Coarse Gravel	Coarse Gravel
CROO_02324D	Coarse Gravel	Coarse Gravel
CROO_02318	Fine Cobble	Fine Cobble
CROO_02250	Fine Cobble	Fine Cobble
UNN604_0515	Very Coarse Gravel	Very Coarse Gravel
CROO_02112	Fine Cobble	Fine Cobble
CROO_01997	Very Coarse Gravel	Very Coarse Gravel
CROO_01982	Fine Cobble	Fine Cobble
CROO_01965	Fine Cobble	Fine Cobble
UNN604_0240	Very Coarse Gravel	Very Coarse Gravel
CROO_01859	Very Coarse Gravel	Very Coarse Gravel
CROO_01838	Very Coarse Gravel	Very Coarse Gravel
CROO_01834	Coarse Gravel	Coarse Gravel
CROO_01834_U	Very Coarse Gravel	Very Coarse Gravel
CROO_01832	Fine Cobble	Fine Cobble
CROO_01765	Very Coarse Gravel	Very Coarse Gravel
CROO_01756	Very Coarse Gravel	Very Coarse Gravel
CROO_01629U	Medium Gravel	Medium Gravel
CROO_01629D	Medium Gravel	Medium Gravel
CROO_01629D2	Coarse Gravel	Coarse Gravel
CROO_01629	Coarse Gravel	Coarse Gravel
CROO_01473	Very Coarse Gravel	Very Coarse Gravel
CROO_01394	Very Coarse Gravel	Fine Cobble
CROO_01394U	Very Coarse Gravel	Very Coarse Gravel
CROO_01394D	Medium Gravel	Medium Gravel
CROO_01321	Medium Gravel	Medium Gravel

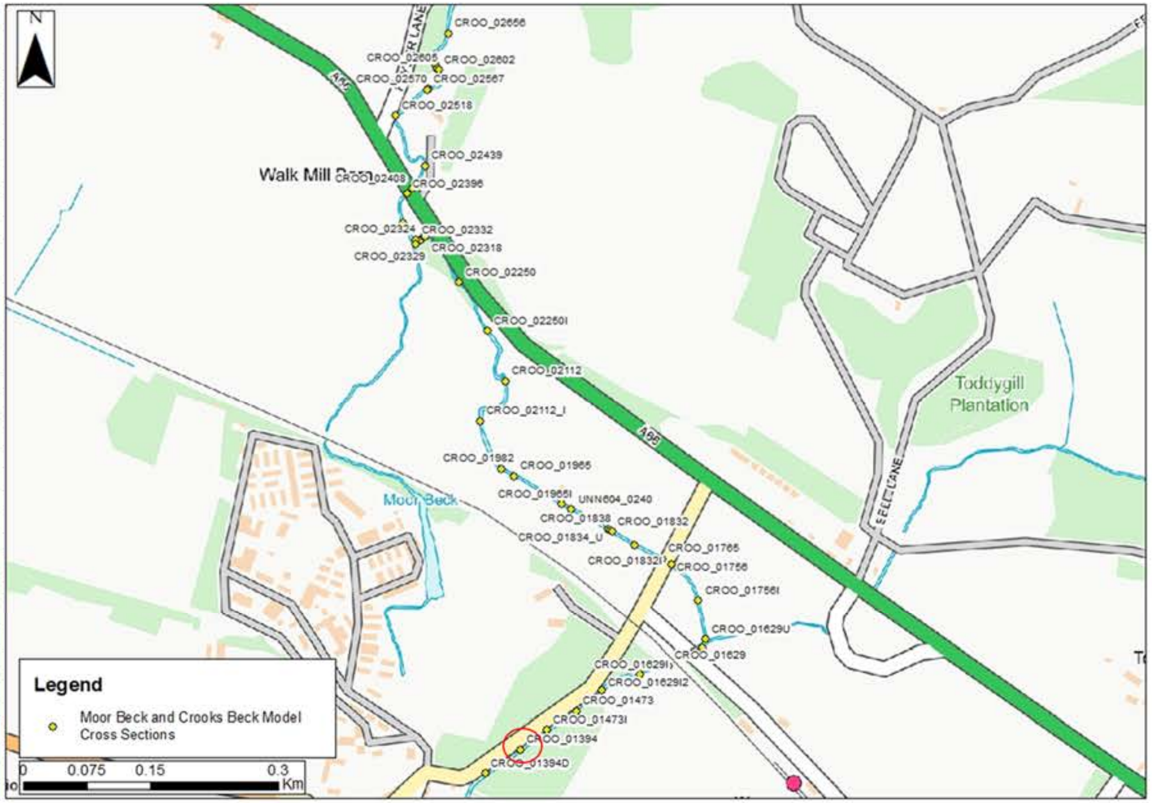


Plate 89: 1-in-20 Year Flood Event comparison of in channel maximum size of sediment entrained on Moor Beck and Crooks Beck between the Post Development and Baseline Scenarios

Model Cross Sections	Baseline Q20 Sediment Size Moved	PostDev Q20 Sediment Size Moved
CROK_00790	Very Coarse Gravel	Very Coarse Gravel
CROK_00750	Medium Gravel	Medium Gravel
CROK_00731U	Medium Gravel	Medium Gravel
CROK_00731	Coarse Gravel	Coarse Gravel
CROK_00728	Coarse Gravel	Coarse Gravel
CROK_00625	Fine Gravel	Fine Gravel
CROK_00572	Fine Gravel	Fine Gravel
CROK_00568	Fine Gravel	Very Fine Gravel
CROK_00565	Fine Gravel	Fine Gravel
CROK_00560	Fine Gravel	Fine Gravel
CROK_00553	Fine Gravel	Fine Gravel
CROK_00467	Very Coarse Sand	Very Coarse Sand
CROK_00430	Very Coarse Sand	Very Coarse Sand
CROK_00374	Coarse Silt	Coarse Silt
CROK_00331	Fine Silt	Fine Silt
CROK_00300	Fine Silt	Fine Silt
CROK_00299	Medium Gravel	Medium Gravel
CROK_00296	Fine Gravel	Fine Gravel
CROK_00292	Medium Gravel	Medium Gravel
CROK_00283	Very Fine Gravel	Very Fine Gravel
CROK_00239U	Coarse Gravel	Coarse Gravel
CROK_00239	Very Coarse Gravel	Very Coarse Gravel
CROK_00213	Fine Gravel	Fine Gravel
CROK_00171	Medium Gravel	Medium Gravel
CROK_00164	Very Coarse Sand	Very Coarse Sand
CROK_00150	Fine Gravel	Fine Gravel
CROK_00120	Coarse Gravel	Coarse Gravel

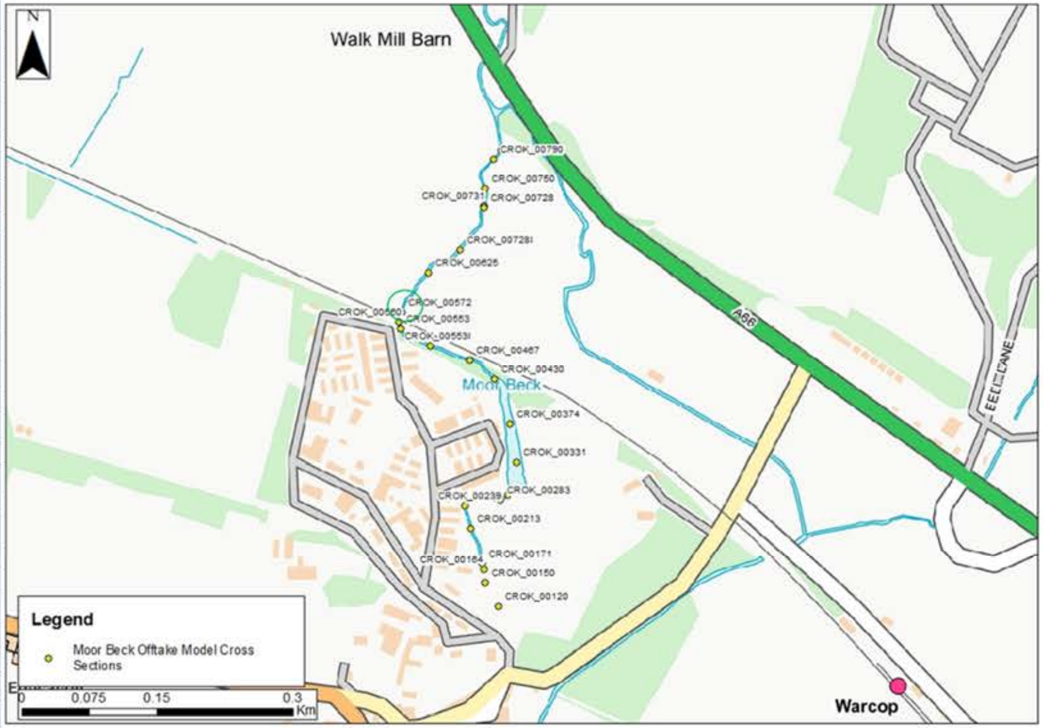


Plate 90: 1-in-20 Year Flood Event comparison of in channel maximum size of sediment entrained on Moor Beck (Offtake) between the Post Development and Baseline Scenarios

Model Cross Sections	Baseline Q20 Sediment Size Moved	PostDev Q20 Sediment Size Moved
TODY_00446	Fine Cobble	Fine Cobble
TODY_00322U	Medium Gravel	Medium Gravel
TODY_00322	Medium Gravel	Medium Gravel
TODY_00315	Very Coarse Gravel	Very Coarse Gravel
TODY_00303	Medium Gravel	Medium Gravel
TODY_00297	Very Coarse Gravel	Fine Cobble
TODY_00247	Medium Gravel	Very Coarse Gravel
TODY_00229	Very Coarse Gravel	Very Coarse Gravel
TODY_00172	Very Coarse Gravel	Very Coarse Gravel
TODY_00154	Fine Cobble	Fine Cobble
TODY_00104	Coarse Gravel	Coarse Gravel

Plate 91: 1-in-20 Year Flood Event comparison of in channel maximum size of sediment entrained on Eastfield Sike between the Post Development and Baseline Scenarios

1-in-100 year + 94% climate change flood event

Floodplain shear stress analysis

14.9.3.138 Under existing conditions in the 1-in-100 Year + 94% Climate Change Year Flood Event, an overland flow route is observed on the left bank floodplain, as water spills over the existing A66 carriageway and onto the floodplain. This overland flow route crosses the existing road between the A66 carriageway and Warcop and re-enters the channel on the right bank of the Eastfield Sike and the left bank of the Moor Beck upstream of the confluence between the two watercourses. The same overland flow route observed in the 1-in-2 Year and 1-in-20 Year Flood Event between the Moor Beck and Moor Beck (Offtake) is present (Plate 92: Baseline 1-in-100 Year + 94% Climate Change Flood Event maximum size of sediment entrained).

14.9.3.139 The typical range of material that can be mobilised on the floodplain ranges between sands and coarse gravels.

