Understanding Gully Blocking in Deep Peat

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Executive Summary

This report aims to provide evidence based recommendations for suitable site characteristics for the implementation of gully blocking as a method of moorland restoration. The specific context is re-vegetation of areas of the Peak District National Park by the Moors for the Future partnership. The report consists of three main studies. The first is an extensive photographic survey of natural re-vegetation on the Bleaklow and Kinder Scout plateaux. The set of georeferenced photographs produced provide a useful baseline for further monitoring of these sites. The photographs generated five hypotheses about mechanisms of natural re-vegetation which occurred in specific geomorphic contexts: Colonisation of redeposited peat surfaces by *Eriophorum angustifolium* in three contexts, 1) peat flats, 2) behind gully blocks, and 3) as a result of reduced stream power in broad gullies. 4) Colonisation of bare peat floored gullies by *Eriophorum vaginatum* and 5) Colonisation of bare mineral floors by a range of vegetation types.

The second main component of the study was a quantitative field survey of natural revegetation at 149 gully sites in seven areas across Bleaklow and Kinder Scout. At each of these sites vegetation and morphometric data were collected. The survey confirms that natural re-vegetation is widespread in the study area, and provided supporting evidence for mechanisms 1, 2 and 4 above. The survey identified two classes of gully in the study area; Type A which are steep and narrow and Type B which are shallower, wider and deeper. Re-vegetation assemblages vary between these gully types. Natural gully blocks are common, average 0.4 m high and are more prevalent in the steeper Type A gullies. A potential natural analogue 'target' for artificial gully blocking is provided by naturally blocked gully sites re-vegetated with *E. angustifolium* cover. These gullies are characterised by relatively low slope angles and re-deposited peat. A key finding is that relatively low depths of sediment accumulation are required to allow *E. angustifolium* colonisation of natural block sites.

The third major component of the study was a survey of 357 existing artificial gully blocks installed on Within Clough and Kinder Scout by the National Trust. These blocks have been in place for less than a year, consequently none of the blocks exhibit significant re-vegetation. Instead success was judged by sediment accumulation behind the blocks. The natural analogues suggest that this is a precursor to successful vegetation colonisation. 83% of the existing blocks showed some sediment accumulation. Block height and sediment supply are key controls on sediment accumulation. Sediment accumulation varies significantly between block types with stone wall and wood fencing most efficient, plastic piling less efficient and the hessian sack blocks working very poorly.

Several important caveats to the findings of this study should be noted. The current findings are a result of rapid survey of a poorly understood system. The time and cost limitations of this work mean that this is not a definitive study of gully blocking, but a collation of empirical data with the explicit purpose of guiding future blocking. Particular problems exist with interpretation of the existing artificial gully block dataset because of the variable timing of blocking, the variable techniques, and the varying contexts. Because the blocking programme was never planned as a controlled study of these effects it has not been possible to entirely remove the effects of covariance of these variables from the findings. For these reasons the recommendations outlined below are relatively conservative. They represent blocking locations where we are reasonably confident that blocking might succeed. However there are examples from the natural dataset which demonstrate re-vegetation is possible for block types and locations outside the envelope of the recommendations. It is therefore not unreasonable, should local circumstance dictate, to pursue further experimental blocking beyond the recommended range of conditions.

Combining the evidence from the naturally re-vegetated sites and analysis of the existing gully blocks the following key recommendations are made:

- Gully blocking should occur before extensive revegetation of interfluves.
- Wooden fencing, plastic piling and stone walls are all effective gully blocking methods.
- Efforts should focus on blockage of sites with slopes less than 0.11 m/m (6º).
- Block spacing should not exceed 4 metres. Minimum spacings as a function of gully depth can be derived from figure 27.
- Target gully block height should be 45 cm. 25 cm should be a minimum height.
- Maximum block widths of 4 m
- Planting of blocks with *Eriophorum angustifolium* once stable sedimentation has been achieved
- Development of experimental approaches to promoting sediment deposition and revegetation in type B gullies based on the observation of natural processes.

Table of Contents

List of Figures

Cover photographs: Left, gully blocking by plastic piling on Within Clough

Right, natural revegetation of a gully in the Upper North Grain catchment on Bleaklow

Figure

List of Tables

Acknowledgements

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3.1 Introduction

3.1.1 Background to the Project

The blanket peat moorlands of the South Pennines are some of the most severely eroded peatlands in the world. Erosion of the peat has a range of undesirable consequences including habitat loss, impacts on water supplies, loss of amenity and oxidation of the carbon content of peat yielding carbon dioxide to the atmosphere.

Erosion control is therefore a land management priority in Pennine peatlands. Much of the erosion occurs through the development of dense networks of deep gullies in the peat. A recent approach to erosion control in this environment has been to block the gullies with the aim of raising water tables and promoting revegetation.

Gully blocking in deep peat as distinct from blocking of artificial drainage ditches within peatlands is an approach to moorland restoration and erosion control which has only very recently been contemplated. As such there is very little formalised experience of the technique and no rigorous empirical evidence to support ongoing gully blocking. It is a premise of this report that since peat gully erosion is primarily a geomorphological process that criteria for the location of gully blocks must in large part be based on understanding of the geomorphology and hydrology of the system.

Recent work on the controls on gully erosion of blanket peat (Evans and Warburton in press) suggests a series of key parameters which a priori we would expect to influence the success of gully blocking. These geomorphological parameters such as slope and sediment supply together with gully blockage, artificial or natural, are key in creating temporary surface stability which promotes re-vegetation and stabilisation of the gully system. The relative importance of these parameters is best assessed by careful evaluation of the limited previous experience of gully blocking in Pennine blanket peats. An important component of this project has therefore been the careful assessment of the site characteristics of previous gully blocking work on Bleaklow and Kinderscout carried out by the National Trust.

Evans et al. (2002) developed the hypothesis that the extensive natural re-vegetation of eroded peat gullies in the North Pennines, which is also observed to a lesser degree in the current study area, is controlled at least in part through natural blockage of the gully system. According to this hypothesis three factors are essential to natural, and by extension potentially to artificial re-vegetation of eroded peat gullies. These are initial effective blockage of gully impeding drainage, accumulation of fine re-deposited peat behind the gully block, and colonisation of the unconsolidated sediments by pioneer species, most likely *Eriophorum angustifolium.* The initial natural blockage of gullies is initiated by oversteepening of gully walls by fluvial action, and the mass failure of vegetated blocks of peat onto the gully floor (figure 3.1). A second premise of this report is therefore that natural re-vegetation of eroded blanket peat by these mechanisms represents a useful natural analogue for artificial gully blocking.

Figure 3.1 Blockage of a gully by natural failure

The numbers of pre-existing artifical gully blocks are relatively small and their range of landscape contexts is limited. It is therefore appropriate to take advantage of the concept of a natural analogue for gully blocking through assessment of relevant site and catchment characteristics of naturally re-vegetated gullies. Therefore a second component of this study is to assess controls on natural re-vegetation of eroded peat gullies.

3.1.2 Aim of the Research

The aim of this research is therefore to develop our understanding of the controls on successful blockage and re-vegetation in order to develop guidelines for identifying locations where gully blocking is likely to be an efficient and effective means of moorland erosion control.

3.1.3 Approach

To achieve this aim the project has surveyed recent gully blocking works undertaken by the National Trust in the High Peak. The study has measured a range of site characteristics at gully block locations in an attempt to elucidate key controls on the success of gully blocking. Because the gully blocks studied are less than a year old only the early stages of the gully blocking process have been studied directly. Therefore in order to address this deficiency the project has also surveyed a range of naturally revegetated gully sites within the Bleaklow/Kinderscout plateaux. Some of these sites may be regarded as natural analogues of gully blocking and they represent the range of conditions under which natural revegetation occurs. This provides a useful guide to potentially successful locations for intervention. In addition to the direct practical benefit this work on natural analogues for gully blocking has allowed us to clearly locate the aims and effects of artificial gully blocking within a context of several modes of natural revegetation. Central to achieving this outcome has been an extensive photographic survey of the Kinder Plateau and Bleaklow.

3.2 Baseline Photographic Dataset

3.2.1 Aims

The photographic database was generated by extensive fieldwalking of the study area in order to address the following aims

- To collect set of geo-referenced photographs of natural re-vegetation of the Bleaklow/Kindercout plateaux. This dataset will provide baseline data for ongoing monitoring.
- To observe and record the range of styles of natural re-vegetation present on the Bleaklow/Kinderscout plateaux.
- To assist in selection of sites for intensive study.

3.2.2 Dataset structure

The photographs are delivered in digital format on the accompanying compact disc, also on the disc is a file ‘Photo catalogue.xls’ which lists and categorises the available photography. The photographs comprise two main datasets. The first is photography derived from fieldwalking the study area. These photos are geo-referenced and represent a wide range of re-vegetation forms observed during the project. The second dataset is photographs of the sites studied in detail in the intensive study (sections

3.3 and 3.4 of this report). . For the naturally re-vegetated sites there is one photograph for each site geo-referenced and categorised by area and type. For the artificial gully blocks the photos are geo-referenced and cover whole gullies or sections of the 16 measured gully systems

3.2.3 Hypothetical modes of natural re-vegetation

The initial premise of the work on natural re-vegetation was that natural gully re-vegetation is largely controlled by gully blocking through mass failure of steep gully sides causing local impedance of drainage and colonisation of wet redeposited peat by *Eriophorum angustifolium*. Extensive fieldwalking of the study area has led to some modification of this premise. In fact we have hypothesised three principal modes of re-vegetation. The nature of these hypothesised mechanisms is outlined below, and illustrated with photographs selected from the database.

3.2.3.1 Colonisation of re-deposited peat surfaces by Eriophorum angustifolium.

The most widespread form of re-vegetation encountered in the study area is spread of *Eriophorum angustifolium*. This is most commonly observed in locations where there are significant amounts of soft, wet, eroded and re-deposited peat. Three geomorphological locations appear particularly important in generating these conditions.

1. Peat Flats.

   Where there are extensive areas of low angled bare peat, ‘peat flats’, such as found on fire scars revegetation of redeposited peat at the margins or in local depressions was commonly observed. The most extensive areas of this type were observed on Kinder Scout, and three examples are illustrated below (figures 3.2-3.4), but some areas adjacent to the Moors for the Future restoration sites exhibit this form, and there are further examples on the north flank of Bleaklow.

2. Gully blocks.

   Probably the most widespread form of re-vegetation in the study area is that associated with blocking of gullies by mass failure as outlined in section 3.1.1. Examples of *Eriophorum angustifolium* colonisation of re-deposited peat behind gully blocks are found across the Kinder and Bleaklow plateaux, often with evidence of considerable upstream spread of the vegetated surface above the initial block location. Several examples are illustrated below (figures 3.5-3.7).

3. Peat deposition and revegetation associated with reduced stream power

   Wishart and Warburton (2001) suggested that large gullies may re-vegetate due to reduced stream power reducing the erosion of the gully floor. As eroding gullies develop they evolve from steep v-shaped gullies to broader, flat bottomed gullies at lower slope angles. The broadening of the gully floor, meandering of the flow and consequent reduction in stream slope allow regions of low stream power where re-deposition of peat may occur. In particular the inside of bends along the stream path are zones of preferential deposition. Many examples of *Eriophorum* spread across broad gullies apparently due to this mechanism have been identified (figures 3.8 & 3.9).

Figure 3.2 *Eriophorum angustifolium* colonisation of peat flats on Kinder Scout

Figure 3.3 Extensive redeposited peat on Kinder Scout with marginal spread of *Eriophorum angustifolium*

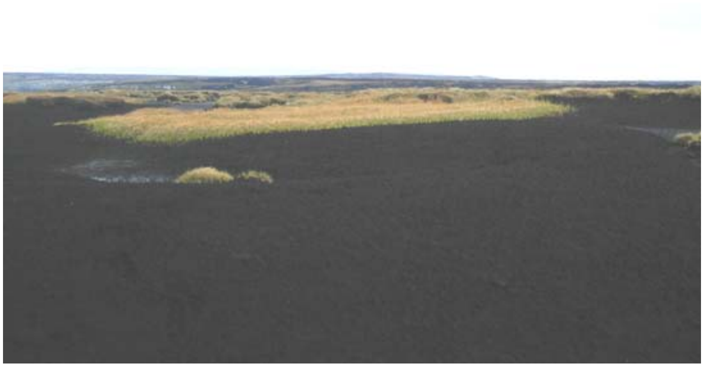


Figure 3.4 Spread of *Eriophorum angustifolium* on bare peat on Kinderscout

Figure 3.5 Mixed *Eriophorum angustifolium* and *Eriophorum vaginatum* colonisation above a gully blockage in Doctors Gate catchment, Bleaklow

Figure 3.6 Impeded drainage and *Eriophorum angustifolium* colonisation above a gully block on Bleaklow

Figure 3.7 extensive *Eriophorum angustifolium* cover of gully with impeded drainage

Figure 3.8 Alternating patches of *Eriophorum* colonisation on the inside of bends

Figure 3.9 Complete colonisation of a broad gully floor by *Eriophorum angustifolium*

3.2.3.2 Colonisation of bare peat floored gullies by Eriophorum vaginatum

Two modes of colonisation of peat floored gullies by Eriophorum vaginatum were noted

1. *Eriophorum vaginatum* colonisation

   In certain locations clumps of *Eriophorum vaginatum* are common pioneer species revegetating bare peat floors of gullies. It is unclear whether these clumps form initially from seed or through mass failure of the banks delivering pre existing plant material to the gully floor. The latter is closely related to the mechanism for re-vegetation of Gullies around Snake Pass proposed by Philips (1954). What is clear is that some of these clumps are mobile. We observed many occasions where clumps were unrooted and appeared to have moved down gully during storm events (Figure 3.10). A common pattern of *Eriophorum vaginatum* colonisation of gully floors is that there are several individual clumps spreading across the floor over a downstream distance of several tens of metres. This suggests that the mobile clumps are a mechanism for propagation of re-vegetation downstream. Figure 3.11 illustrates a gully with extensive *Eriophorum vaginatum* spread.

2. Mixed *Eriophorum vaginatum* and *Eriophorum angustifolium* revegetetation

   One interesting pattern apparent in several gullies is a hybrid form of revegetation between that described in this section and the gully blocking mechanism. This involves impedance of drainage by spreading clumps of *Eriophorum vaginatum* which appear to trap sediment and encourage further colonisation by *Eriophorum angustifolium* (figure 3.12)

Figure 3.10 Mobile clumps of *Eriophorum vaginatum.*

Figure 3.11 Significant extent of *Eriophorum vaginatum* colonisation in Nether North grain, Bleaklow.

Figure 3.12 Mixed *Eriophorum vaginatum* and *Eriophorum angustifolium* colonisation of a gully on Bleaklow

3.2.3.3 Colonisation of bare mineral floors

The final mechanism of gully revegetation identified from the extensive survey is direct colonisation of gully floors, often by species tolerant of rather drier conditions, such as *Vaccinium myrtillus, Empetrum nigrum* and *Deschampsia flexuosa*

Figure 3.13 extensive colonisation of bare mineral floored gully on Kinder Scout by *Vaccinium myrtillus*

3.2.4 Implications of the initial survey

An initial conclusion from the extensive survey is that there is widespread natural re-vegetation of bare peat and mineral surfaces occurring across the Bleaklow and Kinder plateaux. There are however, significant areas, where management intervention is probably required to initiate and accelerate re-vegetation of extensive bare areas. The significant advantage of the observation of widespread natural re-vegetation is the opportunity it provides to develop re-vegetation strategies which take advantage of the natural processes to increase the likelihood of success. We have illustrated that gully blocking is not the only process causing re-vegetation of bare ground in the study area but it is an important one. The following section assesses the controls on successful natural gully blocking with the aim of guiding management intervention. However, rather than to study only gully blocks the research design has been extended to assess a range of eroded and re-vegetated sites across the study area.

3.3 Natural Revegetation of Gully Systems

3.3.1 Introduction

This section further considers natural re-vegetation of gully sites on the Bleaklow / Kinder Scout plateaux. It extends the findings of the extensive survey (section 3.2) by using a quantitative dataset derived from field sampling. Data on gully-floor vegetation cover have been collected from sites at seven different locations on the plateux. The aim is to evaluate both the patterns of revegetation and the relationships between this re-vegetation and potential geomorphological/ hydrological controls. In particular this section:

- explores patterns of gully re-vegetation.
- relates re-vegetation to the physical (morphometric) characteristics of the gullies.
- examines relationships between natural gully blocks and patterns of re-vegetation.

3.3.2 Methods

3.3.2.1 Field locations and sampling

Data were collected in May-July 2004 from gullies in seven separate field areas: Upper North Grain, Nether North Grain, Doctors Gate, Shelf Moor, Bleaklow Meadows, Swains Greave and Kinder Scout. (Figure 14). At each area four to six gullies were chosen for field survey. Field surveys of gully characteristics were made (i) at 50m intervals along the length of each gully and (ii) wherever a clear natural gully block was present. This combination of sample sites both at block locations and at regular spacing along the gullies was designed to allow rapid collation of a dataset containing information of re-vegetation characteristics at both block and non-block locations. A total of 149 sites were surveyed in the study, 80 of which were from block locations.