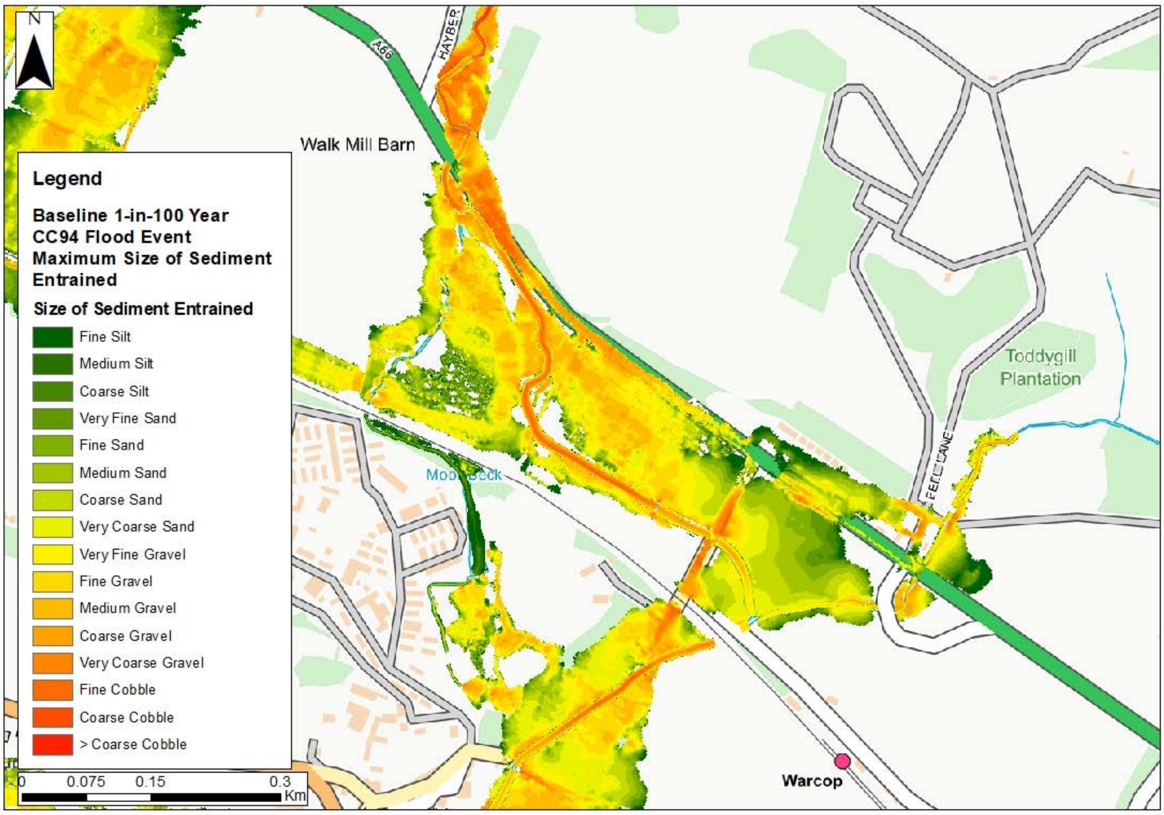


Plate 92: Baseline 1-in-100 Year + 94% Climate Change Flood Event maximum size of sediment entrained

14.9.3.140 In the Post-Development 1-in-100 Year + 94% Climate Change Flood Event, there are minimal variations in the maximum size of material that can be mobilised within the flood compensation structure, in contrast with the variations observed in smaller flood return periods (Plate 93: Post Development 1-in-100 Year + 94% Climate Change Flood Event maximum size of sediment entrained). This is likely a result of the significant flow velocities associated with such a high flood return period across the floodplain between the Moor Beck and the Moor Beck (Offtake) negating the influence that the flood compensation has on the flow dynamics on this area of the floodplain. The typical size of material that can be mobilised within the flood compensation structure ranges between silts to gravels.

14.9.3.141 Water that previously spilled along the existing A66 road is diverted onto the floodplain between the Moor Beck and Moor Beck offtake and into the Moor Beck channel and the flood compensation structure. Despite this, water is still able to enter the left bank floodplain from the Moor Beck channel, as a consequence of the high volume of water conveyed in such a high flood return period. The presence of the embankment associated with the flood compensation structure and the embankments associated with the Warcop Junction disrupt the conveyance of flow across the left bank floodplain, and water subsequently pools on the left bank floodplain. Water is able to enter the floodplain between the Warcop Junction West and Warcop Junction East as a consequence of the high volume of water conveyed in such a high flood return period. The typical size of material that can be mobilised on the left bank floodplain ranges between sands and gravels.

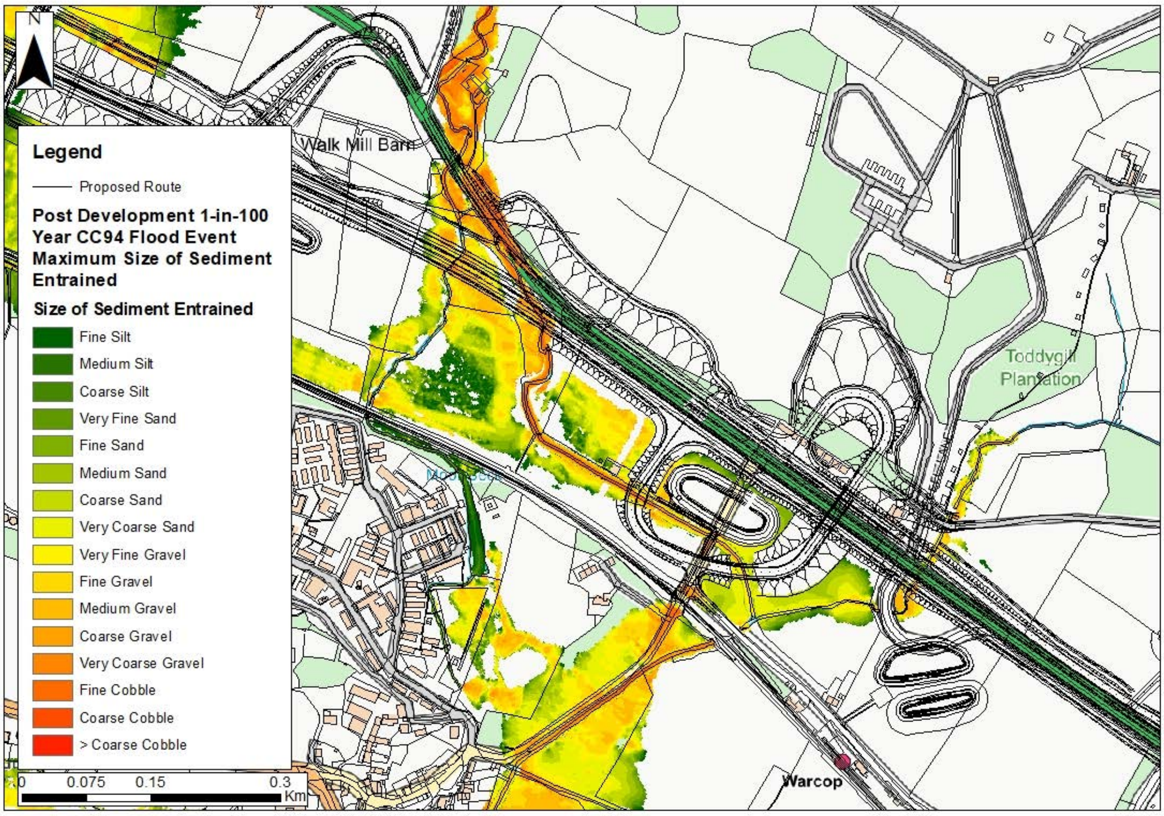


Plate 93: Post Development 1-in-100 Year + 94% Climate Change Flood Event maximum size of sediment entrained

Floodplain velocity comparison analysis

14.9.3.142 Plate 94: 1-in-100 Year + 94% Climate Change Flood Event Change in velocity in the Post Development Scenario compared to the Baseline Scenario presents a comparison between maximum velocities on the floodplain in the Post Development scenario and the Baseline Scenario.

14.9.3.143 Significant variations in maximum velocities were identified across the floodplain to the north of Warcop. The most notable changes in flow velocities were identified on the left bank floodplain of the Moor Beck in the vicinity of the proposed Warcop Junction structure (Plate 94: 1-in-100 Year + 94% Climate Change Flood Event Change in velocity in the Post Development Scenario compared to the Baseline Scenario). The presence of the embankment associated with the flood compensation structure and the embankments associated with the Warcop Junction disrupt the conveyance of flow across the left bank floodplain, and water subsequently pools on the left bank floodplain. This results in significant reductions in flow velocities on the floodplain upstream of the Warcop Junction Embankments, as the existing overland flow route observed in the Baseline Scenario is disrupted. Typical reductions in flow velocities range between 0.1m/s and 0.5m/s.

14.9.3.144 There are significant reductions in flow velocities within the extent of the Warcop Junction embankments and the flood compensation structure in the centre of the junction as a consequence of the loss of the overland flow route on the left bank of the Moor Beck in the Post Development scenario compared to the Baseline scenario, and the loss of flow in this part of the floodplain.

14.9.3.145 The addition of a flood compensation structure on the left and right bank of the Moor Beck generates localised variations in maximum flow velocities on the floodplain. Maximum flow velocities reduce where water pools within the structure, and velocities increase on the right bank floodplain where water is conveyed from the south eastern corner of the structure back into the Moor Beck. Maximum increases in this area of the right bank of the Moor Beck are between 0.1 and 0.5m/s, and in isolated areas are in excess of 0.5m/s. Increases in flow velocities of this magnitude could potentially cause scour of the right bank floodplain.

14.9.3.146 Variations in flow velocities were observed on the floodplain in the vicinity of Eastfield Road, where the existing A66 culvert is to be modified. The replacement of this structure reduces flow impoundment upstream, facilitating the conveyance of more flow downstream and onto the floodplain. This has resulted in small increases and decreases in flow velocities on the floodplain, typically ranging between 0.1 and 0.5m/s.

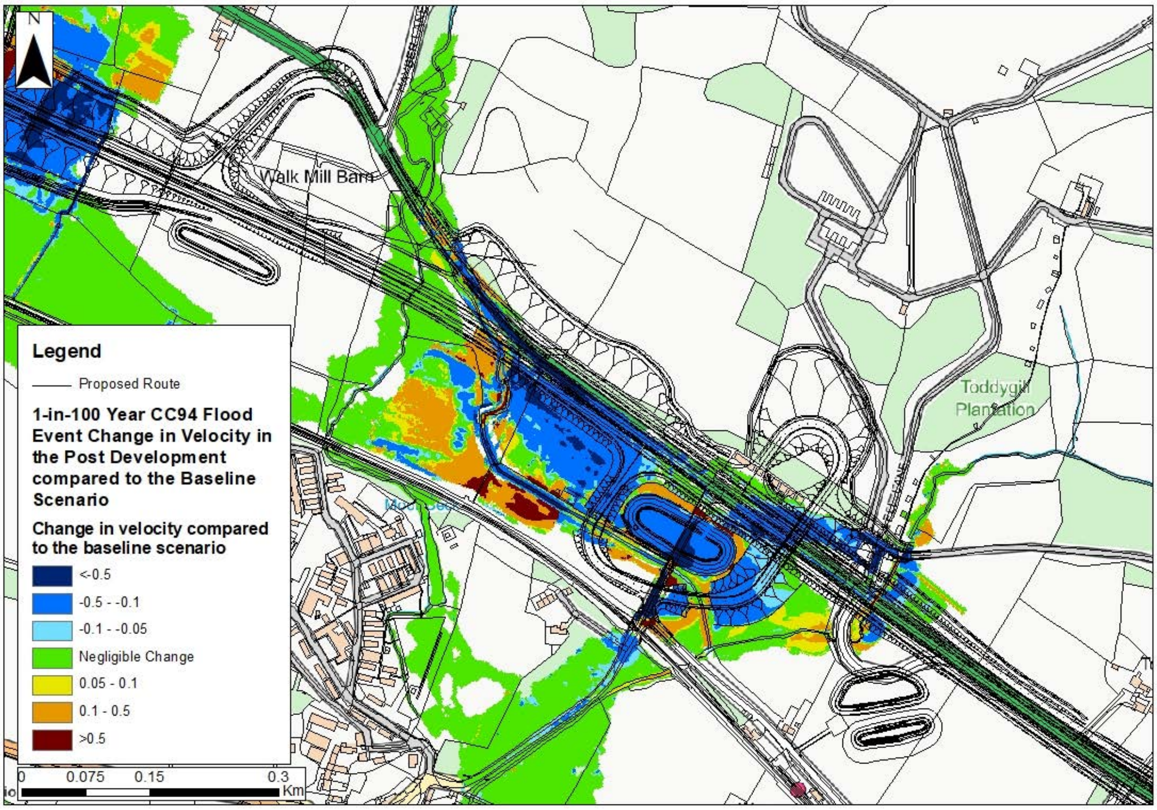


Plate 94: 1-in-100 Year + 94% Climate Change Flood Event Change in velocity in the Post Development Scenario compared to the Baseline Scenario