Table 3.1 Parameters measured in the field survey

Parameter and unit of measurement
Gully width (from top of gully walls) (m)
Gully floor width (m)
Gully depth (m)
Gully floor slope (m m^{-1}) (Local slope)
Depth of redeposited sediment (cm)
Block width (m) (where relevant)
Block height (m) (where relevant)
Block depth (m) (where relevant
Vegetation cover of the gully floor (% by species)
Vegetation cover of the gully walls (% by species)
Vegetation cover of the catchment (% by species)
Presence of gully block at the sampling site (yes/no)

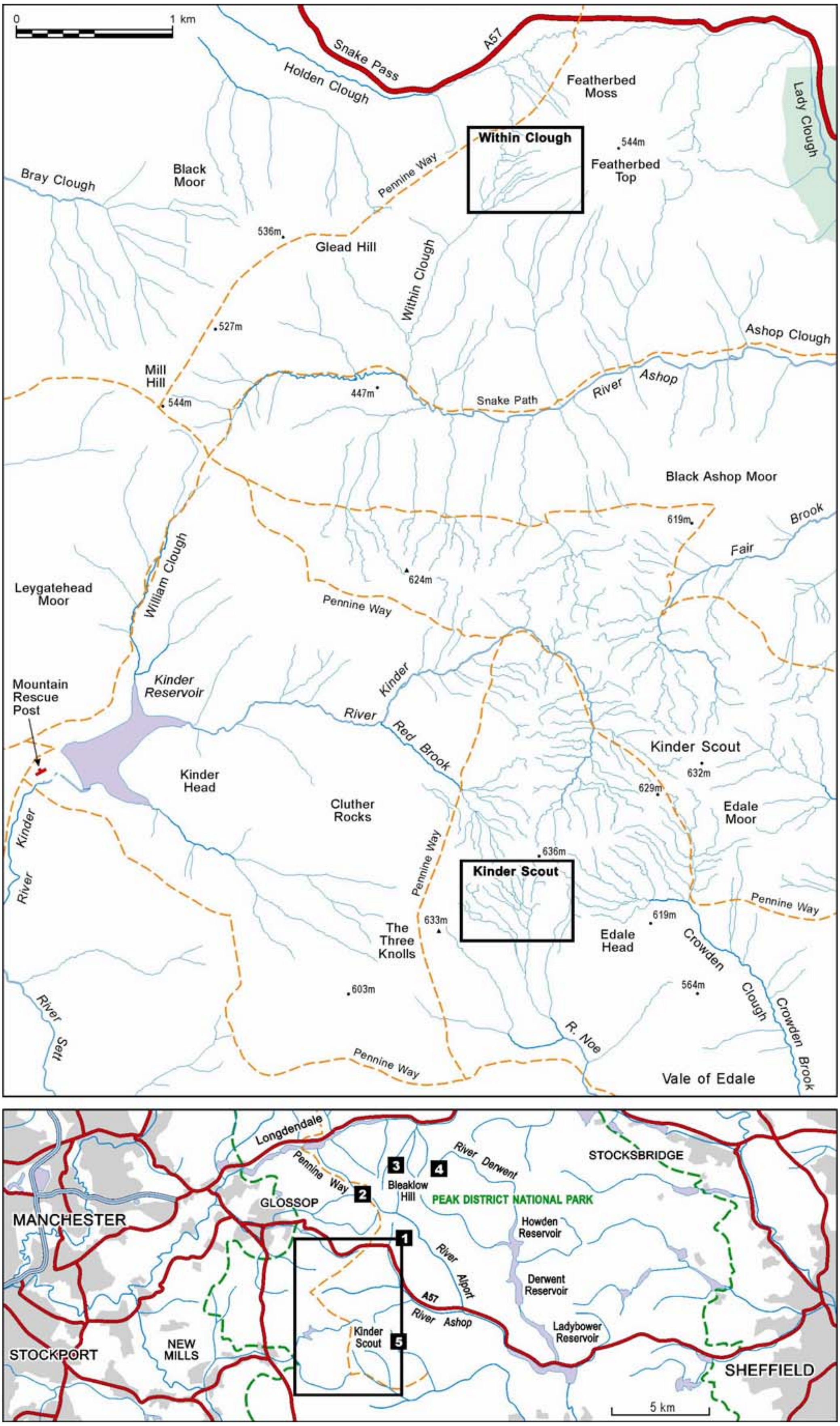


Figure 3.14 Study Locations The upper map is a detail of the box on the location map showing artificial gully block sites. Key to natural re-vegetation sites on location map 1) Upper/Nether North Grain / Doctors Gate. 2) Shelf Moor. 3) Bleaklow Meadows. 4) Swains Greaves. 5) Kinder Scout.

At each sample site a survey of gully characteristics was made, including gully morphometry, vegetation cover and gully block characteristics (where relevant) (Table 3.1). At block locations survey data was collected immediately above the block. Local gully floor slope was measured using a level. The average slope of gully walls was determined geometrically from the other measured variables. Plant cover by species was estimated by eye to the nearest 5%, with % bare peat, % bare mineral substrate and % redeposited mineral substrate (remin) also recorded. Where fine organic (peat) sediments had been deposited in the gully floors, the depth of these deposits were measured by probing. A total of 13 different plant species were recorded in the survey (see Table 3.2). Sphagna were not identified to species level.

Table 3.2Plant species recorded in the gully survey

Full name	Common name	Abbrievated name
Eriophorum vaginatum	Hare tail Cotton grass	Evag
Eriophorum angustifolium	Common cotton grass	Eang
Vaccinium myrtillus	Bilberry	Vmry
Empetrum nigrum	Crowberry	Enig
Rubus Chamerous	Cloudberry	Rcham
Sphagnum spp.	Bog moss	Spha
Juncus effuses	Soft rush	Jeff
Juncus squarrous	Heath rush	Jsqua
Nardus stricta	Mat grass	Nstri
Deschampsia flexuosa	Wavy hair grass	Dcaes
Agrostis teniuis	Common bent	Aten
Polytrichum commune		Pcomm
Erica tetralix	Cross-leaved heather	Etet

3.3.2.2 Data analyses

In addition to basic descriptive statistics, several specific data analysis techniques were employed. Emphasis was on exploring the variation in gully floor vegetation cover, and the morphometric factors associated with this.

Cluster analyses were used to explore (i) variation in the physical attributes of the gully samples and (ii) variation in gully floor vegetation cover. Cluster analysis techniques seek to identify groups of samples with similar data characteristics. In this study cluster analysis of physical (e.g. morphometric) data was carried out using the TwoStep cluster analysis procedure in SPSS, in which the number of clusters was identified using the Baysian Information Criterion (BIC). Cluster analysis of vegetation cover was implemented using TWINSPAN (Hill (1979), a technique commonly employed to classify ecological data.

Sub-sets of the data were also analysed using ordination analysis. Ordination techniques seek to identify gradients in multi-variate data which summarise the key patterns of variation. Detrended correspondence analysis (DCA) (Hill & Gauch 1980) was used to identify the main patterns of floristic variation in sub-sets of the gully floor cover data. DCA is an indirect gradient technique which assumes a unimodal response of species to their environment (ter Braak and Prentice 1988), and provides a robust ordination technique for data that have a large number of taxa and many zero values (i.e. vegetation data). The DCA can be displayed as a species and sample joint plot, in which the samples that lie close to the point of a species are likely to have a high abundance of that species, and the probability of occurrence of a species declines with distance from its location on the plot. In DCA plots, the closer samples plot to one another, the more similar their species compositions. DCA was implemented using CANOCO version 3.1 (ter Braak 1990).

Relationship between vegetation cover and physical gully characteristics were explored using canonical correspondence analysis (CCA) (ter Braak 1986). CCA is a direct gradient analysis technique which can be used to identify the environmental variables that are significantly related to variance in cover data, and is again suitable for data that have a large number of taxa and many zero values (i.e. vegetation data). CCA was implemented using CANOCO version 3.1 (ter Braak 1990). An important feature of CANOCO 3.1 is the ability to identify the minimal number of explanatory variables which explain a statistically significant proportion of the variance in cover data. This is implemented through CANOCO's forward selection procedure, analogous to stepwise multiple regression, with Monte-Carlo permutation tests (999 unrestricted permutations) to test the significance of the selected variables. In this study, CCA with forward selection was used to identify the physical variables which were independently significantly related to variation in gully floor (vegetation) cover. Tests of significant relationships between physical (morphometeric) data were carried out using analysis of variance (ANOVA).

3.3.3 Physical gully characteristics

The ranges and distributions in physical characteristics of the gully sites are shown in Table 3.3 and Figure 3.15. Gully widths range from 1 m to nearly 20 m, although the distribution is heavily negatively skewed and the majority of sites are relatively narrow (e.g. width < 5 m). Gully depths are more normally distributed, although there are a few particularly deep sites (e.g. depth >2.5 m) and also examples of notably shallow systems (e.g. depth < 0.5 m). Gully floor slope (local slope) ranges from almost flat gullies to steep systems with slopes of nearly 0.2 m/m. However, the slope data also show negative skew and the majority of sites are relatively flat with slope < 0.05 m/m.

A large proportion of the sites (95 out of 149) have a layer of relatively unconsolidated fine-grained organic sediment covering the gully floor. This represents re-deposited peat and is generally of shallow depth (typically 20 cm or less), although deposits as great as 75 cm were observed.

Table 3.3 Descriptive statistics on the physical characteristics of the 149 gully sample sites

	Local slope (m/m)	Gully top Width (m)	Gully floor width (m)	Average gully wall slope	Gully depth (m)	Sediment depth (m)	% Floor bare
Mean	0.050	6.00	2.42	0.68	1.27	0.10	38.96
Median	0.036	4.70	1.46	0.39	1.23	0.05	20.00
Standard Deviation	0.041	3.86	2.64	1.37	0.58	0.14	41.40
Minimum	0.000	1.02	0.22	-6.76	0.20	0.00	0.00
Maximum	0.184	19.40	16.14	9.06	2.86	0.75	100.00

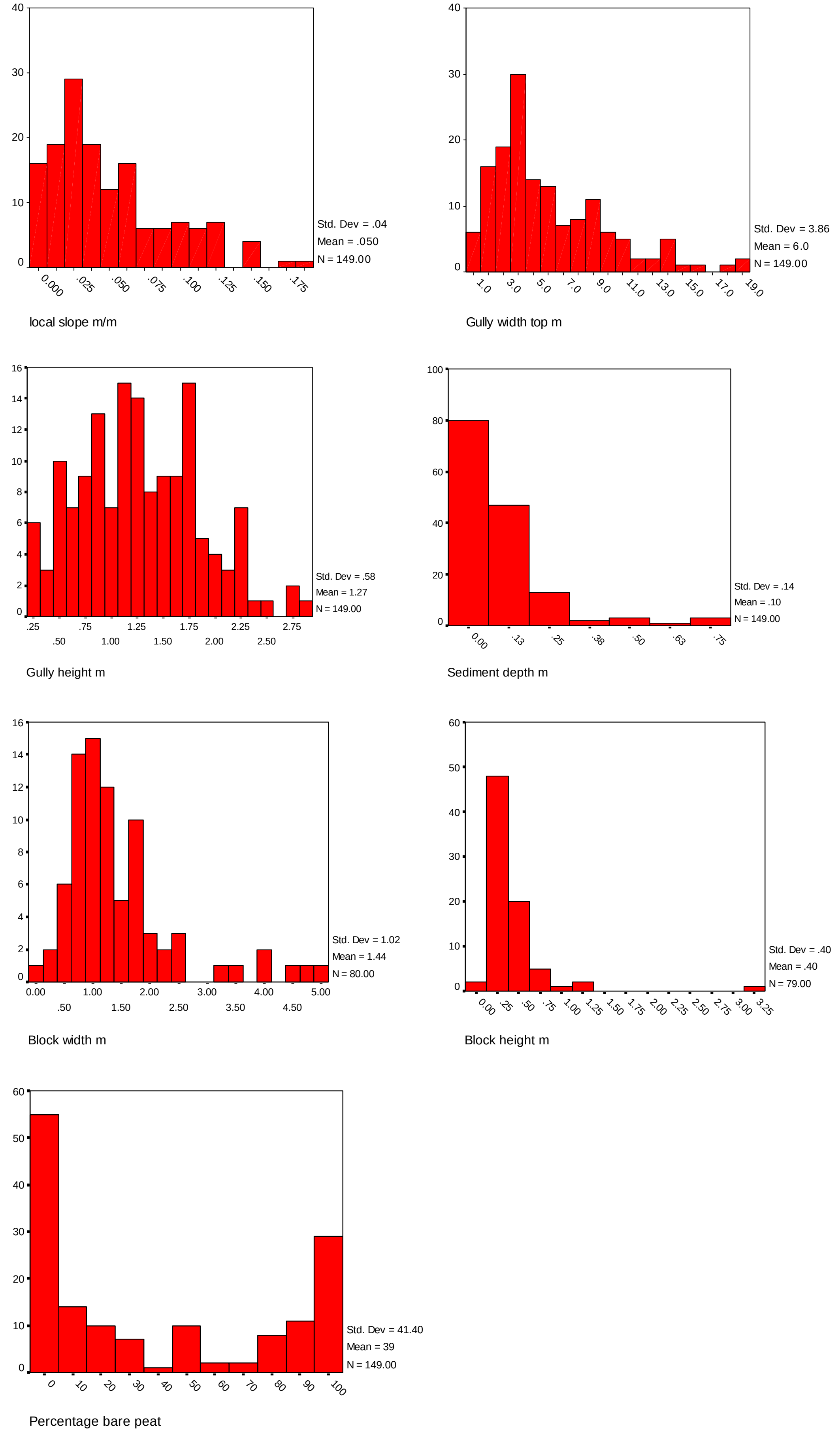


Figure 3.15 Frequency distributions of physical characteristics for the 149 gully sample sites

Cluster analysis was used to identify groups of sites with similar physical characteristics. The analysis was implemented using the Two Step cluster analysis procedure in SPSS. Six physical variables were used in the analysis; gully top width, gully floor width, gully depth, local slope, sediment depth and average gully wall slope. The cluster analysis effectively separated the sites into two types of gully, with significant between-type differences in five of the six variables (the exception being gully wall slope). Summary statistics for the two gully types are shown in Table 3.4, and boxplots of key physical variables for the gully types are shown in Figure 3.16.

Table 3.4 Summary statistics for the two types of gully identified by cluster analysis

	Gully Type A		Gully Type B	
Number of sites	82		67	
Block sites	54		26	
Non-block sites	28		41	
	Mean	Standard deviation	Mean	Standard deviation
Gully depth (m)	0.96	0.41	1.65	0.53
Gully top width (m)	3.60	1.55	8.93	3.81
Gully floor width (m)	1.38	1.01	3.70	3.38
Local slope (m m^{-1})	0.063	0.044	0.035	0.030
Sediment depth (cm)	0.14	0.17	0.05	0.07
	N		N	
Upper North Grain	5		22	
Nether North Grain	14		8	
Doctors Gate	22		6	
Shelf Moss	4		17	
Bleaklow Meadows	6		10	
Swains Greave	17		2	
Kinder Scout	14		2	

Type A gullies represent relatively narrow gullies, with steeper local slopes. These gullies tend to be relatively shallow and are associated with higher mean depths of re-deposited sediment. Type A gullies are well represented at Doctors Gate, Kinder Scout and Swains Greave. Type B gullies represent relatively wider systems, with relatively low relative slopes. These gullies tend to be relatively deep and are associated with relatively low mean depths of re-deposited sediment. Type B gullies are well represented at Upper North Grain, and Shelf Moss. It is notable that within the dataset natural gully block sites are more prevalent in Type A gullies than in Type B gullies (Table 3.4). This is consistent with the hypothesised process of natural gully blocking (see section 3.1.1), in particular through a relationship with narrow gullies. Oversteepening and undercutting of gully walls, with associated gully wall block failure, is more likely in narrow gullies particularly where local gully floor slopes are relatively high.

The classification of all gully sites into Type A and Type B systems does to some extent over-simplify the variability in gully form. In particular variation in the physical characteristics of the gullies is continuous, and there is therefore no 'sharp' boundary between gully types (see Figure 3.17). Nevertheless, the classification is robust and allows effective differentiation of sites based on key geomorphological settings (i.e. gully width, depth and slope; see Figure 3.17). As such it is a useful framework for considering variation in re-vegetation, and potential controls on re-vegetation.

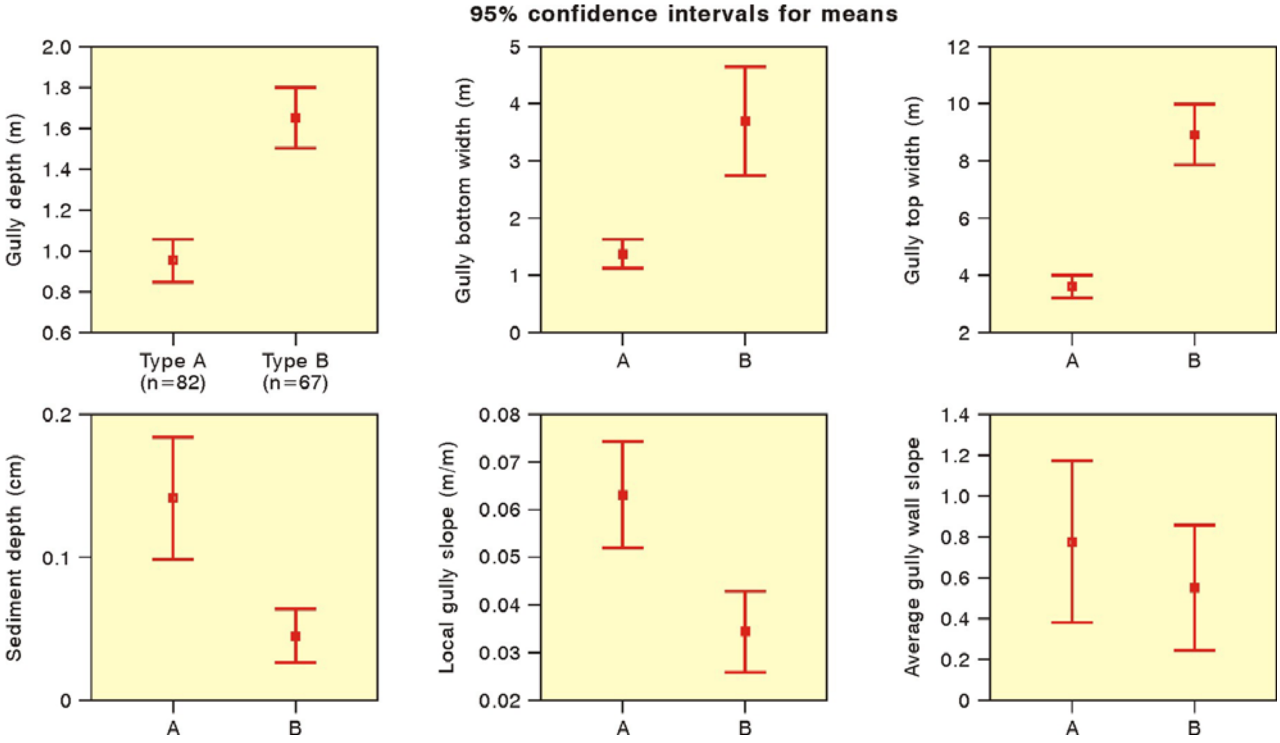


Figure 3.16 Boxplots of key physical variables for Type A and Type B gullies

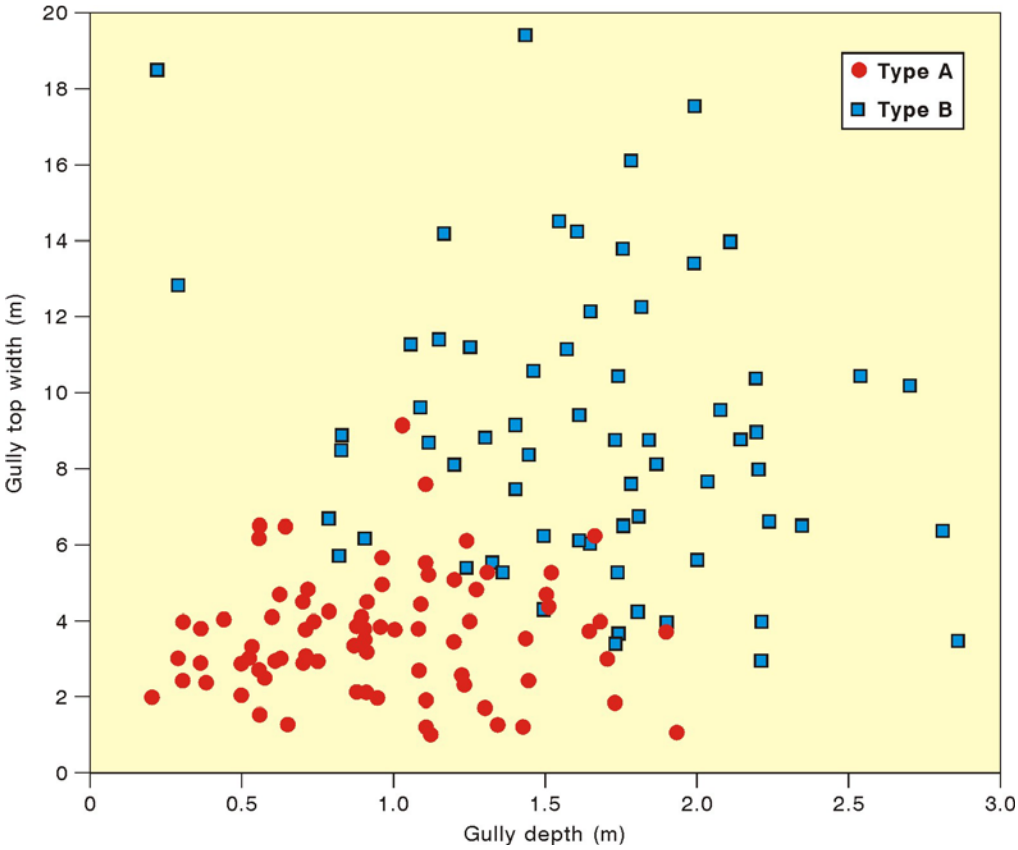


Figure 3.17 Scattergraph of gully width against depth, indicating Type A and Type B gullies

3.3.4 Gully-floor vegetation cover characteristics

Within the dataset the majority of the gully floors are vegetated (Table 3.5). The variable % floor bare (e.g. bare peat or mineral substrata - the inverse of % vegetated) has a strongly bimodal distribution (see Figure 3.15), but the majority of the sites have <30% bare cover (i.e. > 70% vegetation cover). This indicates that significant re-vegetation has taken place at most of the sample sites, an important general observation. Importantly, however, the dataset also contains a significant number of sites (40) with little or no vegetation cover (i.e. >90% bare). Of these 40 un-vegetated gully sites, 26 have bare peat gully floors and 13 bare mineral floors (where gully erosion has penetrated through the peat into the mineral substrate).

Figure 3.18 shows the relationship between species and cover type occurrence and maximum abundance in the gully samples. A group of species plot in the lower left hand corner of the plot, and occur in low abundances in relatively few samples. This group includes, for example, *Erica tetralix*, *Spagnum* spp., *Juncus effuses* and *Nardus* stricta. At the top right hand side of the plot *Eriophorum vaginatum and E. angustifolium* occur in large numbers of the samples, sometimes with complete cover. *Vaccinium myrtillus, Deschampsia flexuosa* and *Empetrum nigrum* are also common, occurring in many of the samples but rarely with complete cover.

Table 3.5 Summary statistics on gully floor cover types

	Peat	**Mineral**	**Remin**	**Evag**	**Eang**	**Vmyr**
Mean	26.91	10.57	1.48	17.32	20.37	6.72
Standard Error	3.03	2.36	0.67	2.03	2.80	1.12
Standard Deviation	36.97	28.76	8.19	24.77	34.20	13.63
Minimum	0	0	0	0	0	0
Maximum	100	100	80	90	100	80
Occurrences	75	23	8	70	52	42
	Enig	**Spha**	**Jeff**	**Jsqua**	**Nstri**	
Mean	4.40	0.81	1.11	0.13	0.81	
Standard Error	0.99	0.29	0.40	0.09	0.31	
Standard Deviation	12.05	3.59	4.86	1.15	3.72	
Minimum	0	0	0	0	0	
Maximum	65	25	25	10	30	
Occurrences	27	9	9	2	9	
	Dcaes	**Pcomm**	**Rcham**	**Etet**	**Aten**	
Mean	7.25	1.14	0.23	0.34	0.27	
Standard Error	1.35	0.39	0.18	0.24	0.21	
Standard Deviation	16.46	4.76	2.20	2.89	2.59	
Minimum	0	0	0	0	0	
Maximum	80	25	25	25	30	
Occurrences	40	10	2	2	2	

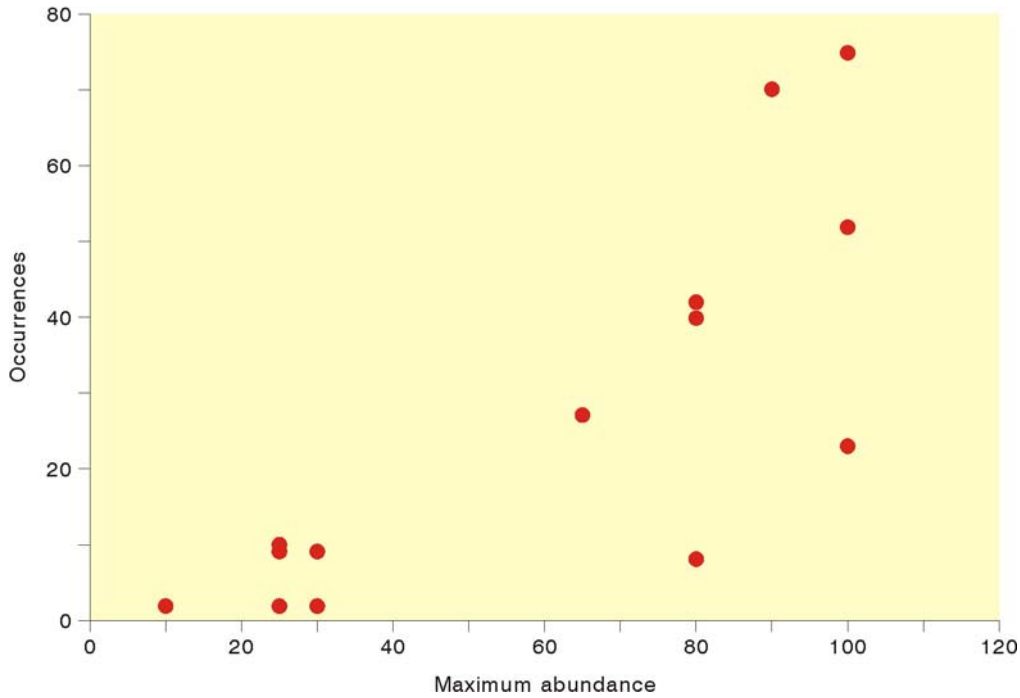


Figure 3.18 Scatterplot of species and cover type occurrence against maximum abundance on the gully floors

3.3.5 Relationships between gully type and re-vegetation assemblages

Having considered variation in the physical characteristics of the study sites, this section evaluates the extent to which the species assemblages of re-vegetated gullies are related to gully type and gully morphometry. It additionally includes an analysis of the relationship between re-vegetation and the composition of surrounding catchment vegetation.

CCA with forward selection and Monte-Carlo permutation tests was used to identify physical variables significantly related to the gully floor vegetation assemblages. This analysis was performed on a sub-set of the samples where ≥50% of the gully floor was vegetated (97 samples). Given the strongly bimodal distribution of the % bare floor variable (see Figure 3.1) a cutoff of 50% effectively separates gully floors which are pre-dominantly re-vegetated from those which are largely bare. An additional CCA was performed which further included catchment vegetation (expressed as species percentages) as potential explanatory variables for the gully floor assemblages. Catchment vegetation could be an important control on re-vegetation as it provides the main source for species spread via vegetative reproduction or through seed source.

The main CCA revealed that three variables have significant relationships with the species assemblages. The most important of these is local gully floor slope ($p = 0.002$). High slopes are associated with higher abundances of *Eriophorum vaginatum* and to a lesser extent *Empetrum nigrum*. Low slopes are associated with higher abundances of *E. angustifolium* and *D. flexuosa*. The second significant variable is gully top width ($p = 0.020$); *D. flexuosa* is associated with wider gullies, bare peat with narrow gullies. These two variables have independent, significant relationships with the species assemblages. The third significant variable is gully type (e.g. Type A or B) ($p = 0.004$). Type A gullies are more closely associated with *E. vaginatum* whereas *D. flexuosa* is associated with Type B gullies. However, the relationship with gully type was not independent of the relationships with local slope and gully width. This is unsurprising given that gully type is partially derived from these variables.

The additional CCA including catchment vegetation revealed significant relationships between gully floor vegetation and the catchment abundance of *E. angustifolium* ($p = 0.050$) and *E. vaginatum* ($p = 0.050$). High abundance of these species in the catchment are associated with higher abundances in the floors of re-vegetated gullies. However, these relationships are not independent of the relationships with physical characteristics and gully type outlined above. In particular there is co-variance between local gully slope and catchment vegetation in the dataset (i.e. gullies with high local slopes had a greater *Eriophourum* spp. cover). Local gully slope has a stronger relationship with variation in gully floor vegetation, and it is therefore not possible to clearly demonstrate an independent relationship with catchment vegetation.

These analyses clearly indicate that there is an important difference in the re-vegetation characteristics of the different gully types. In particular, there are clear relationships between the composition of gully floor re-vegetation and two key physical variables which reflect gully type; local gully slope and gully top width. The following sections consider the re-vegetation characteristics of Type A and Type B gullies in more detail.

3.3.5.1 Gully floor re-vegetation in Type A gullies

The variation in vegetation cover in Type A gullies was described using two techniques; TWINSPAN cluster analysis and DCA (see section 3.3.2.2).

TWINSPAN analysis revealed five groups of samples (Table 3.6), two representing different types of bare gully floors and three groups representing different re-vegetated assemblages. The DCA joint plot, with TWINSPAN groups indicated, is shown in Figure 3.19. The first DCA axis represents 21.9% of the variation in vegetation cover and represents a gradient from bare floored gullies (low scores) to revegetated gullies (high scores). The second DCA axis represents 16.7% of the variation, and effectively separates samples with high axis 1 scores (e.g. re-vegetated samples) into those associated with *E. angustifolium* and those associated with *Empetrum nigrum* and *Vaccinium myrtillus.*

Table 3.6 TWINSPAN vegetation cover groups for Type A gully samples

Group	n	Group characteristics
1	4	Bare floored gullies with mineral floor (% mineral >50%)
2	22	Bare floored gullies with peat floor (% peat >75%) *E. vaginatum* occasionally present
3	18	Gullies dominated by *E. angustifolium* (>50% cover) Other species absent
4	19	Gullies dominated by *E. vaginatum* (>50% cover) *D. flexuosa* occasionally present *V. myrtillus* occasionally present
5	19	Gullies with *V. mytillus* and *E. nigrum* *E. vaginatum* and *E. angustifolium* occasionally present

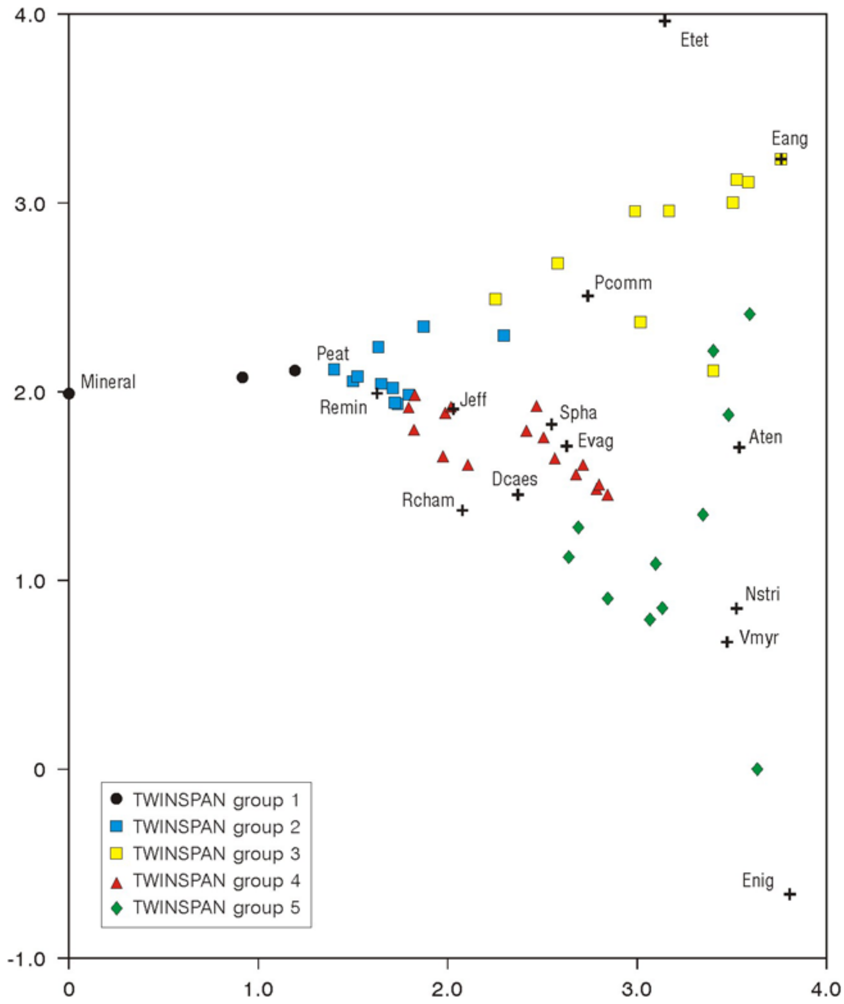


Figure 3.19 DCA joint plot of vegetation cover in Type A gullies

Cover types and species are labelled with abbreviations (see Table 3.2)

DCA largely reinforces the divisions indicated by the TWINSPAN analysis. Additionally two gradients are apparent in the joint plot (Figure 3.19). The first is from the left of the plot to the top right, and represents a gradient of bare floored gullies to those dominated by *E. angustifolium* (e.g. TWINSPAN group 3). The second gradient is from the left of the plot to the bottom right, representing a transition from bare floored gullies, to those dominated by *E. vaginatum* (TWINSPAN group 4), to those characterised by *V. myrtillus* and *E. nigrum* (TWINPAN group 5). Although a few samples are intermediate between the TWINSPAN groups 4 and 5, the two gradients are otherwise pronounced and appear relatively distinct.

CCA with Monte–Carlo permutation tests shows that, of the morphometric variables, only local slope has a significant relationship with the vegetation assemblages within these gullies (p = 0.005). Relatively low slopes in Type A gullies are associated with higher abundances of *E. angustifolium* and relatively high slope angles with *E. vaginatum*. The position of the samples along the gradients identified in Figure 3.19 could be interpreted as different stages in the re-vegetation process. This would suggest two distinct trajectories of re-vegetation within these Type A gullies, possibly controlled by gully slope and associated conditions. These trajectories correspond to the processes of re-vegetation to *E. angustifolium* described in section 3.2.3.1 and to *E. vaginatum* in section 3.2.3.2.

3.3.5.2 Gully floor revegetation in Type B gullies

The variation in vegetation cover in Type B gullies was described using two techniques; TWINSPAN cluster analysis and DCA (see section 3.3.2.2).

TWINSPAN analysis revealed five groups of samples (Table 3.7). Again, two groups represent different types of bare gully floors and three groups represent different re-vegetated assemblages. The DCA joint plot, with TWINSPAN groups indicated, is shown in Figure 3.20. The first DCA axis represents 19.7% of the variation in vegetation cover. It separates out the samples with bare mineral floors (TWINSPAN group 1) which have high axis 1 scores. Low axis 1 scores are associated with samples with high abundances of *E. angustifolium* and bare peat. DCA axis 2 represents 13.9% of the variation, and effectively separates the sites with low axis 1 scores into those dominarted by bare peat (TWINSPAN group 2) and those dominated by *E. angustifolium*.