In-channel shear stress analysis

14.9.3.147 Plate 95: 1-in-100 Year +94% Climate Change Flood Event comparison of in channel maximum size of sediment entrained on the Moor Beck and Crooks Beck between the Post Development and Baseline Scenarios, Plate 96: 1-in-100 Year +94% Climate Change Flood Event comparison of in channel maximum size of sediment entrained on the Moor Beck (Offtake) between the Post Development and Baseline Scenarios and Plate 0-97: 1-in-100 Year +94% Climate Change Flood Event comparison of in channel maximum size of sediment entrained on the Eastfield Sike between the Post Development and Baseline Scenarios present a comparison of the 1-in-100 Year +94% Climate Change Flood Event in-channel maximum sizes of sediment entrained between the Post Development and Baseline Scenarios across the Moor Beck, Moor Beck (Offtake), Eastfield Sike and Crooks Beck respectively.

14.9.3.148 The maximum size of material that can be mobilised at each of the cross sections from the hydraulic model has been calculated for the Moor Beck, Moor Beck (Offtake), Eastfield Sike and Crooks Beck. Red circles indicate areas where the size of material that can be mobilised in the channel could increase in the Post Development Scenario. In these locations slight changes to the composition of the riverbed could occur, with a small risk of scour.

14.9.3.149 Green circles indicate areas where the size of the material that can be mobilised in the channel could decrease in the Post Development Scenario. No erosion is likely here, and there is the potential for a small increase in sediment deposition.

14.9.3.150 All other areas have either no change, or changes in shear stress that are negligible meaning that the typical size of material that can be entrained will not change.

14.9.3.151 On the Crooks Beck, only one cross section, CR00_01394, exhibited a small change in the maximum size of material that can be mobilised (Plate 95: 1-in-100 Year +94% Climate Change Flood Event comparison of in channel maximum size of sediment entrained on the Moor Beck and Crooks Beck between the Post Development and Baseline Scenarios), increasing from Very Coarse Gravel to Fine Cobble. In summary, no significant changes to the riverbed composition arising from the scheme on the Crooks Beck are predicted.

14.9.3.152 On the Moor Beck, six cross sections were identified as experiencing changes in the maximum sizes of material that can be mobilised (Plate 0-97: 1-in-100 Year +94% Climate Change Flood Event comparison of in channel maximum size of sediment entrained on the Eastfield Sike between the Post Development and Baseline Scenarios). Cross sections CR00_01997, CR00_01982, CR00_01859, CR00_01838 and CR00_01756 all experienced reductions in the size of material that can be entrained, from either Fine Cobble to Very Coarse Gravel, or Coarse Cobble to Fine Cobble. Increases in water retention on the floodplain in the vicinity of the flood compensation structure, and the wide underbridge structures conveying the Moor Beck beneath the Warcop Junction structure result in lower shear stress values in the channel. Conveyance of more flow onto the floodplain dissipates flow energy, reducing in-channel flow velocities and shear stresses. Wide underbridge structures improve the conveyance of flow on the floodplain to downstream reaches, mitigating the impoundment of flood waters on the floodplain upstream of the Warcop Junction structure. Therefore, the model predicts no increases in scour of the bed in the vicinity of the junction.

14.9.3.153 Cross Section CR00_02112 experiences significant increases in the maximum size of material that can be mobilised, increasing from Fine Cobble to clasts greater than Coarse Cobble. This significant increase is a result of the close proximity to the viaduct embankment to the left bank of the Moor Beck. This results in an increase of both in-channel and floodplain velocities and shear stresses. Flow is confined through the channel and a narrower floodplain area, which results in the increases in flow velocities and shear stresses. Such significant increases to the maximum size of material that can be mobilised will likely increase the risk of riverbed scour, which could ultimately lead to a change in the structure and composition of the riverbed as well as potential bank instability.

14.9.3.154 On the Moor Beck (Offtake) only three cross sections were identified as experiencing changes in the maximum size of material that can be mobilised (Plate 95: 1-in-100 Year +94% Climate Change Flood Event comparison of in channel maximum size of sediment entrained on the Moor Beck and Crooks Beck between the Post Development and Baseline Scenarios). Cross sections CROK_00568, CROK_00560 and CROK_00553, located in the vicinity of the rail embankment, experienced small reductions in the size of material that can be entrained, reducing from Fine Gravel to Very Fine Gravel. In summary, no significant changes to the riverbed composition arising from the proposed works on the Moor Beck (Offtake) are predicted.

14.9.3.155 Reductions in the size of material that can be mobilised in the Moor Beck (Offtake) are likely a result of the conveyance of additional flow from the flood compensation structure on the left bank floodplain into the channel. Increased volumes of water in the channel upstream of the structure at the rail embankment is causing impoundment, leading to a reduction in velocities and the size of material mobilised. The predicted variations in the size of material that can be entrained at these two locations is unlikely to translate into significant increases to in channel sediment deposition or erosion. Site observations indicated that the typical size of material present on the riverbed on both the Moor Beck (Offtake) ranged between sands and gravels. As changes identified within the hydraulic model in both of these reaches are within the approximate ranges of typical sediment sizes already present on the riverbed, there is unlikely to be a change in the composition and structure of the riverbed.

14.9.3.156 On the Eastfield Sike, only two cross sections were identified as experiencing change in the maximum size of material that can be mobilised (Plate 0-97: 1-in-100 Year +94% Climate Change Flood Event comparison of in channel maximum size of sediment entrained on the Eastfield Sike between the Post Development and Baseline Scenarios). Cross section TODDY_00297 and TODDY_00247, located immediately upstream of the culvert that conveys the Eastfield Sike beneath the access road adjacent to Fell Lane and immediately upstream of the existing A66 culvert respectively, experienced increases in the size of material that can be entrained, increasing from Very Coarse Gravel to Fine Cobble and Medium Gravel to Very Coarse Gravel.

14.9.3.157 Increases in the size of material mobilised marked on the map are likely a result of the replacement of the culvert beneath the existing A66 road with a new structure. Removal of the flow impoundment upstream of the A66 road improves conveyance within the channel, leading to greater velocities and shear stress values. The predicted increase in the size of material that can be mobilised in this reach is unlikely to significantly impact existing sediment transport dynamics or the composition of the riverbed. Typical sizes of bed material noted on the Eastfield Sike during the site visit were predominantly gravels and some coarser material.

Model Cross Section	Baseline Q100CC94 Sediment Size Moved	PostDev Q100CC94 Sediment Size Moved
CROO_02656	>Coarse Cobble	>Coarse Cobble
CROO_02608	Fine Cobble	Fine Cobble
CROO_02605	Coarse Cobble	Coarse Cobble
CROO_02602	>Coarse Cobble	>Coarse Cobble
CROO_02570	Fine Cobble	Fine Cobble
CROO_02567	Very Coarse Gravel	Very Coarse Gravel
CROO_02518	Coarse Cobble	Coarse Cobble
CROO_02439	Fine Cobble	Fine Cobble
CROO_02408	Very Coarse Gravel	Very Coarse Gravel
CROO_02396	Coarse Cobble	Coarse Cobble
CROO_02332	Very Coarse Gravel	Very Coarse Gravel
CROK_00846B	Very Coarse Gravel	Very Coarse Gravel
CROO_02329	Coarse Gravel	Coarse Gravel
CROO_02329D	Very Coarse Gravel	Very Coarse Gravel
CROO_02324	Coarse Gravel	Coarse Gravel
CROO_02324D	Very Coarse Gravel	Very Coarse Gravel
CROO_02318	Fine Cobble	Fine Cobble
CROO_02250	Coarse Cobble	Coarse Cobble
UNN604_0515	Very Coarse Gravel	Very Coarse Gravel
CROO_02112	Fine Cobble	>Coarse Cobble
CROO_01997	Fine Cobble	Very Coarse Gravel
CROO_01982	Coarse Cobble	Fine Cobble
CROO_01965	Fine Cobble	Fine Cobble
UNN604_0240	Fine Cobble	Fine Cobble
CROO_01859	Fine Cobble	Very Coarse Gravel
CROO_01838	Fine Cobble	Very Coarse Gravel
CROO_01834	Coarse Gravel	Coarse Gravel
CROO_01834_U	Coarse Gravel	Coarse Gravel
CROO_01832	Very Coarse Gravel	Very Coarse Gravel
CROO_01765	Very Coarse Gravel	Very Coarse Gravel
CROO_01756	Fine Cobble	Very Coarse Gravel
CROO_01629U	Medium Gravel	Medium Gravel
CROO_01629D	Medium Gravel	Medium Gravel
CROO_01629D2	Medium Gravel	Medium Gravel
CROO_01629	Very Coarse Gravel	Very Coarse Gravel
CROO_01473	Fine Cobble	Fine Cobble
CROO_01394	Very Coarse Gravel	Very Coarse Gravel
CROO_01394U	Coarse Gravel	Coarse Gravel
CROO_01394D	Coarse Gravel	Coarse Gravel
CROO_01321	Medium Gravel	Medium Gravel

Plate 95: 1-in-100 Year +94% Climate Change Flood Event comparison of in channel maximum size of sediment entrained on the Moor Beck and Crooks Beck between the Post Development and Baseline Scenarios

Model Cross Sections	Baseline Q100CC94 Sediment Size Moved	PostDev Q100CC94 Sediment Size Moved
CROK_00790	Very Coarse Gravel	Very Coarse Gravel
CROK_00750	Coarse Gravel	Coarse Gravel
CROK_00731U	Medium Gravel	Medium Gravel
CROK_00731	Coarse Gravel	Coarse Gravel
CROK_00728	Coarse Gravel	Coarse Gravel
CROK_00625	Fine Gravel	Fine Gravel
CROK_00572	Fine Gravel	Fine Gravel
CROK_00568	Fine Gravel	Very Fine Gravel
CROK_00565	Fine Gravel	Fine Gravel
CROK_00560	Fine Gravel	Very Fine Gravel
CROK_00553	Fine Gravel	Very Fine Gravel
CROK_00467	Very Coarse Sand	Very Coarse Sand
CROK_00430	Very Coarse Sand	Very Coarse Sand
CROK_00374	Coarse Silt	Coarse Silt
CROK_00331	Fine Silt	Fine Silt
CROK_00300	Fine Silt	Fine Silt
CROK_00299	Medium Gravel	Medium Gravel
CROK_00296	Fine Gravel	Fine Gravel
CROK_00292	Medium Gravel	Medium Gravel
CROK_00283	Very Fine Gravel	Very Fine Gravel
CROK_00239U	Coarse Gravel	Coarse Gravel
CROK_00239	Very Coarse Gravel	Very Coarse Gravel
CROK_00213	Fine Gravel	Fine Gravel
CROK_00171	Fine Gravel	Fine Gravel
CROK_00164	Very Coarse Sand	Very Coarse Sand
CROK_00150	Fine Gravel	Fine Gravel
CROK_00120	Coarse Gravel	Coarse Gravel