Table 3.7 TWINSPAN vegetation cover groups for Type B gully samples

Group	n	Group characteristics
1	13	Bare floored gullies with mineral floor (% mineral >75%)
2	11	Bare floored gullies with peat floor (% peat >75%) *E. angustifolium* occasionally present
3	13	Gullies dominated by *E. angustifolium* (>75% cover) *E. vaginatum* occasionally present
4	8	Gullies charactrerised by *E. vaginatum* (>25% cover) *D. flexuosa* occasionally present *N. stricta* occasionally present Redeposited mineral sediments common
5	22	Relatively diverse samples *E. vaginatum* and *D. flexuosa* common (typically >25%) Dwarf shrub species often also present (*V. mytillus* and/or *Empetrum nigrum*)

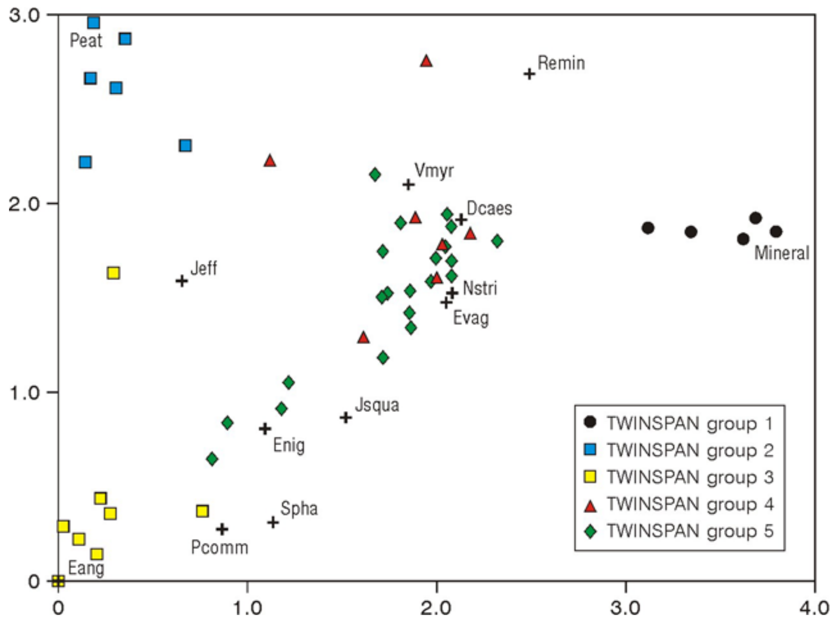


Figure 3.20 DCA joint plot of vegetation cover types in Type B gullies

Cover types and species are labelled with abbreviations (see Table 3.2)

The DCA and its relationship with the TWINSPAN groups are difficult to interpret. The first axis effectively separates mineral floored and peat floored gullies, but clear gradients between vegetation types are not immediately apparent. The more diverse and complex assemblages represented by TWINSPAN groups 4 and 5 plot in the centre of the DCA joint plot. An important feature of the data are the clear distinction between bare and re-vegetated samples – the gullies tend to be completely bare, or completely re-vegetated, and there are relatively few intermediate samples. This means that interpretations of potential gradients of re-vegetation is difficult. The only relatively identifiable between-group gradient is from the *E. angustifolium* samples (group 3) at the bottom left of the plot to the group 5 samples in the centre of the plot. If accepted, this suggests that gully floors dominated by *E. angustifolium* grade into more complex assemblages which include dwarf shrub species. However, the relative lack of transitional samples and the noisy nature of the data make such interpretations injudicious.

CCA with Monte-Carlo permutation tests reveal that three of the physical variables have independent significant relationships with the variation in vegetation cover; sediment depth ($p = 0.001$), the presence of a gully block ($p = 0.009$) and gully top width ($p = 0.004$). Sediment depth is positively related to the abundance of *E. angustifolium*. This demonstrates that *E. angustifolium* is typically growing in gullies with re-deposited peat deposits. The presence of a gully block is associated with higher abundances of *E. vaginatum*. Higher abundances of *D. flexuosa* are associated with non-block sites and wide gullies, possibly representing colonisation of wide mineral floored gullies (see section 3.2.3.3)

3.3.6 Relationships between natural gully blocks and re-vegetation

This section considers if there is a relationship between the recorded presence of a natural gully block and the type of re-vegetation occurring at the site. It therefore addresses the question of whether re-vegetation assemblages vary between blocked and non-blocked sites.

CCA on the dataset of re-vegetated sites (i.e. where vegetation cover ≥50%) showed a significant relationship between occurrence of a block and species assemblages. In particular, occurrence of *D. flexuosa* is associated with non-block sites (possibly reflecting its colonisation of wide mineral floored gullies). However, this relationship is not independent of the strong relationship between local gully slope and species assemblages identified in section 3.3.5. Higher slopes are associated with higher abundances of *Eriophorum vaginatum* and to a lesser extent *Empetrum nigrum*. Low slopes are associated with higher abundances of *E. angustifolium* and *D. flexuosa*. Blocks are more prevalent in relatively steep gullies (e.g. Type A gullies – see Table 3.4). Across all the re-vegetated sites it is therefore not possible to identify a clear effects of blocking on species assemblages. This is a surprise given the perceived importance of the gully blocking process to re-vegetation from the extensive study (see section 3.2.4). However, there are some relationships between blocks and re-vegetation assemblages. In particular within the Type B gullies, which have relatively low slope angles, there is a significant relationship between re-vegetation assemblages and block occurrence. In these systems *D. flexuosa* is associated with non-block sites and *E. vaginatum* more abundant where blocks are present. Again, this relationship may reflect the colonisation of wide mineral floored gullies by *D. flexuosa,* as gully blocks are absent from such systems. Equally *E. vaginatum* is associated with the narrower Type B gullies where blocking is more prevalent.

These results are discussed in section 3.5.2.

3.3.7 Natural gully block characteristics and the effectiveness of blocking

Another important consideration is the 'success' of natural gully blocks. This section therefore considers the relationships between the effectiveness of the natural gully blocks identified in the dataset and the physical and block variables measured in the field. The aim is to identify the characteristics of effective block sites.

In the context of re-vegetation, natural block effectiveness could be represented in two ways. First, an effective block is one with significant re-vegetation of the gully floor behind the block site. This can be defined by the proportion of vegetation cover. Second, an effective block is one behind which a specific target assemblage develops. In this case the most appropriate target assemblage to consider is cover by *E. angustifolium*. Although other more diverse assemblages could be selected (e.g. dwarf shrub assemblages), *E. angustifolium* is a key pioneer species identified in section 3.2.3. Importantly, in the context of assessing block effectiveness in the context of strategy for artificial blocking, *E. angustifolium* is a potential target assemblages for the early stages of re-vegetation (1-5 years)

The 79 sites with natural gully blocks were analysed. If significant re-vegetation is defined as ≥50% vegetation cover, 51 of the block sites are effective and 28 non-effective. One way ANOVA of the physical and block variables against significant re-vegetation (≥50% vegetation cover), however, reveals no significant relationships. Therefore the physical and block variables do not differentiate between re-vegetated and non-revegetated sites as expressed in this way.

Of the 79 block sites 22 sites have *E. angustifolium* cover ≥50%, and can therefore be considered to be re-vegetated by this species. One way ANOVA against the physical and block variables reveals that only local gully slope is significantly different between site with and without *E. angustifolium* re-vegetation (p = 0.04). The E. angustifolium sites are associated with low angled gully floors. It is notable that of the 22 block sites with significant *E. angustifolium* cover, 19 contain re-deposited organic sediments and in moist cases this covering of re-deposited material is relatively this (≤ 10 cm). *E. angustifolium* revegetation behind natural gully blocks therefore occurs at sites with low angled gully floors which have accumulated a thin veneer of re-deposited peat sediments.

These results are discussed in section 3.5.2.

3.4. Analysis of Artificial Gully Blocking on Kinder Scout and Bleaklow

3.4.1 Introduction

Extensive gully blocking has been carried out by the National Trust on the High Peak Estate. This work was undertaken during late 2003. Consequently it is too early to fully evaluate the success of these works. However, as part of this project survey of the majority of the existing blocks was undertaken. This will provide baseline data for further monitoring and also provides the opportunity to analyse the short term development of block sites in a variety of landscape contexts.

3.4.2 Artificial Block Survey Methods

Field survey of 389 individual gully blocks along 16 gully lines (9 on Kinder Scout and 7 at Within Clough) was completed during the period May to July 2004 (Figure 3.14).

The complete data set incorporates gullies blocked by four main techniques; wooden fences, plastic piling, stone walls, and staked hessian sacks. Four main types of data were collected; gully morphology, block size data, sedimentation data, and vegetation data as detailed in Table 3.8.

3.4.3 Patterns of Key parameters

3.4.3.1 Gully vegetation

One immediately obvious pattern emerges from initial inspection of the data which is that almost all of the gullies at all of the sites have no vegetation cover established on the gully floors or on the gully walls. This is unsurprising given the relatively recent blocking of the sites. Consequently the vegetation data are not analysed further here. The local moor surface vegetation is recorded in the digital files accompanying this report and will be a useful resource for further analysis if subsequent post-restoration monitoring demonstrates re-vegetation of the gullies.

3.4.3.2 Gully and block parameters

Distributions of gully, block and sedimentation parameters are plotted in Figure 3.21. Most of the parameters are approximately normally distributed, an exception is sediment depth which is closer to a log normal distribution with a majority of sites having low sedimentation and a tail of sites which have trapped more sediment. Figure 3.21 also plots distributions of sediment depth for Kinderscout and Within Clough separately. This demonstrates that Kinder is closer to a negatively skewed normal distribution. It is also important to note here that the length of time available for sediment accumulation varies between blocks. On Kinder the wooden and stone blocks were installed in April-June 2003 and the black plastic blocks in June/July 2003. The Within Clough blocks were installed in November/December 2003. It seems likely that the longer period of block installation has allowed sediment depths to approach a normally distributed equilibrium whereas the Within blocks are still filling up with large numbers of low sedimentation sites and fewer sites with high sediment depths which are particularly favourable for sedimentation. Block height, Block spacing and Gully width demonstrate bimodal distributions which on closer analysis are mixed distributions comprised of two normally distributed sets of data from the two areas of gully blocking, Kinder and Within Clough. The difference in characteristics between the sites is an important factor to consider in further analysis of the data.

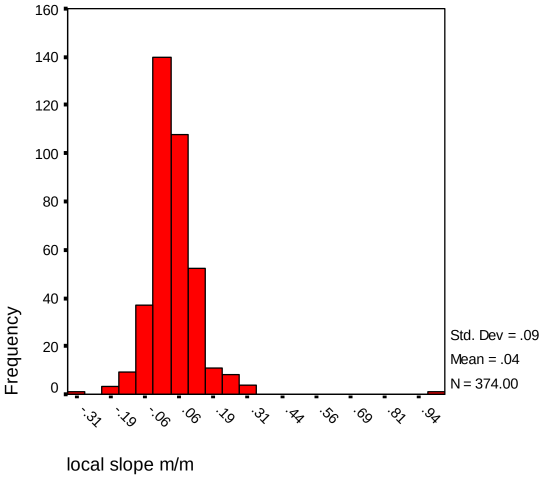
Table 3.9 presents descriptive statistics for the main block and site characteristics for each study area. Analysis of Variance and the Mann Whitney U test confirm that the differences between the mean values are highly significant for all the variables presented at at least the 99% level. Essentially the data are divided into two topographic groups. The Kinderscout blocked gullies are on average twice as wide, deeper, and nearly three times as steep as those on Within Clough. The blocks on Kinder scout are slightly lower slightly wider, more closely spaced and have on average retained three times as much sediment as those on Within Clough.

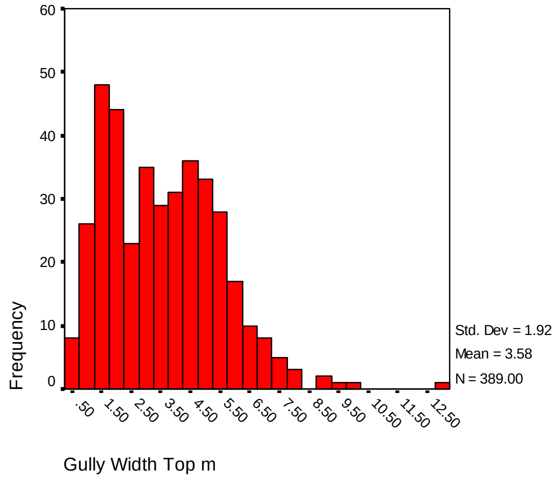
Table 3.8 Summary of data types collected at artificially blocked gully sites

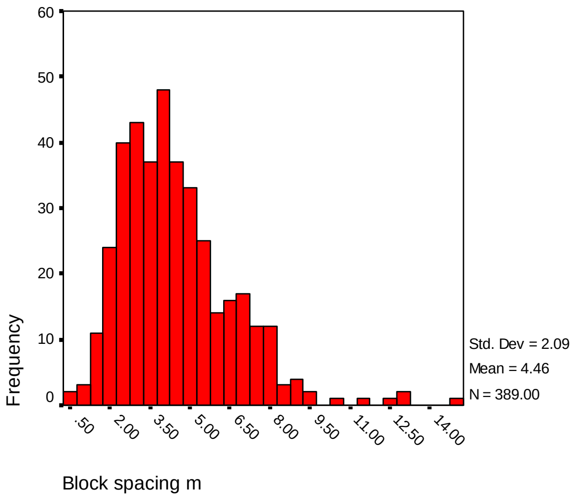
Gully morphology parameters	
Parameter	Survey technique
Gully width (top)	Taped measurement between breaks of slope at upper limit of gully walls
Gully width (floor)	Taped measurement between breaks of slope at foot of gully walls
Gully slope	Levelled height difference between the base of successive blocks. Due to the short period since blocking this is a measure of the original gully floor surface
Gully depth	Measured at gully mid point, half way between successive blocks, perpendicular to a tape stretched between gully sides
Block Parameters	
Block spacing	Taped in the field
Block height	From gully floor to top of block on the downstream side
Block width (top)	Gully wall to gully wall along the top of the block
Block width (base)	Gully wall to gully wall at gully floor level
Sedimentation parameters	
Sediment depth	Difference between upstream and downstream heights of the block, verified by probing. There is some scope for distortion of this value by peat packed behind the blocks on installation, but measurements were taken in almost all cases to the surface of flat redeposited peat extending some distance upstream. The potential error is unquantified but believed to be small.
Sediment Volume	Derived as the half the product of sediment depth, block width (base) and block spacing. This assumes deposition of a sediment wedge with planar surface and triangular cross section
Vegetation parameters	
Gully floor vegetation	Species list and estimates of percentage cover in 5% increments
Gully wall vegetation	Species list and estimates of percentage cover in 5% increments
Local moor surface vegetation	Species list and estimates of percentage cover in 5% increments

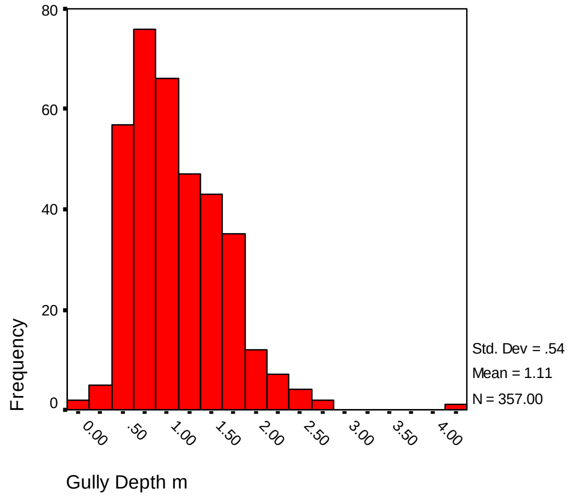
Table 3.9 Descriptive statistics for Within Clough and Kinder Scout Block Sites

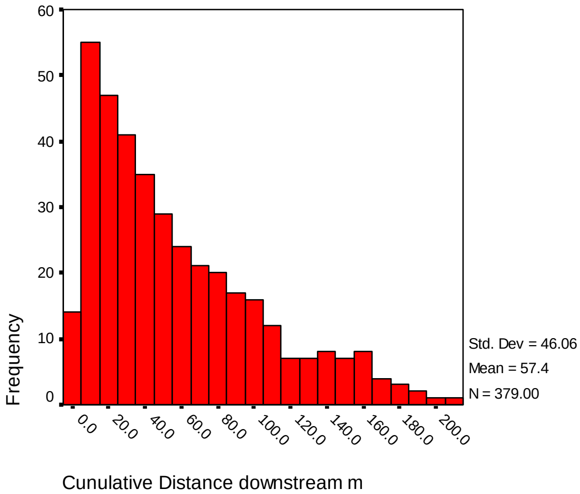
	Kinder Scout			Within Clough		
Parameter	**Mean**	**95% confidence interval**	**2 standard deviation range**	**Mean**	**95% confidence interval**	2 standard deviation range
Gully Width (top) m	4.63	0.23	1.27 – 7.99	2.35	0.20	**0 – 5.11**
Gully Depth m	1.27	0.09	0.06 – 2.48	0.95	0.06	**0.16 – 1.74**
Gully Slope	0.059	0.015	-0.16 – 0.27	0.02	0.01	**-0.12 - .16**
Block Spacing m	3.94	0.22	0.68 - 7.2	5.06	0.35	**0.26 – 9.86**
Block Width m	2.15	0.11	0.57 – 3.73	1.87	0.19	**0 – 4.41**
Block Height m	0.44	0.21	0.13 - 0.73	0.49	0.03	**0.11 - 0.77**
Sediment Depth m	0.19	0.019	0 - 0.464	0.03	0.02	**0 – 0.17**
Sediment Volume m^3	**0.56**	**0.08**	**0 – 1.76**	**0.07**	**0.1**	**0 – 1.41**

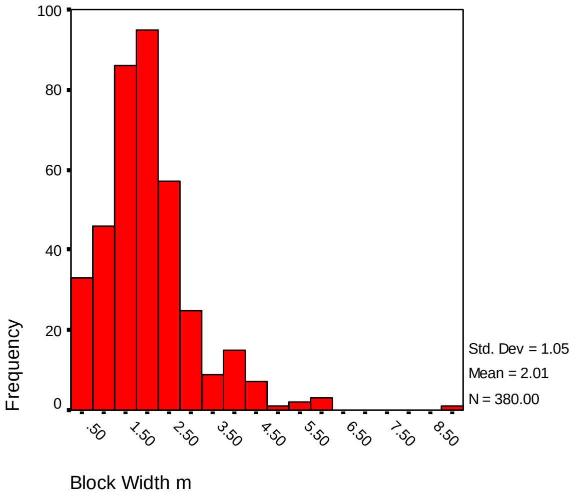

Frequency
Std. Dev = .09
Mean = .04
N = 374.00
local slope m/m


Frequency
Std. Dev = 1.92
Mean = 3.58
N = 389.00
Gully Width Top m


Frequency
Std. Dev = 2.09
Mean = 4.46
N = 389.00
Block spacing m


Frequency
Std. Dev = .54
Mean = 1.11
N = 357.00
Gully Depth m


Frequency
Std. Dev = 46.06
Mean = 57.4
N = 379.00
Cunulative Distance downstream m


Frequency
Std. Dev = 1.05
Mean = 2.01
N = 380.00
Block Width m

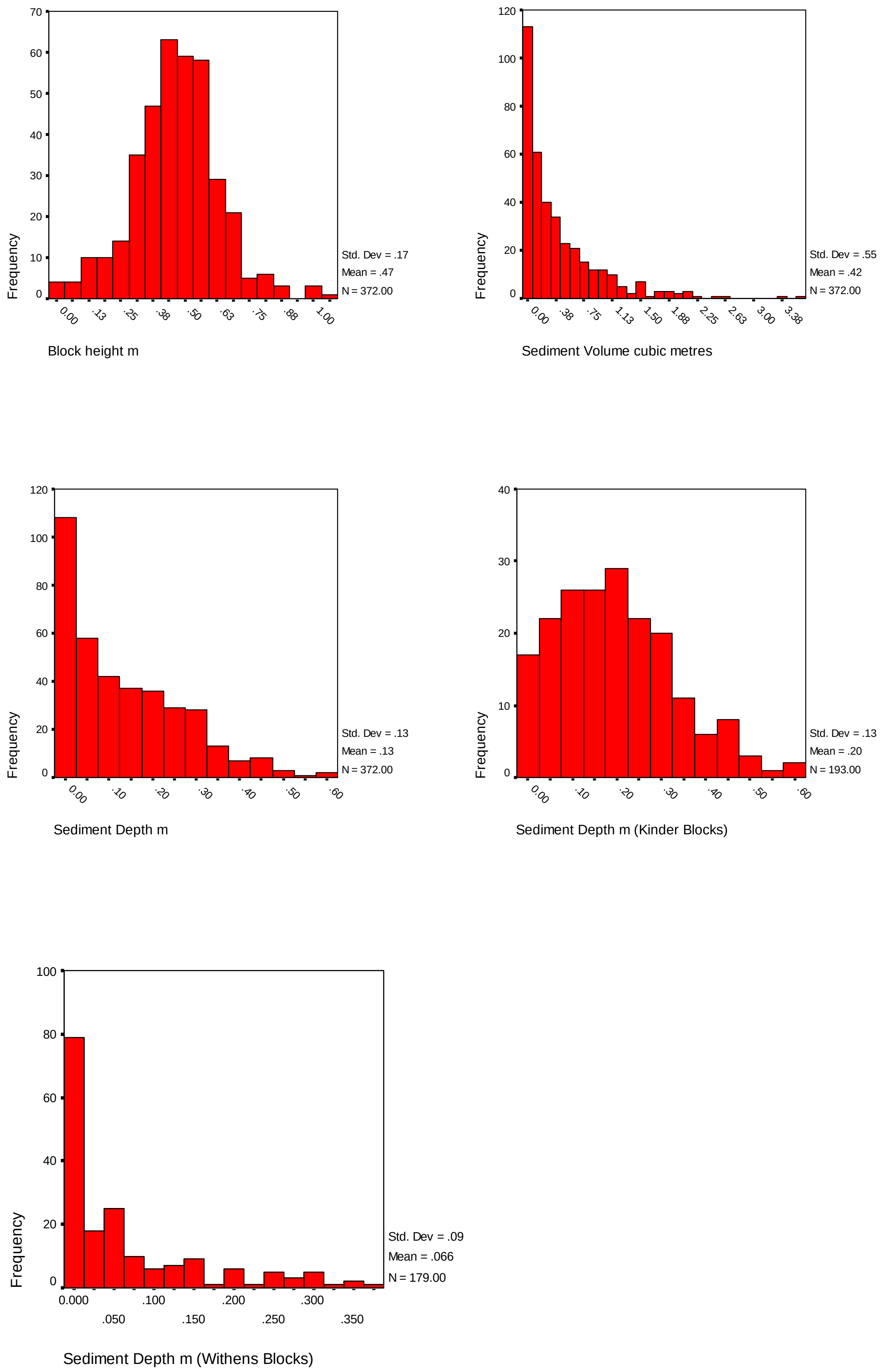


Figure 3.21 Distributions of morphological characteristics of blocked gullies.

3.4.4 Approaches to data analysis

The major difficulty with the artificially blocked dataset is that much of the variation is not controlled. There are differences in time of blocking, block type, and catchment and gully morphologies and considerable covariation between these. In the following analysis wherever possible we have attempted control through selection of data subsets but the following analysis is a best attempt to derive useful management information from an extremely noisy dataset rather than making any claims to be a definitive analysis of controls on gully block success.

The analysis of the artificially blocked sites adopts three strategies.

- A range of theoretically important controls on the functioning of block assemblages within gully systems are assessed against the empirical evidence.
- The data are treated empirically in an attempt to identify correlations between gully and block characteristics and sedimentation.
- The data are aggregated to a gully level to identify patterns of gully blocking efficiency at the catchment scale.

In order to assess the empirical evidence for the success of various gully blocking strategies it is necessary to define success in this context. A successfully blocked gully in the medium term might be defined as one where complete re-vegetation of the gully and consequent reduction in erosion has occurred. In the assessment of the existing gully blocks this is an unsuitable criterion since the short elapsed time since the completion of blocking is insufficient for extensive re-vegetation. Instead this study has assumed that in blocked gullies the predominant re-vegetation type will be establishment in patches of re-deposited peat. The accumulation of peat is a prerequisite to the success of this strategy, therefore a suitable short term indicator of gully blocking success is the accumulation of re-deposited sediment behind the block. In the following analysis the measured sediment depth behind the block is taken as an indication of successful blocking.

3.4.5 Evidence for the nature of controls on sediment accumulation behind artificial blocks

3.4.5.1 Local vs catchment sediment sources.

If gully blocks trap sediment with 100% efficiency then the controls on sediment accumulation within a given block will be entirely local. That is sediment will be derived only from the gully walls between the block and the next upstream block. In contrast if the gully blocks are relatively inefficient sediment traps then sediment is derived both locally and by overpassing of upstream blocks from the entire upstream catchment. In this case the sediment flux to downstream gullies will increase in proportion with the upstream catchment area. If the latter scenario holds then there should be an observable increase in sediment accumulation with increasing distance downstream and consequent increase in upstream catchment area. In order to examine this hypothesis figure 3.22 plots sediment depth against distance downstream from the upper most measured block. There is no strongly consistent downstream trend in sediment depth but there is a marked reduction in variance with downstream blocks displaying consistently low sediment accumulations in contrast to highly variable upstream patterns.

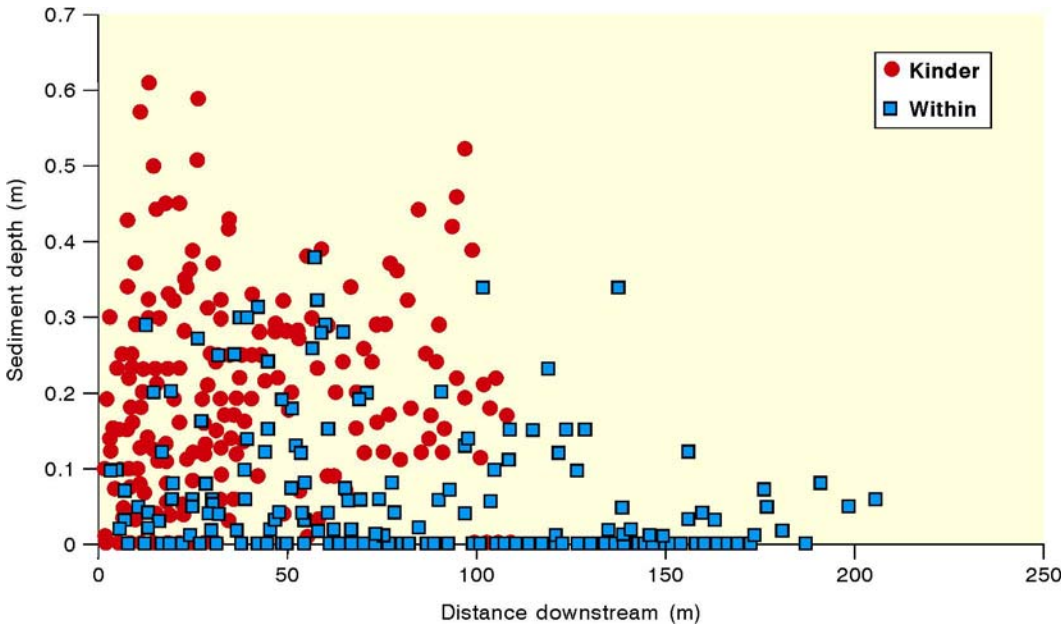


Figure 3.22 Change in sediment accumulation behind gully blocks with downstream distance.

The lack of an increase in sediment accumulation downstream and the noisy form of the data tend to support the hypothesis that the blocks are relatively efficient sediment traps and that controls on sediment accumulation are local. However the apparent reduction in variance downstream suggests an alternative interpretation, namely that some mechanism is limiting maximum sediment accumulation at downstream block sites. A probable mechanism is scour of these downstream locations at high flow since they have larger upstream catchment areas and therefore carry higher discharges. The available data therefore suggest that there may be a catchment area limitation on the efficiency of gully blocking.

Several caveats are required here, Figure 3.22 illustrates the difference between Kinder and Within data points. It is clear that downstream distances of greater than 100 metres are represented only by gully blocks from Within Clough. These sites tend to have lower sediment accumulations and have been blocked for a shorter period of time.

Further the set of points with lowest sediment depth and highest distance on the right hand side of the plot all come from one particular Within gully (WC5). The lower reaches of this gully are blocked with the Hessian Sack technique which field observation suggests have been particularly inefficient.

Further support for the interpretations above was sought through breaking the dataset down by individual gully (Figure 3.23) At this level the noise in the data becomes more apparent and a rather different picture emerges. Linear regression lines were fitted through the datasets for each individual gully with the distance downstream as the independent variable. Of the 17 gullies only 6 produced a significant regression line (95% confidence). Five of these lines had a significant positive gradient and one a negative gradient. Particularly in the Kinder gullies there is a tendency at the gully level for higher sediment accumulation downstream. It should be noted however that with one exception these were relatively short gullies with low numbers of blocks.

In summary the data on the relation between downstream distance (catchment area) and sediment accumulation are noisy and equivocal. Firm conclusions are difficult to reach beyond the observation that the empirical data suggest that at downstream distances of 200 metres sediment accumulation is still probable, and since the data on natural re-vegetation suggest that only relatively thin deposits of peat are required to promote *Eriophorum angustifolium* recolonisation. It might therefore be expected that in time there could be successful re-vegetation of the whole range of the existing gully blocks.

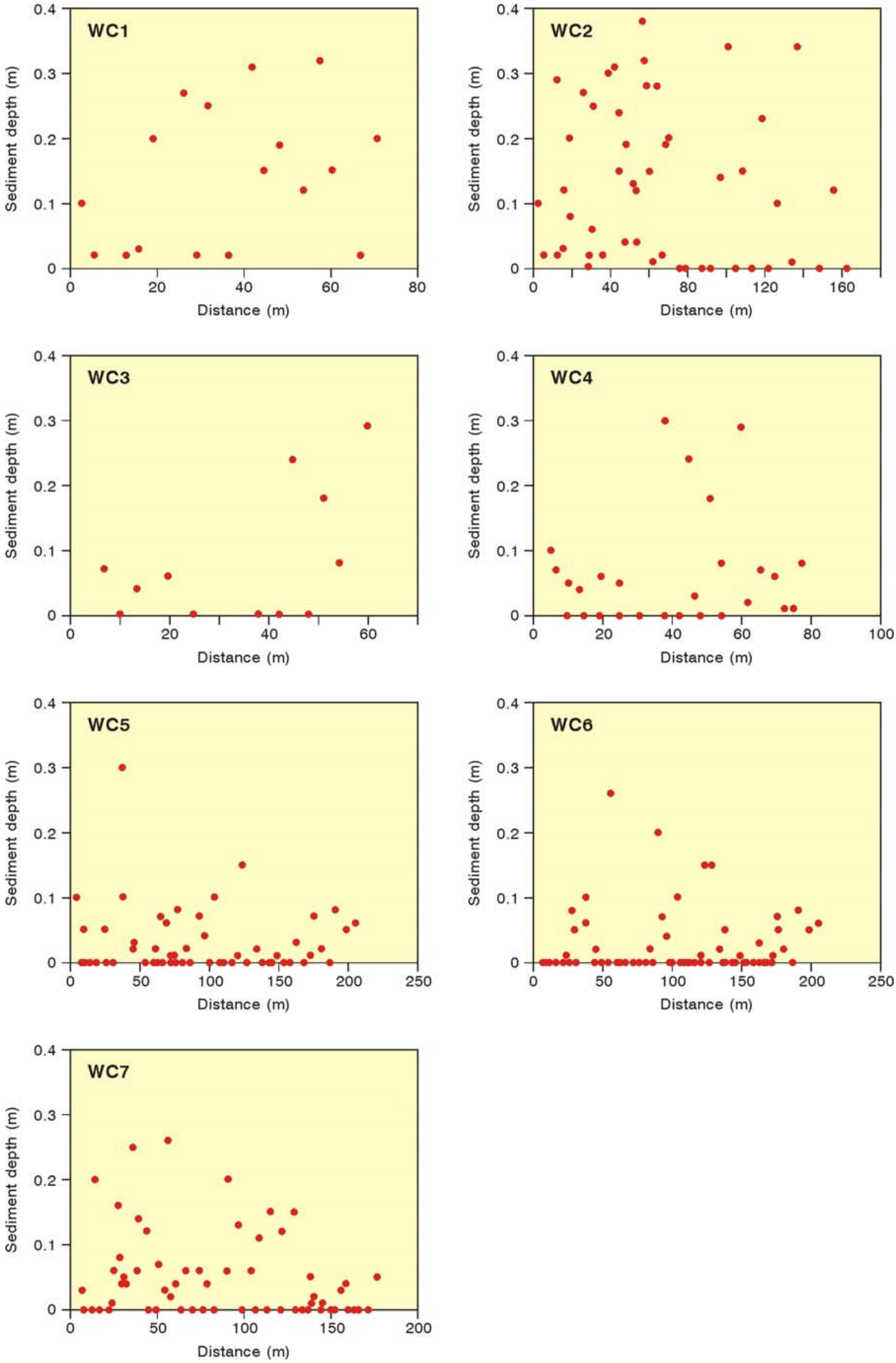


Figure 3.23a Distance downstream plotted against sediment depth Within Clough Gullies

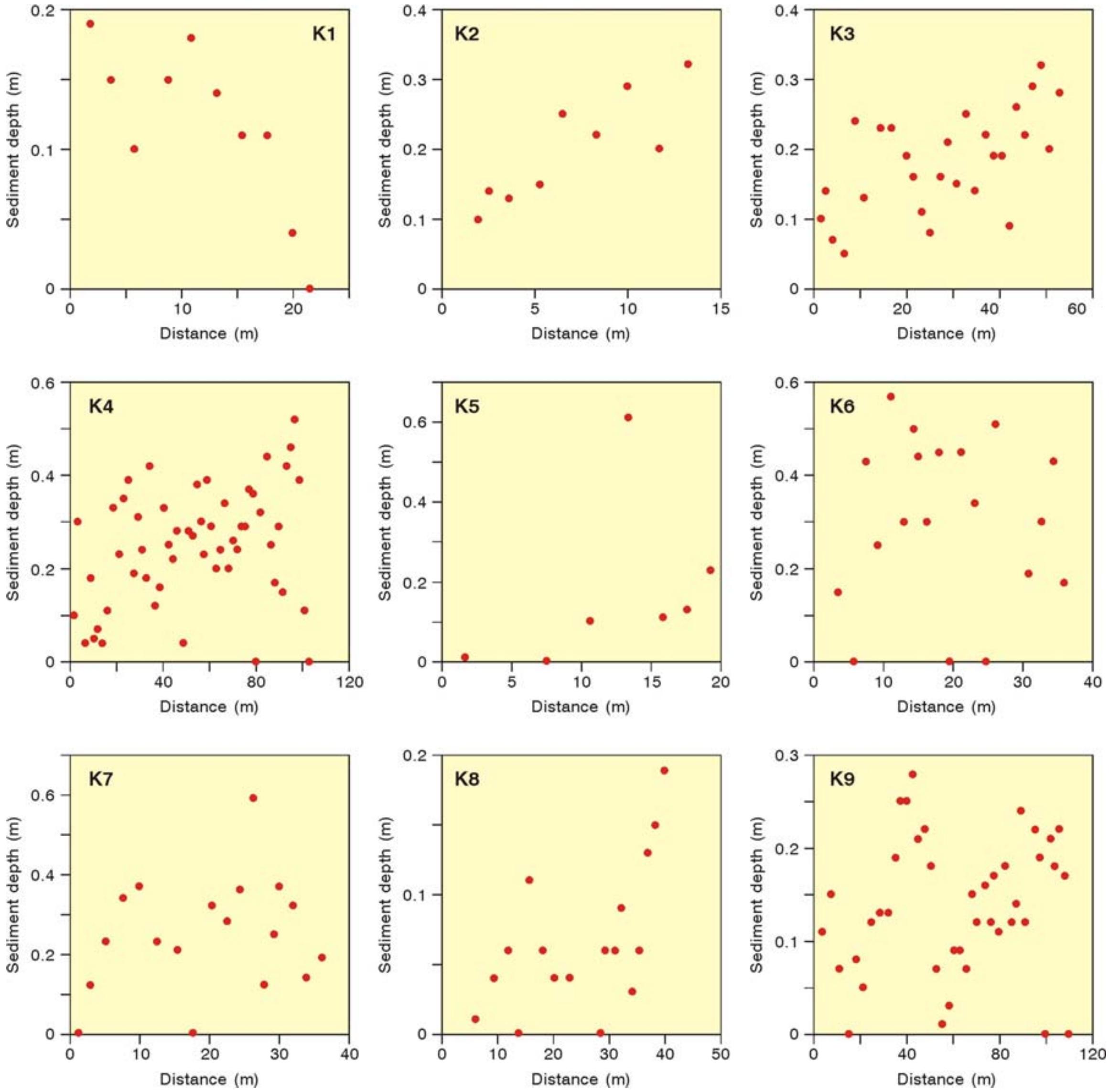


Figure 3.23a Distance downstream plotted against sediment depth Kinder Scout Gullies

3.4.6 Controls on gully block scour

Of the total of 389 gully blocks analysed 297 (76%) show positive sediment accumulation and 92 exhibit scour or no accumulation of sediment. Analysis of variance of the complete dataset for the two groups shows significant differences at the 99% level in mean values of several of the morphological variables, descriptive statistics for these variables are tabulated in table 3.10

The scour sites are narrower, shallower, further downstream and have more widely spaced blocks, these differences are significant at the 99% level, but do not suggest any clear causation for scour.