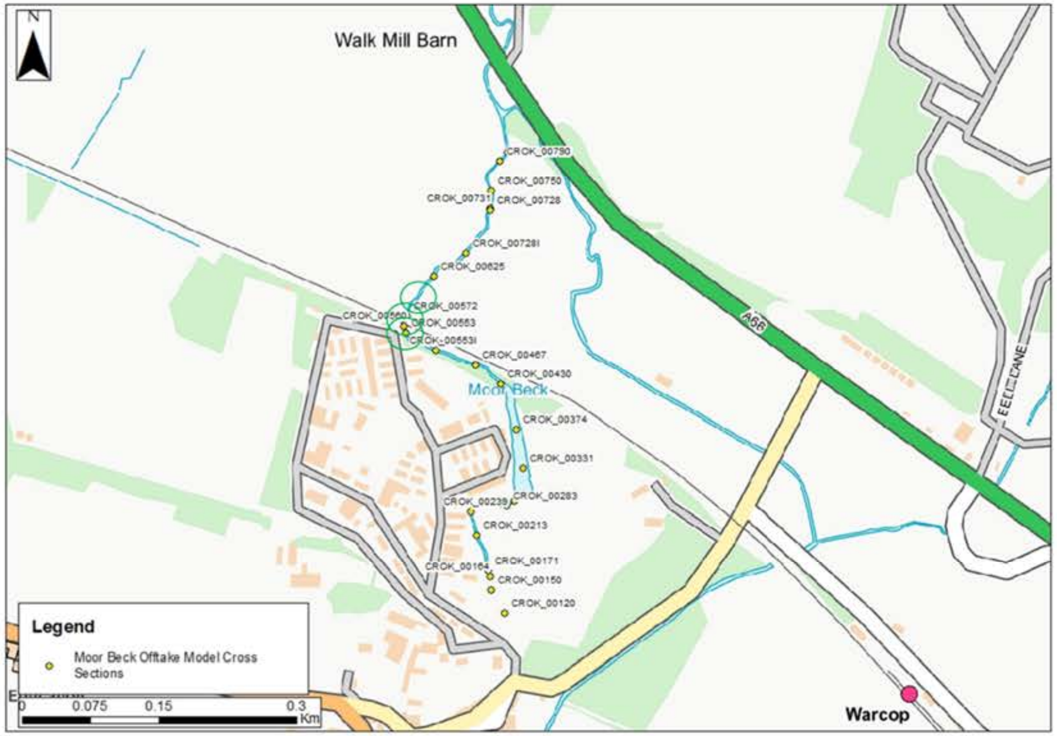


Plate 96: 1-in-100 Year +94% Climate Change Flood Event comparison of in channel maximum size of sediment entrained on the Moor Beck (Offtake) between the Post Development and Baseline Scenarios

Model Cross Sections	Baseline Q100CC94 Sediment Size Moved	PostDev Q100CC94 Sediment Size Moved
TODY_00446	Fine Cobble	Fine Cobble
TODY_00322U	Medium Gravel	Medium Gravel
TODY_00322	Medium Gravel	Medium Gravel
TODY_00315	Very Coarse Gravel	Very Coarse Gravel
TODY_00303	Medium Gravel	Medium Gravel
TODY_00297	Very Coarse Gravel	Fine Cobble
TODY_00247	Medium Gravel	Very Coarse Gravel
TODY_00229	Very Coarse Gravel	Very Coarse Gravel
TODY_00172	Fine Cobble	Fine Cobble
TODY_00154	Coarse Cobble	Coarse Cobble
TODY_00104	Coarse Gravel	Coarse Gravel

Plate 0-97: 1-in-100 Year +94% Climate Change Flood Event comparison of in channel maximum size of sediment entrained on the Eastfield Sike between the Post Development and Baseline Scenarios

Conclusions

Moor Beck

14.9.3.158 According to analysis of the 1-in-2 Year flood event hydraulic model results, no significant morphological changes to the channel and floodplain are predicted as a result of the proposed Moor Beck Viaduct Structure, Warcop Junction Structure and floodplain compensation structure:

- No significant changes to in-channel sediment transport dynamics across the Moor Beck are predicted.
- No significant changes to floodplain sediment transport dynamics and flow velocities are predicted. This is primarily down to the containment of much of the flow within the channel and as such minimal interaction with proposed structures on the floodplain.
- The flood compensation structure improves connectivity to the floodplain and could potentially result in fine material dropping out of transport within the structure. The potential retention of fine material on the floodplain would represent improved geomorphological functioning.

14.9.3.159 According to analysis of the 1-in-20 Year flood event hydraulic model results, minor morphological changes to the channel and floodplain are predicted as a result of the proposed Moor Beck Viaduct Structure, Warcop Junction Structure and floodplain compensation structure:

- No significant changes to in-channel sediment transport dynamics across the Moor Beck are predicted.
- Minor changes to floodplain sediment transport dynamics and flow velocities are predicted. Water that previously spilled along the existing A66 road and onto the left bank floodplain is diverted onto the floodplain between the Moor Beck and Moor Beck offtake and into the flood compensation area. This removes the overland flow route on the left bank of the Moor Beck and, as a consequence, the interaction between the Moor Beck Junction and the overland flow route.
- The flood compensation structure improves connectivity to the floodplain and could potentially result in fine material dropping out of transport within the structure. The potential retention of fine material on the floodplain would represent improved geomorphological functioning.

14.9.3.160 According to analysis of the 1-in-100 Year + 94% Climate Change flood event hydraulic model results, potentially significant morphological changes to the channel and floodplain are predicted as a result of the proposed Moor Beck Viaduct Structure, Warcop Junction Structure and floodplain compensation structure:

- Minor reductions in the size of material that can be entrained in the channel in the vicinity of the Warcop Junction structure are predicted. However, this is unlikely to result in changes to the composition of the riverbed, as changes in the size of material that can be entrained are within the ranges observed on site.
- Significant increases in the size of material that can be entrained in the channel in the vicinity of the Moor Beck viaduct are predicted. This has the potential to result in increases in riverbed scour and a change in the composition of the riverbed as well as bank instability.
- There are significant reductions to flow velocities on the left bank floodplain. The overland flow route is disrupted by the presence of the embankments associated with the Warcop Junction and flood compensation structure. Flow velocities reduce significantly, as water is impounded on the floodplain upstream, and flow is unable to pass through the structure. However, this is unlikely to result in significant change to the composition of the floodplain.
- There are significant increases in flow velocities on the right bank of the Moor Beck where flow is conveyed from the flood compensation structure back into the channel. These increases have the potential to increase scour of the floodplain and riverbanks.

Moor Beck (Offtake)

14.9.3.161 According to analysis of the hydraulic modelling results across all three flood events assessed, no significant changes are predicted associated with the Moor Beck (Offtake) channel.

- Small reductions in the size of sediment that can be entrained in the channel are predicted, as the additional flow conveyed from the flood compensation structure is impounded by the structure associated with the rail embankment.

However, this is unlikely to result in changes to the composition of the riverbed, as changes in the size of material that can be entrained are within the ranges observed on site.

Eastfield Sike

14.9.3.162 According to analysis of the hydraulic modelling results across all three flood events assessed, no significant changes are predicted associated with the Eastfield Sike channel and floodplain.

- Small increases in the size of sediment that can be entrained in the channel are predicted, as the modification of the existing A66 carriageway culvert reduces flow impoundment, increases conveyance of flow in the channel and leads to small increases to in channel flow velocities. However, this is unlikely to result in changes to the composition of the riverbed, as changes in the size of material that can be entrained are within the ranges observed on site.

- Small variations in flow velocities on the Eastfield Sike floodplain are predicted. The modification of the existing A66 carriageway culvert reduces flow impoundment upstream, facilitating the conveyance of more flow downstream and onto the floodplain. This has resulted in small increases and decreases in flow velocities on the floodplain. However, these are insignificant.

Mitigation Measures

14.9.3.163 The assessment reported in this assessment is based on a precautionary worst case scenario. As such, the mitigation identified in this assessment as being required to mitigate the likely significant effects reported are based on this worst case scenario. It may be the case that as detailed design of the Project evolves, it becomes apparent that a lesser form of mitigation is required to achieve the same outcome. As such, the EMP secures the 'maximum' extent of mitigation required (as identified in this assessment) but also, where appropriate, includes mechanisms (e.g. by way of further surveys or modelling) to establish, pre-construction and during detailed design, whether the identified mitigation can be refined such that a lesser extent is required to achieve the outcome reported in this assessment. The fundamental point is that the mitigation identified in this assessment is secured by the EMP, where required to achieve the outcome reported in this assessment.

14.9.3.164 A number of changes to in-channel sediment transport dynamics, floodplain sediment transport dynamics and floodplain velocities on the Moor Beck associated with the proposed structures in the vicinity of Warcop were identified in the assessment. The following mitigation measures, secured by the Project Design Principles (Application Document 5.1.1) and Environmental Management Plan (Application Document 2.7), which is a certified document under DCO, will be implemented at detailed design stage:

- Green scour protection measures will be implemented on the left bank of the Moor Beck in the vicinity of the Moor Beck Viaduct structure to mitigate the risk of floodplain and riverbank scour.
- Green scour protection measures will be implemented on the right bank floodplain of the Moor Beck in the vicinity of the Warcop Junction West structure to mitigate the risk of floodplain and riverbank scour.
- Increasing the roughness of the floodplain, by planting riparian tree cover and floodplain tree cover will be implemented. This will act to slow flow conveyance on the floodplain, reducing flow velocities and mitigating the risk of scour on the floodplain and on the riverbanks of the Moor Beck.

- Increasing the roughness within the flood compensation structure will be implemented. This will improve the storage of fine material during flood events, as well as provide habitat benefits.
- Realignment of the Moor Beck in the reach between the Moor Beck Viaduct and the Warcop Junction structure. This will reduce flow velocities and redirect flow energy away from the embankment associated with the Moor Beck Viaduct. This will reduce the risk of scour in the vicinity of the embankment in the 1-in-100 Year + CC94 Flood Event.
- Feasibility and design development of these options will be undertaken during detailed design. Any future plans will be developed to ensure there is no change to the conclusions set out within the Habitats Regulations Assessment Stage 1: Likely Significant Effects Habitats (Application Document 3.5) and Regulation Assessment Stage 2: Statement to Inform Appropriate Assessment (Application Document 3.6). Additional geomorphological modelling may be required on a iterative basis to inform detailed design of mitigation. It will be used to demonstrate that the detailed design achieves the outcomes relied upon within the HRA LSE and HRA SIAA and appropriate mitigation is developed to mitigate any potential adverse effects on geomorphology.
- As part of National Highways' maintenance, inspections of potential scour on the Moor Beck Viaduct crossing and Warcop Junction embankment will be conducted. Should any adverse changes be reported, appropriate mitigation plans to address this will be developed and implemented by National Highways. The Environment Agency and Natural England will be consulted on impacts to geomorphology.