In fact 62% of the scour sites occur in just three gullys on Within Clough with extensive use of the pegged Hessian sack technique. The Within gullies are typically narrower and shallower, and the Hessian sack blocks are largely used in the lower half of the gullies. The results of the Analysis of Variance are therefore strongly affected by covariance between the Hessian sack blocks and particular morphological contexts.

If the analysis is repeated for the set of plastic blocks (135 blocks spanning Within Clough and Kinder Scout). Only Block Spacing and Block Height remain significantly different between the scoured and sedimented groups (at 99% and 95% significance levels respectively)

Table 3.10 characteristics of scoured and sedimented sites.

		N	Mean	Std. Error	95% Confidence Interval for Mean	
					Lower Bound	Upper Bound
Gully Width Top	Scour	92	3.046	.1851	2.678	3.413
	Sedimentation	297	3.745	.1126	3.523	3.967
	Total	389	3.580	.0975	3.388	3.771
Gully Depth	Scour	81	.9628	.05142	.8605	1.0652
	Sedimentation	276	1.1553	.03307	1.0902	1.2204
	Total	357	1.1116	.02839	1.0558	1.1674
Block Spacing	Scour	92	5.2239	.27951	4.6687	5.7791
	Sedimentation	297	4.2242	.10537	4.0169	4.4316
	Total	389	4.4607	.10614	4.2520	4.6693
Distance downstream	Scour	83	80.2587	5.77414	68.7721	91.7453
	Sedimentation	296	51.0217	2.43925	46.2212	55.8223

Table 3.11 Parameters shown by Analysis of Variance to be significantly different between scoured and sedimented sites with plastic blocks

		N	Mean	Std. Error	95% Confidence Interval for Mean	
					Lower Bound	Upper Bound
Block Spacing	Scour	26	5.61	.61	4.36	6.86
	Sedimentation	109	4.00	.18	3.63	4.37
	Total	135	4.31	.20	3.92	4.70
Block Height	Scour	26	.36	.04	.28	.45
	Sedimentation	109	.44	.013	.41	.46
	Total	135	.42	.013	.39	.45

Table 3.12 Parameters shown by Analysis of Variance to be significantly different between scoured and sedimented sites with plastic blocks on Kinder only.

		N	Mean	Std. Error	95% Confidence Interval for Mean	
					Lower Bound	Upper Bound
Block Spacing	Scour	26	3.99	1.4	1.1	6.8
	Sedimentation	109	3.46	.21	3.21	3.88
	Total	135	3.51	.22	3.07	3.95

Removing the Within Clough blocks in an attempt to control for the period of sediment accumulation leaves a rather small dataset of plastic blocks on Kinder. Repeating the Analysis of Variance shows only block spacing as a significant control.

The tentative conclusion drawn from this analysis is that perhaps unsurprisingly the failed blocks are associated with block characteristics rather than gully morphology. The scoured blocks are more widely spaced and possibly lower than the blocks with measurable sedimentation (Table3.11 and 3.12).

3.4.7 Effect of gully blocking technique on sediment accumulation

Four types of artificial block were in use in the study area. These were Wooden fencing, Plastic piling, Stone walls and Pegged Hessian sacks. In order to assess the effect of block type on success mean values of sediment accumulation and site characteristics were compared between groups. Table 3.13 For comparison Tables 3.14 and 3.15 present the same data for the Kinder and Within Clough sites separately. Analysis of variance and Mann Whitney U tests confirm that the differences in mean values tabulated below are significant at the 99% level. Several patterns emerge:

For the total dataset five parameters show significant differences between block types as determined by two way analysis of variance.

Wood and stone show higher local slopes, gully depths and sediment accumulations than either plastic or Hessian. However, if the Kinder dataset is taken alone then there is no significant effect of slope or gully depth. For the purposes of this analysis the two month difference in data of installation of wood/stone blocks and plastic blocks on Kinder is disregarded. This is regarded as reasonable as it represents only about 15% of the elapsed time and the extra months are summer months typically characterised by low sediment accumulation.

- Hessian blocks are the tallest and most widely spaced
- Hessian blocks have been installed mostly at the downstream end of long gullies whereas stone and wooden gullies have much lower average downstream distance.
- Maximum sediment accumulation occurs behind wood and stone blocks. Hessian blocks have much the lowest sediment accumulation. Plastic blocks trap approximately half the sediment of wood and stone. This pattern is true of the Kinder dataset as well as the total dataset suggesting a real difference in trap efficiency between the block types.

- Wood and stone blocks have been installed in wider gullies (gully top measurement), but the actual blocks on average narrower, indicating that they have been installed in gullies where gully walls have lower slope

3.4.8 Correlation analysis of measured parameters

Table 3.16 presents the results of correlation analysis of the entire site and block characteristic dataset. Correlations between the gully morphology parameters display predictable patterns as gullys become wider, deeper and less steep downslope. Of particular interest are correlations with the chosen measure of blocking success, i.e. depth of sediment accumulation. For the total dataset there are clear correlations between sediment depth and site and block parameters. Depth of sediment accumulation is positively correlated with gully width, depth, slope and block height, and negatively correlated with block width, spacing and distance downstream. Looking at the Kinder dataset alone (tables 3.17 and 3.18) to remove the effect of variable sedimentation time slope, gully depth and block height are positively correlated with sedimentation. Larger sediment accumulation in larger gullies is consistent with a sediment supply control on sediment accumulation rates and the positive association with block height suggests an association between block size and trapping efficiency. A positive association between sediment accumulation and gully slope is surprising and may be indicative of increased rates of downcutting and hence sediment supply on steeper slopes. The weak negative association with block width is presumably a function of area of deposition increasing faster than sediment supply as gully width increases

Table 3.13 Mean values of sediment depth and gully parameters which differ significantly between block types.

		n	mean	Standard Deviation	Standard Error
local slope	Wood	129	0.065	0.126	0.011
	Stone	17	0.044	0.076	0.018
	Plastic	206	0.028	0.063	0.004
	Hessian	22	0.013	0.091	0.019
	Total	374	0.041	0.093	0.005
Gully Width Top	Wood	134	4.749	1.419	0.123
	Stone	18	6.803	1.544	0.364
	Plastic	215	2.689	1.575	0.107
	Hessian	22	2.520	1.225	0.261
	Total	389	3.580	1.924	0.098
Gully Depth	Wood	125	1.302	0.597	0.053
	Stone	18	1.443	0.797	0.188
	Plastic	192	0.960	0.415	0.030
	Hessian	22	1.083	0.413	0.088
	Total	357	1.112	0.536	0.028
Block Spacing	Wood	134	3.973	1.583	0.137
	Stone	18	4.943	1.272	0.300
	Plastic	215	4.558	2.265	0.154
	Hessian	22	6.085	2.638	0.562
	Total	389	4.461	2.093	0.106
Distance downstream	Wood	124	34.489	27.727	2.490
	Stone	18	19.641	11.174	2.634
	Plastic	215	65.843	45.712	3.118
	Hessian	22	135.340	29.520	6.294
	Total	379	57.425	46.058	2.366
Block height	Wood	117	0.445	0.171	0.016
	Stone	18	0.433	0.121	0.029
	Plastic	215	0.464	0.161	0.011
	Hessian	22	0.608	0.192	0.041
	Total	372	0.465	0.168	0.009
Sediment Depth	Wood	134	0.212	0.142	0.012
	Stone	18	0.247	0.144	0.034
	Plastic	215	0.084	0.092	0.006
	Hessian	22	0.025	0.052	0.011
	Total	389			

Table 3.14 descriptive statistics for site and block parameters which are significantly (99%) different between block types on Kinder Scout

		N	Mean	Std. Deviation	Std. Error
Gully Width Top	Wood	134	4.749	1.4192	.1226
	Stone	18	6.803	1.5442	.3640
	Plastic	58	3.687	1.5823	.2078
	Total	210	4.632	1.6796	.1159
Block Dist.	Wood	134	3.9731	1.58265	.13672
	Stone	18	4.9433	1.27227	.29988
	Plastic	58	3.5752	1.73125	.22732
	Total	210	3.9463	1.63320	.11270
cumul dist downstream	Wood	124	34.4887	27.72684	2.48994
	Stone	18	19.6411	11.17449	2.63385
	Plastic	58	50.5293	31.46322	4.13132
	Total	200	37.8042	29.21087	2.06552
Block Width	Wood	125	1.9683	.63496	.05679
	Stone	18	2.0039	.56068	.13215
	Plastic	58	2.5724	.97418	.12792
	Total	201	2.1458	.78832	.05560
Sediment Depth	Wood	134	.2121	.14170	.01224
	Stone	18	.2467	.14390	.03392
	Plastic	58	.1160	.07507	.00986
	Total	210	.1885	.13455	.00929

Table 3.15 descriptive statistics for site and block parameters which are significantly (95%) different between block types on Within Clough

		N	Mean	Std. Deviation	Std. Error
Block spacing	Plastic	157	4.9211	2.33410	.18628
	Hessian	22	6.0845	2.63792	.56241
	Total	179	5.0641	2.39633	.17911
cumul dist downstream	Plastic	157	71.5006	48.84050	3.89790
	Hessian	22	135.3395	29.52002	6.29369
	Total	179	79.3467	51.33396	3.83688
Block height	Plastic	157	.4745	.18078	.01443
	Hessian	22	.6077	.19178	.04089
	Total	179	.4908	.18683	.01396
Sediment Depth	Plastic	157	.0721	.09444	.00754
	Hessian	22	.0250	.05198	.01108
	Total	179	.0663	.09152	.00684

Table 3.16 Correlation matrix of site and block characteristics for the complete dataset of artificial gully blocks

Total dataset

	Slope	**Gully Width Top**	**Gully Depth**	**Block Spacing**	**Distance downstream**	**Block Width**	**Block Ht Top**	**Block height bottom**	**Sediment Depth**
Slope	1	.070	.018	-.237(**)	-.123(*)	-.078	-.179(**)	-.021	.216(**)
Gully Width Top	.070	1	.332(**)	-.019	-.185(**)	.425(**)	-.332(**)	-.091	.313(**)
Gully Depth	.018	.332(**)	1	-.062	.133(*)	.055	-.280(**)	-.020	.326(**)
Block spacing	-.237(**)	-.019	-.062	1	.083	.121(*)	.201(**)	.096	-.122(*)
Distance downstream	-.123(*)	-.185(**)	.133(*)	.083	1	.074	.328(**)	.184(**)	-.255(**)
Block Width	-.078	.425(**)	.055	.121(*)	.074	1	.114(*)	.096	-.113(*)
Block height	-.021	-.091	-.020	.096	.184(**)	.096	.646(**)	1	.189(**)
Sediment Depth	.216(**)	.313(**)	.326(**)	-.122(*)	-.255(**)	-.113(*)	-.544(**)	.189(**)	1

** Correlation is significant at the 0.01 level (2-tailed).

* Correlation is significant at the 0.05 level (2-tailed).

Table 3.17 Correlation matrix for site and block characteristics at Within Clough

Within

	Slope	Gully Width Top	Gully Depth	Block Spacing	Distance downstream	Block Width	Block Ht Top	Block height bottom	Sediment Depth
Slope	1	-.079	-.031	-.126	-.076	-.079	-.004	.029	.038
Gully Width Top	-.079	1	.291(**)	.086	.197(**)	.800(**)	.046	-.029	-.108
Gully Depth	-.031	.291(**)	1	-.017	.277(**)	.237(**)	-.213(**)	-.164(*)	.085
Block spacing	-.126	.086	-.017	1	.040	.101	.119	.052	-.064
Distance downstream	-.076	.197(**)	.277(**)	.040	1	.258(**)	.155(*)	.122	-.193(**)
Block Width	-.079	.800(**)	.237(**)	.101	.258(**)	1	.175(*)	.153(*)	-.178(*)
Block height	.029	-.029	-.164(*)	.052	.122	.153(*)	.765(**)	1	.036
Sediment Depth	.038	-.108	.085	-.064	-.193(**)	-.178(*)	-.426(**)	.036	1

** Correlation is significant at the 0.01 level (2-tailed).

* Correlation is significant at the 0.05 level (2-tailed).

Table 3.18 Correlation matrix for site and block characteristics on Kinder Scout

Kinder Scout

	Slope	Gully Width Top	Gully Depth	Block spacing	Distance downstream	Block Width	Block Ht Top	Block height bottom	Sediment Depth
Slope	1	-.059	-.069	-.274(**)	.028	-.161(*)	-.182(*)	-.005	.174(*)
Gully Width Top	-.059	1	.139	.290(**)	.021	.063	-.126	.020	.130
Gully Depth	-.069	.139	1	.054	.409(**)	-.212(**)	-.054	.206(**)	.264(**)
Block Spacing	-.274(**)	.290(**)	.054	1	-.225(**)	.293(**)	.026	.081	.059
Distance downstream	.028	.021	.409(**)	-.225(**)	1	-.112	.062	.159(*)	.115
Block Width	-.161(*)	.063	-.212(**)	.293(**)	-.112	1	.340(**)	.059	-.276(**)
Block height	-.005	.020	.206(**)	.081	.159(*)	.059	.508(**)	1	.554(**)
Sediment Depth	.174(*)	.130	.264(**)	.059	.115	-.276(**)	-.418(**)	.554(**)	1

** Correlation is significant at the 0.01 level (2-tailed).

* Correlation is significant at the 0.05 level (2-tailed).

3.4.9 Control of Block height on sediment accumulation

Figures 3.24 and 3.25 plot block height against sediment accumulation broken down by individual gully line. There is a clear positive association between sediment depth and block height. On one level this is obvious as l;arge blocks can eventually trap more sediment. Once they fill up large blocks will correlate perfectly with high sediment deposition as the plots converge on the black 1:1 line on the two plots. However since the blocks are largely not full, because of the relatively brief interval since installation, the observation that there is a correlation between accumulation and block height implies that the sediment trapping efficiency of taller blocks is increased. The association with block height is much weaker for the Within Clough gullies, and appears strongest for gullies with higher sediment accumulation. We interpret this pattern as indicative of scour or block failure in these gullies which causes deviation from a general pattern of increasing trap efficiency. It is important to note that the three gullies on Within Clough with the lowest association between block height and sediment accumulation are those with significant numbers of Hessian sack block type which were widely observed to have fail

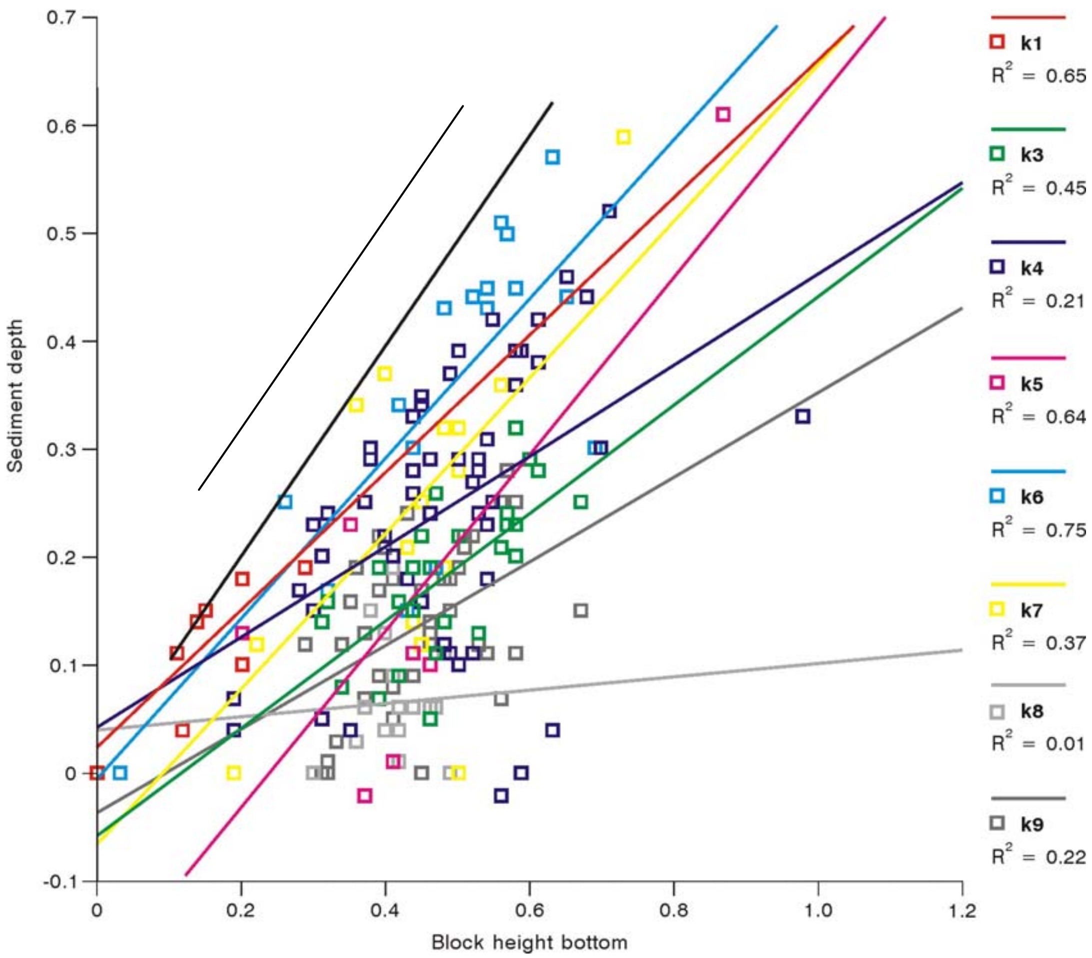


Figure 3.24 Relation between block height and sediment accumulation, KinderScout Blocks