Annex A: Temple Sowerby to Appleby site photographs

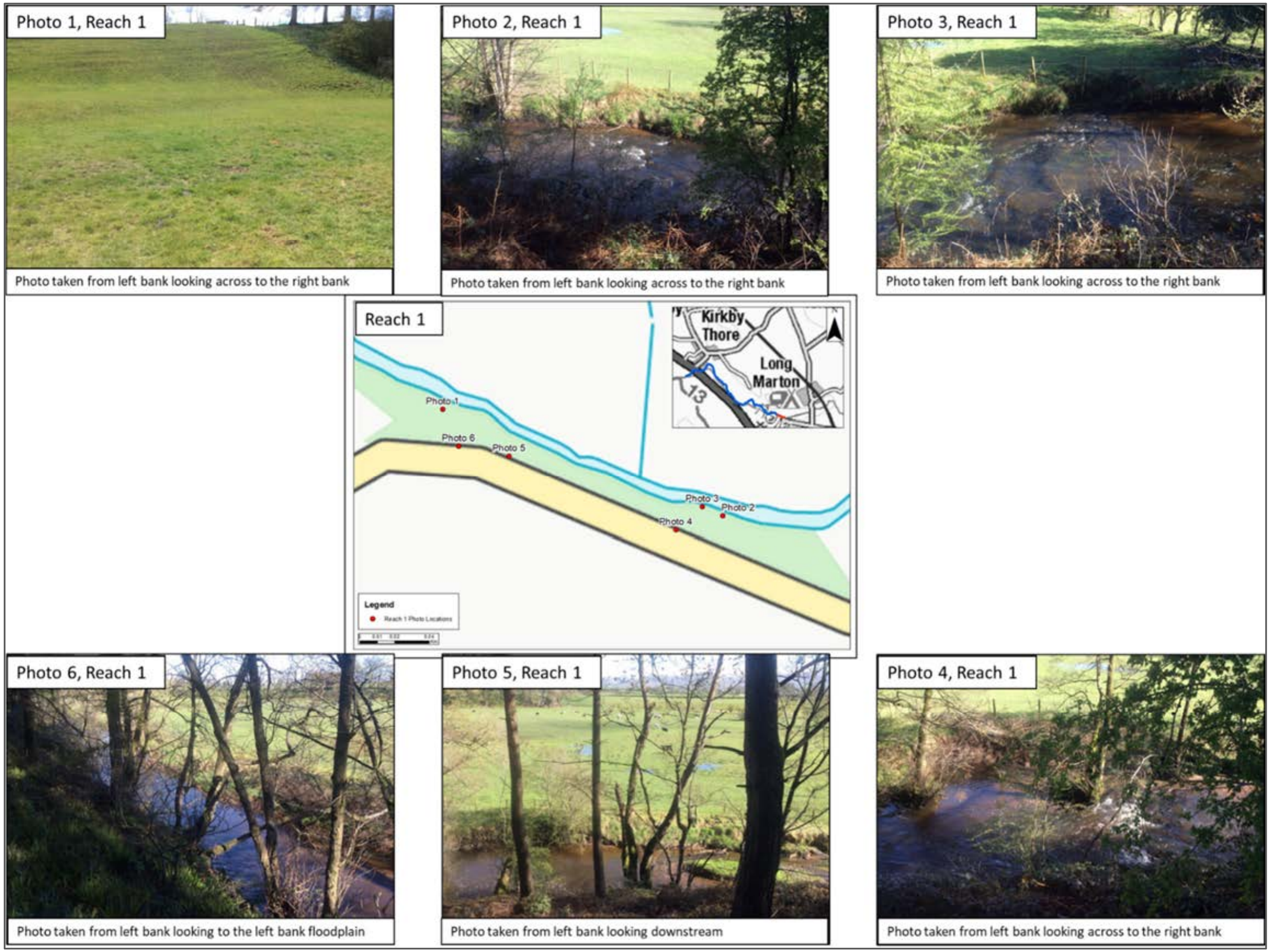


Plate 98: Location of photos taken during the survey of Trout Beck Reach 1

Plate 99: Location of photos taken during the survey of Trout Beck Reach 2

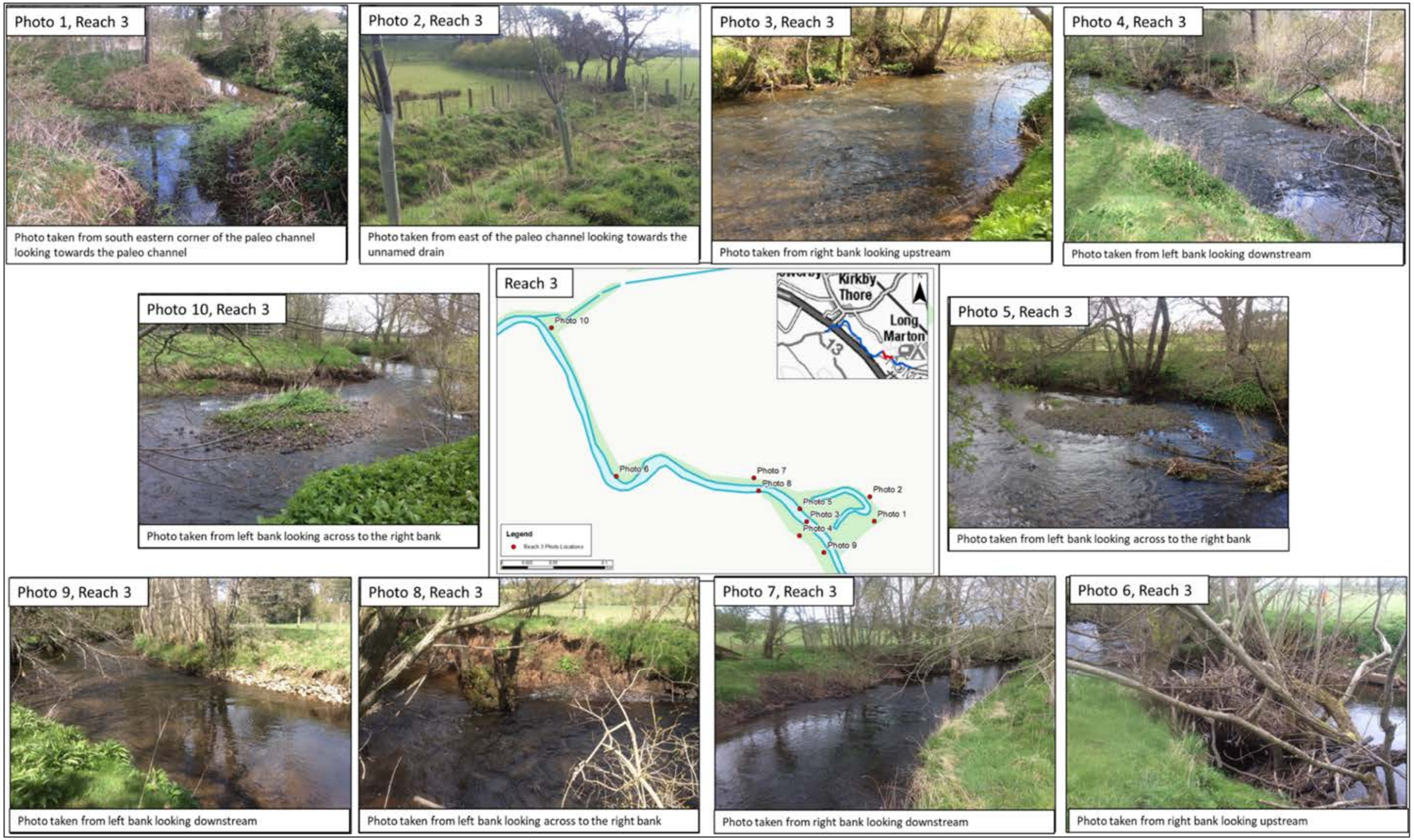


Plate 100: Location of photos taken during the survey of Trout Beck Reach 3

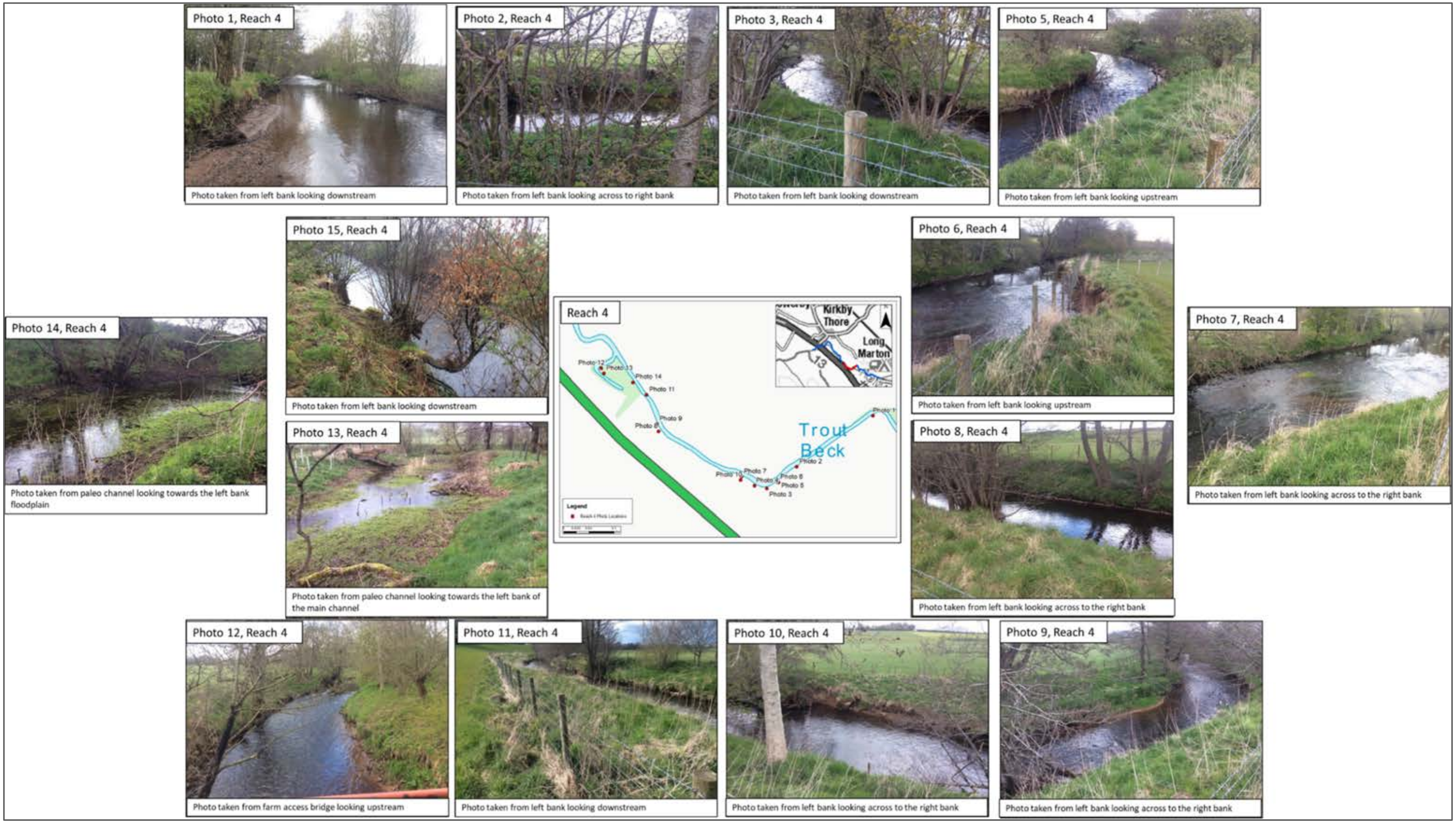


Plate 101: Location of photos taken during the survey of Trout Beck Reach 4

Plate 102: Location of photos taken during the survey of Trout Beck Reach 5

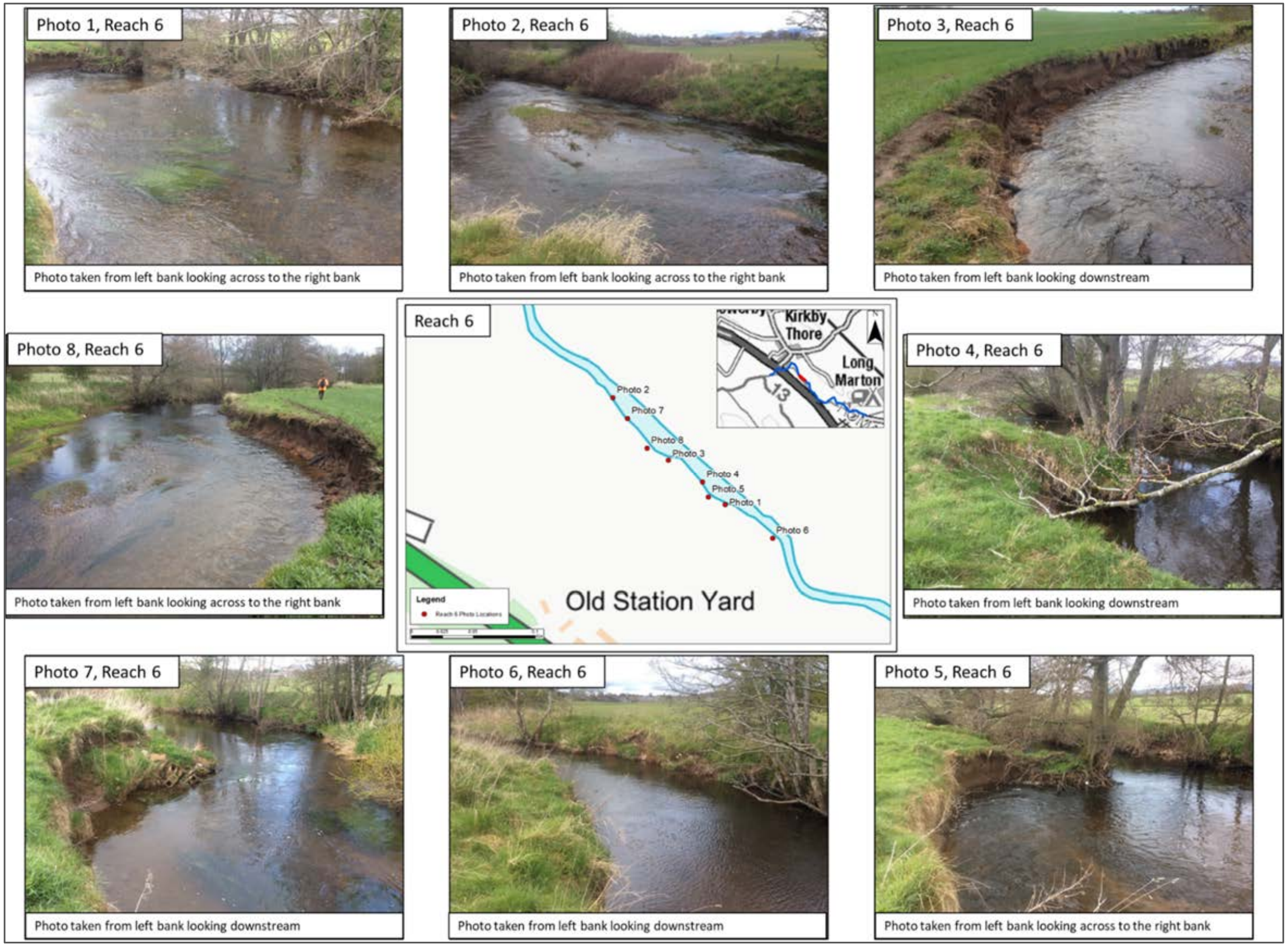


Plate 103: Location of photos taken during the survey of Trout Beck Reach 6

Plate 104: Location of photos taken during the survey of Trout Beck Reach 7

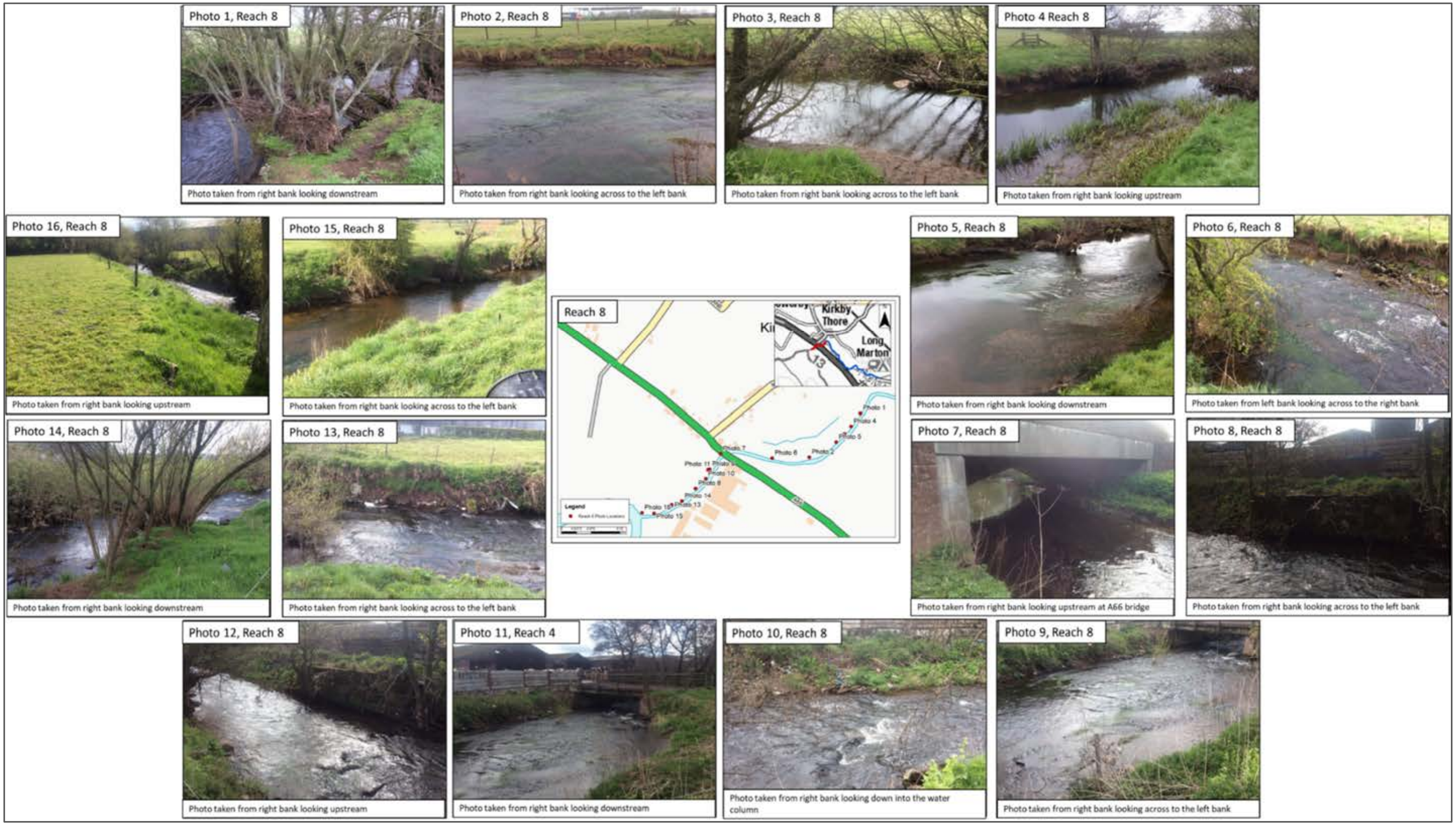


Plate 105: Location of photos taken during the survey of Trout Beck Reach 8

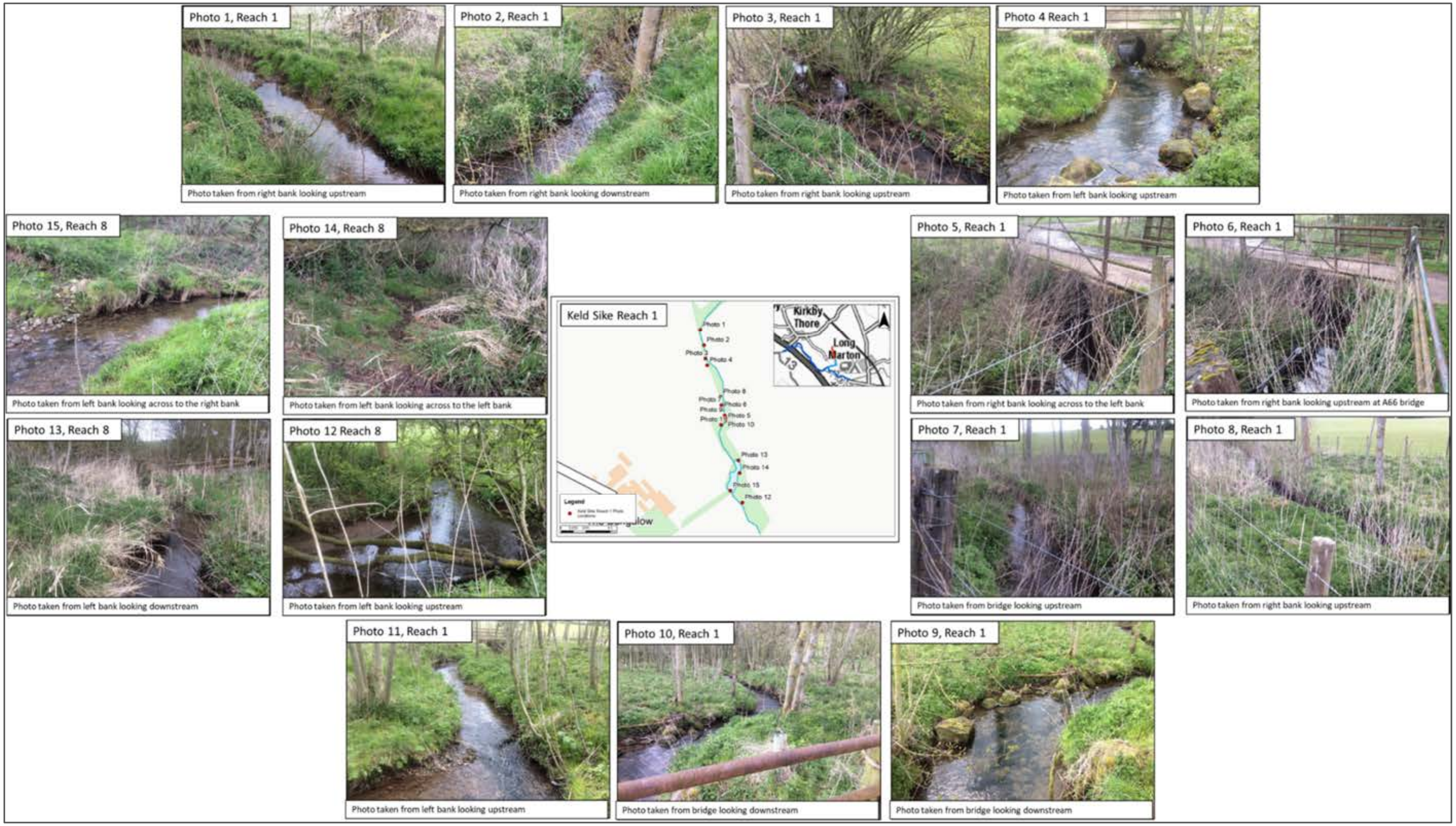


Plate 106: Location of photos taken during the survey of Keld Sike Reach 1

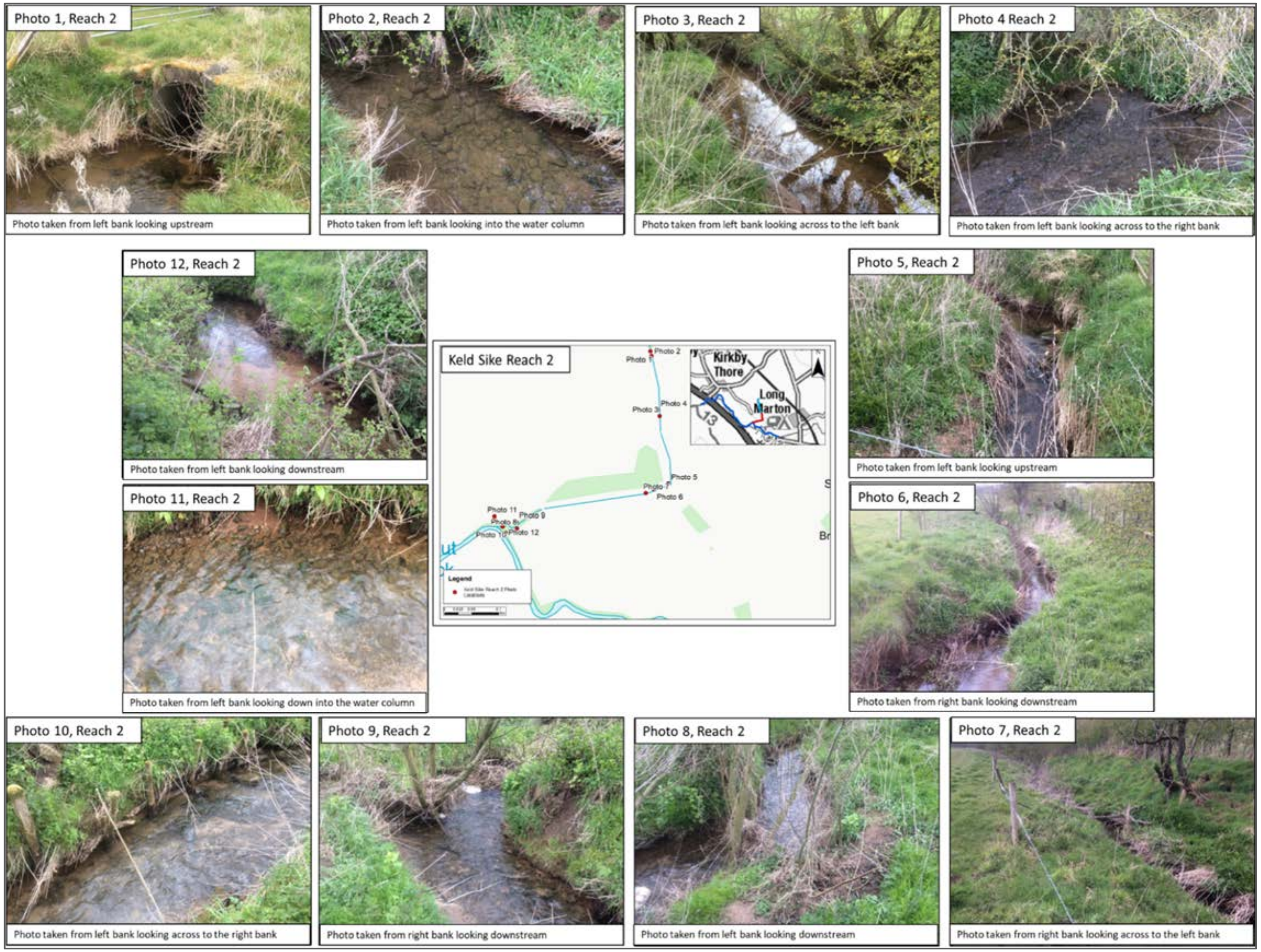


Plate 107: Location of photos taken during the survey of Keld Sike Reach 2

Annex B: Appleby to Brough site photographs

Plate 108: Hayber Beck site photographs

Plate 109: Moor Beck site photographs

Plate 110: Moor Beck (Offtake) site photographs

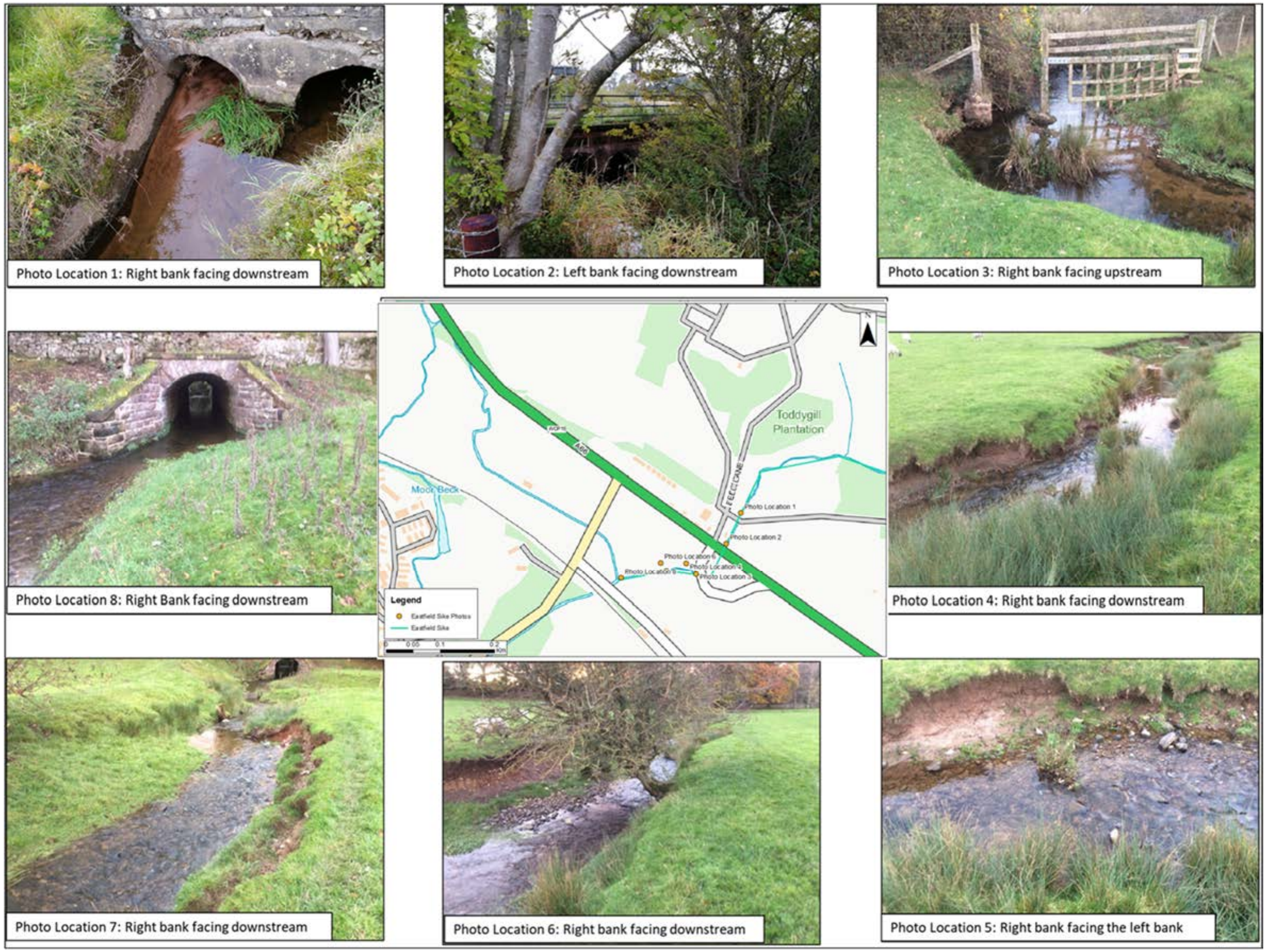


Plate 111: Eastfield Sike site photographs

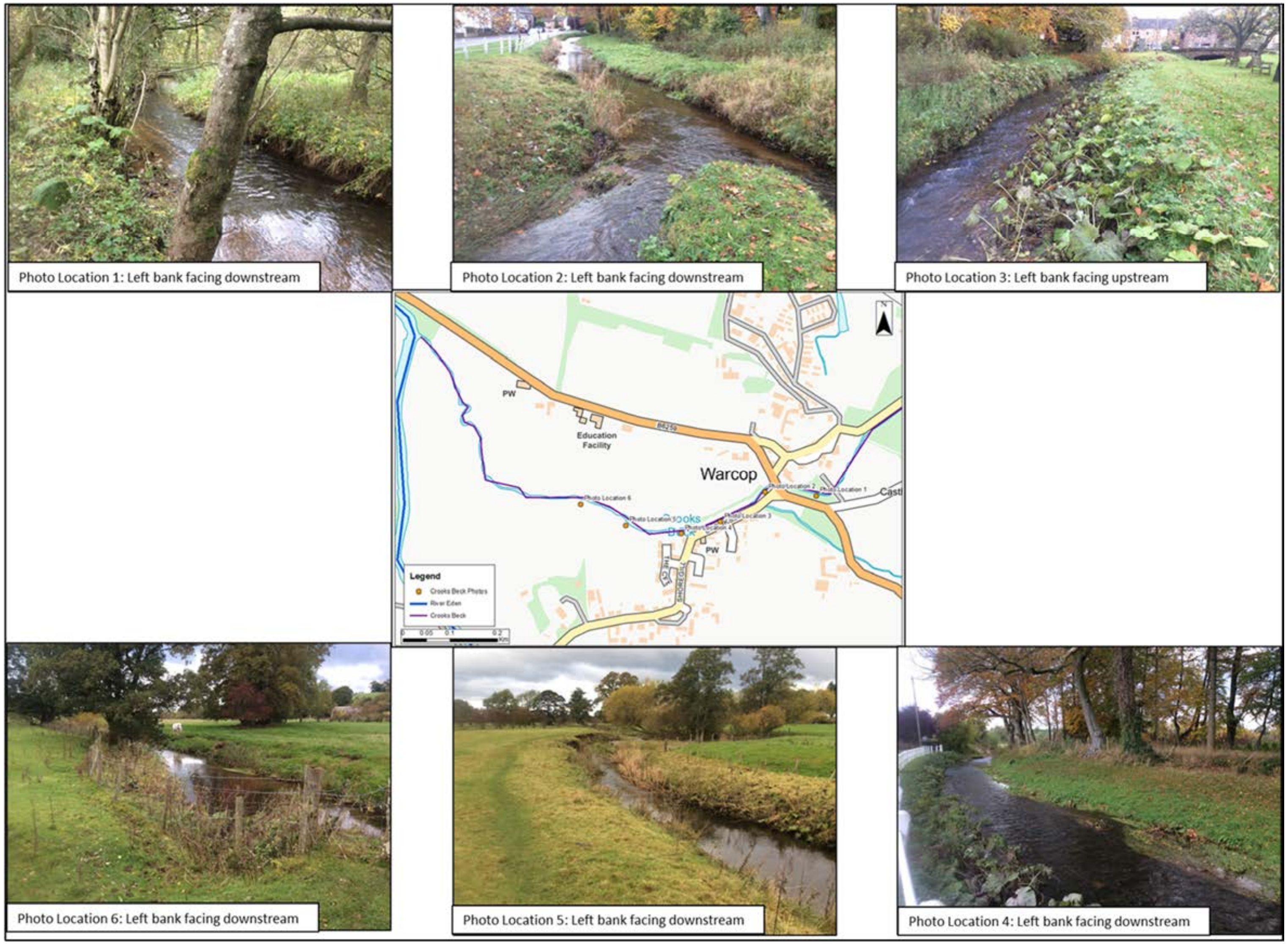


Plate 112: Crooks Beck site photographs

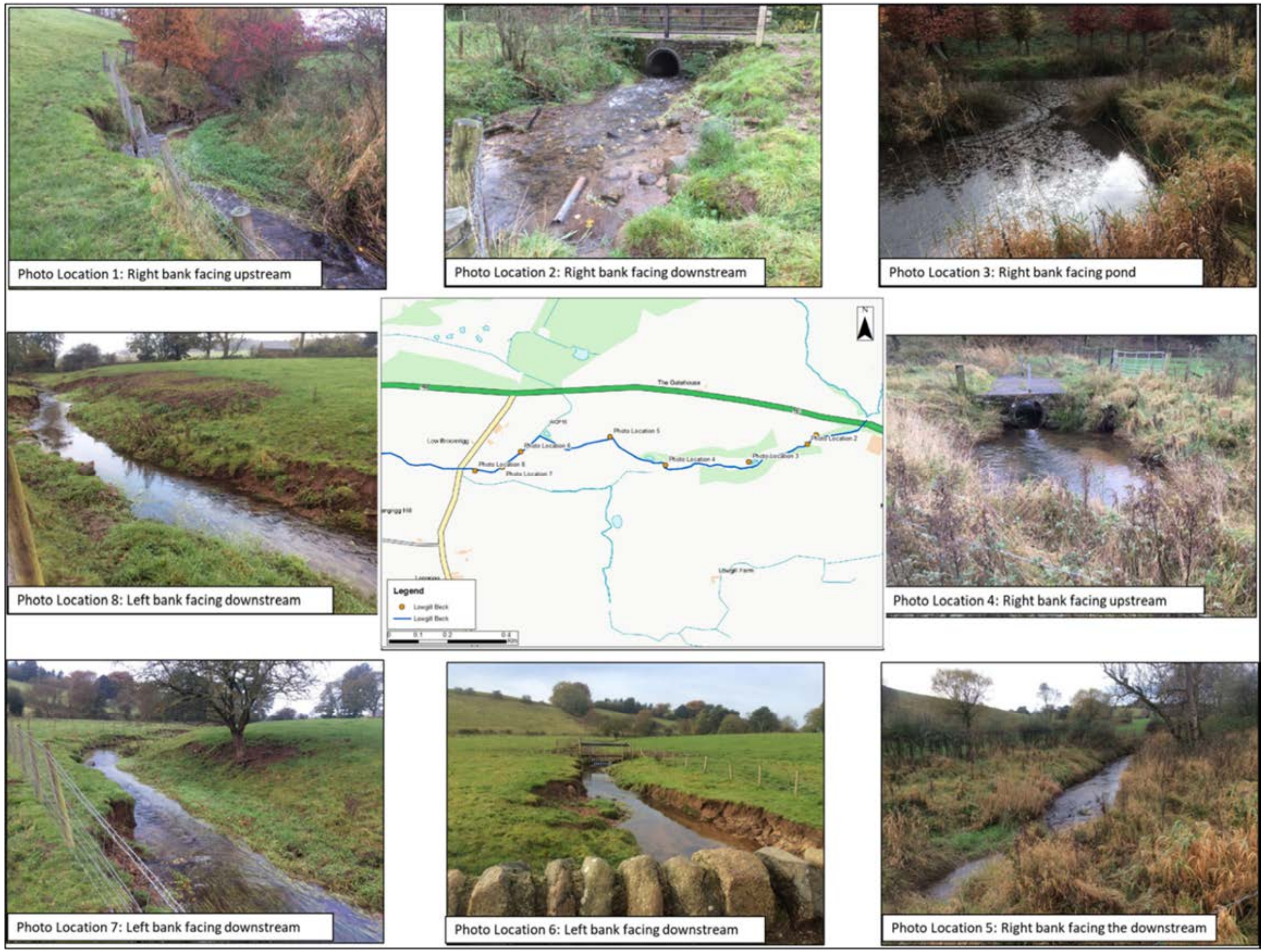


Plate 113: Lowgill Beck (The Gatehouse) site photographs

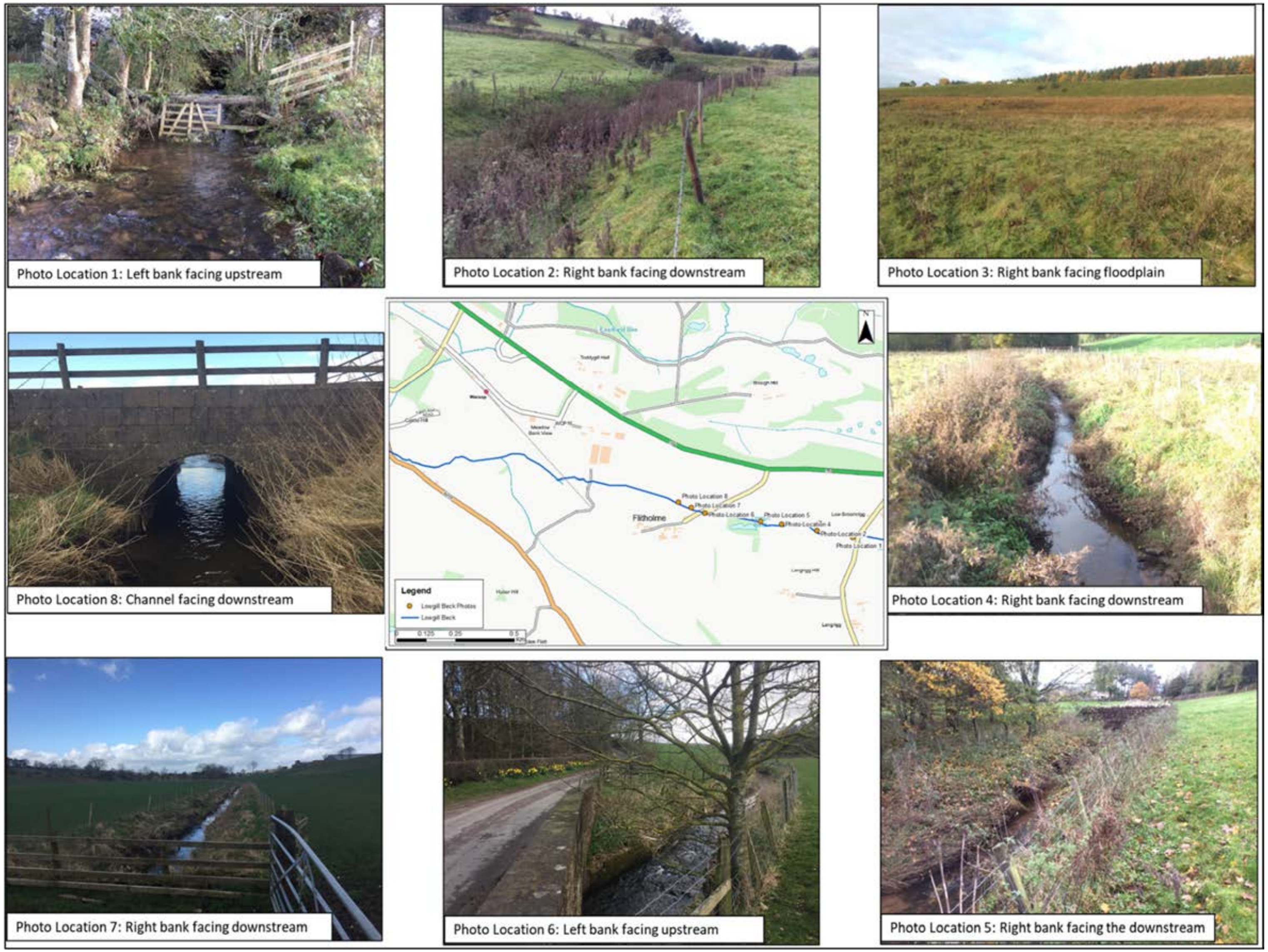


Plate 114: Lowgill Beck (Flitholme) site photographs

Annex C: Sediment sampling methodology

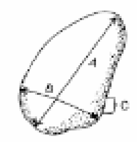
Wolman Pebble Count

Various publications describe the Wolman Pebble Count procedure. This technique requires the observer to measure sizes of random particles using a gravelometer. Particles