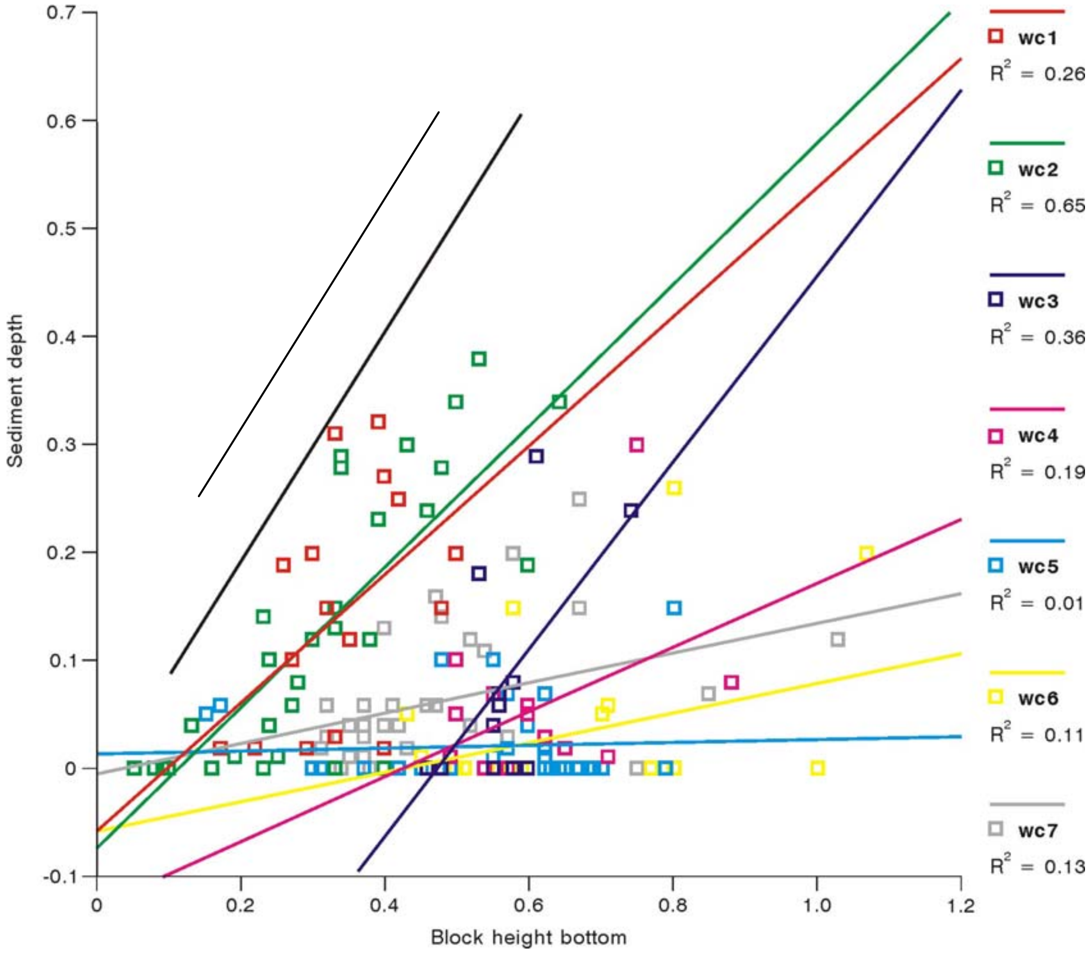


Figure 3.25 Relation between block height and sediment accumulation, Within Clough locks

3.4.10 Aggregated block data – by gully analysis

The final mode of analysis applied to the artificial gully block data is to try and identify patterns at the scale of the gully or catchment. Several significant trends emerge at the scale of the total dataset (Figure 3.26). There is a positive relationship between gully width and sediment accumulation, gully depth and sediment accumulation and gully slope and sediment accumulation. However when the data are broken down by location (Figure 3.26) what appear to be significant relationships in the whole dataset are revealed to be a function of the large difference in mean sediment accumulation between Kinder and Within Clough. As we cannot eliminate the possibility that this is a function simply of the longer blockage period on Kinder these relationships must be treated with extreme caution.

3.4.10.1 Sediment supply

The strongest predictor of sediment accumulation at the gully scale for both datasets is what we have termed the sediment supply index. This is defined as the product of gully depth and block spacing. As such it is proportional to the area of bare gully wall which is a potential sediment source for each block. For the total block dataset the association between this parameter and sediment accumulation is not strong, most likely because of the noisy nature of the dataset and the multiple controls on sediment accumulation at a

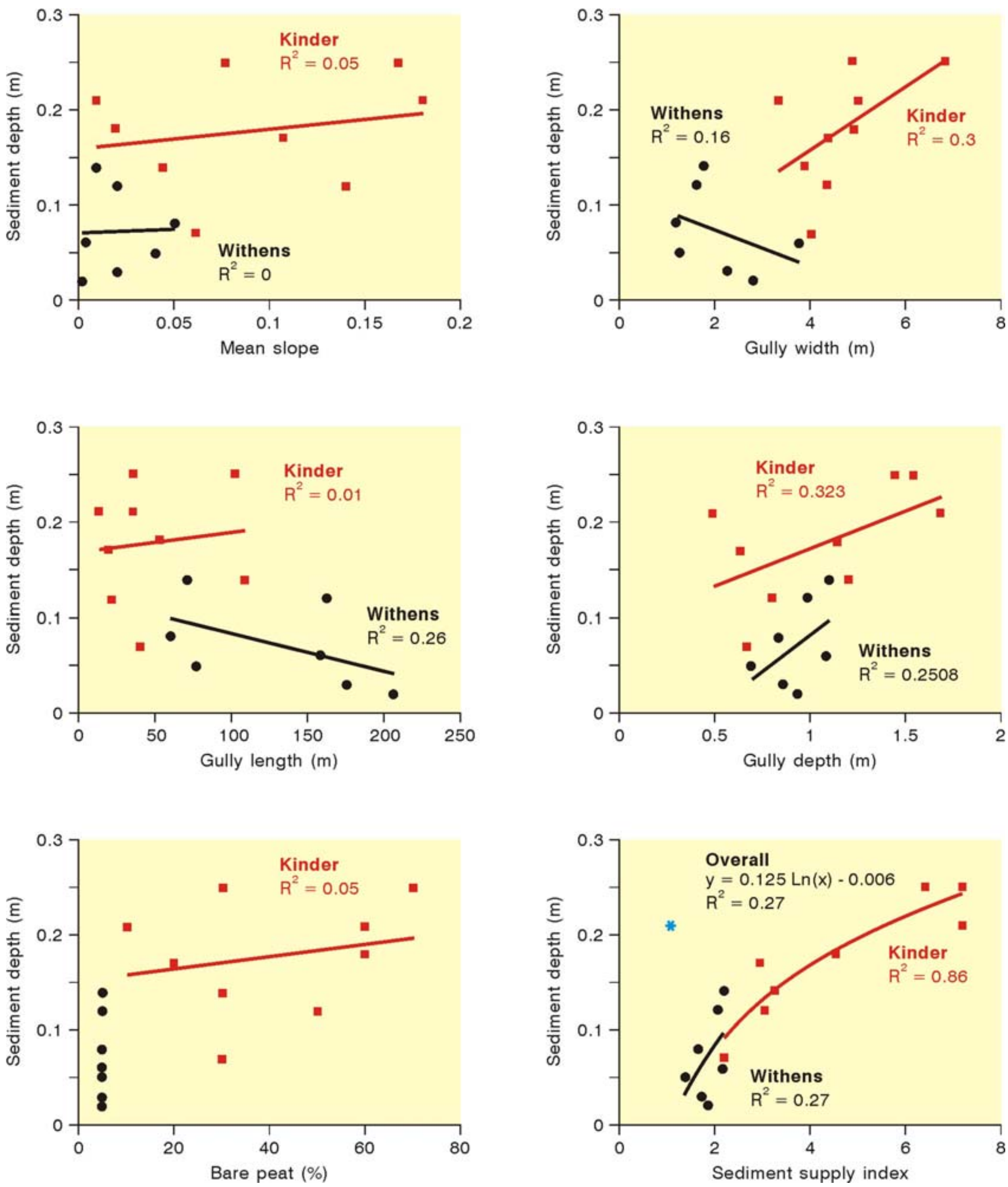


Figure 3.26 Association between site and gully characteristics and sediment accumulation at the gully scale.

site. At the gully scale where some of this contingent variation is averaged out the logarithm of the sediment supply index is strongly positively correlated with sediment accumulation. There is one clear outlier marked by the star in Figure 3.26. This is gully K2 which is a short series of 8 blocks. They are unusual in that the gully is extremely shallow and narrow. If this outlier is excluded the logarithmic relation illustrated in Figure 3.26 results which has an R^2 value of 0.85. The correlation exists in both Kinder and Within gullies although it is stronger for Kinderscout sites. At the gully scale therefore the data strongly support the ideal of a local sediment supply control on sediment accumulation behind blocks.

3.4.10.2 Catchment Cover

There is a significant positive association between sediment depth and the percentage of bare peat in the catchment for the whole dataset. This supports the notion of a sediment supply control on sediment accumulation at a catchment scale. However breaking down the data between Kinder and Within Clough removes any significant relationship. The total dataset suggest that there are therefore two components of catchment sediment supply which should be considered in site selection; the nature of in gully sediment supply and the wider sediment supply status of the catchment. However because of the differing blockage times at the two sites this assertion cannot be substantiated with the present data

3.4.10.3 Timescales

An important caveat regarding the apparent link between sediment supply and sediment accumulation at the gully scale is the timescale over which this study was conducted. After approximately 6-9 months of sedimentation (varying by site) the results of this study clearly indicate enhanced deposition at sites with high sediment supply. It is possible to conclude from this observation that if relatively rapid sediment accumulation is a requirement of the gully blocking programme then sites with good sediment supply are required.

What is at present unknown is the longer term trajectory of sites with lower sediment supply. Two possible scenarios can be envisaged. In the first continued trapping of sediment over an extended time period eventually fills the blocks at lower sediment flux sites to a level which will allow revegetation. An alternate view is that these sites never attain much thicker sediment accumulations because the sediment budget of the individual blocks has reached an equilibrium between supply and scour. Essentially the problem is that the timespan of this study is too short to assess whether the observed form of block sedimentation is an equilibrium form. Ongoing monitoring, particularly of the Within Clough sites is required to answer this question.

3.4.10.4 Gully length

Another pattern which clearly emerges at the gully scale in the whole dataset is the negative association of gully length (a proxy for catchment area) previously identified in the total block dataset. The pattern is very suggestive of scour in larger catchments. However breaking down the data between Kinder and Within Clough reveals that the pattern is a function of significant differences in mean accumulation between the two sites. This may relate to differing periods of blockage but the trend is also strongly affected by four points in the lower right quadrant of figure 3.26 and two of these catchments include a large number of the hessian sack blocks which appear to be very unsuccessful. The failure of these blocks, their localisation in a few gullies and their concentration at the lower end of systems is a significant problem for interpretation of the complete dataset at a range of scales. Again the only conclusion which can be drawn here is a very tentative suggestion that until further work is completed the conservative approach would be to limit the size of blocked catchments to the scale of the existing works (as these are largely successful)

3.5 Discussion and Recommendations

3.5.1 Processes of re-vegetation

A key finding from both the extensive and quantitative field surveys is that re-vegetation of gully floors is widespread (section 3.4). It is also clear, however, that different types of re-vegetation are occurring, as expressed by the variation in species cover in the re-vegetated gullies. There is also clear evidence that the characteristics of re-vegetation assemblages are related to the type and morphology of the gullies (section 3.5).

This confirms that a variety of re-vegetation processes are occurring, and that these vary with the detailed geomorphological setting of the gully sites. In particular, the analysis in section 3 show the importance of gully floor slope and gully width on revegetation characteristics, such morphometric variation being effectively represented by the classification of gullies into Types A and B.

In this context *E. angustifolium* is a key species to consider, as it provides a potential target for the early stages of re-vegetation following artificial gully blocking. Importantly *E. angustifolium* cover is associated with sites with low gully slope angles. In the Type B gullies *E. angustifolium* is also associated with the presence of re-deposited peat deposits. These geomorphological settings are consistent with the hypothetical modes of *E. angustifolium* colonisation outlined in sections 2.3.1, and the data therefore provide empirical support for these processes.

Interestingly, the field survey data also provide empirical support for extensive colonisation of bare peat floored gullies by *Eriophorum vaginatum*. This species is an important component of re-vegetation in both Type A and Type B gullies, although associated particularly with Type A gullies (narrow with high local gully slopes). These gully conditions are consistent with those that would promote small-scale mass failure of gully banks (see section 2.3.2), one of the hypothetical models by which clumps of *E. vaginatum* could colonise gully floors. There is evidence from the Type A gullies of a gradient from bare gully floors to *E. vaginatum* colonisation and then to increased cover by dwarf shrubs (*V. mytillus* and *E. nigrum*). However, this interpretation assumes spatial samples can be used to represent a temporal sequence – a problematic assumption given the potentially highly dynamic nature of vegetation change in the gully systems.

Empirical support is less clear cut for the two other hypothetical modes of natural revegetation; i) Peat deposition and revegetation associated with reduced stream power and ii) colonisation of bare mineral floors by species tolerant of drier conditions. These modes of re-vegetation would be expected to occur in wide systems e.g. Type B gullies. Many of the Type B gully sites are indeed vegetated by species tolerant of drier conditions (e.g. *V. mytillus*, *E. nigrum* and *D. flexuosa* see section 3.5.2), and this may represent direct colonisation onto mineral floors. However, the nature of the underlying substrate was not recorded in sufficient resolution to allow this to be verified. The relatively limited number of Type B gully sites also restricts the empirical support for the stream power mode of revegetation (section 2.3.1.3), although the extensive survey highlighted this as a potentially important process.

3.5.2 Natural gully blocks

A key finding is that natural gully blocks are common in these systems (see Table 3.4). They are particularly prevalent in Type A gullies, and this is consistent with the conditions required to promote mass failure of gully banks; narrow gullies with steep gully floor slopes where bank undercutting is more likely, and collapsed blocks are more likely to be of sufficient size to create significant blockage.

However, the links between natural blocks and modes of re-vegetation are less clear. No significant and/or clear cut differences could be identified between the types of re-vegetation at block and non-block sites, or between the presence/absence of a block and the % gully floor revegetated.

Although initially surprising, there are a number of explanations for this finding. First, the issue of equifinality – different processes of revegetation may lead to similar vegetation assemblages. In particular *E. angustifolium* revegetation occurs behind block sites, but can also occur in peat flats where no block is present (see section 3.2.3.1. Second, it may be that the dataset does not adequately represent the extent to which each block has effectively constricted drainage and impacted on sediment deposition processes. Such detailed measures are difficult to obtain from rapid field survey, and are complicated by the dynamics of block formation and development. Field identification of blocked locations was not always straightforward, and partial blocks are poorly represented. It may also be the case that blocks are transient features. Third, there is no time control on the block sites i.e. we do not know how old the blocks are and for how long revegetation processes have been acting. There is some evidence of vegetation gradients within the survey data, and these suggest possible trajectories of revegetation development (see section 3.5). These are intriguing, and if they can be confirmed could be key factors in developing restoration strategies. However, the dataset used here is too small to adequately represent the current vegetation gradients, and in any case other methods are required for such confirmation (e.g. palaeoecological analysis of gully deposits).

Nevertheless, the natural gully block data do provide important analogues for artificial gully blocking. In particular, a finding with important implications for artificial gully blocking is the relationship between blocking and successful re-vegetation by *E. angustifolium* (see section 3.3.7). The data show that block sites where *E. angustifolium* has successfully colonised have low local gully floor slopes and a thin covering of re-deposited peat sediments.

3.5.3 Effectiveness of Gully blocking

3.5.3.1 Limitations of the current study

The gully blocking dataset on which this report is based is derived from pre-existing gully blocks installed as a practical conservation exercise by the National Trust. Although the works were carefully considered they were not designed as a controlled experiment to test the effectiveness of various techniques. Therefore the conclusions of this report must be assessed in the light of two important limitations.

- Transient or equilibrium conditions

  One issue which arises with respect to many of the analyses of artificial block sites above is the influence of the short time elapsed between blocking and survey. Sediment accumulation behind the blocks has been taken as an indication of successful blockage and a precursor to re-vegetation. However it is unknown whether the contemporary sediment depths represent an equilibrium condition. Further deposition may be balanced by scour at high flow, or alternatively current conditions may be a transient state where sediment depth is incrementally increasing to an eventual end point which can be no greater than the height of the blocks. A related issue is the variable time since gully blocking. In separating analysis of the Kinder and Within blocks we are assuming that the Within blocks at least are still in the transient condition and therefore not directly comparable to the Kinder data. Where the Kinder data is analysed alone the assumption is of equilibrium conditions. If this assumption is breached then the recommendations below relating to sediment accumulation are conservative. Interestingly one piece of evidence supports the view that both sites have reached an equilibrium form and that is the consistency of the relationship with sediment supply index across both sites. One essential piece of continuing monitoring is assessment of the continued development of the sediment wedge at the two sites. Another years data will allow stronger conclusions to be drawn from the current dataset.

- Distribution of block types

  Because of the range of block types used in the existing works and their non-random distribution in some cases it is difficult to disentangle block type effects from site conditions and vice versa. Fortunately there is a large set of plastic blocks which allows analyses which eliminate block type as a factor but in some instances, where this subset does not span the full range of site conditions it has been impossible to entirely eliminate potential error associated with block types. This is a particular problem with the Hessian sack type blocks which are concentrated at the lower ends of gullies

3.5.3.2 Block types

The data support observations in the field which suggest that the experimentation with pegged Hessian sacks as a gully blocking technique has been unsuccessful. These block sites have much the lowest mean sediment accumulation. Both wooden and stone blocks have high sediment accumulation. The most surprising finding is that plastic piling blocks consistently trap approximately 50% of the sediment accumulation of wooden and stone blocks despite similar average block heights. Part of the explanation for this is that the plastic piling has on average been installed in wider gullies, but only by a factor of about 25%. It appears therefore that the particular form of the plastic blocks, or perhaps their impermeability is reducing their efficiency as sediment traps. One possibility is that the greater retention of water by the plastic blocks retards sediment consolidation and enhances scour during storm events.

3.5.3.3 Role of sediment supply

Unsurprisingly sediment supply appears to be an important predictor of the amount of sediment accumulation behind blocks. If the development of the sediment wedge behind the blocks is still in a transient condition this is consistent with greater rates of sediment flux consequently sedimentation behind the blocks. If the sediment wedge is in an equilibrium condition with deposition balanced by scour, sufficient sediment supply is important to balance scour at high flow.

At the local scale positive correlations of sediment depth with gully depth and width, indicate the importance a sufficient area of eroding peat to supply sediment to the blocks. The strongest predictor of sedimentation at the gully scale is the sediment supply index derived as a proxy for this area. The implications of this correlation for implementation of blocking are considered further below.

5.3.4 Block spacing

Block spacing is negatively correlated with gully slope in the existing gully block dataset. This is because the blocks have been installed using the head to toe principle such that the base of an upslope block is level with the top of the downstream block. Given the overall success of the existing blocks in retaining sediment this seems a reasonable starting point for recommendations on block spacing.

There is a suggestion from the correlation analysis and from the analysis of scoured blocks that wider spacing of blocks is likely to reduce the effectiveness of blocks as sediment traps. For the set of all plastic blocks mean block spacing for scoured blocks is 5.6 m whereas it is 4.0 m for sites with sediment accumulation. It should be noted that the set of scoured blocks in this analysis is small (26 blocks) and shows large variation in spacing so this result is tentative. Also the data on all plastic blocks span Kinder and Within so the timing of block installation introduces further uncertainty. However, the data provide some grounds for limiting block spacing. Average spacing for the set of successful blocks of all types is 4.22 m with 95% of blocks in the range 0.6 – 7.8 m. On this basis it is suggested that block spacings exceeding 8 m are unlikely to be effective and that a target spacing should be 4 m.

Block spacing is a component of the sediment supply index. From the results of section 3.4.10.2 and the relation derived in Figure 3.27 it is possible to establish the necessary block spacing for a given gully depth to achieve a required sediment depth. It has been established in section 5.2 that the depth of sedimentation required for establishment of *Eriophorum angustifolium* in natural conditions is not high. The average value for all the surveyed natural sites is 0.1 m and the average for re-vegetated sites is 0.12 m. Figure 26 shows the relation between sediment depth and the critical minimum Sediment supply index required to achieve it in the current dataset. Figure 27 shows for a range of gully depths the minimum block spacing required to achieve a given sediment supply index for gullies of various depths. These calculations reveal that in order to achieve a sediment depth of 0.12 m a critical sediment supply index of 2.8 is required. This translates into minimum block spacings of 0.7 – 2.8 metres for a range of gully depths from 1 – 4 metres. It should be noted that these values relate only to the gullies studied for this report. It is reasonable however to extrapolate these guidelines to other gully systems in the Peak District in similar topographic contexts and with similar climatic conditions.

It should also be noted that these are not absolute guidelines for block spacing, they are simply the spacings required to achieve particular sediment depths in the 6-9 month timeframe that the current blocks have been installed. It may be that in longer periods similar sediment depths can be achieved at lower sediment supply rates. The question relates to uncertainty over whether the current sediment deposits are in equilibrium. If they are in equilibrium the spacings identified here may be regarded as a reasonable. If sediment accumulation is continuing at the study sites then they are a conservative estimate of minimum spacings.

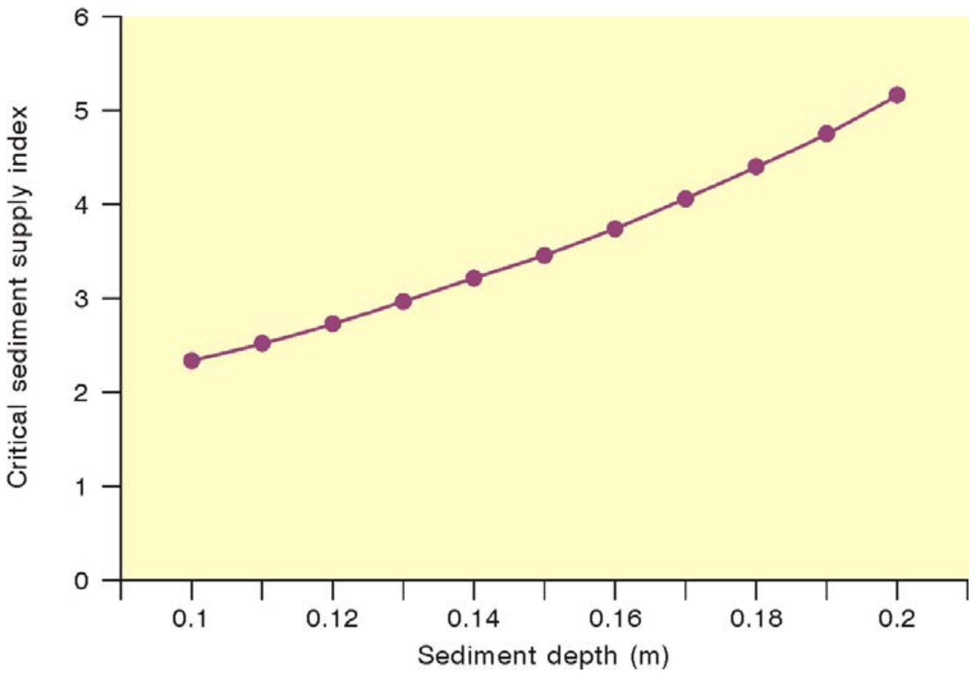


Figure 3.27 Critical values of sediment supply index required to achieve a given sediment depth

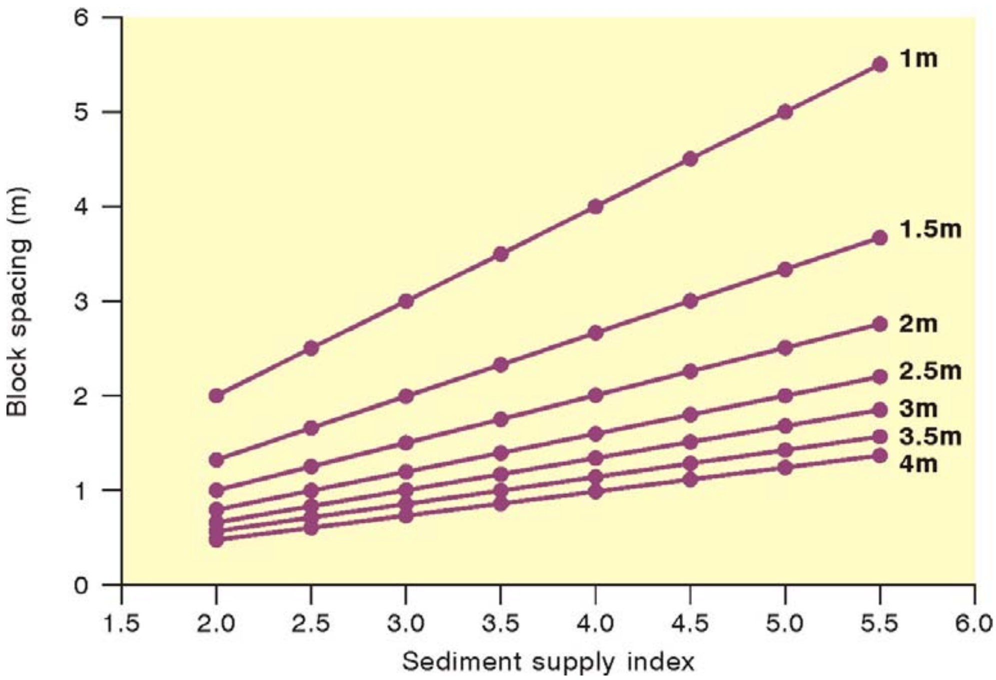


Figure 3.28 Block spacings required to achieve sediment supply index values for gullies of varying depth

3.5.3.5 Block height

Although noisy the data on the existing gully blocks clearly indicate that higher blocks trap more sediment. This is consistent with reduced scour through deeper pools at high flow. The height of block required to achieve a given sediment depth varies with the efficiency of the block type. For wooden and stone blocks the slope of the block height-sediment depth relation is close to 0.5. The plastic blocks are more noisy but here the slope is nearer to 0.25. Therefore in order to achieve a sediment depth of 0.12 m (in line with average conditions at sites with natural re-vegetation) block heights of 0.24 m and 0.48 m are required for the wood/stone blocks and plastic blocks respectively. Another way to assess appropriate block height is to examine the failed blocks. Mean block height is significantly different between the set of scoured blocks (0.36 m) and those where there has been sedimentation (0.44 m). This suggests that the risk of complete block failure through scour is higher for lower blocks. 95% of the successful blocks have heights in the range 0.16 – 0.76 m . The data on natural re-vegetation reveal that the mean height of natural blocks is 0.40 m. On the basis of these data a conservative recommendation for target block heights is 0.45 m (similar to the mean of the existing blocks) and a reasonable minimum block height is 0.25 cm.

3.5.3.6 Gully Slope

The available data do not provide clear evidence of the role of slope in successful gully blocking. 95% of successful blocks lie in the range 0 – 0.24 m/m. Blocked sites on Kinder Scout show a positive correlation between gully slope. This has been interpreted above as a sediment supply effect. Data from the naturally re-vegetated sites suggest that locations with successful *Eriophorum angustifolium* colonisation of blocked gullies have a mean slope of 0.04 with a range of 0.002 – 0.11. It may be therefore that whilst sediment retention is possible at slopes up to 0.24 (13º) successful re-vegetation is limited to lower slopes.

Further limitations on local slope are crated by the head to toe technique of block installation and the recommendations on block size and spacing above. If a maximum block spacing of 4 m is combined with a block height of 0.45 m the maximum local slope is 0.11 (6º). This is very similar to the maximum slope where successful natural *Eriophorum angustifolium* colonisation is observed. Local slope of 0.11 is therefore an appropriate conservative estimate of maximum local slopes consistent with successful blocking and re-vegetation.

3.5.3.7 Gully dimensions

95% of the successfully blocked gullies lie in the range 0 – 7.5 m width (top width) and 0.1 – 2.2 m depth. The artificially blocked gullies are therefore Type A gullies in the classification adopted in section 3. This is appropriate since it implies that the gullies where artificial blocking is being attempted are of similar dimension to those where it tends to be an important mechanism of re-vegetation naturally. 95% of natural block widths are in the range 0.5 – 3.5 m whilst 95% of the artificial blocks studied are in the range 0-4 m wide. Gully depth and at some sites width are positively correlated with sediment accumulation, so that it is desirable to block large gullies where it is technically feasible. 4 m is a reasonable maximum for block width. Gully depth is important only as a sediment supply parameter.

Although it may be technically possible to construct blocks on wider gullies the wider deeper gullies (type B) tend to be further downstream, have larger catchment areas and higher discharge so that catastrophic block failure is a concern. However the natural re-vegetation data clearly demonstrate that re-vegetation of wider gullies is possible, however complete blockage may not be the appropriate technique. One possibility is to experiment with creating zones of deposition within broad deep trunk gullies. Rather than blocks low baffles might promote a winding channel with lower stream power and local deposition of sediment. There are considerable benefits to attempting revegetation of these large gullies. Observation of naturally revegetating gullies suggest that once initial vegetation is achieved at a point sediment trapping promotes upstream migration of the vegetation cover. Successful downstream revegatation would mitigate one of the concerns over gully blocking which is that in the long term blocks might be removed by nick point migration. Although the evidence base is rather thin at present the rewards of this type of work should be high. It is therefore a profitable avenue for some experimental conservation work.

3.5.3.8 Catchment characteristics

Because the measure of block success identified for this study was local sediment accumulation the site and block characteristics dominate prediction of successful blocks. Investigation of the effects of downstream distance from the headwater (a surrogate for catchment area) indicate a tendency for greater scour in downstream locations (larger catchments) which is logically consistent. However the pattern cannot be unambiguously demonstrated because it is confounded by the downstream location of the bulk of the unsuccessful Hessian sack blocks. No solid recommendations as to catchment size can be made. 95% of the successful blocks in the current study are within 130 metres of the gully head. In fact the limitations on block size probably limit blocking of the type envisaged in this study to headwater areas as gully dimensions increase rapidly downstream.

The other catchment characteristic consistently associated with block success defined as sediment accumulation is the percentage area of bare peat in the catchment. Essentially more bare peat in the catchment increases the sediment supply and produces greater sediment flux through the blocks and greater sediment accumulation. Successful blocks occurred in catchments with all degrees of re-vegetation but greatest sediment accumulation was associated with more bare peat in the catchment. One implication of this observation is that where catchments with extensive bare peat are being re-vegetated it may be useful to install blocks ahead of efforts to re-vegetated the catchment. This is consistent with observations from the natural re-vegetations sites that re-vegetation tends to intiate in the gullies and spread from these locations.

3.5.4 Recommendations for blocking strategies for Moors for the Future Sites

This study is one of the first of its type, remarkably little is known about natural re-vegetation of eroded peatlands and even less about gully blocking in this context. Therefore the recommendations below are heavily dependent on the rapid survey work done in support of this report. We have therefore taken a conservative approach and the recommendations here describe contexts where we are reasonably confident that the evidence suggests gully blocking should be successful. In fact there are examples of successful blocking in a wider range of contexts within the dataset. Where conditions on the ground dictate it may be possible within reason to experiment with block locations which fall outside these optimum conditions.

3.5.4.1 Block types

- Wooden fencing, plastic piling and stone walls are all effective gully blocking methods.
- Plastic blocks accumulate significantly less sediment but are still effective sediment traps. Although wood and stone are optimum, at a given site logistic and aesthetic considerations are probably paramount in selecting one of these methods.
- The hessian sack technique is not considered effective.

3.5.4.2 Block height and spacing

- Block spacing should not exceed 4 metres. Minimum spacings as a function of gully depth can be derived from figure 27.
- Target gully block height should be 45 cm. 25 cm should be a minimum height.

3.5.4.3 Gully Slope

- Efforts should focus on blockage of sites with slopes less than 0.11 m/m (6º).

3.5.4.4 Gully dimensions

- Maximum block widths of 4 m.

- Development of expermimental approaches to promoting sediment deposition and revegetation in type B gullies based on the observation of natural processes.

3.5.4.5 Catchment Characteristics

- The empirical data support successful blocking only in headwater areas (<130 m from the gully head) but the evidence is weak on this point
- Successful blocking can occur with any degree of catchment vegetation but bare peat areas accelerate sediment accumulation
- Gully blocking should occur before extensive revegetation of interfluves.

3.5.4.6 Planting

The work on natural revegetation clearly suggests that the natural revegetation trajectory associated with gully blocking is an initial spread of *Eriophorum angustifolium* in conditions of temporary substrate stability. Planting of this species in wet sediment behind gully blocks is therefore desirable to accelerate this process. We would recommend planting at least a year after initial blocking to allow development of an equilibrium sediment deposit behind the blocks prior to planting.

3.5.5 Recommendations for post-restoration monitoring

The following recommendations are made on the basis that the field measurements are straightforward and suitable for implementation by volunteers. We would recommend at least three days of professional time on an annual basis to collate and analyse the data.

3.5.5.1 Monitoring sediment depth

One of the key parameters of interest in the short term is the development of the sediment wedge behind the blocks. Monitoring of existing and new block sites at 3 monthly intervals for the first year and perhaps annually thereafter would cast some light on the time required to achieve equilibrium sediment depths. The required measurements are height of the gully block measured front and back. Initial measurements at installation are required for the new blocks. For existing blocks the data in this report will act as a reference level.

3.5.5.2 Periodic photography

Annual photographic survey would provide rapid cost effective monitoring of percentage vegetation cover behind blocks. This would be of particular interest in monitoring the rate of spread of planted *Eriophorum.* The photographs should supplement rapid on site estimates of percentage cover.

3.5.5.3 Vegetation composition survey

Once the block sites begin to revegetate rapid survey of vegetation composition at perhaps one and five year intervals would provide useful information on the trajectory of vegetation change behind artificial blocks. The initial survey will be of particular interest in sites where colonisation is natural, the five year survey should apply to planted sites and natural sites.

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