smaller than 2 mm are placed in a category of <2mm. A step-toe procedure is frequently used to randomly select particles for quantification.

Size Class	Size Range (mm)
Sand	<2
Very Fine Gravel	2-4
Fine Gravel	4-6
Fine Gravel	6-8
Medium Gravel	8-11
Medium Gravel	11-16
Coarse Gravel	16-22
Coarse Gravel	22-32
Very Coarse Gravel	32-45
Very Coarse Gravel	45-64
Small Cobble	64-90
Medium Cobble	90-128
Large Cobble	128-180
Very Large Cobble	180-256
Small Boulder	256-512
Medium Boulder	512-1024
Large Boulder	1024-2048
Very Large Boulder	2048-4096

Wolman Pebble Count Procedure

1. Select a reach for sediment particle size distribution quantification. For stream characterization, sample pools and riffles at the same proportion the occur in the stream reach.
2. Start transect at a randomly selected point (throw a pebble) along the edge of stream. Take one step into the water perpendicular to flow and, while averting your eyes, pick up the first pebble touching your index finger next to your big toe.
3. Measure the b-axis by determining which hole the pebble fits through in the gravelometer and record in data book. For embedded pebbles or those that are too large to move, measure the shortest axis visible.
4. Take another step across the stream and repeat the previous steps until you reach the opposite side. Establish a new transect and begin the process over again. If your stream reach is relatively narrow (<2 m), you can modify the method by walking upstream in a zig-zag pattern instead of perpendicular to flow. In general, you will need to collect 100 measurements in order to accurately quantify pebble distributions.
5. After data is collected, plot data by size class (log_2 scale) and frequency to determine distributions. For example the D_{50} is the particle size that 50% of the samples are equal to or smaller than.



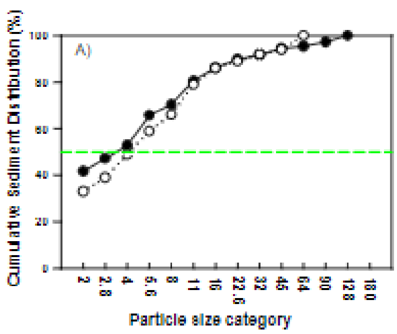


Plate 115: Sediment sampling methodology